Current Innovations of Wearable UV Sensor Devices for Skin Cancer Prevention: A Scoping Review

Submitted in Fulfilment of the Requirements for the ManagiDiTH Master's Program—Managing Digital Transformation in the Health Sector

Maria Ivanel

Supervisor: André Filipe Xavier da Glória, Professor Doctor, ISCTE - University Institute of Lisbon

Date: 27 February 2026

Co-funded by the European Union

Current Innovations of Wearable UV Sensor Devices for Skin Cancer Prevention: A Scoping Review

Submitted in Fulfilment of the Requirements for the ManagiDiTH Master's Program—Managing Digital Transformation in the Health Sector

Maria Ivanel

Supervisor: André Filipe Xavier da Glória, Professor Doctor, ISCTE - University Institute of Lisbon

Date: 27 February 2026

Co-funded by the European Union

Acknowledgements

I consider completing this journey an important milestone in both my personal and professional life. I want to take this opportunity to thank all those who contributed to the completion of this thesis in their own ways.

First and foremost, I would like to express my deepest gratitude to my supervisor, Professor Doctor André Filipe Xavier da Glória, who has guided me, has been available and very patient, and has provided me with valuable feedback on everything we did.

I also acknowledge all the professors who took part in this incredible journey of the ManagiDiTH Master's Program.

To all participants who completed the anonymous questionnaire, I appreciate the time you took to participate in this study. Your willingness to share your views and experiences is very important for the development of this research.

To my colleagues, I am grateful for your cooperation during this time. One of the important lessons I have learned from this experience is to have faith in myself, which will continue to guide me in life.

I want to thank my family for their never-ending support and encouragement, which has given me the power to overcome all hurdles in achieving this goal.

Finally, I thank my husband for his tolerance and support during this period. His presence in my life and his contribution to my success would have made the journey much tougher for me.

To all of you who have been involved in this process, I am grateful.

Abstract

Prolonged UVR exposure remains a preventable risk factor for skin cancer. Recently, wearable UV sensors have been suggested as a way to encourage sun-protective behaviour through a digital health approach. However, evidence on whether these devices influence behaviour remains limited.

The aim of the current research was to review recent literature concerning wearable UV sensors for skin cancer prevention and to develop an evidence-informed concept of a wearable UV sensor paired with a smartphone app.

In addition to a scoping review of peer-reviewed English-language journal articles and full conference papers from 2021 to 2025, a cross-sectional structured questionnaire survey (n = 66) assessing sun-protective behaviours, level of awareness, users' preferences, and barriers to use was conducted. Survey data were analysed using IBM SPSS Statistics (version 30).

Two main categories of sensing mechanisms were identified: passive photochromic or colourimetric systems and active photoelectric or electronic sensors. Behavioural impact varied among different studies and, in some cases, appeared to be influenced by the presence of specific behaviour change components like goal setting, reminders, or personal feedback. Survey results supported a preference for a wrist-worn form and helped to form the design of the concept.

Based on these findings, the DermUVtrack concept was developed: a wrist-worn UV sensor that combines UV exposure monitoring with real-time feedback and behaviour-change intervention. Generally, wearable UV sensors could be useful in skin cancer prevention when implemented in multi-component behaviour change interventions.

Keywords: wearable devices, UV sensors, skin cancer prevention, behaviour change, digital health

JEL Classification: I12, O33

Index

Acknowledgements ii

Abstract iii

Index of Figures vii

Index of Tables ix

Glossary x

Introduction 1

1.1. Background 1

1.2. Problem Statement 2

1.3. Research Questions 3

1.4. Objectives and Aims 4

1.5. Significance of the Study 4

1.6. Scope of Study 4

1.7. Thesis Structure 5

Chapter 2: Conceptual and Theoretical Framework 6

2.1. Burden of skin cancer and why exposure measurement matters 6

2.1.1. Global and regional burden 6

2.1.2. UVR mechanisms and exposure metrics 7

2.1.3. Prevention limits and measurement gap 9

2.2. Wearable UV dosimetry modalities and design constraints 11

2.3. Passive sensing 11

2.3.1. Passive film dosimetry: polysulphone as the reference cumulative badge 11

2.3.2. Passive Colourimetric and Photochromic Wearables: Interpreting UV Irradiation at the Point of Excitation 13

2.3.3. Photochromic examples 15

2.3.4. Passive photocatalytic dosimetry 17

2.4. Active sensing 18

2.4.1. Active examples: patch and connected devices 19

2.5. Bio-integrated colourimetric nanosensors 20

2.6. Hybrid systems 22

Chapter 3: Methodology 23

3.1. Overall design and rationale 23

3.2. Scoping review questions and framework 23

3.3. Eligibility Criteria 23

3.4. Information Source and Search Strategy 24

3.5. Study selection and data charting process 24

3.6. Data items and synthesis plan 25

3.7. Questionnaire rationale 27

3.8. Questionnaire instrument 27

3.9. Data management and variable preparation 28

3.10. Statistical analysis plan 28

Chapter 4: Results 30

4.1. Evidence map summary 30

4.2. Main Results of Scoping Review 31

4.2.1. Taxonomy of Wearable UV Sensors 31

4.2.2. Behaviour Change and Engagement 32

4.2.3. Effects on UV Dose and Sunburn 34

4.3. Results of Survey Questionnaire 35

4.3.1. Participant Characteristics 35

4.3.2. Exposure to the sun, sunburn, and sun protection behaviours 36

4.3.3. Attitudes and Perceived Knowledge 36

4.3.4. Digital Health Engagement 36

4.3.5. Acceptability and preferences of the UV wearable concept 37

4.3.6. Perceived benefits and barriers (E-items): item-level results and indices 37

4.3.7. Exploratory bivariate associations 38

Chapter 5: Discussion 40

5.1. Interpretation of Results 40

5.2. Limitations of the Study 44

5.3. Suggestions for Future Research 44

Chapter 6: Proposal 46

6.1. Architecture and App Concept of *DermUVtrack,* a Wrist-Worn ZnO-Based Photoelectric UV Dosimeter 46

Conclusion 50

Bibliographic References and Sources 52

Appendices 59

Appendix A: Overview of databases and search strategies 59

Appendix B: Scoping Review Tables 62

Appendix C: Survey Questionnaire 73

Index of Figures

Figure 2.1. Schematic representation of human skin cross-sectional anatomy and differential UVR penetration. (Adapted from Craig et al., 2018). 8

Figure 2.2. Dose-response curve of PSP film demonstrating the relationship between the change in absorbance at 330 nm (ΔA330) and varying levels of incident UVR exposure. Cropped from Diffey (2020). 12

Figure 2.3. Polysulphone film badge holders are used for personal UV dosimetry. (a) Early large badge mount. (b) 30 × 30 mm cardboard holder with a central 10 × 15 mm aperture (single-aperture mount). (c) Alternative 30 × 30 mm holder with four circular apertures (6 mm diameter) intended to improve reliability but requiring longer pre-/post-exposure absorbance measurements. Adapted from Diffey (2020). 13

Figure 2.4. Colourimetric UV patch with smartphone-mediated interpretation. (a) Patch colour field output; (b) on-skin deployment; (c) smartphone scanning/readout interface. Adapted from Huang & Chalmers (2021). 14

Figure 2.5. Adhesive textile label for UV indication. The label changes colour under solar UV exposure and is shown applied to clothing to demonstrate on-garment use and visibility. Adapted from Bao et al. (2020). 14

Figure 2.6. HMBAB paper-based photochromic wearable prototypes. (a) Chest-card format; (b) bracelet format. Adapted from Gao et al. (2023). 15

Figure 2.7. Wristband integration of a PNCs–DBM UV sensing cell. The sensing cell is sealed with fluorescence-free PDMS films and fixed within the band groove. Adapted from Chen et al. (2024). 16

Figure 2.8. Hackmanite-based photochromic textile print with app readout. UV exposure increases colour intensity on a cap print, enabling UVI estimation via the Sensoglow smartphone app. Adapted from Lawrynowicz et al. (2024). 16

Figure 2.9. Fully printed smart UV sensor patch with smartphone interaction. (a) Printed patch (scale bar shown). (b) Example smartphone-mediated interaction during on-wrist use. Cropped from Dong et al. (2023). 19

Figure 2.10. Porous UV sensor patch for week-long on-skin monitoring. (a) On-forearm deployment. (b) Representative week-long current response trace. Adapted from Kim et al. (2023). 20

Figure 2.11. Single-human pilot test of photochromic tattoo feasibility in vivo. (a) Baseline appearance; (b) Activated appearance showing a visible colour change following UV exposure. Cropped from Butterfield et al. (2024). 21

Figure 3.1. PRISMA flow diagram for the scoping review. Adapted from Page et al. (2021) 26

Figure 4.1. Spearman correlations between purchase likelihood (1–5) and selected attitudes or indices. 39

Figure 6.1. Proposed block-level architecture of *DermUVtrack* for a wrist-worn ZnO-based photoelectric UV dosimeter (sensor-to-app pathway). 47

Figure 6.2. DermUVtrack, system-level concept view: wrist-worn sensing module, low-power processing and buffering, BLE transmission, and smartphone-based feedback (dashboard, alerts, and trends). 48

Figure 6.3. Conceptual app UI mock-ups illustrating real-time status, alert prompts, exposure history, and weekly summary feedback. 49

Index of Tables

Table A1. Database search strategy and date of last search..... 59
Table B1. Characteristics of articles included in the scoping review on wearable UV sensor (n = 29). 62
Table B2. Classification of UV-sensor wearables (n = 22). 65
Table B3. Intervention characteristics, empirical effects on behaviours and compliance (n = 5). 70
Table B4. Evidence on the effects of UV-sensor wearables on individual UV dose and sunburn (n = 3). 71

Glossary

Abbreviation/symbol	Meaning
ADC	Analogue-To-Digital Conversion
AFE	Analogue Front End
BCC	Basal Cell Carcinoma
BLE	Bluetooth Low Energy
CIE	International Commission on Illumination
CM	Cutaneous Melanoma
CPD/CPDs	Cyclobutane Pyrimidine Dimer(S)
cSCC	Cutaneous Squamous Cell Carcinoma
DALY	Disability-Adjusted Life Year
DNA	Deoxyribonucleic Acid
ETFE	Ethylene Tetrafluoroethylene
ILO	International Labour Organisation
IQR	Interquartile Range
ITO	Indium Tin Oxide
MED	Minimal Erythema Dose
MIS	Melanoma In Situ
n	Subgroup Sample
N	Total Sample Size
NFC	Near-Field Communication
nm	Nanometre
NMSC	Non-Melanoma Skin Cancer
PAF	Population-Attributable Fraction
PCC	Population–Concept–Context
PD	Photodiode
PDMS	Polydimethylsiloxane
PET	Polyethylene Terephthalate
PNCs	Perovskite Nanocrystals
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews
PSP	Polysulphone
RCT	Randomised Controlled Trials
SAW	Surface Acoustic Wave
SED	Standard Erythemal Dose
SPF	Sun Protection Factor
UI	User Interface
UV	Ultraviolet
UVA	Ultraviolet A
UVB	Ultraviolet B
UVI	Ultraviolet Index
UVR	Ultraviolet Radiation

Term	Definition
Beta-endorphins	Endogenous neuropeptides associated with analgesic properties and the regulation of mood, which are referenced in the context of the well-being benefits of sun exposure.
CsPbCl3	Inorganic materials that are potential absorbers for Perovskite solar cells and active material for sensor devices.
CuO	Copper(II) oxide
Cytotoxic potential	A measure of the ability of an exposure to cause cellular injury and death; in this text, UVA is described as oxygen-dependent.
Laminated structure	Stratified material structure, which has been used to describe the photochromic film in combination with a matrix material.
Matrix (material)	The material phase in which the functional components of a sensor structure are embedded.
Sunburn incidence	The occurrence rate of sunburn has been documented as an empirical data point within existing knowledge.
TiO_2	Titanium dioxide
Wearable UV sensor	A body-worn device designed to quantify or provide information about ultraviolet exposure, often incorporating feedback mechanisms.
ZnO	Zinc oxide

Introduction

1.1. Background

Terrestrial solar ultraviolet radiation (UVR) in the wavelength range of 295-400 nm is well established as harmful to human skin and recognised as a major cause of photocarcinogenesis and photoageing (Lawrence et al., 2025). Because different spectral bands carry different energies, their biological effects are not equivalent. They penetrate human skin to different depths, thereby causing distinct molecular injuries (Zhu et al., 2025). Mechanistically, ultraviolet B (UVB) has a high potential to directly damage DNA and form cyclobutane pyrimidine dimers (CPDs) (Hughes & Bishop, 2022). In contrast, the cytotoxic potential of ultraviolet A (UVA) is oxygen-dependent and leads to oxidative DNA damage (Zhu et al., 2025). Moderate exposure has been found to confer several health benefits, including increased vitamin D levels, therapeutic effects for conditions such as psoriasis, eczema, and dermatitis, and improvements in mood via beta-endorphins, which are associated with increased well-being (Sivamani et al., 2009).

The major health effects of UVR exposure include cutaneous melanoma and keratinocyte cancers, such as basal cell carcinoma (BCC) and cutaneous squamous cell carcinoma (cSCC) (Garbe et al., 2024). Melanoma has been estimated to account for 331,722 cases and 58,667 deaths worldwide (Wang et al., 2025). Non-melanoma skin cancers rank as the world's fifth most common cancer, resulting in 1,234,533 cases and 69,416 deaths (Wang et al., 2025). Among individuals with fair skin, ultraviolet (UV) exposure has been implicated in 95% of keratinocyte cancer cases and 70% to 95% of melanoma cases (Garbe et al., 2024). Taken together, these figures emphasise a significant, preventable burden strongly associated with daily exposure behaviours and protective decisions.

Avoiding high-intensity UV exposure is an essential preventive strategy (Garbe et al., 2024). UV intensity peaks during the hour before and the hour after solar noon, accounting for 50-75% of the day's total UV exposure (Garbe et al., 2024). In line with this, the World Health Organisation (WHO) recommends sun protection measures when the UV Index (UVI) is 3 (moderate) or higher (Garbe et al., 2024). For topical skin protection, broad-spectrum, tinted sunscreen with SPF 30+ is considered effective against UVR (Guan et al., 2021, p. 826). It should be applied to the face, ears, uncovered areas of the scalp, neck, and all exposed skin (Garbe et al., 2024). Moreover, flavonoids are supplementary to sunscreen, acting through UV absorption, antioxidant effects, and modulation of DNA signalling pathways (Monisha et al., 2025).

Against this background, there has been sustained acceptance of the need for wearable UV-sensing devices. A range of devices has been developed for use by researchers and consumers. These can be categorised as exposure sensors or dosimeters, including electronic devices, photochromic

stickers, and passive colourimetric films. These devices provide either real-time or cumulative measures of personal UV exposure and are generally presented as tools to support prompt adherence to sun-protection recommendations. Table B2 synthesises the device types and feedback modalities identified in the scoping review, indicating how they are intended to support moment-to-moment conformity to established sun-protection recommendations.

1.2. Problem Statement

Sun safety recommendations from various sources typically present brief lists of protective measures (Thoonen et al., 2023, p. 7178). While these recommendations reflect population-level guidance, they do not consider in sufficient detail the factors that contribute to inter-individual variability in the skin's response to UVR. Additionally, they neglect the conditions of sun exposure, which limit their ability to support individualised, time-sensitive decisions. Skin phototype is generally considered a significant factor in the skin's response to UVR (Troya-Martín et al., 2025). However, lifestyle and working conditions, patterns of sun exposure, environmental conditions (climate and environmental pollution), and dermatological conditions can equally play a fundamental role in the individual's response (Troya-Martín et al., 2025, p. 2). In the present thesis, UV protection is considered a behavioural challenge in which the intensity and timing of UVR are significant. Accordingly, personal UV dosimetry represents a shift away from general guidance towards individual-level UV dose. However, existing evidence on wearable devices for decision-relevant tailoring, such as limit adjustment, skin type selection, and taking into consideration sunscreen and clothing behaviour, is reported less consistently than that on exposure display or alerting.

This change has been facilitated by simultaneous advances in the miniaturisation of electronics and materials, leading to the successful development of wearable UV sensors (Huang & Chalmers, 2021, p. 966). This has accelerated the pace of progress in personal UV monitoring technology over the last decade. The technologies are designed to reduce the discrepancy between the forecast of environmental UV exposure and individuals' actual exposure to UVR by adjusting for variables such as clothing coverage, indoor-outdoor transitions, reflective surfaces, and the nature of the individual's activities. Moreover, the existing wearable device landscape is characterised by a substantial presence of wrist-worn devices, with relatively few studies focusing on other modalities, such as skin patches or textiles. This raises the concern that the measured dose may not reflect the true level of exposure. However, for personal UV monitoring devices to be effective in preventing UV damage, they must meet several competing requirements, including accuracy, user-friendliness, comfort, attractive design, affordability, and minimal maintenance (Zou et al., 2020). Consequently, the evaluation of the effectiveness of wearable UV technologies must consider the nature of the feedback provided, how it

is interpreted, and how it is used by individuals (Robinson et al., 2021). The need for this approach is also emphasised by the inconsistency in reporting spectral coverage (UVA/UVB differentiation) and exposure metrics, which affects the level of comparability.

Wearable UV sensor technology has evolved through several generations, from simple photochromic materials that provide qualitative information to users to more complex technologies that provide multimodal feedback (Araki et al., 2017). Earlier technologies were simple, relying on photochromic materials that changed colour in the presence of UVR. At the same time, advances in photochromic chemistry, semiconductor physics, nanotechnology, and materials have expanded the scope for developing UV sensor technologies, including novel forms and modalities (Lee & Armani, 2016). The evolution of wearable technology has followed the trend from rigid to flexible electronics, the combination of energy-harvesting technologies, the use of skin-friendly materials, and the incorporation of digital technologies into sensor systems (Shi et al., 2018). Finally, although the existing set of studies is largely focused on technology development and validation, evidence of effectiveness is limited and diverse. When behavioural studies are reported, outcomes are largely focused on acceptability, intentions, or other related aspects, with relatively fewer studies reporting objective measures of UV dose or sunburn endpoints. The reported adherence and implementation challenges also indicate that effectiveness would likely depend on more than the sensor's capability to detect UV dose.

Therefore, the present thesis will utilise a sequential multi-method approach which combines findings from a scoping review of wearable UV-sensing technologies with a questionnaire survey to identify the significant behaviours and perceptions that influence the adoption of prevention-related practices. More specifically, the scoping review maps technology and evidence, while the survey assesses awareness, acceptability, and barriers relevant to prevention-oriented use. The proposed approach clearly targets existing gaps in device modalities, reporting practices, and outcome measures. It seeks to bridge the gap between exposure tracking and decision-support functionality for prevention in daily life.

1.3. Research Questions

This thesis addresses three research questions. First, what categories of wearable UV sensors are reported in the literature, and how are they categorised by form factor, technological framework, UVA/UVB spectrum coverage, and application functionalities? Second, which behaviour change characteristics are employed, and what empirical effects have been documented for sun-protective behaviours and compliance? Third, what does the evidence suggest about the effects of wearable UV sensors on individual UV dose and sunburn incidence?

1.4. Objectives and Aims

The objective of this scoping review is to define and synthesise the existing collection of literature regarding wearable UV sensors and their applications in skin cancer prevention. As identified in the research questions provided above, this research intends to define the scope of wearable technology through a detailed explanation of form factors, sensing technologies, and application functionalities. It also seeks to identify engagement strategies and behavioural support functions integrated within the technology, including sunscreen application, seeking shade, protective clothing, and compliance. Furthermore, where sufficiently comparable evidence is available, this research also seeks to assess reported outcomes of wearable technology on individual UV dose and sunburn incidence. A questionnaire has also been designed to explore sun-protective behaviours and user perceptions of wearable technology and its prevention-oriented applications.

1.5. Significance of the Study

The contemporary wearable technology landscape ranges from simple UV exposure trackers to multifunctional devices that measure additional cutaneous variables, such as skin moisture, thereby integrating health monitoring in daily life and providing continuous streams of user-personalised information (Frasier et al., 2025). Within this landscape, UV sensor technology is characterised by its capacity to promote sun-safe behaviours and support the prevention of skin cancer (Frasier et al., 2025). Therefore, the significance of the current thesis rests not only in synthesising the heterogeneous technology landscape but also in explaining opportunities to enhance the preventive value of wearable UV sensing technology in everyday contexts.

1.6. Scope of Study

The purpose of this study is to explore the various types of wearable UV-sensing technology, focusing on devices that can measure an individual's UV exposure and provide user feedback to support decision-making for skin cancer prevention. The study centres on near-body or on-body UV-sensing technology, such as wrist-worn devices, adhesive skin patches, and any other types of wearable devices that deliver user feedback on UV exposure levels. Examples include visual or electronic displays, as well as devices that can connect to smartphones. The study comprises a scoping review of device types and a population survey examining awareness, acceptability, usefulness, and barriers to adoption. The study attempts to identify the types of wearable UV-sensing devices and users' perspectives. It does not establish clinical effectiveness, diagnostic ability, therapeutic capacity, or accuracy of the devices.

1.7. Thesis Structure

This thesis is organised into two parts over seven chapters. Part I encompasses the contextual framework and methodology. The first chapter establishes the study by presenting the background, problem statement, research questions, objectives and aims, significance, scope, and an overview of the thesis structure. The second chapter reviews and synthesises the existing literature relating to wearable UV sensors, highlighting technological developments and a previous scoping review. The third chapter outlines the method implemented in the scoping review and questionnaire survey, providing the research's methodological model.

Part II is focused on the empirical evidence obtained from the research methods, which culminates in the form of a research proposal. The fourth chapter presents the results obtained from the scoping review and the questionnaire, which are further organised around the research questions to identify gaps and limitations in both the technology and the literature. The fifth chapter synthesises the results obtained from the scoping review and the questionnaire survey to deliver a cohesive view of the research that culminates in interpretations, implications, and recommendations aimed at leading future inquiries in this domain. The sixth chapter presents a proposal for a new solution based on the results of the research from the previous chapter. The final chapter concludes the thesis with a synopsis of the research, including the principal findings of the study.

Chapter 2: Conceptual and Theoretical Framework

2.1. Burden of skin cancer and why exposure measurement matters

This section summarises the burden of cutaneous melanoma (CM) and non-melanoma skin cancer (NMSC) to highlight the relevance of UVR exposure assessment for prevention. It then links wavelength-dependent mechanisms to the practical need for wearable UV dosimetry.

2.1.1. Global and regional burden

Cutaneous melanoma and non-melanoma skin cancers represent an important and increasing public health burden (Mittal et al., 2024). A 2024 review reports that, in 2020, over 57,000 people died from melanoma, accounting for 80% of all skin cancer-related deaths (Gieniusz et al., 2024, p. 1). In the same year, new cases of melanoma globally reached 325,000, with an upward annual trajectory (Gieniusz et al., 2024, p. 1, referring to Huang et al., 2023). In the United States specifically, melanoma remains among the most diagnosed cancers: skin melanoma is identified as a nation-leading fifth most diagnosed cancer in the country, with 97,610 new cases projected for 2023 (Cahoon et al., 2024, p. 1, referring to Siegel et al., 2023).

NMSC has a markedly higher incidence in lighter-skinned populations. It is also described as the most frequently diagnosed neoplasm in Western nations, with over 156,000 incidents recorded annually in the United Kingdom (Walsh & Hardwicke, 2024, p. 820). Within the NMSC taxonomy, basal cell carcinoma (BCC) is the predominant subtype. These neoplasms represent the most prevalent category of malignancy experienced among Caucasian populations, accounting for approximately 75% of all skin cancer diagnoses (Walker & Hardwicke, 2022, p. 39). Although NMSC has a relatively low mortality rate (around 1%), deaths mainly reflect advanced cutaneous squamous cell carcinoma (cSCC), which is frequently costly and resource-intensive to treat (Walsh & Hardwicke, 2024, p. 820).

Significant geographic disparities indicate that the skin cancer burden varies noticeably by region. New Zealand and Australia have the highest incidence rates of skin cancer, while European countries have recorded the largest incidence and mortality rates of melanoma skin cancer (Roky et al., 2025). By contrast, North America and Asia have the highest incidence rates as well as mortality rates of non-melanoma skin cancers (Karampinis et al., 2025, p. 2). These patterns present an interaction of a multitude of factors such as ambient UVR, behavioural exposure patterns, demographic age structure, and access to healthcare services.

In addition to incidence and mortality rates, skin cancer also produces substantial economic and social costs, including reduced life expectancy, productivity losses, and long-term care needs related to disfigurement or advanced disease. WHO/ILO Joint Estimates indicate a substantial burden

attributable to occupational UVR exposure. An estimated 1.6 billion workers were exposed to occupational UVR in 2019, equivalent to 28.4% of the working-age population (Pega et al., 2023, p. 1). Population-attributable fractions (PAFs) were found to be 29.0% in NMSC-associated mortality as well as 30.4% among disability-adjusted life years (DALYs) (Pega et al., 2023, p. 1). NMSC burden accounted for 18,960 deaths and 0.5 million DALYs attributable to occupational exposure, with this number nearly doubling between 2000 and 2019 (Pega et al., 2023, p. 1). These statistics are important because transparent, official estimates of occupational UVR exposure and attributable burden of NMSC can support national planning, budgeting, implementation and monitoring of policies and systems. This can protect workers from occupational UVR exposure to prevent the attributable NMSC burden and reduce the associated inequalities (Pega et al., 2023, p. 2). Occupational estimates are particularly informative because they operationalise UVR exposure using standardised, erythemally weighted metrics.

Notably, WHO derived these PAFs using an adjusted annual mean erythemally weighted daily dose of environmental and occupational UVR exposure (Pega et al., 2023, pp. 3, 15). This direct application of an erythemally weighted indicator illustrates the utility of standardised measures of exposure when ascertaining population burden and when jurisdictions are compared. The same logic motivates dose concepts such as minimal erythema dose (MED), which translates exposure into skin-type–specific thresholds. At the individual level, UV dose is considered relative to an individual's level of skin sensitivity, and patients are graded to determine a MED (Heckman et al., 2013). MED is the UVR dose that will induce minimal erythema, specifically sunburn or flush due to capillary engorgement, of an individual's skin several hours afterwards. Exposure to UV in the future must be at intervals shorter than the MED in order not to burn (Heckman et al., 2013, p. 4). These burden estimates highlight why UVR exposure is a modifiable target for prevention and policy. The following subsection describes how the wavelength-dependent biology of UVR influences the selection of exposure metrics for prevention and risk communication.

2.1.2. UVR mechanisms and exposure metrics

However, prevention depends not only on awareness but on how exposure is quantified and communicated. Understanding UVR photobiology is foundational for prevention and risk communication. UVA accounts for 95% of UVR reaching the Earth's surface and has longer wavelengths (320–400 nm) (Craig et al., 2018, p. 579). UVB is twenty times less abundant but comprises shorter wavelengths (290–320 nm) (Craig et al., 2018, p. 579). These spectral differences have ramifications in terms of tissue interaction. UVB penetrates the epidermal layer, causes sunburn and directly damages DNA (Cahoon et al., 2024, p. 1). UVA (320–400 nm) penetrates deeper into the dermis and is associated

with indirect DNA modification through oxidative stress. Figure 2.1 illustrates differential penetration by wavelength. This distinction is important in dosimetry, since the endpoint used in measurement must be relevant to the wavelength sensitivity. It has been associated with approximately threefold stronger immunosuppressive effects upon the skin compared to UVB (Cahoon et al., 2024, p. 1). Because UVA and UVB differ in tissue penetration and biological effects, dosimetry must remain attentive to wavelength and endpoint.

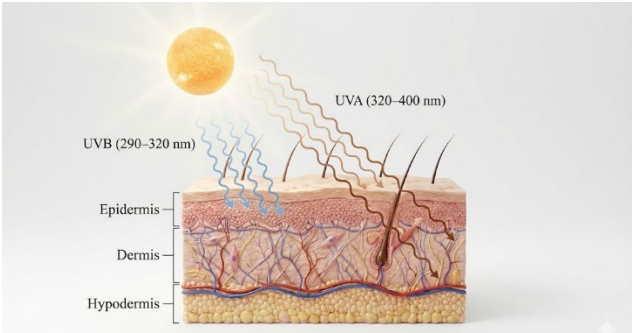


Figure 2.1. Schematic representation of human skin cross-sectional anatomy and differential UVR penetration. (Adapted from Craig et al., 2018).

At the molecular level, UVB photons act directly on cellular DNA to form two typical photolesions: cyclobutane pyrimidine dimers (CPDs) and pyrimidine pyrimidone photoproducts, with CPDs accounting for an estimated 80% of UVB-induced mutations (Craig et al., 2018, pp. 579, 580). UVA can also induce canonical DNA lesions, leading to CPD formation, reinforcing its relevance to carcinogenic risk (Craig et al., 2018, p. 580).

Epidemiological patterns are closely correlated with photobiological mechanisms, as both acute and cumulative exposures to UVR present adverse effects. In case-control analyses, sunburn emerged as the most frequently evaluated risk factor for melanoma (Kwa et al., 2025, p. 1239). Additionally, cumulative exposure is identified as a key risk indicator (Kwa et al., 2025). Cumulative sun exposure is quantified by the total hours of sun exposure or cumulative UV flux, which serves to estimate both location-specific and wavelength-specific (280–330 nm) radiant energy per unit area accumulated throughout an individual's lifetime (Kwa et al., 2025, p. 1242). Likewise, most studies that investigated location-specific average UVI indicated that residence in regions with elevated UVI values is positively correlated with increased incidence of melanoma (Kwa et al., 2025, p. 1242).

Prospective evidence supports the core role of early-life exposures. In the general population, melanoma risk increased by about 3% for each additional intense sunburn before age 15. This association was not attenuated by eye colour, hair colour, skin complexion, ambient UVR, gender, or reported time outdoors (Mai et al., 2025, p. 483). Increased risks remained in co-participants with brown or hazel eye colour, brown or black hair colour, low UVR, and less time spent outdoors on weekdays and weekends (Mai et al., 2025, p. 483). This reinforces that photoprotection in childhood

is of universal importance regardless of phenotypes and behaviours. Artificial sources of UV provide additional risk (Jin et al., 2025, p. 2). Most recent meta-analyses have revealed that the incidence of melanoma is 1.3-fold higher among sunbed users, and much higher (1.8- to 2.5-fold) among those younger than 30 to 35 years and among frequent users between the ages of 10 and 40 years (Jin et al., 2025, pp. 2, 13).

Finally, observed incidence patterns determine diagnostic and surveillance practices. Population-based data have revealed that the incidence of CM has increased significantly over the past four decades without a corresponding shift in mortality, which raised concern about overdiagnosis (Maghfour et al., 2024, p. 637). This trend is mainly explained by melanoma in situ (MIS) and thin invasive CM (0.01–0.8 mm), which accounted for 82.6% of cases between 2000 and 2019 (Maghfour et al., 2024, p. 638). These findings support interventions such as preventing childhood sunburn and controlling indoor tanning, alongside appropriately calibrated screening that maximises benefits while minimising downstream overtreatment. These mechanistic and epidemiological patterns help to explain the importance of UV exposure measurement and communication, which in turn relates to the problems with adherence and measurement described in the following section.

2.1.3. Prevention limits and measurement gap

Traditional photoprotection is grounded in effective preventive science, yet it frequently underperforms in practice because individuals fail to sustain protective behaviours over long periods. Numerous sun protection programmes have been developed worldwide and increasingly rely on digital platforms due to their potential reach and cost advantages (Lim et al., 2024, p. 2025). Although these programmes are reported to reduce the prevalence of sunburn, their effects on actual incidence and mortality rates of skin cancer are described as limited (Lim et al., 2024, p. 2025). These restricted effects are likely to indicate, in part, persistent adherence challenges. A key contributor is non-adherence to recommended behaviours, consistent with broader adherence challenges within healthcare (Sarkany, 2025, p. 546).

Concrete adherence gaps in sun protection are significant. In a survey across twenty countries, only 24.05% reported applying sunscreen every two hours outdoors (Lim et al., 2024, p. 2027). Among those who did not reapply, the most common explanation was that they did not think to reapply sunscreen every two hours (“it does not occur to me”) (27.79%) (Lim et al., 2024, p. 2028). High-risk exposure behaviours also remain common. Almost half the respondents (48%) admitted being outside between 10 AM and 4 PM, illustrating that availability is a significant factor in defining high-risk exposure timing (Lim et al., 2024, p. 2028). Context can also constrain feasible protection. Although shade was relatively popular with respondents (41.2%), it is not always available in coastal areas and

during recreational activities. Moreover, the relatively low uptake of sun-protective clothing, for example, hats (38.4%) and long-sleeved shirts (11.8%), may be a less favourable behavioural target for public health policy (Akerlof, 2023, p. 128). Clinical samples also mirror these deficiencies. Even when sunscreen is used, SPF values selected can be lower than recommended, and complementary measures such as wearing sunglasses, hats, and long sleeves are reported less often. Collectively, these prevention programmes focus on effective sunscreen use, encourage the adoption of protective clothing, and target younger age groups to promote long-lasting sun-safe behaviours (Koumaki et al., 2024, pp. 13, 11).

Even when they are used, real-world applications can significantly reduce the efficiency of protection. During holidays, even under observation, participants applied sunscreen at 0.5-0.8 mg/cm² below the optimal application amounts. Under these “real-life” conditions, the efficiency of a sunscreen with an SPF 50 product has been described as noticeably lower, with values of SPF 3-5 (Sarkany, 2025, pp. 544, 546). Evidence also suggests that a cancer diagnosis may lead to an initial behaviour change that decreases over time. One study assessed the UV exposure behaviours of patients after a diagnosis of malignant melanoma and reported decreased exposure to the sun during the first summer (Sarkany, 2025, p. 546). However, by the third summer after diagnosis, participants returned to their previous sunburning behaviours and levels of solar exposure, despite being under a five-year observation schedule with a dermatologist (Sarkany, 2025, p. 546).

Measurement practices may perpetuate these challenges. Many prevention studies aim to reduce UVR exposure by promoting sun-protective behaviours, which are traditionally assessed using self-report measures (Parsons et al., 2021, p. 2). Determining an individual's UVR exposure is increasingly feasible with the availability of personal UVR monitors. Personal UV monitoring devices can provide a more feasible way to measure an individual´s UV exposure and may be integrated into skin cancer interventions. Early findings suggest that feedback is associated with reduced weekend UVR exposure and improved implementation of some preventive behaviours, although reactivity remains a concern (Parsons et al., 2021, pp. 1-2). This example shows how objective monitoring can be used in conjunction with self-report to provide a better assessment of exposure.

At the same time, targeted adherence support is potentially effective in high-risk groups. An individualised adherence intervention, rigorously matching behaviour change techniques to determinants with insufficient photoprotection, enhances photoprotection and therefore lowers the UVR dose reaching the face (Walburn et al., 2025, p. 729). Importantly, greater exposure to the intervention dose was associated with a lower UVR dose to the face, and exploratory analysis suggests that psychological processes may have contributed. The intervention was cost-effective and did not compromise emotional well-being (Walburn et al., 2025, p. 736). Taken together, persistent adherence

gaps and reliance on self-report create a measurement gap that supports the case for personal UVR monitoring.

2.2. Wearable UV dosimetry modalities and design constraints

Wearable UV sensors can be classified according to whether they use photoelectric and/or colourimetric (photochromic) technology. At a functional level, these sensors either convert UV exposure into an electric signal or change colours in response to irradiation (Zou et al., 2020). The latter does not require any electrical power but relies on several photochemical processes triggered by UV exposure (Zou et al., 2020, p. 3). Even though UV sensors are entering the mass market, the technology still faces challenges that need to be overcome to achieve solutions that are highly reliable, low-cost, and user-friendly for society (Zou et al., 2020, p. 25).

The following sections will evaluate the modalities in a similar manner with regard to the requirements for calibration, the interpretability of the output, wearability constraints, including visibility and durability, as well as the implications for feedback and behaviour change. From the perspective of digital health, the sensing technology defines boundary conditions for the potential effectiveness of an intervention. Passive sensors are inherently suited to cumulative dose detection and can therefore support user self-assessment of risk but often do not enable direct detection and continuous logging of the UVI. Active sensors enable precise temporal detection and connectivity, but are associated with calibration, power, and data management complications. Hybrid technology has emerged specifically for overcoming the shortcomings of relying exclusively on either photochromic visibility or electronics (Zou et al., 2020, p. 26). Passive systems are scrutinised first because they highlight the importance of cumulative dose measurement and the essential constraints regarding action spectra, calibration, and interpretability.

2.3. Passive sensing

Passive sensing systems are primarily focused on cumulative exposure rather than real-time exposure monitoring. Accordingly, the following subsections will compare the use of passive films, photochromic, and photocatalytic systems regarding calibration requirements and the interpretability of the output.

2.3.1. Passive film dosimetry: polysulphone as the reference cumulative badge

Passive personal UV dosimetry emerged from a need to monitor cumulative UV exposure without electronics, reflecting the lack of documented data on real-world UV exposure levels (Diffey, 2020, p. 1). Over the last four decades, the plastic film dosimeter called polysulphone (PSP) has been the most widely used personal instrument for monitoring UV exposure (Diffey, 2020, p. 2). The physical principle

is that the PSP film degrades under UVR, with a decrease in tensile strength, producing a shift of the original broad absorption band from the near-UV region towards the visible region with increasing doses (Diffey, 2020, p. 2). The passive instrument is designed to quantify absorbance changes from pre- to post-exposure at 330 nm, expressed as exposure magnitude (ΔA330) (Diffey, 2020, p. 2). As shown in Figure 2.2, ΔA330 increases with incident UV dose, supporting its use as a cumulative exposure measure.

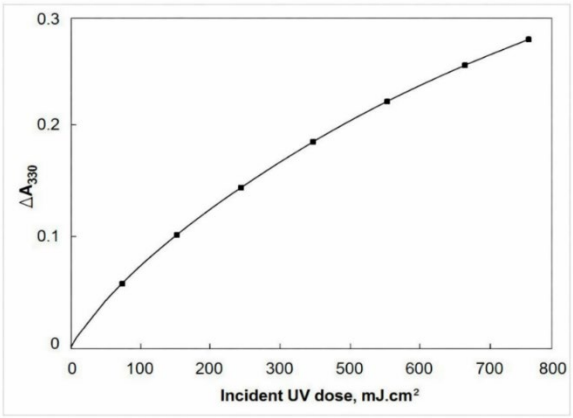


Figure 2.2. Dose-response curve of PSP film demonstrating the relationship between the change in absorbance at 330 nm (ΔA330) and varying levels of incident UVR exposure. Cropped from Diffey (2020).

Passive dosimetry badges also illustrate a critical principle of UV dosimetry, namely that spectral sensitivity should ideally match the action spectrum of the photobiological endpoint being measured, typically erythema (Diffey, 2020, p. 2). However, the spectral sensitivity of polysulphone does not sufficiently match the erythema action spectrum, making calibration a key methodological requirement. This incompatibility can be addressed through calibration, provided that the spectral distribution of incident radiation is known. Consequently, distinct calibration is necessary for each UV source (Diffey, 2020, pp. 3-4). Calibration may also vary with environmental conditions, as spectral disparities can be affected by altitude and ozone (Diffey, 2020, p. 4).

However, passive film badges have limitations as safety instruments. The strengths of passive film badges include low weight, portability, low cost, no power requirement, temperature stability, and the ability to measure the total UV dose (Huang & Chalmers, 2021). Limitations include time-consuming data collection and calibration, potentially complex instruments, and the inability to provide UVI measurements “even in principle” instantaneously (Huang & Chalmers, 2021, p. 973). In terms of functionality, this requires each badge to be individually consulted for data (approximately 5-10 seconds per badge), which has motivated automation approaches for simultaneous reading and printing of multiple badges (Diffey, 2020, p. 3).

Additional constraints relevant to device stability design include a restricted dynamic range due to saturation, potentially requiring replacement on a daily to weekly basis, and a dark reaction in which ΔA330 continues to change after exposure has ceased (Diffey, 2020, p. 3). The initial badge designs for

the PSP were more conspicuous, thereby accentuating the significance of miniaturisation as a practical necessity (Diffey, 2020, p. 5). As illustrated in Figure 2.3, early PSP badges were relatively noticeable, which reinforces miniaturisation as a critical requirement for wearability.

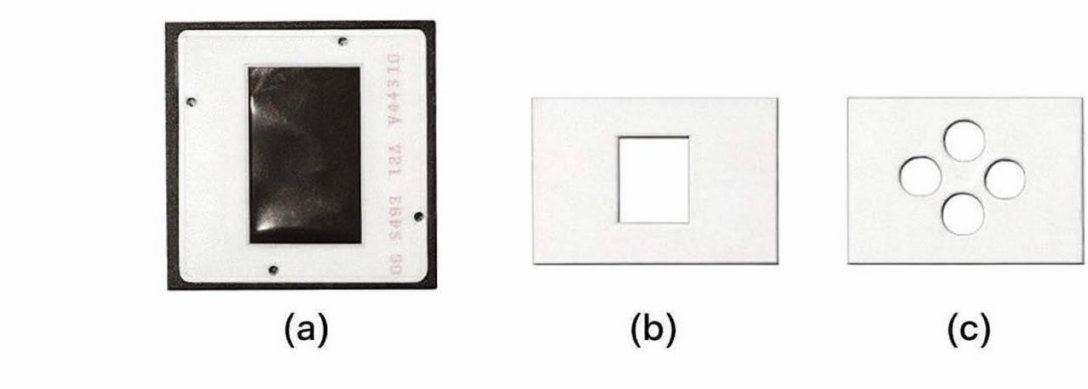


Figure 2.3. Polysulphone film badge holders are used for personal UV dosimetry. (a) Early large badge mount. (b) 30 × 30 mm cardboard holder with a central 10 × 15 mm aperture (single-aperture mount). (c) Alternative 30 × 30 mm holder with four circular apertures (6 mm diameter) intended to improve reliability but requiring longer pre-/post-exposure absorbance measurements. Adapted from Diffey (2020).

2.3.2. Passive Colourimetric and Photochromic Wearables: Interpreting UV Irradiation at the Point of Excitation

Colourimetric wearable UV sensors aim to address the longstanding mismatch between UV exposure (excitation) and visible detection: UV-induced skin damage is not directly visible at the time of exposure, and while erythema may not be noticed until 24 hours post-exposure (Huang & Chalmers, 2021, p. 973). Therefore, the wearable sensor has a pivotal role in localising the chemical-photochemical signal at the point of excitation to measure cumulative UV dose through colourimetric analysis (Huang & Chalmers, 2021, p. 967). As shown in Figure 2.4, this principle can be implemented as a patch that produces a stable, legible colour field, which is then interpreted through a smartphone-mediated reading workflow.

Mechanistically, photochromic sensors modify colour in response to UV irradiation without requiring electrical power. This response is driven through a series of photochemical reactions in which the photochromic material switches from one photostate to another with a specific absorption profile (Zou et al., 2020, pp. 3-4). This reversibility of photochromic systems is further explained through photoswitching mechanisms, including photoinduced ring-opening and closing reactions and trans-cis isomerisation, enabling repeated switching between optical states (Zou et al., 2020, p. 7). From a translation and integration perspective, the simplicity of colour-change output makes it easy to integrate into a range of flexible materials such as paper, polydimethylsiloxane (PDMS), polyethylene naphthalate, low-density polyethylene, and silicon films, providing a simple way of detecting UV irradiation (Zou et al., 2020, p. 4). From the user interface perspective, photochromic sensors are

attractive as they offer naked-eye monitoring of the UV detection process (Zou et al., 2020, p. 26). However, translating photochromic wearables into a dosimeter technology presents challenges. Compared to photoelectric sensors, photochromic devices may demonstrate lower sensitivity, which can limit detection at very low exposure unless supported by a secondary device for quantitative interpretation. In this configuration, integration into a technological interface means that the wearable serves as a chemical sensor and as a human-device interface (Zou et al., 2020, p. 26).

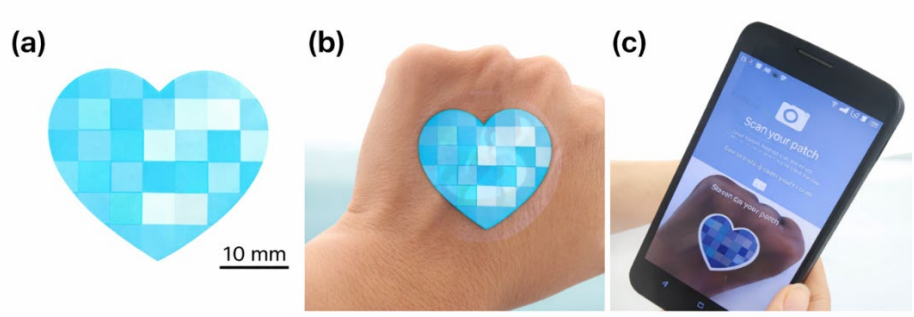


Figure 2.4. Colourimetric UV patch with smartphone-mediated interpretation. (a) Patch colour field output; (b) on-skin deployment; (c) smartphone scanning/readout interface. Adapted from Huang & Chalmers (2021).

Beyond material mechanisms, passive systems also vary in how colour change is packaged for everyday use and how users are prompted to act on the signal. Bao et al. (2020) present a wearable textile design in which colour change serves as an intuitive exposure index, enabling the textile to detect UV levels through a colour change under everyday conditions. To address practical laundry constraints, the design is extended through a removable label approach that uses a strong colour change as an intuitive UVI, based on colourimetry. For this approach, an adhesive label is attached to clothing to detect UVR, and both the detection process and wearability evaluation are presented in Figure 2.5 (Bao et al., 2020, pp. 7-8). This approach is then generalised to serve as a maintenance strategy, whereby the labels are placed on any required part of the clothing needed and then removed during laundry to increase convenience and potentially extend the product lifespan (Bao et al., 2020, p. 8).

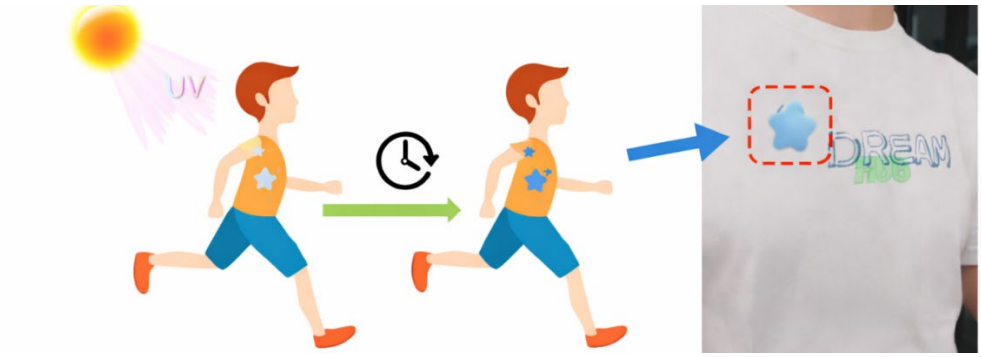


Figure 2.5. Adhesive textile label for UV indication. The label changes colour under solar UV exposure and is shown applied to clothing to demonstrate on-garment use and visibility. Adapted from Bao et al. (2020).

Consumer-centred wearables are distinguished by a focus on simple placement, such as stickers or wristbands, and action-oriented prompts, such as reapplying sunscreen or seeking shade, rather than quantifying dose (Zou et al., 2020, p. 24). However, these wearables are also identified as scalable but information-sparse, providing only a qualitative indication of UVR (Zou et al., 2020, p. 26).

2.3.3. Photochromic examples

The following examples illustrate variation in the visibility of output, reversibility, interpretability, and feasibility of integration into wearable form factors.

Schiff Bases. The photochromic Schiff-base material described by Gao et al. (2023) is based on a benzonitrile Schiff base, namely (E)-4-((2-hydroxy-4-methoxybenzylidene)amino)benzonitrile (HMBAB) (Gao et al., 2023, p. 1). The significance of this photochromic material in wearable devices is presented through proposed applications in wearable form factors. HMBAB was prepared as a wearable sensor on paper and intended for use as a chest card or a bracelet-style wearable (Figure 2.6). The device exhibits visible colour changes that vary with sunlight intensity and can provide an early warning of high-dose UVR through naked-eye observation (Gao et al., 2023, p. 1). The significance of this wearable device in outdoor applications is further emphasised in the article, which notes that it shows visible colour changes across different solar environments and can provide an early warning of high-dose UVR during outdoor activities (Gao et al., 2023, p. 8). In summarising the prospective applications of the wearable device in wearable technology, it has been described in terms of its feasibility, usability, low cost, rapid responsiveness, wireless fabrication method, and detectability through visual observation (Gao et al., 2023, p. 8).

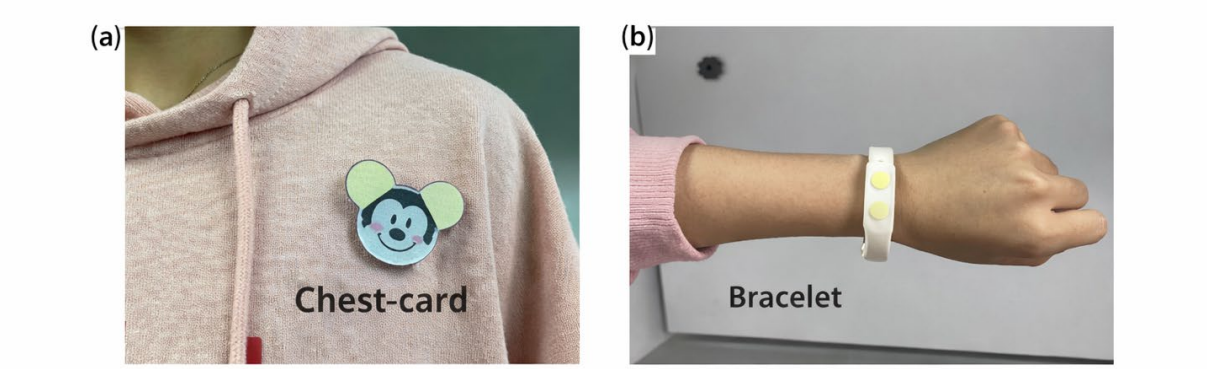


Figure 2.6. HMBAB paper-based photochromic wearable prototypes. (a) Chest-card format; (b) bracelet format. Adapted from Gao et al. (2023).

Perovskite nanocrystals. Chen et al. (2024) introduce the role of perovskite nanocrystals in visually interpretable UV dose sensing and note the increasing interest in research on perovskite nanocrystals (PNCs), given their strong fluorescence emission, tunable emission colours, and long carrier diffusion lengths. This tunability is achieved through a simple ion-exchange reaction, in which the emission peak

wavelength is adjusted across the visible spectrum (Chen et al., 2024, p. 1). In terms of dosimetry, the obtained CsPbCl3 PNCs dispersed in dibromomethane (PNCs-DBM) combination are described as exhibiting a narrow emission peak width and a continuous change in fluorescence emission colour across a wide colour range. The colour varies from purple to blue to cyan to green in response to prolonged UV exposure, facilitating the design and construction of a visually interpretable, accurate, and sensitive UV dose sensor for determining UV exposure (Chen et al., 2024, p. 8). As shown in Figure 2.7, the UV sensing cell loaded with the PNCs–DBM system is sealed with fluorescence-free PDMS films and fixed within the groove of a wristband, illustrating a wearable implementation of this visually interpretable sensing approach.

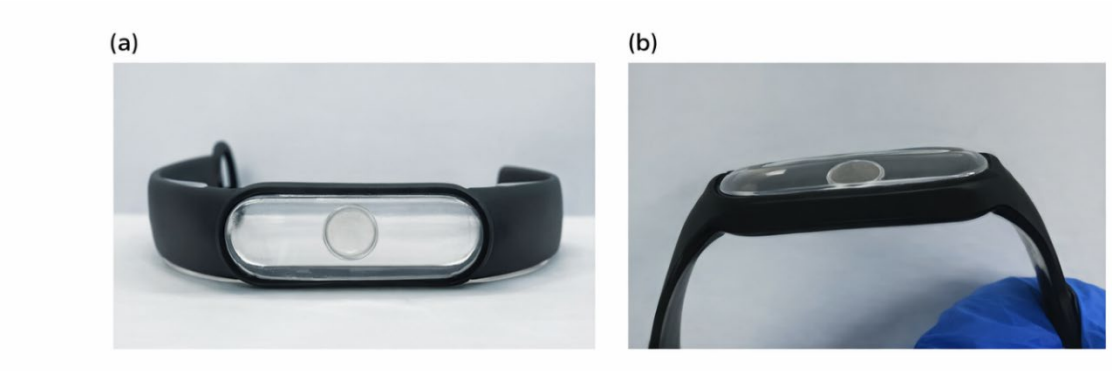


Figure 2.7. Wristband integration of a PNCs–DBM UV sensing cell. The sensing cell is sealed with fluorescence-free PDMS films and fixed within the band groove. Adapted from Chen et al. (2024).

Mineral photochromism. Lawrynowicz et al. (2024) examine the potential of hackmanite-based photochromic minerals for use as passive wearable UV detection technology. The researchers suggest that photochromic minerals such as hackmanite can be used to develop wearable UV sensor devices that do not require batteries. The researchers also suggest that the use of hackmanite in textile materials would increase the prevalence of UV monitoring for various applications, such as preventing sunburn (Lawrynowicz et al., 2024, p. 1). As illustrated in Figure 2.8, hackmanite-loaded coatings can be used in textile prints, for example, on a cap, where changes in colour intensity can be used to measure UVI and analysed using the proprietary “Sensoglow” app.

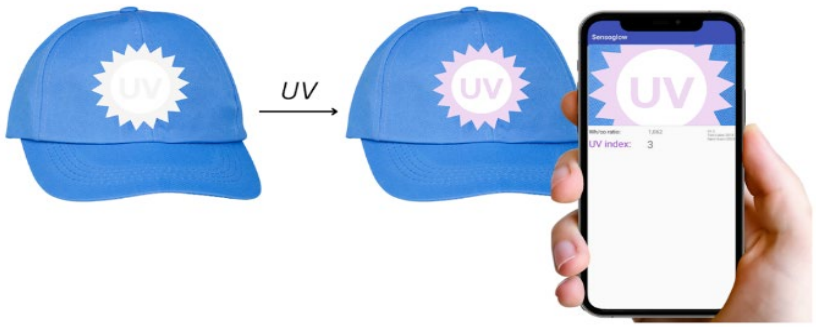


Figure 2.8. Hackmanite-based photochromic textile print with app readout. UV exposure increases colour intensity on a cap print, enabling UVI estimation via the Sensoglow smartphone app. Adapted from Lawrynowicz et al. (2024).

From the performance perspective, the photochromic fabric changes reversibly from white to purple in approximately 15 seconds under both UVA and UVB irradiation, followed by complete reversal of the colouration within 50 minutes under white light illumination (Lawrynowicz et al., 2024, p. 1). Material-wise, the reasoning is presented as follows: these photochromic minerals combine the light, flexible, and versatile properties of organic materials with the high thermal, chemical, and optical stability of inorganic materials (Lawrynowicz et al., 2024, p. 2). Further, it is stated that the output is controllable and that various colours, such as pink, purple, blue, and yellow, can be easily achieved. Reversibility of the response is explained in terms of an electronic transition within an immutable crystal lattice, allowing an indefinite number of cycles of colouration and discolouration (Lawrynowicz et al., 2024, p. 2).

Overall, these examples illustrate that photochromic wearables can provide low-power signalling. However, their usability depends on whether the output can be reliably interpreted under varying lighting and use conditions (Zou et al., 2020, p. 26). The emphasis on paper- and textile-based materials highlights affordability, whereas integrating sensing cells into a wristband form factor may better support output stability (Gao et al., 2023; Chen et al., 2024; Lawrynowicz et al., 2024).

2.3.4. Passive photocatalytic dosimetry

TiO_2 hydrogel. Botti et al. (2023) offer a passive photochemical sensing method rooted in titanium dioxide (TiO_2) photocatalysis. They situate TiO_2 within its established role as a UV absorber, including its application in commercial sunscreen products that counteract erythema, burning, and long-term UV exposure-related damage to skin tissues (Botti et al., 2023, p. 2). The sensing mechanism is explained by UV-induced redox cycling within TiO2, which yields oxygen and hydroxyl radicals that, in the presence of methylene blue (MB), initiate a reaction leading to the production of leukomethylene. The resultant discolouration can be seen by the naked eye (Botti et al., 2023, p. 2). At the technological level, the paper describes the development of a UVR sensor based on a PAA/TiO_2/MB composite hydrogel (Botti et al., 2023, p. 9). A key application purpose is that the rate of discolouration can be tailored according to the UV exposure limit for various skin types by adjusting the ratio of titanium dioxide to dye material (Botti et al., 2023, p. 1). The reported response time varies between 30 minutes and 1.5 hours, aiming to position the technology for public use. This is framed as a need to strike a balance between sufficient UV exposure to prevent Vitamin D deficiency and avoiding excessive UV exposure that can increase the risk of skin cancer (Botti et al., 2023, p. 1).

Gold nanoparticle formation in paper substrates. Choleva et al. (2025) describe a paper-based UV dosimeter or indicator based on the photochemical reduction of gold cationic surfactant complexes (Choleva et al., 2025, p. 1). The principle of the dosimeter is based on the association between UVR

and the hydration-dependent development process. Under UV exposure, chloride ions are photoreductively eliminated from the CTA-AuCl4− complex, which in turn causes the reduction of Au ions and the nucleation of small Au particles. The particles nucleate, are then transferred to the paper surface by capillary action, and further aggregate to form gold nanoparticles, which cause blue-purple colouration on the paper surface (Choleva et al., 2025, p. 1). The usability of the device is then highlighted through the activation mechanism, which is made possible due to the ease of use and availability of the paper material, as it can be simply activated by wetting the material's surface (Choleva et al., 2025, p. 1). This is further supported by the argument that paper devices are versatile and cost-effective, requiring only one drop of water to respond to the need at any given time (Choleva et al., 2025, p. 9). The study further indicates the possibility of using paper in wearable, soft, and stretchable UV photodetector devices that can be activated at any time (Choleva et al., 2025, p. 9). The interpretation is noted to depend on the illumination conditions, such as the intensity of diffused light and the stability of light intensity (Choleva et al., 2025, p. 9).

Among these passive photocatalytic indicators, battery-free operation and cumulative visibility are key advantages. However, response time and illumination-dependent interpretation limit their suitability for continuous measurement (Botti et al., 2023; Choleva et al., 2025).

2.4. Active sensing

Current advances in UV sensing include active (electronic) transduction and signal processing, commonly referred to as photoelectric UV sensors. Such sensors can be rated based on criteria, including photocurrent, suitable on/off current ratio, responsivity, detectivity, and rise or decay times. In terms of intrinsic functionality, active sensors can be characterised by a response that occurs only in the presence of UVR. A reset occurs when UV exposure ceases (Zou et al., 2020, p. 5). While this reset characteristic allows immediate real-time measurements, it is less suited to capturing an individual's overall cumulative UVR, in terms of either MED or daily doses (Zou et al., 2020, p. 5). Thus, active and wearable technology sensors often work under a dual-mode radiometer-dosimeter system, in which radiometer measurements relate to instantaneous UVI (Huang & Chalmers, 2021). Dosimeter measurements refer to overall doses, and active radiometers can be post-analysed to derive overall doses from corresponding instantaneous levels of radiation (Huang & Chalmers, 2021, p. 966).

At the device-chain level, active measurement relies on conventional optoelectronic architecture. In this case, the incident photons produce an electric current using photodiodes. The electric current is then amplified using a transimpedance amplifier (Huang & Chalmers, 2021). The signals are then transmitted through a digital interface, onboard memory, and/or a wireless connection to a smartphone (Huang & Chalmers, 2021, p. 970). The validity of the measured values is closely associated

with the calibration process. The spectral responsivities of the materials of measurement and the photodiodes are not inherently aligned to the erythema action spectrum.

Historically, active sensors emerged in response to passive film badges that were not sufficient in determining the variations in the rate of exposure. The development of a miniature electro-optical UV sensor made possible the electro-optical measurement system, in which the sensor is electrically linked to a data logger attached to clothing or the wrist (Diffey, 2020, p. 8).

2.4.1. Active examples: patch and connected devices

In engineering research, active sensors are represented as elastic, skin-contacting photoelectric patches that highlight UV sensitivity properties and robustness under mechanical wear. Dong et al. (2023) describe the design of a wearable smart UV sensor patch fabricated completely using printing technology. They detail the calibration of a ZnO sensor to UV light excitation and present tests of response and recovery times, flexibility, and robustness (Dong et al., 2023, p. 5). As shown in Figure 2.9, the fully printed UV sensor patch is used in conjunction with a smartphone interaction workflow, linking the on-body device form factor with user-facing readout and feedback.

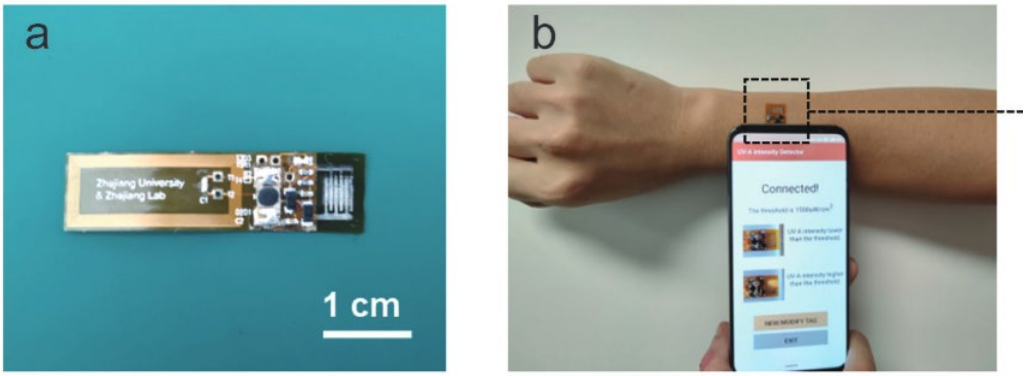


Figure 2.9. Fully printed smart UV sensor patch with smartphone interaction. (a) Printed patch (scale bar shown). (b) Example smartphone-mediated interaction during on-wrist use. Cropped from Dong et al. (2023).

The second active approach attempts to address long-term usability issues related to by-products of the skin (sweat, desquamated cells, sebum), promoting porous areas for supporting optoelectronic functionality over the long term (Kim et al., 2023, p. 1). The sensor is embedded in a three-dimensionally porous patch to support one week of UV monitoring in real time. In vivo functionality was also supported for one week of forearm fixation with no biotoxicity under real-time UVA monitoring with four-hourly measurements (Kim et al., 2023, pp. 1, 8). Figure 2.10 shows the on-skin deployment and representative week-long monitoring output supporting the feasibility of sustained use.

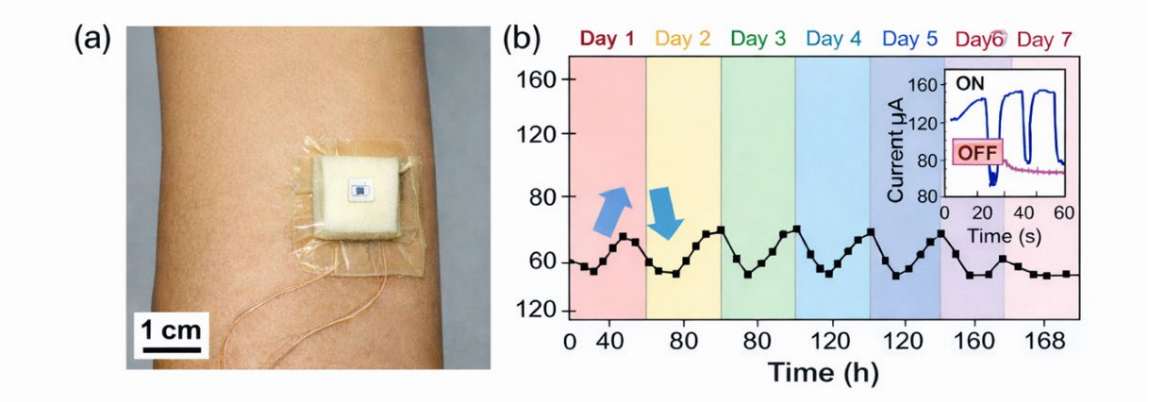


Figure 2.10. Porous UV sensor patch for week-long on-skin monitoring. (a) On-forearm deployment. (b) Representative week-long current response trace. Adapted from Kim et al. (2023).

On the consumer-engaged side, an example is “My Skin Track UV” by L’Oréal (distributed by La Roche-Posay), a battery-free, waterproof wearable sensor that can be clipped to attire, enabling several wearable designs. The sensor wirelessly sends updates to the consumer via a smartphone interface using NFC when paired with the mobile app (Zou et al., 2020, p. 20). Separately, another system described by Lin et al. (2024) is an autonomous wearable UV sensor that leverages solar harvesting. It analyses current UV levels at 1-Hz resolution, stores data in flash memory, and optionally uses BLE to enable real-time data transfer and recommendations (Lin et al., 2024, p. 2). Behavioural context is also collected, including baseline sunscreen and garment use and changes in intention following the interaction, thereby illustrating the potential for integrating real-time UV measurement with behavioural feedback (Lin et al., 2024, p. 3).

These examples also illustrate the rationale for more recent developments, which focus on increasing wear duration and minimising the burden while maintaining legibility. With the benefits comes a set of limitations that are associated with the active wearable sensors. They include the need for calibration, issues with power and data handling, and dependence on smartphones and internet connectivity (Zou et al., 2020, p. 26). The accuracy of the measurements depends on the spectral sensitivity of the sensors used, which does not necessarily align with the action spectrum for erythema (Huang & Chalmers, 2021). Furthermore, active sensors might not be best suited to measure cumulative UV dose (Zou et al., 2020, p. 5), while the prolonged use of the sensor is impacted by sweat and skin by-products (Kim et al., 2023, p. 1).

2.5. Bio-integrated colourimetric nanosensors

Bio-integrated colourimetric nanosensors are proposed as a new approach for UV sensing that explicitly addresses the existing challenges faced by surface-based wearables. In the literature on wearable technology, existing challenges are considered in relation to lifespan, wearability, cost, appearance, and coexistence with sunscreens (Butterfield et al., 2024, p. 1). As a new trajectory, the

implantation of bio-integrated nanosensors is considered a positive factor, as they are not readily perceptible to the human eye and have a long lifespan (Butterfield et al., 2024). This trajectory fits well with the need for UV sensing not only through on-body wearables but also through temporary tattooing and skin-conformal thin layers as a technology interface (Zou et al., 2020, p. 25).

Another key consideration for bio-implantable materials is the need for reversibility, as the application is intended for repeated use (Zou et al., 2020, p. 25). This is particularly relevant given that most wearable materials used for colourimetric sensing applications have been shown to degrade permanently upon UVR (Butterfield et al., 2024, p. 1). Under these conditions, diarylethene-doped nanoparticles have been designed to achieve high photoreversibility and appropriate sensitivity for an intradermal UV dosimeter that saturates at physiologically relevant doses (Butterfield et al., 2024).

Evidence for quantitative interpretability is offered through ex vivo validation studies on pork skin that assess detectable changes in UV dose in the CIE LAB colour space (ΔE*ab), resistance to drift phenomena, and display strongly self-similar dose-response curves relative to UV indicators (Butterfield et al., 2024, p. 6). Consequently, this offers the potential for viable quantitative measurement of UV dose through colourimetric analysis for intelligent tattoos (Butterfield et al., 2024, p. 6). The topic is also linked to practical use conditions regarding the ability of UV sensors to potentially provide visible signs of the effects of sunscreen administration, although with variations based on skin types (Butterfield et al., 2024, pp. 6-7). Feasibility in human subjects is established by a single-subject pilot study, in which the tattoo healed similarly to a normal tattoo without any side effects and functioned properly at different post-tattoo times with 100 activation and deactivation cycles, indicating a possible lifetime measured in years (Butterfield et al., 2024, pp. 8-9). As shown in Figure 2.11, the single-subject pilot supports in vivo feasibility, with the tattoo healing normally and remaining functional through repeated activation–deactivation cycles. At the same time, the translational limitations are determined, among which is the possible impact of the epidermal layers on the tattoo in vivo (Butterfield et al., 2024, p. 9).

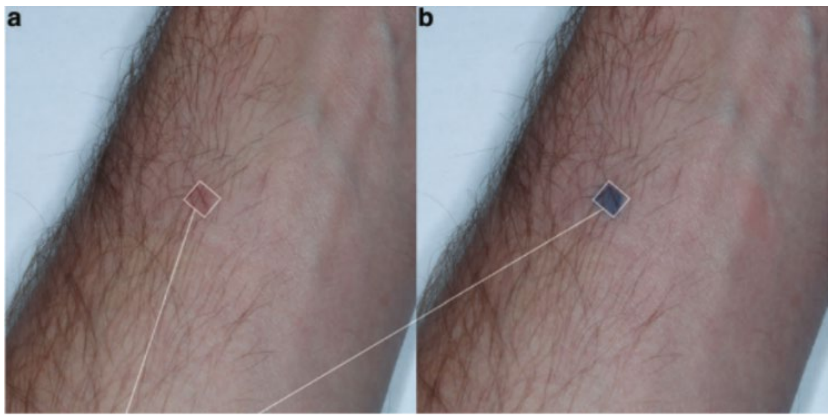


Figure 2.11. Single-human pilot test of photochromic tattoo feasibility in vivo. (a) Baseline appearance; (b) Activated appearance showing a visible colour change following UV exposure. Cropped from Butterfield et al. (2024).

2.6. Hybrid systems

Hybridisation is proposed to overcome the limitations of visibility offered by photochromic and electronic sensing. The need for a hybrid approach is explained in terms of overcoming constraints associated with photochromic-enabled clothing that may delay analysis, as well as population constraints arising from the need for smartphones and internet connectivity (Zou et al., 2020, p. 26).

A typical example of a wearable hybrid system is the integration of an electronically functional sensor substrate with an NFC interface. In this system, an intelligent NFC tag is produced using a flexible printed circuit board technique, described as “integrating the sensor into the NFC tag” (Dong et al., 2023, p. 5). The system is reported to adopt an action-oriented approach rather than a data-processing approach, in which the UV intensity is transmitted via either on/off status or LED intensity, effectively enabling a direct behavioural signal without necessarily interacting with the application (Dong et al., 2023). The next relevant study is introduced as the first battery-free electronic UV radiometer powered by a smartphone through NFC technology (Huang & Chalmers, 2021, p. 9).

Another direction of hybridisation involves reducing on-body electronics by relocating sensing to a tested structure, with a sensing part located outside the Surface Acoustic Wave (SAW) path. The sensing part of the impedance-loaded SAW sensor is coupled to the interdigital transducer, enabling reflection modulation without placing the UV-sensitive material within the SAW wave path (Karapetyan et al., 2019, p. 70).

Finally, the process of textile hybridisation is introduced in the maintenance layer, where the maintenance of electronics occurs. This is followed by the removal of an adhesive label containing a UV intensity measurement on the garment, which is removed before washing to prolong its lifespan (Bao et al., 2020, pp. 7-8).

Chapter 3: Methodology

3.1. Overall design and rationale

The thesis utilised a two-component design to address research questions concerning wearable UV sensors for skin cancer prevention. The first component comprised a scoping review in accordance with the methodological principles and reported in accordance with the PRISMA-ScR checklist (Tricco et al., 2018). Following this approach, the review explored the landscape of wearable UV devices, associated behavioural mechanisms, and the reported effects of these devices. The second component comprised a strictly quantitative, cross-sectional questionnaire survey examining end-user behaviours and perceptions regarding the adoption of wearable UV technologies.

3.2. Scoping review questions and framework

The scoping review was guided by three research questions. First, what categories of wearable UV sensors are reported in the literature, and how are they categorised by form factor, technological framework, UVA/UVB spectrum coverage, and application functionalities? Second, which behaviour change characteristics are employed, and what empirical effects have been documented for sun-protective behaviours and compliance? Third, what does the evidence suggest about the effects of wearable UV sensors on individual UV dose and sunburn incidence?

These questions were subsequently framed in a Population–Concept–Context (PCC) structure to support eligibility: populations at risk of solar UVR exposure were the target population, UV sensor wearables were the central concept, and primary prevention of skin cancer was the context.

3.3. Eligibility Criteria

Eligibility criteria were determined a priori to ensure alignment with the research questions and the PCC framework. Studies were eligible if they employed quantitative, qualitative or mixed-methods designs, including randomised and non-randomised intervention studies and experimental studies. In contrast, reviews, editorials, conference abstracts without full text, theses and dissertations, and other forms of grey literature were excluded. Studies were included if they investigated wearable UV-sensing technologies intended for individual-level measurement of solar UV exposure and/or for providing feedback to promote sun-protective behaviour as part of a primary prevention strategy. Eligible study designs included experimental validation of prototypes, simulated-use studies, observational studies, and intervention studies, including those with or without human participants, provided they were relevant to wearable UV sensing in a practical prevention context.

Wearable devices were defined as body-worn devices, including patches, badges, smart jewellery, and smartwatches. These devices integrate a UV sensor to monitor UV exposure and provide feedback

or data at the individual level. Studies of smartphone-only applications that measure UV exposure using environmental forecasts without a wearable sensor were excluded. However, studies were eligible if smartphone apps served as the interface for wearable sensors.

Additionally, studies were required to report at least one relevant outcome related to skin cancer prevention. These outcomes included erythemal UV dose, cumulative UV exposure, and exposure to sunlight or shade. They also included sun-protective behaviour, such as sunscreen application, shade-seeking, and the use of protective clothing and headwear. Furthermore, the outcomes addressed behavioural, psychological, and acceptability-related aspects of device use and sun protection, including usability, user satisfaction, and risk perceptions. Implementation considerations were charted, namely costs, feasibility, and integration into health systems. These outcome categories informed the a priori data charting framework and the synthesis tables reported in Tables B1–B4. Lastly, only peer-reviewed articles and full conference papers written in English between 1 January 2021 and 7 September 2025 were considered.

3.4. Information Source and Search Strategy

The searches were conducted in biomedical and interdisciplinary databases, including EBSCO (ISCTE Discovery), PubMed, and Scopus. The choice of databases was intended to capture literature related to medicine, public health, behavioural studies, and engineering on the theme of UV exposure, digital health and wearables.

In each database, a core search string with combined keywords of UVR, wearable devices, and sun protection was first used. To minimise the risk of topic-specific information being missed, three additional search strategies were created that correlated with each research question and applied as complete searches across databases. The searches were adapted for the syntax of the databases (for example, MeSH in PubMed and TITLE-ABS in Scopus). The search string query and the three research question specification blocks for each database are presented in Appendix A.

3.5. Study selection and data charting process

All the records were imported into the software Rayyan, where duplicates were removed using automated detection and subsequent manual review, resulting in the final version of the library used for screening. Study selection occurred in two phases. Firstly, the screening of titles and abstracts in Rayyan was based on predetermined eligibility criteria. This was followed by the removal of the studies whose titles and abstracts indicated a failure to meet the predetermined selection criteria. However, the selection of the articles whose eligibility could not be determined from the abstract was retained for the full-text assessment. Secondly, the full-text articles were examined by the same reviewer. To enhance the reliability of data charting, the academic supervisor independently screened a sample of

studies and verified the consistency and validity of the extracted data, with any discrepancies clarified through discussion. The number of articles retrieved, screened, excluded, and included, together with the primary reasons for the exclusion at full text, is provided in the PRISMA-ScR flow diagram presented in Figure 3.1.

After the final set of studies was established, data extraction was conducted using data charting tables. The structure of the data charting tables was pre-tested on a small number of articles and then implemented across the entire set.

3.6. Data items and synthesis plan

The data items were specified a priori to map directly to the three research questions and to ensure consistency in documenting device characteristics, behaviour change components, outcome evidence (UV metrics, behaviours, acceptability), and implementation considerations.

Data items were defined in advance using a structured charting form to facilitate evidence mapping between studies in line with the research questions. For all studies included in this review, bibliographic details and contextual characteristics were charted (author(s), year, journal, country, study design, and participants [population; number of participants]), along with the wearable UV sensor and its associated digital components, and the primary objective. These study-level characteristics are reported in Table B1.

To address the first research question, device characteristics were charted using a taxonomy of form factor, technological framework, UV spectral coverage, and application functionalities. These device classification outputs are presented in Table B2.

To address the second research question, behaviour change characteristics and evaluation outcomes were charted, including behavioural targets and outcomes assessed, empirical effects on sun-protection behaviours (sunscreen, shade, protective clothing), and compliance with wearable use and application. These intervention-focused data are synthesised in Table B3.

To address the third research question, studies were charted for the presence of comparators and design features, relevant UV-related endpoint(s), effects on individual UV dose, effects on sunburn incidence, and a narrative summary of reported findings. These outcome-focused data are synthesised in Table B4.

The review was conducted in accordance with the a priori protocol. No deviations occurred that changed the scope of the review or the eligibility criteria.

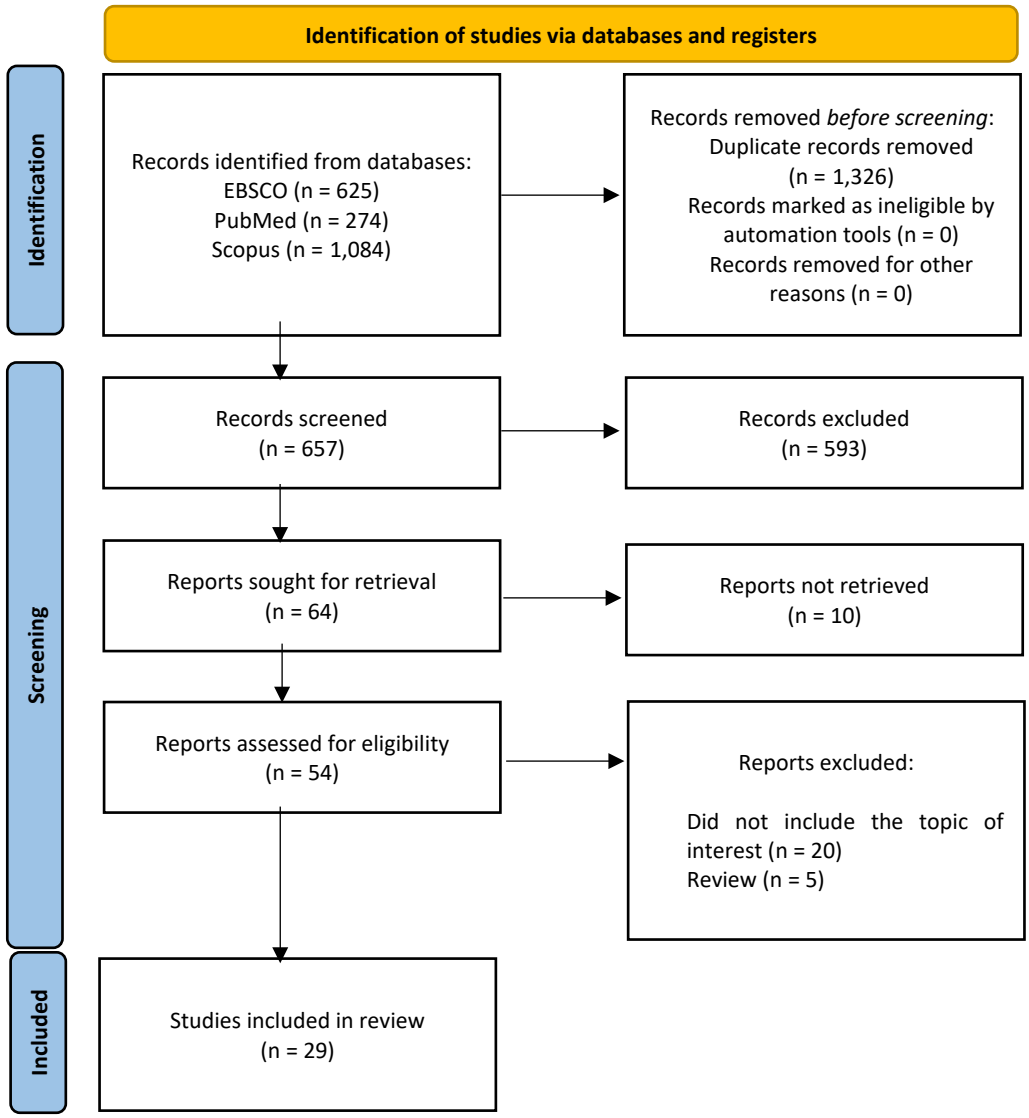


Figure 3.1. PRISMA flow diagram for the scoping review. Adapted from Page et al. (2021)

3.7. Questionnaire rationale

The survey was explicitly motivated by the results of this scoping review, which highlighted rapid advancement in breadth but slower progression in translational depth. Among the included studies are those based on experimental development and laboratory validation, often without human participants, and success is defined primarily in terms of feasibility and sensing, rather than prevention or behaviour change. What is perhaps most critical is that the results for wearables as tools for behaviour change are mixed, with reported effects depending on what is included with the wearables, such as counselling, structured goal setting, app content, and implementation fidelity. Specifically, the included studies suggest that, within this body of research, information delivery alone may not be effective. At the same time, behaviour scaffolding, such as goal setting and repeated prompts, appears to be a more valuable strategy for reducing exposure. The review also highlighted the potential risk compensation associated with “protective” app features, such as sunscreen use or alarms, and their impact on decision heuristics, with a need to also consider protective behaviours and perceptions of safety.

The survey therefore quantified baseline levels of UV risk and protective behaviours, as well as digital readiness to support the proposed wearable UV sensor and smartphone application concept. It also assessed awareness and experience with UV monitoring, as well as benefits and barriers to adoption and continued use, such as accuracy, privacy, and cost. Eligible participants were adults aged 18 years and above. Inclusion was via convenience sampling, using university mailing lists and professional networks. The survey was open from 3 December 2025 to 14 January 2026.

Ethical clearance was not required for this study, which used this questionnaire survey. The study was conducted on a voluntary basis, with participants providing consent as described on the first page of the online questionnaire. No direct identifiers were collected, and the results were aggregated for the study. The results were securely stored, with access restricted to the researcher.

3.8. Questionnaire instrument

Questionnaire items were developed for this study and were informed by the scoping review findings. The instrument was not derived from validated psychometric scales, and no formal pre-testing or psychometric validation was undertaken. Therefore, results are interpreted primarily as descriptive and exploratory. The questionnaire consisted of six domains (A–F), each corresponding to one of the translational determinants identified in the scoping review. The domains are as follows:

A. Participant profile and UV risk indicators (age, gender, country, education level, occupation, skin type, personal and/or family history of skin cancer).

B. UV exposure and sun protection practices (time spent outdoors, sunburn frequency, sunscreen use, other sun protection habits, attitudes towards tanning, perceived risk).
C. Digital readiness (use of wearables, health-related smartphone apps).
D. Awareness and prior use of UV monitoring (prior exposure to UV wearables, prior use of UV monitoring apps/devices).
E. Acceptance, perceived benefits, and barriers (Likert scale for perceived benefits, ease of daily use, aesthetics, willingness to receive notifications, privacy and accuracy concerns, cost barriers, social endorsement, data integration, and additionally, purchase likelihood).
F. Preferences for design and implementation (preferred wearable format, preferred alert types, usage contexts).

Most of the items were ordinal, nominal and scale. The Likert-type and behavioural frequency items were used for the attitudinal and intention questions. For the Likert-type questions, a 5-point Likert scale was used.

3.9. Data management and variable preparation

For data management and preparation, the first step was to import the data into "IBM SPSS Statistics" (v30). Variable naming was standardised, and text was preserved in the variable labels. All variables were checked for completeness and plausibility.

Likert-type questions were coded as labelled strings ("4 – Agree"), and their numeric equivalents (1 to 5) were also computed for convenience in calculations and association tests. The original labelled variables were retained for maximum interpretability.

3.10. Statistical analysis plan

Given the cross-sectional design and the predominantly nominal or ordinal level of measurement of the questionnaire items, the analysis primarily focused on descriptive statistics and bivariate association tests.

Characteristics of participants, UV risk indicators, sun exposure behaviours, protection strategies, digital readiness/awareness, and preferences for design/implementation were analysed using frequencies and percentages for nominal variables. For Likert-type scales and other ordinal variables, the distribution of responses was reported. Where appropriate, central tendency was summarised using medians and interquartile ranges (IQR).

Where appropriate, composites were developed to represent underlying constructs. These were computed as mean item scores across related variables. The composites were Perceived Benefits (E1, E2, E3, E4, E5, E9, E10) and Perceived Barriers (E6, E7, E8). The internal reliability of these composites was assessed using Cronbach's alpha.

The association between adoption outcomes (purchase intent) and potential predictors (awareness, wearable usage, perceived benefits/barriers, and some behavioural variables) was analysed using the Chi-square test of independence for grouped nominal variables and Spearman's rank correlation coefficient (ρ) for ordinal variables. All tests were two-tailed with statistical significance set at $p < .05$.

Chapter 4: Results

4.1. Evidence map summary

Table B1 (n = 29) in Appendix B indicates that publications are concentrated in the most recent period (2021-2025), with a peak in 2024 (n = 12, 41%). The next highest count is 2022 (n = 6, 21%). Similar values are reported in 2021 (n = 4, 14%) and 2023 (n = 4, 14%), with the lowest in 2025 (n = 3, 10%).

Most included publications are in sensors/materials or other engineering fields (n = 24, 83%), with the smallest subset in clinical or public health-related journals (n = 5, 17%). Geographically, the evidence base is dominated by studies from China (n = 11, 38%), the United States (n = 6, 21%), and the Republic of Korea (n = 5, 17%). Fewer are from India (n = 2, 7%). Single-country or across-country collaborative studies comprise Brazil, Australia, China-Russia, China-Germany, and Finland-Denmark (n = 1 each; 3%).

In terms of study design, experimental studies are most common (n = 22, 76%). These are followed by randomised controlled trials (RCTs) (n = 3, 10%) and observational studies (n = 2, 7%). One study is an experimental development/validation usability study (n = 1, 3%), and one is a developmental/proposal-based study (n = 1, 3%). Human participants aligned consistently with the study design, as most studies had no human participants (n = 18, 62%). Among studies with human participants (n = 6, 21%), a defined sample size was reported. A further three studies (n = 3, 10%) included human participants but did not define the sample size, and two studies did not specify the participants' details (n = 2, 7%).

Wearable UV sensors (or their components) vary substantially in form factor. Among devices with a specified body location, wrist-worn devices were most common (n = 8, 28%), followed by fibre-based devices or textiles (n = 6, 21%), and skin or patch-based devices (n = 3, 10%). Specialised systems include chest monitors, a cap-based design, or a “band” device with unspecified location (each n = 1, 3%). A substantial proportion is classified as flexible wearables without a specific location on the body (n = 9, 31%).

Digital integration varies among studies, ranging from personalised smartphone apps (n = 11, 38%) to Bluetooth connectivity (n = 8, 28%). One system uses the near-field communication function to interact with an Android app (n = 1, 3%). However, some studies explicitly report cloud upload or server storage (n = 2, 7%). A substantial proportion of the studies specifically do not use a smartphone or any digital component (n = 10, 34%). Overall, the primary stated goal is technology development and validation (n = 22, 76%). A smaller set is related to translational evaluation studies (n = 6, 21%), focusing on exposure assessment and outcome measures of symptoms, behaviour, usability studies, and sunburn-related outcomes. The remaining study is proposal-based (n = 1, 3%). The distribution of studies by publication year, discipline, geography, and study design is summarised in Table B1. The

next subsection identifies the technological platforms and sensing mechanisms reported for the included devices (Table B2).

4.2. Main Results of Scoping Review

4.2.1. Taxonomy of Wearable UV Sensors

Based on the studies included in Table B2 (n = 22) in Appendix B, the most common platform format is wrist-worn (as bracelets, wristbands, wrist-type monitors, or wristband-integrated electronics). Other categories include skin-attached patches or stickers, textiles or garment-attached sensors and devices placed on the head or chest. The categories may not be mutually exclusive, as at least one study includes multiple formats.

From a technological perspective, devices can be classified into two principal classes. First, passive photochromic or colour-changing methods (n = 9, 41%) rely on visible colour changes or fluorescence. They are described as power-free or readable with the naked eye, sometimes with further processing.

Within photochromic materials, the matrix is typically PDMS, combined with a photochromic film in a laminated structure. Other approaches include photochromic perovskite nanoparticles in solvents to induce fluorescence. Further examples include spiropyran-derivative photochromic materials electrospun with polyurethane to induce colour change in textiles, and mineral photochromic materials such as hackmanite used in textiles and prints. A further subgroup uses cellulose-based materials (bacterial cellulose films or textiles), with photochromic dyes produced through microbial fermentation. In parallel, hydrogel colourimetric technologies form a distinct group. These use a wearable hydrogel as the colourimetric sensor, with dye photo-oxidation encapsulated within an ionic hydrogel matrix for wrist-worn use.

Second, the photoelectric category (n = 13, 59%) focuses on semiconductor or junction materials to quantify UV exposure effects, often incorporating wireless connectivity and smartphone-based display. Materials are more heterogeneous, but the designs are clearly device oriented. Examples include inorganic semiconductors such as ZnO (as nanorods for UV detection or within an electrolyte-gated transistor). III-N materials, such as InGaN/GaN, are also used in microphotodetectors within skin-conforming porous patches, optimised for sensitivity across relevant UVA bands. Other systems use heterojunctions such as CuO, carbon hydrogel, ZnO, and carbon with an ion-conductive hydrogel interconnection to support strain persistence and Bluetooth alarm signalling. Perovskites such as CsPbCl3 or methylammonium lead chloride are also integrated into wristband platforms with flexible circuitry and smartphone display. Organic photodetectors are represented by photomultiplication-type devices incorporating an identified organic component on polyethylene terephthalate (PET)/ indium tin oxide (ITO) substrates. Finally, some implementations use pre-packaged UV sensors with

microcontrollers and energy-harvesting components, such as ethylene tetrafluoroethylene (ETFE) solar panels or commercial UV sensors.

Spectral coverage is reported inconsistently, limiting comparability across entries in the table: some instruments target the UVA region (such as 365 nm), others specifically describe the ability to detect both UVA and UVB, while a few indicate the ability to detect UVC. In contrast, several entries describe the extent of coverage as “not specified” or do not document differentiation between UVA and UVB.

However, reported application functionalities converge around exposure tracking and protection-oriented feedback, including real-time intensity estimation, total dose tracking, UVI presentation, and threshold alerts through mobile apps or wireless connectivity. Examples include real-time estimation and alerts through apps, personalised alerts with total dose, and erythemally weighted exposure with variable daily limits. Additional functions include threshold alerts for patients with skin conditions and real-time transmission of user inputs on sunscreen and clothing. Other features include variable thresholds and logging, real-time UVA with cumulative daily UVB exposure, and smartphone presentation of UVI or intensity displays.

A smaller but visible subset focuses on robustness and wearability under deformation and typical daily-life conditions (such as durability under bending and extended storage, washing and flexibility, stretchable textile functionality, and use in the presence of sweat and skin by-products). Taken together, the application functionalities column of Table B2 indicates that technological capability and interface delivery of UV exposure remain the dominant focus. However, decision-criteria tailoring is less frequently described, including skin type chosen by the user, adjustability of exposure limits, observation/removal of sunscreen and logging of sunscreen use with SPF adjustment. Table B2 predominantly comprises technology development and validation studies. A smaller subset addresses user engagement and behaviour and is synthesised in Table B3.

4.2.2. Behaviour Change and Engagement

Table B3 in Appendix B synthesises five intervention studies (n = 5) that position wearable UV sensors as tools to support behaviour, using heterogeneous designs that extend clinical endpoints, objective UV exposure, habit assessment, and acceptability or usability outcomes.

Across the literature, the behavioural aim is uniformly stated as reducing UV risk via feedback, goal setting, or alerting, yet empirical results show marked heterogeneity. Dumont et al. (2024) specified behaviour change via real-time tracking and individualised alerting designed to encourage sunscreen use, protective garment use, and seeking shade, as well as track secondary endpoints including actinic keratoses, non-melanoma skin cancers, psychosocial variables, and behavioural

outcomes. However, recorded rates of sunscreen application were low (typically once or twice per week). The study mentioned that individuals with more than one lesion at disenrolment had a higher mean daily dose than those with 0 or 1 lesions (0.60 versus 0.33 SED), indicating a relationship between higher UV dose and lesion burden in this sample. Sunburn incidence was not reported, and shade-seeking or protective garment use was not tracked as behavioural endpoints. Lin et al. (2024) focused on baseline behavioural assessment and intentions, reporting changes towards intended sunscreen use, protective garment use, and increased UV awareness. However, the study did not assess UV dose or sunburn outcomes, effectively anchoring the outcome in intentions and subjective learning. By contrast, the study proposed a companion smartphone application for individualised tracking, without assessing its utility. Robinson et al. (2021) assessed the impact of a wearable device, goal setting, and daily text messaging, reporting a reduction in UVR from day 1–10 to day 11–21, as well as the absence of sunburn during the intervention, suggesting a more direct behavioural technique-objective outcome relationship in the dataset. Vogel et al. (2023) assessed change using a composite score of six sun behaviours. They reported no statistically significant differences in objectively measured dose during peak times, as well as full-day measurement, nor in self-reported sunburn rates. This indicates a lack of behavioural impact despite the provision of devices, but reporting greater attentiveness to the device/application in ways that could have impacted behavioural outcomes. Finally, Yang et al. (2023) focused the intervention on skin-specific tracking designed to alert users to sunscreen application and prevent erythema. Though the study reported no clinical outcomes and no sunburn outcomes, it contributed primarily to the evidence on wearability and the absence of cutaneous side effects.

Across Table B3, behavioural effects are most often demonstrated through engagement, acceptability, and self-report measures. Objective UV dose and sunburn results are less frequently documented and, where reported, demonstrate variable or study-specific effects.

Compliance data also suggest the potential for, and the limitations of, adherence and implementation: Dumont et al. (2024) reported summer compliance with wearables of over 75% and less than 50% after November, with weekly use and threshold setting. Lin et al. (2024) found a high level of adherence to use and functions, though no use of the application. Robinson et al. (2021) reported daily use with smartphone synchronisation and perceptions of the value of real-time data. Vogel et al. (2023) reported 75% use of the devices at least five days a week and a high rate of application downloads, though significant technical problems (about 40%) affected use. Yang et al. (2023) reported a focus on comfort and the absence of adverse reactions in everyday use. Overall, these data support a cautious conclusion. The wearables appear generally acceptable and usable in these studies, though the observed behavioural and exposure outcomes are highly inconsistent and, in some cases, heavily circumscribed by outcome choices and implementation considerations.

4.2.3. Effects on UV Dose and Sunburn

Table B4 summarises three clinical trials (n = 3) examining whether wearable UV sensors can reduce UV dose and sunburn incidence, while indicating that observed effectiveness varies with device features and outcome selection.

In terms of endpoints, Table B4 describes mixed effects that are, in some instances, endpoint-specific effects. Dumont et al. (2024) studied a wearable dosimeter (Shade UV sensor) in addition to standard UV protection counselling, compared to counselling alone, in a senior population with actinic keratosis over six months. The main outcome was the actinic keratosis incidence rate. Secondary outcomes included non-melanoma skin cancer incidence and UV exposure in Standard Erythemal Dose (SED), although a change in the group mean UV dose was not specified. Instead, the study specifies that, in August and September, individuals with more than one lesion at disenrolment had a higher mean daily dose than those with 0 or 1 lesions (0.60 versus 0.33 SED; $p = 0.0354$). Sunburn incidence was not evaluated, and sunscreen use in the intervention group was reported as once or twice a week during summer. In this regard, results were inconclusive for actinic keratosis (20% reduction in incidence rate ratio; $p = 0.44$) but differed for non-melanoma skin cancer (95% reduction in incidence rate ratio; $p = 0.024$), indicating that the signal varied by outcome in this study.

Conversely, Robinson et al. (2021) mention effectiveness through changes in the dose of UVR over time and the added value of structured behaviour change practices. In a randomised study of melanoma patients lasting 21 days, both groups used a wearable UV sensor with a smartphone app and text messages daily. Nonetheless, structured goal setting is compared with unstructured goal setting. The main endpoint was the decrease in daily UV doses from Days 1-10 to Days 11-21, with the aim of keeping doses below each participant's maximum tolerated dose. The study reports a significant decrease in daily UVR doses following goal setting. However, the decrease was more pronounced with structured goal setting as opposed to unstructured goal setting. Notably, there was no sunburn during the intervention period. Vogel et al. (2023) provide a more cautionary note in a 12-week telehealth RCT among melanoma survivors conducted across two summer waves of 2020 and 2021. The intervention group received the Shade (second generation) wrist wearable with an application providing exposure notifications, a sunscreen notification application, and real-time exposure information. The control group received the same wearable with a research application that recorded exposure without exposure information or notifications. The primary outcome was the composite sun-habit score at 12 weeks. For UV dose, the table reports a difference between sunscreen-feature users in sunscreen-modified UVR exposure and objective UVR exposure (median 63 vs 87 J/m^2). The table further indicates higher objective exposure among sunscreen-feature users than among non-users (median 87 vs 56 J/m^2; $p = 0.03$). Rates of sunburn did not significantly differ between groups (control

14.4% vs intervention 12.7%; p = 0.75). Both groups reported rates of <15% during the intervention and 30% at baseline. The overall assessment is clearly negative at the between-group level regarding significant changes in sun-protection behaviours, UVR exposure, or rates of sunburn. These patterns are attributed to device problems, high levels of existing protection behaviour at baseline, and insufficient sun protection messages in the intervention application. Survey results are included to contextualise user preferences and barriers relevant to the proposed UV wearable concept.

4.3. Results of Survey Questionnaire

Survey questionnaire results are reported for 66 respondents. The results are presented for participant characteristics, sun exposure and protection, attitudes and knowledge, digital health engagement and UV monitoring, acceptability and preference of the concept of a UV wearable, perceived benefits and barriers (E-items), as well as exploratory bivariate findings.

4.3.1. Participant Characteristics

Most participants were aged between 18 and 24 years (42.4%, n = 28) or 25 and 34 years (27.3%, n = 18). Fewer participants were aged 35-44 (12.1%, n = 8), 45-54 (15.2%, n = 10), or ≥55 years (3.0%, n = 2). Two-thirds of participants were female (66.7%, n = 44), and one-third were male (33.3%, n = 22). Most participants reported residing in Portugal (89.4%, n = 59), followed by Greece (4.5%, n = 3), and Ireland, Romania, Spain, and Switzerland (each 1.5%, n = 1).

Most participants reported holding a bachelor's degree (48.5%, n = 32) or a master's degree (25.8%, n = 17). Fewer participants reported having a secondary degree (16.7%, n = 11), a doctoral degree (6.1%, n = 4), a primary degree (1.5%, n = 1), or "other" (1.5%, n = 1).

Most participants were employed (54.5%, n = 36), followed by students (36.4%, n = 24) and self-employed/freelancers (9.1%, n = 6). The most reported skin type was fair/light skin that burns easily but tans little (47.0%, n = 31). Fewer participants reported having light/medium skin that sometimes burns but gradually tans (33.3%, n = 22). Less frequently reported categories included light brown/olive skin that rarely burns (10.6%, n = 7), very fair/pale-white skin that always burns but never tans (6.1%, n = 4), very dark/black skin that never burns (1.5%, n = 1), and "don't know/prefer not to say" (1.5%, n = 1). No participants reported a diagnosis of skin cancer (100% "No", N = 66). Regarding family history, 10.6% of participants (n = 7) reported having a close relative diagnosed with skin cancer, 86.4% (n = 57) reported no family history, and 3.0% (n = 2) selected "I don't know/prefer not to say".

4.3.2. Exposure to the sun, sunburn, and sun protection behaviours

For a usual weekday in spring, summer, or autumn, the most common time spent outdoors was 1-2 hours (39.4%, n = 26), followed by 30-60 minutes (27.3%, n = 18). Less frequently reported categories were 2-4 hours (16.7%, n = 11), >4 hours (9.1%, n = 6), and <30 minutes (7.6%, n = 5).

Regarding sunburn frequency, the most common response was 1-2 times per year (39.4%, n = 26), and less than once per year was also common (36.4%, n = 24). Of the sample, 12.1% (n = 8) reported never experiencing sunburn, 9.1% (n = 6) stated sunburn between 3 and 4 times per year, and 3.0% (n = 2) reported ≥5 times per year. For the derived item on high-frequency sunburn (≥3 times per year), 12.1% of the sample responded “Yes” (n = 8).

When at the beach or pool, the most common response regarding sunscreen use (SPF≥30) was “very frequently” (51.5%, n = 34), followed by “often” (25.8%, n = 17). “Occasionally” and “rarely” were reported by 19.7% (n = 13) and 3.0% (n = 2), respectively.

Other protective behaviours varied in terms of frequency, with hat/cap use reported by 30.3% as “often” or “very frequently”, 30.3% as “occasionally”, 22.7% as “rarely”, and 16.7% as “never”. Covering clothing was reported by 48.5% as “often” or “very frequently”, 21.2% as “occasionally”, 25.8% as “rarely”, and 4.5% as “never”. Sunglasses use was reported by 60.6% as “often” or “very frequently”, 21.2% as “occasionally”, 10.6% as “rarely”, and 7.6% as “never”. Finally, seeking shade during peak hours was reported by 69.7% as “often” or “very frequently”, 22.7% as “occasionally”, and 7.6% as “rarely”, with no respondents selecting “never”.

4.3.3. Attitudes and Perceived Knowledge

Most respondents agreed or strongly agreed that they like having a suntan (63.7%), compared with neutral (24.2%) and disagree/strongly disagree (12.1%). Most respondents also agreed or strongly agreed that sun exposure is dangerous in their country, with 68.2% selecting this option, compared with 21.2% neutral and 10.6% disagree/strongly disagree. Concern about skin cancer risk was also frequent, with 65.2% selecting agree/strongly agree, 27.3% neutral, and 7.5% disagree/strongly disagree. Finally, perceived sufficiency of information about sun protection was less consistent, with 57.5% selecting agree/strongly agree, 30.3% neutral, and 12.1% disagree/strongly disagree.

4.3.4. Digital Health Engagement

Current usage of wearables was 36.4% (yes, every day: 28.8%, n = 19; yes, occasionally: 7.6%, n = 5). A further 27.3% reported past wearable use (n = 18), and 36.4% reported never having used a wearable (n = 24). Among the wearables mentioned at least once (n = 25), smartwatches were most popular, accounting for 72.0% (n = 18), followed by fitness bands/activity trackers (36.0%, n = 9) and

sports watches (12.0%, n = 3). The percentages are based on the proportion of cases and do not sum to 100% since the question was a multiple-response item, allowing selection of more than one category (total selections = 30).

The use of health-related smartphone apps was 63.7% (yes, one or two apps: 57.6%, n = 38; yes, several apps: 6.1%, n = 4), whereas 36.4% reported never having used such apps (n = 24).

Awareness of wearable UV sensors was low: 80.3% of respondents had not heard of them (n =53), 16.7% had heard of them (n =11), and 3.0% were unsure (n =2). Previous use of UV monitoring devices or apps was also uncommon: 92.4% had never used them (n = 61), 6.1% had used them in the past (n = 4), and 1.5% reported current use (n = 1).

4.3.5. Acceptability and preferences of the UV wearable concept

The purchase likelihood for a UV wearable priced at 30-50 euros was: very unlikely: 13.6% (n = 9), unlikely: 27.3% (n = 18), neither unlikely nor likely: 30.3% (n = 20), likely: 22.7% (n = 15), very likely: 6.1% (n = 4). The mean purchase likelihood score on the 1-5 scale was 2.80 (SD = 1.13). When grouped, 40.9% were unlikely or very unlikely (n = 27), 30.3% were neutral (n = 20), and 28.8% were likely or very likely (n = 19).

The most preferred device format was a watch (36.4%, n = 24) or a wristband (31.8%, n = 21), followed by a skin patch/sticker (10.6%, n = 7). The least preferred formats were clips for clothing and glasses/accessories, each with 7.6% (n = 5). Furthermore, 6.1% of respondents expressed that they would not use any of the provided formats (n = 4). The most preferred alert methods were a smartphone notification (50.0%, n = 33) or a vibration on the device (30.3%, n = 20). A change of colour or light on the device was chosen by 18.2% (n = 12), and only 1.5% would choose sound-based alerts (n = 1). The situations for using the device were mostly at the beach or swimming pool (42.4%, n = 28) or during everyday activities such as walking or running (36.4%, n = 24). Other options were using the device during outdoor sports/exercising (9.1%, n = 6) and during weekend outdoor activities (4.5%, n = 3). In addition, 7.6% (n = 5) reported that they did not see themselves using the wearable UV sensors.

4.3.6. Perceived benefits and barriers (E-items): item-level results and indices

Across E1-E10, the level of agreement was high among the benefit-oriented items (E1-E5, E9-E10), while for the barrier-oriented items (E6-E8), it was more mixed. The item-level descriptive results are summarised below, using a 1-5 scale to measure the level of agreement. The results are presented below:

- E1 (avoid sunburn): M = 3.83, SD = 0.81; agree/strongly agree = 72.7% (n = 48);
- E2 (help prevent skin cancer): M = 3.94, SD = 0.80; agree/strongly agree = 75.8% (n = 50);

- E3 (use if easy in daily life): M = 3.76, SD = 0.93; agree/strongly agree = 72.7% (n = 48);
- E4 (use if discreet/aesthetically pleasing): M = 3.83, SD = 0.97; agree/strongly agree = 74.2% (n = 49);
- E5 (willing to receive phone notifications): M = 3.88, SD = 1.00; agree/strongly agree = 75.8% (n = 50);
- E6 (privacy concern): M = 3.23, SD = 1.24; agree/strongly agree = 40.9% (n = 27);
- E7 (accuracy/reliability concern): M = 3.82, SD = 0.96; agree/strongly agree = 71.2% (n = 47);
- E8 (price as barrier): M = 4.38, SD = 0.92; agree/strongly agree = 90.9% (n = 60);
- E9 (recommend to at-risk friends/family): M = 4.17, SD = 0.85; agree/strongly agree = 77.3% (n = 51);
- E10 (value of integrating UV with other health data): M = 4.02, SD = 0.87; agree/strongly agree = 77.3% (n = 51).

Composite indices of perceived benefits and barriers were computed as the mean of the relevant items. The perceived benefits index (E1, E2, E3, E4, E5, E9, E10) had a mean of 3.92 (SD = 0.65), a median of 4.00, and an interquartile range (IQR) of 3.60–4.40; 56.1% scored ≥4.00 (n = 37). Internal consistency was high (Cronbach's α = .850; 7 items). The perceived barriers index (E6, E7, E8) had a mean of 3.81 (SD = 0.85), a median of 4.00, and an IQR of 3.33–4.33; 51.5% scored ≥4.00 (n = 34). Internal consistency was acceptable (α = .733; 3 items). Exploratory analyses are reported to indicate which perceived benefits and barriers align with purchase likelihood, although sparse expected counts limit inference.

4.3.7. Exploratory bivariate associations

Exploratory tests were conducted to assess relationships between purchase likelihood and selected behavioural and attitudinal variables.

No association was found between grouped purchase likelihood (unlikely/neutral/likely) and status of being a wearable user ($\chi^2(2) = 3.052$, $p = 0.217$; $N = 66$). Similarly, no association was found between grouped purchase likelihood (unlikely/neutral/likely) and prior awareness of wearable UV sensors ($\chi^2(2) = 1.686$, $p = 0.430$; $N = 64$), with sparse expected counts (50.0% of cells < 5, minimum expected count = 3.09).

A statistically significant positive correlation was observed between purchase likelihood (1-5) and E1 (avoid sunburn) ($\rho = 0.247$, $p = 0.046$; $N = 66$), E2 (help prevent skin cancer) ($\rho = 0.255$, $p = 0.039$; $N = 66$), E9 (recommend to at-risk friends/family) ($\rho = 0.264$, $p = 0.032$; $N = 66$), and the perceived benefits index (E1, E2, E3, E4, E5, E9, E10) ($\rho = 0.248$, $p = 0.044$; $N = 66$). A statistically significant negative correlation was observed for E8 (price as barrier) ($\rho = -0.245$, $p = 0.048$; $N = 66$). No significant

correlation was observed with the perceived barriers index (E6, E7, E8) (ρ = 0.038, p = 0.762; N = 66). No significant correlation was observed with prior awareness of UV wearables (D1) (ρ = -0.074, p = 0.561; N = 64). These associations are visually summarised in Figure 4.1.

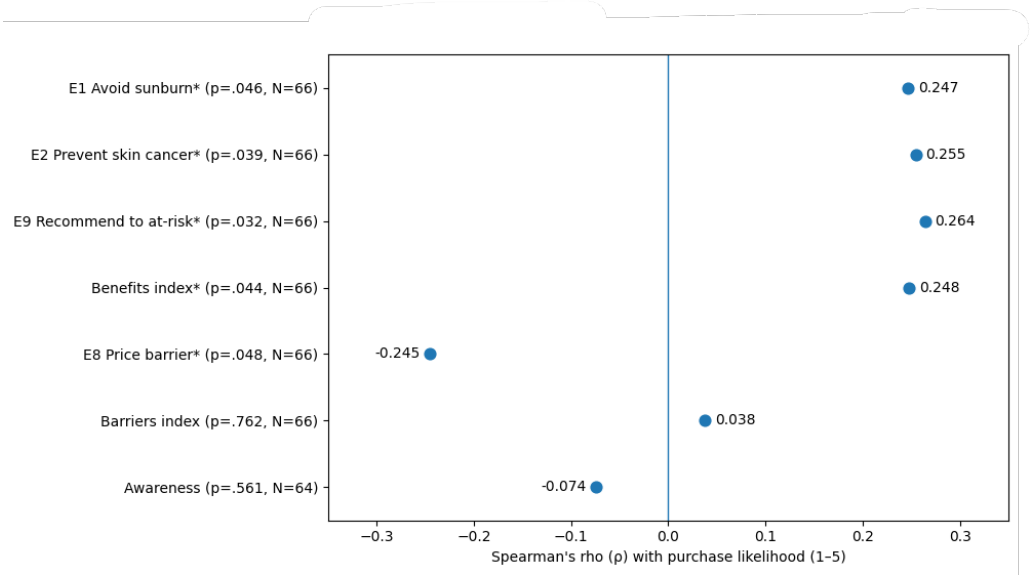


Figure 4.1. Spearman correlations between purchase likelihood (1–5) and selected attitudes or indices.

A statistically significant association was found between ordinal sunburn frequency and sunscreen use (1 - 5) ($\chi^2(12) = 21.862$, p = 0.039; N = 66). Sparse expected counts were observed in this crosstabulation (75.0% of cells with expected count <5; minimum expected count = 0.06).

Chapter 5: Discussion

5.1. Interpretation of Results

This thesis examined the role of wearable UV sensors in skin cancer prevention by integrating two evidence components: a scoping review of device types and evaluation approaches, and a user survey investigating behaviours, attitudes, digital use, and acceptability of the UV wearable concept. To interpret these results within the digital health prevention context, it is necessary to articulate a plausible causal connection between sensing, feedback, and behaviour change. Across both components, the evidence indicates rapid technological development, while findings on downstream prevention impact remain inconsistent.

The scoping review indicates a heterogeneous yet structured landscape of wearable UV sensing, in which engineering development and validation predominate over human-outcome evaluation. Most publications occur between 2021 and 2025, peaking in 2024, and are primarily published in sensors/materials/engineering journals. These articles predominantly comprise experimental studies without human participants. Consequently, stated objectives are mainly oriented towards technology development and validation. This evidence has direct implications for prevention. The field is currently focused on feasibility, sensing capabilities, and integration, with comparatively little evaluation of whether devices can change human behaviours in real-world contexts.

Regarding form factor, wrist-based and flexible wearable devices dominate, with additional representation from fibre/textile-based devices and more specialised placements such as skin patches. The survey supports the practical appeal of wrist-based form factors. When presented with a UV wearable concept, respondents preferred watches (36.4%) or wristbands (31.8%), while the remaining respondents preferred skin patches/stickers (10.6%) or other accessories. Therefore, the predominant form factor (watches or wristbands) in the development literature is also the preferred form among participants in everyday use.

A significant contribution of Table B2 is that it identifies devices not only by their form factor but also by their sensing mechanism and material strategy. Two technical classifications of wearable UV sensors can be distinguished: passive photochromic or colour-change (41%) and photoelectric solutions (59%). This distinction is important for prevention, as it suggests different user experiences and behavioural mechanisms. Passive systems integrate interpretation into the sensing material, providing a low-burden user experience. Immediate visibility (colour or fluorescence change) is achieved when they are implemented in wearables, for example, as photochromic layers based on polydimethylsiloxane (PDMS), cellulose substrates with photochromic dyes, mineral photochromic textile coatings, and hydrogel colourimetric structures. The preventive benefit of passive

photochromic solutions lies in frictionless visibility and low dependence on digital infrastructure, although this depends on whether interpretation is adequate and actionable in real-world exposure contexts.

In contrast, photoelectric solutions generate electronic signals and depend on a digital layer for interpretation and feedback. They use semiconductor structures, including ZnO-based components, III-nitride microphotodetectors embedded in porous substrates, heterojunction configurations linked through ion-conductive hydrogel interfaces, perovskite materials incorporated into flexible electronic circuits, and organic-based photodetectors. These devices offer preventive benefits that involve measuring levels of UV exposure, tracking trends in UV exposure over time, and providing a customised user experience. However, this is subject to various implementation issues that involve the accuracy and reliability of the device, its connectivity capabilities, power supply constraints, and user feedback interfaces.

Notably, digital feedback expectations and the design-to-use gap suggest a more substantial gap between device designs and user expectations. In the scoping review, a substantial proportion of studies did not incorporate a smartphone or digital component (34%), whereas others incorporated a personalised application (38%) and Bluetooth technology (28%). Within the survey sample, digitally mediated feedback was preferred as an alert mechanism. The most selected alert modality was a smartphone notification (50.0%), followed by device vibration (30.3%), whereas 18.2% preferred a colour/light change, and almost no participants preferred sound. However, both non-digital and digital designs are represented in the literature. These findings suggest that prevention-oriented designs may be more acceptable when they incorporate established smartphone notification mechanisms. This interpretation is consistent with the relatively high proportion of participants reporting health application use (63.7%), indicating that app-mediated feedback would not be unfamiliar within this sample.

The materials and sensing synthesis further clarifies that the device category is not merely a matter of classification but also of interface and interpretability. For example, a passive photochromic system that changes colour with exposure is functionally different from an instrumented photoelectric system that quantifies exposure and can generate numerical feedback. This supports the proposed approach in the prevention framework, where actionability is related to the interpretability of the feedback, not only to the sensing technology itself.

The synthesis further highlights a comparability limitation in exposure. Spectral response and differentiation between UVA and UVB are not consistently specified across devices. As a result, similarity of form factor does not necessarily equate to interpretability of exposure outputs, which is likely to be essential if users are expected to respond to thresholds or cumulative measures as part of

prevention. In this context, the limited spectral clarity is related to the synthesis problem, as well as the implementation problem.

Across the intervention studies summarised in Table B3, wearable UV sensors are described as tools for behavioural support through feedback, goal setting, reminders, and alerts. However, reported outcomes vary widely in depth and type, ranging from feasibility and acceptability to self-reported intentions, and, less consistently, objective exposure and sunburn outcomes. Across the reviewed studies, intervention benefit is most consistently evidenced by self-reported outcomes, whereas objective UV dose and sunburn outcomes are absent, unquantified, or mixed. This pattern supports a prevention-relevant interpretation: sensing and feedback may be necessary components of intervention design, but they do not guarantee behaviour change in real-world conditions. The benefit is more likely when the intervention effectively bridges awareness and actionable self-regulation.

The comparative studies in the review suggest that behavioural scaffolding may be important. In Robinson et al. (2021), a wearable sensor was combined with a mobile app and text messaging. The results demonstrated that the reduction in UV exposure was more significant for the achievement of structured goals than for the achievement of unstructured goals, while no sunburn was reported during the study. This pattern is consistent with a pathway in which the intervention supports behaviour change through explicit goal-based self-regulation rather than awareness alone. According to Vogel et al. (2023), the proposed feature-rich wearables are not necessarily protective. In that study, there was no significant between-group improvement in sun protection practices, UV exposure, or sunburn, alongside discrepancies between app-calculated exposure time and objectively measured UV exposure in sunscreen feature users. Taken together, these studies indicate that the addition of system features does not always lead to behaviour change, particularly if the information provided is insufficiently contextualised. Baseline behaviour is not adequately addressed, or there are barriers to usability and engagement that hinder effective system use.

The survey results help explain the apparent gap between awareness and protective behaviour. The participants showed possible motivational ambivalence, reporting awareness of the risk of skin cancer, expressing concern about skin cancer risk, and reporting a preference to attain a suntan. In such a context of motivational ambivalence, awareness alone may not necessarily translate into actual behaviour change. This accords with the review's suggestion that monitoring alone may need to be supplemented with support that is timely, action-enabling, and persuasive enough to offset the exposure-seeking behaviours that can occur during periods of high UV risk.

The results of the survey on acceptability and perceived value also contribute to the feasibility of adoption. Purchase likelihood of the 30-50 euros UV wearable was found to be moderate (M = 2.80), with more respondents reporting that they were unlikely to purchase the product than likely to purchase it. The respondents perceived the benefits of the wearable to be high (M = 3.92), with high

internal reliability. Participants also perceived barriers to purchasing the wearable as high (M = 3.81). Purchase likelihood correlated with some perceived benefit items and the benefit index, but it was not correlated with the overall barriers index, prior wearable use, or knowledge of UV wearable products. However, the individual price-barrier item showed a weak negative correlation with purchase likelihood. This could imply that purchase likelihood, and thus initial acceptance, is less related to prior wearable adoption and more to whether perceived benefits are sufficiently clear to justify engagement. This interpretation is consistent with the scoping review's emphasis that technical reliability and compliance with wearable use are not trivial issues in real-world conditions.

The controlled evidence base (Table B4) is small but informative about how prevention outcomes may be more or less likely. Across the three studies, reported effects varied by endpoint and appeared sensitive to ancillary intervention components (counselling, structured goal setting, app components) and to the endpoints selected (clinical lesions, UV dose, behavioural endpoints). Dumont et al. (2024) illustrate endpoint sensitivity and reporting limitations, where the incidence of actinic keratosis was inconclusive, and the incidence of non-melanoma skin cancer was more favourable. Robinson et al. (2021) provide clearer support for a pathway in which exposure reduction is linked to structured goal setting, although the short trial duration prevents conclusions regarding the maintenance of benefits in the longer term. Vogel et al. (2023) stress the importance of component performance and integration in interventions, with no significant between-group effects on sunburn incidence and objective exposure measures. The study underscores the prevention relevance of evaluating interventions beyond experimental settings by taking into consideration exposure contexts and implementation.

These findings shed further light on implementation and real-world prevention. The survey indicates substantial outdoor exposure time (most frequently 1–2 hours on a typical weekday) and non-negligible sunburn experiences, supporting an ongoing need for preventive support in everyday contexts. An exploratory association was found between sunburn frequency and the use of sunscreen, although the expected cell counts were small and should be interpreted carefully. This association does not imply directionality. With respect to implementation, intended use was concentrated in high-exposure settings (beach or pool) and routine outdoor activities (walking or running), precisely the contexts in which wearable alerts and feedback may be useful. These patterns help contextualise null effects in controlled studies when baseline protection is already high in some populations, while also suggesting that prevention tools may be most useful for supporting repeated decision-making in routine exposure settings rather than only episodic high-risk events.

The overall evidence suggests that measurement comparability is an understudied but important contributor to overall effectiveness. The materials synthesis identified inconsistencies in spectral reporting and unclear differentiation between UVA and UVB in some devices, while also showing that

intended app functions (cumulative dose, UV index, and threshold-based alerts) tend to converge. If preventive benefit depends on threshold-based determinations and feedback, then inconsistencies in measurement definitions may impair scientific interpretability and user understanding. The reduction in interpretability may lower the probability of engagement and reduce the overall preventive effect.

5.2. Limitations of the Study

As indicated by the scoping review, the evidence landscape remains concentrated on experimental development and validation, with relatively few controlled or observational studies in humans. This distribution limits the scope for definitive conclusions regarding prevention outcomes, because most identified studies are not designed to demonstrate changes in UV dose, sunburn, or other clinically important endpoints. In the controlled studies, the number of studies was small (n = 3), and endpoints varied substantially, ranging from clinical lesions to behavioural composites to exposure metrics. This review indicates inconsistencies in the reporting of spectral coverage and the differentiation of UVA and UVB, thus creating challenges for interpreting the results obtained from exposure outputs.

Although the survey provides insight into user context, it has several limitations. The number of participants was relatively small (N = 66), and they were predominantly residents of Portugal. The age range was also biased towards a younger population, and no participants reported a diagnosis of skin cancer. Inferential analyses were exploratory, and at least one statistically significant chi-square result involved sparse expected cell counts.

5.3. Suggestions for Future Research

In sum, the combined evidence indicates several priorities for prevention-oriented knowledge development in wearable UV sensors. First, there is a need for more human evaluation studies that move beyond feasibility to outcomes that are explicitly prevention-oriented. The controlled studies already suggest that effectiveness is endpoint- and scaffolding-specific. Therefore, further evaluations should assess which behavioural procedures are required for benefit, including structured versus unstructured approaches and the nature of the information delivered via applications or alerts.

Second, comparability should be treated as a core design and reporting priority rather than a minor technical detail. Improved standardisation in reporting spectral coverage and in distinguishing between UVA and UVB would strengthen comparability across devices and support user understanding. Although many systems converge on similar app functionality (tracking, cumulative dose, and threshold-based alerts), standardised reporting would improve both scientific synthesis and the practical interpretability of feedback.

Third, implementation-oriented research is required to address the sustainability of use. While the review highlights technical problems and seasonal patterns of non-adherence, the survey indicates

that adoption may be driven more by perceived benefits than by prior use of wearable activity monitors or awareness of UV wearable products. Future research should therefore address not only sensing accuracy but also field reliability, the clarity and actionability of feedback, and perceived value in contexts that users prioritise (beach/pool activities and general outdoor activities). Future surveys and mixed-methods work should also examine acceptability across groups with different risk profiles and motivations, given that this survey included no diagnosed participants and few participants reporting a family history. The combined findings suggest that motivational ambivalence (concern about skin cancer risk alongside a preference for tanning) may be an important determinant of whether feedback translates into behaviour change. Accordingly, future research could investigate how alert modalities function across motivational profiles and baseline protection behaviours, using outcomes that measure exposure and sunburn.

Chapter 6: Proposal

6.1. Architecture and App Concept of *DermUVtrack,* a Wrist-Worn ZnO-Based Photoelectric UV Dosimeter

This section outlines a thesis concept for a wrist-worn UV dosimeter that utilises a ZnO-based photoelectric UV transducer and a smartphone application to provide feedback. The objective is to propose a cohesive, technically feasible architecture and interaction model, informed by the mapped literature. It also aims to avoid any assertion of validated accuracy for dosimetry or behavioural efficacy.

The thesis concept proposes a wrist-worn device, referred to as *DermUVtrack*, that utilises electronically instrumented UV sensing rather than the passive colour-change technique commonly used in many wrist-worn devices. This is a logical extension of instrumented UV wearables, which acquire quantitative signal data and transmit it wirelessly.

The material selected for the photoelectric sensing concept in DermUVtrack is ZnO, as it supports photoelectric sensing and provides an electrical output response to UVR, and it was presented in flexible, wearable-compatible configurations in the scoping review. The literature reviewed also used ZnO as a UV sensor in nanorod form and as a semiconductor material in flexible electrolyte-gated transistors (Kim et al., 2024; Vieira et al., 2022). Some potential benefits of using ZnO include its low cost, flexibility, and compatibility with relatively simple fabrication techniques (Vieira et al., 2022). This issue is especially important for the proposed concept, as the cost appeared to be a considerable barrier to purchase in the questionnaire survey. 90.9% of participants agreed or strongly agreed that the price could become a purchase barrier. The photoelectric sensing approach fits the concept in terms of the architecture since it should provide an electrical output that can be processed, digitised, stored, and then sent to a mobile phone as feedback on the exposure level.

The *DermUVtrack* wrist-worn device is envisioned as a wristband-style device comprising a small pod containing a ZnO-based photoelectric UV transducer on the dorsal aspect of the wrist. This placement provides practical exposure to ambient UVR during normal activity and aligns with the common wrist-worn platform, as represented by most devices in the review and survey findings.

For practical application, a housing is provided for the sensor assembly, which is sealed and made of elastomers to withstand repeated bending, torsion, perspiration, and skin by-products. The optical window is also made of a UV-transparent material to ensure proper exposure of the sensing area while minimising direct contact between electrode interfaces and sweat, as well as diminishing abrasion. The optical window is considered a key component of the interface.

The sensing component is a ZnO-based photoelectric UV transducer integrated on a flexible substrate, including electrodes and an encasement for wear on human skin. In ZnO, incident UV

photons generate electron-hole pairs, which are then separated under a bias voltage (in photoconductive mode) or a built-in junction field (in photovoltaic or photodiode mode). The device then provides a measurable electrical signal that varies with incident UVR within the sensor's responsive band.

For practical purposes, the ZnO-based sensing element is considered a subsystem within the *DermUVtrack* wearable platform rather than a standalone component. The detector is expected to be exposed to normal wear and tear, including deformation, temperature variations, and moisture and sweat. A mechanically compliant interface layer may be considered for this application, consisting of a thin hydrogel or elastomeric interlayer to improve conformal contact and reduce artefacts from bending and micro-motion. However, the UV-to-electrical transduction mechanism remains ZnO-based and photoelectric.

For the purposes of this thesis, the sensor's electrical signal is considered a proxy of UV exposure rather than a guaranteed absolute dosimeter. Calibration against a reference UV radiometer, together with characterisation of spectral, angular, and temperature responses, is considered a prerequisite for any potential thesis work.

Block-level architecture:

- ZnO-based photoelectric UV sensor stack (transducer);
- Analogue front end (AFE): biasing/readout and amplification/filtering (transimpedance conversion for photocurrent);
- Analogue-to-digital conversion (ADC);
- Low-power microcontroller: sampling, timestamping, basic local logic;
- Local buffer: short-term storage to handle intermittent connectivity;
- Bluetooth Low Energy (BLE) communication;
- Smartphone app: visualisation, thresholds, alerts, and summaries.

Figure 6.1 provides a simplified block diagram of *DermUVtrack,* the proposed sensing-to-app pathway.

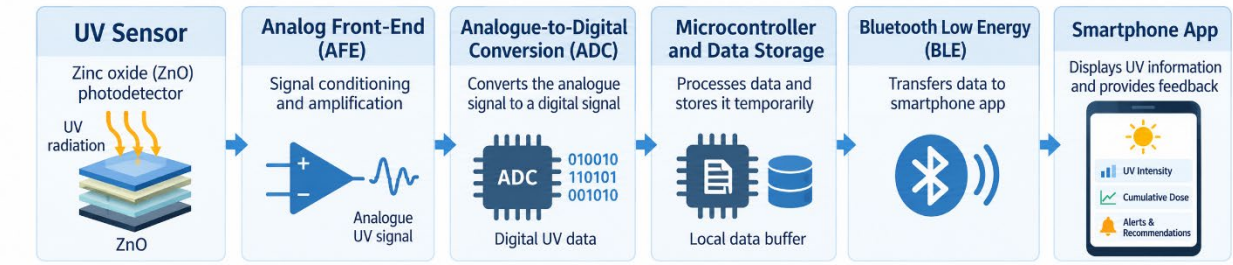


Figure 6.1. Proposed block-level architecture of *DermUVtrack* for a wrist-worn ZnO-based photoelectric UV dosimeter (sensor-to-app pathway).

Figure 6.2 should be viewed as a conceptual representation of the end-to-end data path. The sensing element is assumed to be a ZnO-based photoelectric transducer, with interface layers chosen to ensure proper operation of the sensor in a wearable configuration.

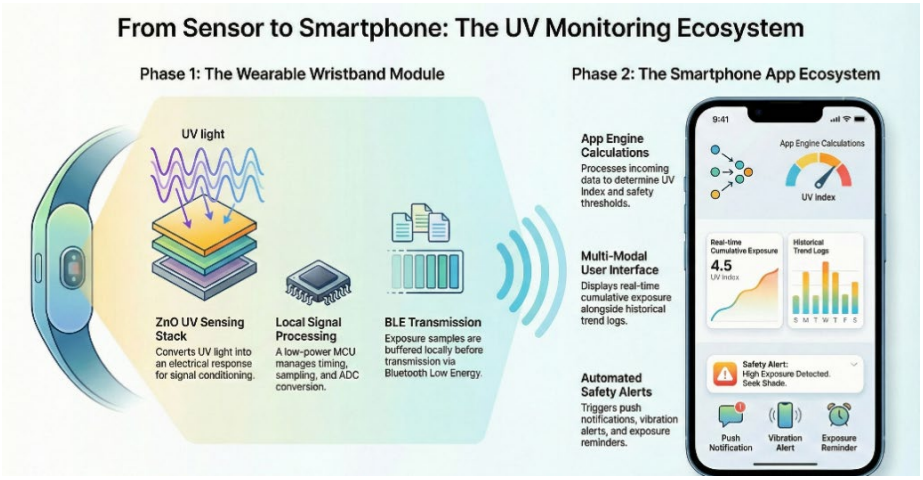


Figure 6.2. DermUVtrack, system-level concept view: wrist-worn sensing module, low-power processing and buffering, BLE transmission, and smartphone-based feedback (dashboard, alerts, and trends).

The power source assumes a compact rechargeable battery contained in the pod structure, together with a basic power management function that includes charging, regulation, and low-battery indication. Alternative energy-harvesting approaches (thin-film solar) may also be considered. However, these are not necessarily required to support the fundamental concept.

Another recurring limitation observed among the devices under investigation is the inconsistent reporting of spectral emphasis or exposure metrics, which hampers clear interpretation and inter-device comparability. To address this limitation at the level of the proposed system, the application should clearly articulate a fundamental reporting aspect to the user. This includes the spectral emphasis of the ZnO transducer, the measured quantity (a photocurrent-derived proxy irradiance level), and the sampling interval. Additionally, the application should define cumulative exposure and clarify how an exposure indicator value is computed or mapped from the sensor output, along with the underlying assumptions used to perform this calculation.

The *DermUVtrack* wearable is intended to provide real-time and cumulative proxy estimates of exposure to UVR and supports decision-making by delivering threshold-based warnings and goal setting. It sends push notifications intended to prompt preventive measures as the risk of UVR exposure increases. The weekly summary is intended to allow users to reflect and plan ahead without requiring significant interaction on a daily basis.

To encourage continued interaction with *DermUVtrack*, the design minimises user interaction by limiting optional and non-essential input. The system allows continued operation even in typical conditions with intermittent smartphone connectivity. The app interface covers most of the user functions identified in the literature as most common for users of UV-based wearable devices. The

interface relies primarily on push notifications to avoid user interaction. The proposed user interface set comprises a real-time interface, referred to as Today, an alert screen for preventive measures, history screens (week/month/year), and a weekly summary screen to plan (Figure 6.3).



Figure 6.3. Conceptual app UI mock-ups illustrating real-time status, alert prompts, exposure history, and weekly summary feedback.

Moreover, evaluative and intervention research in this area shows that, on its own, information display is often insufficient, and success depends on accompanying features. As a result, this construct includes a minimum level of structured behavioural support features while keeping interaction friction low. It includes a personalised threshold-setting process that utilises user-specified limits and alert thresholds. It also includes a light-touch goal-setting process, which promotes protective behaviour without requiring extensive user intervention.

Where there is a potential for risk compensation, as indicated by the evidence base, the language and framing of the user interface should be adjusted to ensure that, rather than providing reassurance, users are made aware that feedback is intended to encourage precautionary behaviour.

Disruptions to use, such as those related to connectivity, and decreasing user engagement are technical and usability limitations that are highlighted as ongoing issues.

The concept includes features that emphasise reliability, such as:

- offline sampling (continued measurement in the absence of a persistent phone connection);
- local buffering and synchronising upon reconnection;
- simple and reliable alert logic that helps prevent notification fatigue;
- basic quality checks (including attention to missing data windows or sensor saturation) that improve the interpretability of log data.

This concept realises the mapped evidence as a coherent design for *DermUVtrack* with smartphone-mediated feedback. It includes a ZnO-based photoelectric UV transducer suitable for instrumented measurement, an encapsulation-based design for wearability, a notification-based application interface with minimal structured behavioural support, and Bluetooth Low Energy-based electronics with local buffering. Transparency regarding spectral emphasis and exposure metric definitions is considered a specification requirement to improve interpretability.

Conclusion

This thesis demonstrates that the use of wearable UV sensing is an emerging digital health intervention, though it is not uniformly well-supported by the available evidence, for the prevention of skin cancer. Based on mapped literature, the design space is wide, encompassing passive colour-changing materials and electronically active sensors. However, most of the literature is more focused on development rather than on demonstrating the effectiveness of everyday use. Accordingly, within the scope of the thesis, the preventive benefit is less related to measuring UV exposure and more to translating the measurement into understandable, credible, and actionable information that users can use repeatedly in real-world settings.

The survey results support this interpretation, as respondents were aware of the risks of UV exposure, reported motivations to engage in UV-exposing behaviour, and expressed a preference for low-cost, low-effort wearable solutions with discreet and actionable alerts. However, low awareness of UV wearables and moderate interest at consumer price points suggest that value, understandability, and ease of use are the key drivers. These factors, rather than the novelty of the sensing capability, appear to be important determinants of practical adoption.

Considering the synthesis of these findings, the proposed concept design seeks to actualise the notion of a “prevention-ready” wearable UV sensing approach implemented as a wrist-worn dosimeter with smartphone-based feedback. The concept is grounded in an electronically instrumented pathway (ZnO-based photoelectric UV) for quantified exposure assessment and decision support. The proposed system could facilitate the conversion of exposure information into quantified and actionable recommendations for protection. It then aims to address the gap identified in the literature between translating exposure information into protective behaviour.

In summary, the present work seeks to provide an integrated understanding of the existing wearable UV sensing landscape and its limitations in prevention, while offering a proposed design pathway for wearable UV sensors. This integrates the user’s needs and the existing literature on wearable-based exposure monitoring. The primary implication is that wearable-based UV exposure monitoring should be assessed by the extent to which it supports the decrease of harmful exposure through reliable devices and high-quality feedback.

Bibliographic References and Sources

Akerlof, K. L. (2023). Promoting environmentally friendly sun-protection behaviours among coastal state residents. Environmental Science & Policy, 142, 121–130. https://doi.org/10.1016/j.envsci.2023.02.007

Araki, H., Kim, J., Zhang, S., Banks, A., Crawford, K. E., Sheng, X., Gutruf, P., Shi, Y., Pielak, R. M., & Rogers, J. A. (2017). Materials and Device Designs for an Epidermal UV Colourimetric Dosimeter with Near-Field Communication Capabilities. Advanced Functional Materials, 27(2), 1604465. https://doi.org/10.1002/adfm.201604465

Bao, B., Fan, J., Wang, Z., Wang, Y., Wang, W., Qin, X., & Yu, D. (2020). Sodium deca-tungstate /polyacrylic acid self-assembled flexible wearable photochromic composite fabric for solar UV detector. Composites Part B: Engineering, 202, 108464. https://doi.org/10.1016/j.compositesb.2020.108464

Botti, S., Bonfigli, F., D'Amato, R., Rodesi, J., & Santonicola, M. G. (2023). Colorimetric Sensors Based on Poly(acrylic Acid)/TiO2 Nanocomposite Hydrogels for Monitoring UV Radiation Exposure. Gels, 9(10), 797. https://doi.org/10.3390/gels9100797

Butterfield, J. L., Quigley, J. R., & Bruns, C. J. (2024). Smart Tattoos of Intradermally Implanted Photochromic Nanosensors for Personal UV Sensing and Dosimetry. Advanced Functional Materials, 34(40), 2405831. https://doi.org/10.1002/adfm.202405831

Cahoon, E. K., Mandal, S., Pfeiffer, R. M., Wheeler, D. C., Sargen, M. R., Alexander, B. H., Kitahara, C. M., Linet, M. S., & Mai, J. Z. (2024). Ambient ultraviolet A, ultraviolet B, and risk of melanoma in a nationwide United States cohort, 1984-2014. Journal of the National Cancer Institute, 116(12), 1928–1933. https://doi.org/10.1093/jnci/djae186

Chen, J., Sun, R., Zheng, J., Zhang, W., Huang, Y., Shao, J., & Chi, Y. (2024). Photochromic Perovskite Nanocrystals for Ultraviolet Dosimetry. Small, 20(29), 2311993. https://doi.org/10.1002/smll.202311993

Choleva, T. G., Karagianni, V. I., & Giokas, D. L. (2025). Hydrochromic paper-based dosimeter for monitoring UV light exposure based on the photochemical formation of gold nanoparticles. Microchimica Acta, 192(3), 169. https://doi.org/10.1007/s00604-025-07020-4

Craig, S., Earnshaw, C. H., & Virós, A. (2018). Ultraviolet light and melanoma. The Journal of Pathology, 244(5), 578–585. https://doi.org/10.1002%2Fpath.5039

de Troya-Martín, M., Rodríguez-Martínez, A., Rivas-Ruiz, F., Subert, A., Arellano-Mendoza, M., Calzavara-Pinton, P., de Gálvez, M. V., Gilaberte, Y., Goh, C., Lim, H. W., Schalka, S., Wolf, P., & González, S. (2025). Personalized Photoprotection: Expert Consensus and Recommendations From a Delphi Study Among Dermatologists. Photodermatology, Photoimmunology & Photomedicine, 41(1), e70001. https://doi.org/10.1111/phpp.70001

Diffey, B. (2020). The Early Days of Personal Solar Ultraviolet Dosimetry. Atmosphere, 11(2), 125. https://doi.org/10.3390/atmos11020125

Dong, H., Liu, W., Li, Y., Chen, X., & Wang, D. (2023). Fully Printed Flexible Zinc Oxide Patch for Wearable UV Light Sensing. Advanced Electronic Materials, 9(12), 2300469. https://doi.org/10.1002/aelm.202300469

Frasier, K., Li, V., Sobotka, M., Vinagolu-Baur, J., & Herrick, G. (2025). The role of wearable technology in real-time skin health monitoring. JEADV Clinical Practice, 4(1), 21–29. https://doi.org/10.1002/jvc2.587

Gao, L., Liu, Y., Zhang, M., Zhao, X., Duan, Y., & Han, T. (2023). Fabricating a photochromic benzonitrile Schiff base into a low-cost, reusable, paper-based wearable sensor for naked-eye dosimetry of UV radiation. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 295, 122586. https://doi.org/10.1016/j.saa.2023.122586

Garbe, C., Forsea, A.-M., Amaral, T., Arenberger, P., Autier, P., Berwick, M., Boonen, B., Bylaite, M., del Marmol, V., Dreno, B., Fargnoli, M. C., Geller, A. C., Green, A. C., Greinert, R., Hauschild, A., Harwood, C. A., Hoorens, I., Kandolf, L., Kaufmann, R., … Brochez, L. (2024). Skin cancers are the most frequent cancers in fair-skinned populations, but we can prevent them. European Journal of Cancer, 204, 114074. https://doi.org/10.1016/j.ejca.2024.114074

Gieniusz, E., Skrzydlewska, E., & Łuczaj, W. (2024). Current Insights into the Role of UV Radiation-Induced Oxidative Stress in Melanoma Pathogenesis. International Journal of Molecular Sciences, 25(21). https://doi.org/10.3390/ijms252111651

Guan, L. L., Lim, H. W., & Mohammad, T. F. (2021). Sunscreens and Photoaging: A Review of Current Literature. American Journal of Clinical Dermatology, 22(6), 819–828. https://doi.org/10.1007/s40257-021-00632-5

Heckman, C. J., Chandler, R., Kloss, J. D., Benson, A., Rooney, D., Munshi, T., Darlow, S. D., Perlis, C., Manne, S. L., & Oslin, D. W. (2013). Minimal Erythema Dose (MED) Testing. Journal of Visualized Experiments : JoVE, (75), 50175. https://doi.org/10.3791/50175

Huang, X., & Chalmers, A. N. (2021). Review of Wearable and Portable Sensors for Monitoring Personal Solar UV Exposure. Annals of Biomedical Engineering, 49(3), 964–978. https://doi.org/10.1007/s10439-020-02710-x

Hughes, B. K., & Bishop, C. L. (2022). Current Understanding of the Role of Senescent Melanocytes in Skin Ageing. Biomedicines, 10(12), 3111. https://doi.org/10.3390/biomedicines10123111

Jin, S.-G., Johnson, J., Kim, P. Y., & Pfeifer, G. P. (2025). UVA-induced DNA damage and mutations in human melanocytes: Relevance for melanoma mutations. Nucleic Acids Research, 53(17). https://doi.org/10.1093/nar/gkaf905

Karampinis, E., Koumaki, D., Sgouros, D., Nechalioti, P.-M., Toli, O., Pappa, G., Papadakis, M., Georgopoulou, K.-E., Schulze-Roussaki, A.-V., & Kouretas, D. (2025). Non-Melanoma Skin Cancer: Assessing the Systemic Burden of the Disease. Cancers, 17(4), 703. https://doi.org/10.3390/cancers17040703

Karapetyan, G. Ya., Kaydashev, V. E., Zhilin, D. A., Kutepov, M. E., Minasyan, T. A., & Kaidashev, E. M. (2019). A surface acoustic wave impedance-loaded high sensitivity sensor with wide dynamic range for ultraviolet light detection. Sensors and Actuators A: Physical, 296, 70–78. https://doi.org/10.1016/j.sna.2019.07.010

Kim, J. H., Park, S. Y., Kim, M. K., Park, W. H., Doh, I., Joe, D. J., & Lee, H. E. (2023). Long-Term UV Detecting Wearable Patches Enabled by III-N Compound Semiconductor-Based Microphotodetectors. Advanced Optical Materials, 11(13), 2203083. https://doi.org/10.1002/adom.202203083

Koumaki, D., Evangelou, G., Gregoriou, S., Kouloumvakou, S., Manios, A., Katoulis, A., Zacharopoulos, G., Chernyshov, P., Papadakis, M., Kassotakis, D., Manios, G., Rovithi, E.,

Zografaki, K., Doxastaki, A., Gkiaouraki, I., Petrou, D., Marazaki, F., Mylonakis, D., De Bree, E., & Krasagakis, K. (2024). Skin Cancer Knowledge, Sun Exposure, Photoprotection Behavior, and Perceived Barriers Associated with Skin Cancer Types in a Greek Cohort: A Cross-Sectional Study on the Island of Crete. Cancers, 16(24), 4226. https://doi.org/10.3390/cancers16244226

Kwa, M., Ravi, M., Elhage, K., Schultz, L., & Lim, H. W. (2025). The risk of ultraviolet exposure for melanoma in Fitzpatrick skin types I-IV: A 20-year systematic review with meta-analysis for sunburns. Journal of the European Academy of Dermatology and Venereology : JEADV, 39(7), 1239–1253. https://doi.org/10.1111%2Fjdv.20316

Lawrence, K. P., Douki, T., Sarkany, R. P. E., Acker, S., Herzog, B., & Young, A. R. (2025). Improved photoprotection in the UVA/visible radiation boundary region is essential to prevent DNA damage, oxidative stress and gene expression changes in human skin. JEADV Clinical Practice, 4(2), 440–450. https://doi.org/10.1002/jvc2.586

Lawrynowicz, A., Vuori, S., Palo, E., Winther, M., Lastusaari, M., & Miettunen, K. (2024). Transforming fabrics into UV-sensing wearables: A photochromic hackmanite coating for repeatable detection. Chemical Engineering Journal, 494, 153069. https://doi.org/10.1016/j.cej.2024.153069

Lee, M. E., & Armani, A. M. (2016). Flexible UV Exposure Sensor Based on UV Responsive Polymer. ACS Sensors, 1(10), 1251–1255. https://doi.org/10.1021/acssensors.6b00491

Lim, H. W., Saint Aroman, M., Skayem, C., Halioua, B., Perez Cullell, N., Ben Hayoun, Y., Baissac, C., Bergqvist, C., Taieb, C., Richard, M.-A., & Ezzedine, K. (2024). Sun exposure and protection habits: Self-reported attitudes, knowledge and behaviours. Journal of the European Academy of Dermatology and Venereology: JEADV, 38(10), 2024–2033. https://doi.org/10.1111/jdv.20080

Lin, C., Du, Y., Pendse, N., Fernandes, G., Alshurafa, N., & Pedram, M. (2024). Self-Sustaining Wearable UV Sensor for Passive and Continuous Sun Protection. 2024 IEEE 20th International Conference on Body Sensor Networks (BSN), 1–4. https://doi.org/10.1109/BSN63547.2024.10780588

Long, G. V., Swetter, S. M., Menzies, A. M., Gershenwald, J. E., & Scolyer, R. A. (2023). Cutaneous melanoma. Lancet (London, England), 402(10400), 485–502. https://doi.org/10.1016/S0140-6736(23)00821-8

Maghfour, J., Li, P., Piontkowski, A., Ozog, D., Mi, Q.-S., & Veenstra, J. (2024). Melanoma incidence and mortality: Exploring the impact of regional ultraviolet (UV) radiation and socioeconomic status in the context of Breslow thickness. Journal of the American Academy of Dermatology, 90(3), 637–640. https://doi.org/10.1016/j.jaad.2023.11.003

Mai, J. Z., Sargen, M. R., Linet, M. S., Ike, E., Gorsuch, B. L., Kitahara, C. M., Cahoon, E. K., & Alexander, B. H. (2025). Impact of personal sun sensitivity and ultraviolet radiation on the association between blistering sunburns and melanoma. Journal of the American Academy of Dermatology, 93(2), 483–485. https://doi.org/10.1016/j.jaad.2025.04.048

Mittal, V., So, J. Y., Li, S., Swetter, S. M., Linos, E., Van Horn, L., Neuhouser, M. L., Stefanick, M. L., & Tang, J. Y. (2024). Associations between dietary and supplemental vitamin A intake and melanoma and Non-Melanoma skin cancer. Skin Health and Disease, 4(6), e462. https://doi.org/10.1002/ski2.462

Monisha, J., Rahul, D., Ragul, C., & Ramprasad, B. (2025). Recent trends of sunscreen cosmetics Innovative approaches in sunscreen development: Beyond UV protection. Journal of Neonatal Surgery, 14(15s), 2231–2240. https://www.jneonatalsurg.com/index.php/jns/article/view/4687

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, n71. https://doi.org/10.1136/bmj.n71

Parsons, B. G., Nagelhout, E. S., Wankier, A. P., Hu, N., Lensink, R., Zhu, A., Nottingham, K., Grossman, D., Jensen, J. D., & Wu, Y. P. (2021). Reactivity to UV Radiation Exposure Monitoring Using Personal Exposure Devices for Skin Cancer Prevention: Longitudinal Observational Study. JMIR mHealth and uHealth, 9(9), e29694. https://doi.org/10.2196/29694

Pega, F., Momen, N. C., Streicher, K. N., Leon-Roux, M., Neupane, S., Schubauer-Berigan, M. K., Schüz, J., Baker, M., Driscoll, T., Guseva Canu, I., Kiiver, H. M., Li, J., Nwanaji-Enwerem, J. C., Turner, M. C., Viegas, S., & Villeneuve, P. J. (2023). Global, regional and national burdens of non-melanoma skin cancer attributable to occupational exposure to solar ultraviolet radiation for 183 countries, 2000–2019: A systematic analysis from the WHO/ILO Joint Estimates of the Work-related Burden of Disease and Injury. Environment International, 181. https://doi.org/10.1016/j.envint.2023.108226

Robinson, J. K., Durst, D. A., Gray, E., Kwasny, M., Heo, S. Y., Banks, A., & Rogers, J. A. (2021). Sun exposure reduction by melanoma survivors with wearable sensor providing real-time UV exposure and daily text messages with structured goal setting. Archives of Dermatological Research, 313(8), 685–694. https://doi.org/10.1007/s00403-020-02163-1

Roky, A. H., Islam, M. M., Ahasan, A. M. F., Mostaq, M. S., Mahmud, M. Z., Amin, M. N., & Mahmud, M. A. (2025). Overview of skin cancer types and prevalence rates across continents. Cancer Pathogenesis and Therapy, 3(2), 89–100. https://doi.org/10.1016/j.cpt.2024.08.002

Sarkany, R. (2025). Sun protection. Medicine, 53(8), 544–547. https://doi.org/10.1016/j.mpmed.2025.05.005

Shi, Y., Manco, M., Moyal, D., Huppert, G., Araki, H., Banks, A., Joshi, H., McKenzie, R., Seewald, A., Griffin, G., Sen-Gupta, E., Wright, D., Bastien, P., Valceschini, F., Seité, S., Wright, J. A., Ghaffari, R., Rogers, J., Balooch, G., & Pielak, R. M. (2018). Soft, stretchable, epidermal sensor with integrated electronics and photochemistry for measuring personal UV exposures. PLOS ONE, 13(1), e0190233. https://doi.org/10.1371/journal.pone.0190233

Sivamani, R. K., Crane, L. A., & Dellavalle, R. P. (2009). The Benefits and Risks of Ultraviolet Tanning and Its Alternatives: The Role of Prudent Sun Exposure. Dermatologic Clinics, 27(2), 149–154. https://doi.org/10.1016/j.det.2008.11.008

Thoonen, K., Woodhouse, S., Minto, C., Blane, S., & Talati, Z. (2023). Patterns of Sun Protection Behaviours among Australian Adolescents and Adults over a Six-Year Period. Current Oncology, 30(8), 7178–7188. https://doi.org/10.3390/curroncol30080520

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., . . . Straus, S. E. (2018). PRISMA Extension for Scoping Reviews (PRISMA-SCR): Checklist and explanation. Annals of Internal Medicine, 169(7), 467–473. https://doi.org/10.7326/m18-0850

Walburn, J., Norton, S., Sarkany, R., Canfield, M., Sainsbury, K., McCrone, P., Araújo-Soares, V., Morgan, M., Boadu, J., Foster, L., Heydenreich, J., Mander, A. P., Sniehotta, F. F., Wulf, H. C., & Weinman, J. (2025). A personalized and systematically designed adherence intervention improves photoprotection in adults with xeroderma pigmentosum (XP): Results of the XPAND randomized

controlled trial. British Journal of Dermatology, 192(4), 728–737. https://doi.org/10.1093/bjd/ljae393

Walsh, H. S., & Hardwicke, J. (2024). Non-melanoma skin cancer: Diagnosis and current recommendations on management. Surgery (Oxford), 42(11), 820–826.

Wang, M., Gao, X., & Zhang, L. (2025). Recent global patterns in skin cancer incidence, mortality, and prevalence. CHINESE MEDICAL JOURNAL, 138(2), 185–192. https://doi.org/10.1097/CM9.0000000000003416

Zhu, W., Ren, H., Liu, Y., Li, Z., Luo, X., Meng, H., & Dong, Y. (2025). Key targets and pathways in skin photoaging: A comprehensive review. Journal of Dermatologic Science and Cosmetic Technology, 100101. https://doi.org/10.1016/j.jdsct.2025.100101

Zou, W., Sastry, M., Gooding, J. J., Ramanathan, R., & Bansal, V. (2020). Recent Advances and a Roadmap to Wearable UV Sensor Technologies. Advanced Materials Technologies, 5(4), 1901036. https://doi.org/10.1002/admt.201901036

Scoping review references

Chen, J., Sun, R., Zheng, J., Zhang, W., Huang, Y., Shao, J., & Chi, Y. (2024). Photochromic Perovskite Nanocrystals for Ultraviolet Dosimetry. *Small*, *20*(29), 2311993. https://doi.org/10.1002/smll.202311993

Chen, T., Liu, Z., Sha, Sha., Wang, R., Chen, S., Sun, Y., Zheng, H., & Chen, A. (2025). A Real-Time Solar UVA Dose Monitor Based on Recyclable Azobenzene-Containing Elastomer Fabrics. *Advanced Materials*, *37*(43), e07832. https://doi.org/10.1002/adma.202507832

Chen, Y., Cao, Z., Zhang, J., Liu, Y., Yu, D., & Guo, X. (2022). Wearable ultraviolet sensor based on convolutional neural network image processing method. *Sensors and Actuators A: Physical*, *338*, 113402. https://doi.org/10.1016/j.sna.2022.113402

Dickey, A. K., Berkovich, J., Leaf, R. K., Jiang, P. Y., Lopez-Galmiche, G., Rebeiz, L., Wheeden, K., Kochevar, I., Savage, W., Zhao, S., Campisi, E., Heo, S. Y., Trueb, J., LaRochelle, E. P. M., Rogers, J., Banks, A., & Chang, J. (2024). Observational pilot study of multi-wavelength wearable light dosimetry for erythropoietic protoporphyria. *International Journal of Dermatology*, *63*(11), 1584–1591. https://doi.org/10.1111/ijd.17166

Dumont, E. L. P., Kaplan, P. D., Do, C., Banerjee, S., Barrer, M., Ezzedine, K., Zippin, J. H., & Varghese, G. I. (2024). A randomized trial of a wearable UV dosimeter for skin cancer prevention. *Frontiers in Medicine*, *11*, 1259050. https://doi.org/10.3389/fmed.2024.1259050

Guo, D., Yang, L., Zhao, J., Li, J., He, G., Yang, D., Wang, L., Vadim, A., & Ma, D. (2021). Visible-blind ultraviolet narrowband photomultiplication-type organic photodetector with an ultrahigh external quantum efficiency of over 1 000 000%. *Materials Horizons*, *8*(8), 2293–2302. https://doi.org/10.1039/D1MH00776A

Han, J., Deng, Z., Wang, R., Liu, Z., Sun, Y., & Chen, A. (2024). Skin-Friendly Flexible Ultraviolet Detectors Based on Reversibly Deformable Worm-Like Polymer Nanoparticles. *Macromolecular Rapid Communications*, *45*(11), 2400021. https://doi.org/10.1002/marc.202400021

Hong, J., Yao, D., Wang, H., Ding, Q., Luo, Y., Yu, J., Zhang, H., Zeng, L., Yang, B., Wang, B., Tao, K., & Wu, J. (2024). Stretchable, stable and high-performance optoelectronic sensors based on

hydrogel for ultraviolet imaging and wireless alarm. *Science China Materials*, *67*(6), 1926–1937. https://doi.org/10.1007/s40843-024-2879-2

Jeong, S.-M., Yang, J., Seo, K., Seo, H. S., Ju, S., & Lim, T. (2024). Fiber-based hydrophobic and stretchable UV-photochromic textile. *AIP Advances*, *14*(1), 015124. https://doi.org/10.1063/5.0178875

Kim, J. H., Park, S. Y., Kim, M. K., Park, W. H., Doh, I., Joe, D. J., & Lee, H. E. (2023). Long-Term UV Detecting Wearable Patches Enabled by III-N Compound Semiconductor-Based Microphotodetectors. *Advanced Optical Materials*, *11*(13), 2203083. https://doi.org/10.1002/adom.202203083

Kim, K.-Y., Lee, D.-H., Lee, Y.-A., Cho, Y.-A., Choi, J.-H., Kim, J.-H., & Kim, H.-S. (2024). Design and Batch Fabrication of Stretchable Bifunctional Sensor Using Polyaniline and ZnO Nanostructures for Tensile and UV Sensing. *IEEE Sensors Journal*, *24*(12), 19791–19800. https://doi.org/10.1109/JSEN.2024.3397821

Lawrynowicz, A., Vuori, S., Palo, E., Winther, M., Lastusaari, M., & Miettunen, K. (2024). Transforming fabrics into UV-sensing wearables: A photochromic hackmanite coating for repeatable detection. *Chemical Engineering Journal*, *494*, 153069. https://doi.org/10.1016/j.cej.2024.153069

Li, J., Liu, Y., Gu, Z., Sun, P., Liu, K., Xu, D., Gao, C., & Xu, W. (2024). Scalable, Green, Flexible Photochromic Bacterial Cellulose for Multicolor Switching, Photo-patterning, and Daily Sunlight UV Monitoring. *Small*, *20*(30), 2309514. https://doi.org/10.1002/smll.202309514

Lin, C., Du, Y., Pendse, N., Fernandes, G., Alshurafa, N., & Pedram, M. (2024). Self-Sustaining Wearable UV Sensor for Passive and Continuous Sun Protection. *2024 IEEE 20th International Conference on Body Sensor Networks (BSN)*, 1–4. https://doi.org/10.1109/BSN63547.2024.10780588

Lin, L., Shen, L., Zhang, J., Xu, Y., Fang, Z., Müller-Buschbaum, P., & Zhong, Q. (2021). Ionic Hydrogels Based Wearable Sensors to Monitor the Solar Radiation Dose for Vitamin D Production and Sunburn Prevention. *ACS Applied Materials & Interfaces*, *13*(38), 45995–46002. https://doi.org/10.1021/acsami.1c13027

Mahitha, M., Madhav, S. V., M, K., & Babu, A. D. (2025). UV Exposure Real-Time Monitor for Skin Protection. *2025 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, 1–7. https://doi.org/10.1109/SCEECS64059.2025.10940631

Ponnambalam, N., V, D. G., Banu, R., Bharadwaj, I., Yogi, K. S., & Suraskar, R. (2025). Real-Time UV Exposure and Vitamin D Tracking for Personalized Health Monitoring with Alerts for Safe Exposure Limits. *2025 6th International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV)*, 7–13. https://doi.org/10.1109/ICICV64824.2025.11085538

Robinson, J. K., Durst, D. A., Gray, E., Kwasny, M., Heo, S. Y., Banks, A., & Rogers, J. A. (2021). Sun exposure reduction by melanoma survivors with wearable sensor providing real-time UV exposure and daily text messages with structured goal setting. *Archives of Dermatological Research*, *313*(8), 685–694. https://doi.org/10.1007/s00403-020-02163-1

Stump, T., Fastner, S., Jo, Y., Chipman, J., Haaland, B., Nagelhout, E., Wankier, A., Lensink, R., Zhu, A., Parsons, B., Grossman, D., & Wu, Y. (2023). Objectively-Assessed Ultraviolet Radiation Exposure and Sunburn Occurrence. *International Journal of Environmental Research and Public Health*, *20*(7), 5234. https://doi.org/10.3390/ijerph20075234

Vieira, D. H., Nogueira, G. L., Morais, R. M., Fugikawa-Santos, L., Seidel, K. F., & Alves, N. (2022). ZnO-based electrolyte-gated transistor (EGT) applied as multiparametric UV-sensing device. *Sensors and Actuators A: Physical*, *347*, 113989. https://doi.org/10.1016/j.sna.2022.113989

Vogel, R. I., Luo, X., Brown, K., Jewett, P., Dona, A. C., Nagler, R. H., Ahmed, R. L., Martinson, B. C., & Lazovich, D. (2023). A UVR-sensor wearable device intervention to reduce sun exposure in melanoma survivors: Results from a randomized controlled trial. *PLOS ONE*, *18*(2), e0281480. https://doi.org/10.1371/journal.pone.0281480

Wu, Z., Liao, K.-F., Xiao, L.-P., Zhong, S.-J., Gong, M., & Wang, G.-J. (2024). Spiropyran-Containing Reusable and Wearable All-in-One Ultraviolet Monitoring and Shielding Textiles for Sun Protection. *Chinese Journal of Polymer Science*, *42*(12), 1933–1940. https://doi.org/10.1007/s10118-024-3188-3

Yang, J., & Ju, S. (2022). Washable and stretchable fiber with heat and ultraviolet color conversion. *RSC Advances*, *12*(35), 22351–22359. https://doi.org/10.1039/D2RA03948F

Yang, Z., Zhao, J., Liang, C., & Jiang, H. (2023). Materials and Device Design for Epidermal UV Sensors with Real-Time, Skin-Color Specific, and Naked-Eye Quasi-Quantitative Monitoring Capabilities. *Advanced Materials Technologies*, *8*(7), 2201481. https://doi.org/10.1002/admt.202201481

Yu, Z., Xu, J., Gong, H., Li, Y., Li, L., Wei, Q., & Tang, D. (2022). Bioinspired Self-Powered Piezoresistive Sensors for Simultaneous Monitoring of Human Health and Outdoor UV Light Intensity. *ACS Applied Materials & Interfaces*, *14*(4), 5101–5111. https://doi.org/10.1021/acsami.1c23604

Zhang, L., Wan, P., Xu, T., Kan, C., & Jiang, M. (2021). Flexible ultraviolet photodetector based on single ZnO microwire/polyaniline heterojunctions. *Optics Express*, *29*(12), 19202. https://doi.org/10.1364/OE.430132

Zhang, X., Cheng, R., Deng, Y., Liu, Z., Liu, X., Liu, Z., Sun, B., Liao, G., & Shi, T. (2024). Tailoring performance of perovskite-based tunneling photodetector for portable monitoring of ultraviolet radiation risk. *Nano Energy*, *122*, 109282. https://doi.org/10.1016/j.nanoen.2024.109282

Zhao, J., Zhang, Y., Liu, F., Yan, M., Wang, X., & Wang, W. (2022). Sunlight-Responsive Titania–Hydrated Tungsten Oxide Heteronanoparticles/Paper-Based Color-Switching Film for Solar Ultraviolet Radiation Monitors. *ACS Applied Nano Materials*, *5*(3), 4009–4017. https://doi.org/10.1021/acsanm.2c00003

Zhou, Y., Qiu, X., Wan, Z., Long, Z., Poddar, S., Zhang, Q., Ding, Y., Chan, C. L. J., Zhang, D., Zhou, K., Lin, Y., & Fan, Z. (2022). Halide-exchanged perovskite photodetectors for wearable visible-blind ultraviolet monitoring. *Nano Energy*, *100*, 107516. https://doi.org/10.1016/j.nanoen.2022.107516

Appendices

Appendix A: Overview of databases and search strategies

Table A1. Database search strategy and date of last search.

Database	Global search string focus	RQ-specific supplementary search blocks	Date of last search
EBSCO (ISCTE Discovery)	(TI(wearable* OR "smart watch" OR smartwatch* OR wristband* OR patch* OR "electronic skin" OR clip* OR textile* OR "smart textile*") OR AB(wearable* OR "smart watch" OR smartwatch* OR wristband* OR patch* OR "electronic skin" OR clip* OR textile* OR "smart textile*")) AND (TI(ultraviolet OR UV OR UVA OR UVB OR "UV index") OR AB(ultraviolet OR UV OR UVA OR UVB OR "UV index")) AND (TI(sensor* OR dosimeter* OR radiometer* OR photodiode* OR colorimetric OR photochromic OR "UV monitor*") OR AB(sensor* OR dosimeter* OR radiometer* OR photodiode* OR colorimetric OR photochromic OR "UV monitor*") AND (TI(human* OR participant* OR bench OR laboratory OR calibration OR accuracy OR "UV dose" OR sunburn* OR sunscreen* OR shade OR adherence OR usability OR "system usability scale" OR SUS OR efficiency OR operational OR cost*) OR AB(human* OR participant* OR bench OR laboratory OR calibration OR accuracy OR "UV dose" OR sunburn* OR sunscreen* OR shade OR adherence	**RQ 1:** (TI(wearable* N5 (sensor* OR dosimeter* OR radiometer* OR photodiode* OR patch* OR clip* OR "electronic skin" OR textile*)) OR AB(wearable* N5 (sensor* OR dosimeter* OR radiometer* OR photodiode* OR patch* OR clip* OR "electronic skin" OR textile*))) AND (TI(ultraviolet OR UV OR UVA OR UVB OR "UV index") OR AB(ultraviolet OR UV OR UVA OR UVB OR "UV index")) AND (TI(human* OR participant* OR bench OR laboratory OR calibration) OR AB(human* OR participant* OR bench OR laboratory OR calibration)) **RQ 2:** (TI(wearable* OR smartwatch* OR wristband* OR patch* OR "electronic skin" OR clip*) OR AB(wearable* OR smartwatch* OR wristband* OR patch* OR "electronic skin" OR clip*)) AND (TI(ultraviolet OR UV OR UVA OR UVB) OR AB(ultraviolet OR UV OR UVA OR UVB)) AND (TI(sensor* OR dosimeter* OR radiometer* OR photodiode*) OR AB(sensor* OR dosimeter* OR radiometer* OR photodiode*)) AND (TI(behaviour* OR behavior* OR sunburn* OR erythema OR "UV dose" OR exposure OR sunscreen* OR shade OR adherence OR compliance OR engagement OR JITAI OR "goal setting" OR notification* OR alert* OR "text message*" OR SMS OR intervention* OR trial) OR AB(behaviour* OR behavior* OR sunburn* OR erythema OR "UV dose" OR exposure OR sunscreen* OR shade OR adherence OR compliance OR engagement **RQ 3:** (TI(wearable* OR smartwatch* OR wristband* OR patch* OR "electronic skin" OR clip*) OR AB(wearable* OR smartwatch* OR wristband* OR patch* OR "electronic skin" OR clip*)) AND (TI(ultraviolet OR UV OR UVA OR UVB) OR AB(ultraviolet OR UV OR UVA OR UVB)) AND (TI(sensor* OR dosimeter* OR radiometer* OR photodiode*) OR AB(sensor* OR dosimeter* OR radiometer* OR photodiode*)) AND (TI(effectiv* OR efficac* OR outcome* OR "UV dose" Or sunburn* OR usability OR "system usability scale" OR SUS OR economic* OR cost OR "cost-effect*" OR efficiency OR operational OR workflow* OR accuracy OR calibration OR "Bland-Altman" Or MAE Or RMSE Or MAPE) OR AB(effectiv* OR efficac* OR outcome* Or "UV dose" OR sunburn* OR usability OR "system usability scale" OR SUS Or economic* OR cost Or "cost-effect*" OR efficiency Or operational OR workflow* OR accuracy OR calibration OR "Bland-Altman" OR MAE OR RMSE OR MAPE)) AND (TI(human* OR participant* OR bench OR laboratory) OR AB(human* OR participant* OR bench OR laboratory))OR JITAI OR "goal setting"	07/09/2025

	OR usability OR "system usability scale" OR SUS OR efficiency OR operational OR cost*))	OR notification* OR alert* OR "text message*" OR SMS OR intervention* OR trial) AND (TI(human* OR participant*) OR AB(human* OR participant*))	
PubMed	(("Wearable Electronic Devices"[Mesh] OR wearable*[tiab] OR "smart watch"[tiab] OR smartwatch*[tiab] OR wristband*[tiab] OR "wrist band*"[tiab] OR clip*[tiab] OR badge*[tiab] OR patch*[tiab] OR "electronic skin"[tiab] OR e-skin[tiab] OR textile*[tiab] OR "smart textile*"[tiab]) AND ("Ultraviolet Rays"[Mesh] OR ultraviolet[tiab] OR UV[tiab] OR UVA[tiab] OR UVB[tiab] OR "UV index"[tiab]) AND (sensor*[tiab] OR dosimeter*[tiab] OR radiometer*[tiab] OR photodiode*[tiab] OR colorimetric[tiab] OR photochromic[tiab] OR "UV monitor*"[tiab]) AND (human*[tiab] OR participant*[tiab] OR bench[tiab] OR laboratory[tiab] OR calibration[tiab] OR accuracy[tiab] OR "UV dose"[tiab] OR sunburn*[tiab] OR sunscreen*[tiab] OR shade[tiab] OR adherence[tiab] OR usability[tiab] OR "System Usability Scale"[tiab] OR SUS[tiab] OR efficiency[tiab] OR operational[tiab] OR cost*[tiab]))	**RQ 1:** (("Wearable Electronic Devices"[Mesh] OR wearable*[tiab] OR "smart watch"[tiab] OR smartwatch*[tiab] OR wristband*[tiab] OR "wrist band*"[tiab] OR clip*[tiab] OR badge*[tiab] OR patch*[tiab] OR "electronic skin"[tiab] OR e-skin[tiab] OR textile*[tiab] OR "smart textile*"[tiab]) AND ("Ultraviolet Rays"[Mesh] OR ultraviolet[tiab] OR UV[tiab] OR UVA[tiab] OR UVB[tiab] OR "UV index"[tiab]) AND (sensor*[tiab] OR dosimeter*[tiab] OR radiometer*[tiab] OR photodiode*[tiab] OR colorimetric[tiab] OR photochromic[tiab] OR "UV monitor*"[tiab]) AND (human*[tiab] OR participant*[tiab] OR bench[tiab] OR laboratory[tiab] OR calibration[tiab] OR accuracy[tiab] OR "UV dose"[tiab] OR sunburn*[tiab] OR sunscreen*[tiab] OR shade[tiab] OR adherence[tiab] OR usability[tiab] OR "System Usability Scale"[tiab] OR SUS[tiab] OR efficiency[tiab] OR operational[tiab] OR cost*[tiab])) **RQ 2:** (("Wearable Electronic Devices"[Mesh] OR wearable*[tiab] OR smartwatch*[tiab] OR wristband*[tiab] OR clip*[tiab] OR patch*[tiab] OR "electronic skin"[tiab]) AND ("Ultraviolet Rays"[Mesh] OR ultraviolet[tiab] OR UV[tiab] OR UVA[tiab] OR UVB[tiab]) AND (sensor*[tiab] OR dosimeter*[tiab] OR radiometer*[tiab] OR photodiode*[tiab]) AND ("Health Behavior"[Mesh] OR behaviour*[tiab] OR sunburn*[tiab] OR erythema[tiab] OR "UV dose"[tiab] OR exposure[tiab] OR sunscreen*[tiab] OR "Sunscreening Agents"[Mesh] OR shade[tiab] OR "Protective Clothing"[Mesh] OR adherence[tiab] OR compliance[tiab] OR engagement[tiab] OR "behavior change technique*"[tiab] OR BCT[tiab] OR JITAI[tiab] OR "just-in-time"[tiab] OR "goal setting"[tiab] OR notification*[tiab] OR alert*[tiab] OR "text message*"[tiab] OR SMS[tiab] OR intervention*[tiab] OR trial[tiab]) AND (humans[Mesh] OR human*[tiab] OR participant*[tiab])) **RQ 3:** (("Wearable Electronic Devices"[Mesh] OR wearable*[tiab] OR smartwatch*[tiab] OR wristband*[tiab] OR clip*[tiab] OR patch*[tiab] OR "electronic skin"[tiab]) AND ("Ultraviolet Rays"[Mesh] OR ultraviolet[tiab] OR UV[tiab] OR UVA[tiab] OR UVB[tiab]) AND (sensor*[tiab] OR dosimeter*[tiab] OR radiometer*[tiab] OR photodiode*[tiab] AND (effectiv*[tiab] OR efficac*[tiab] OR outcome*[tiab] OR "UV dose"[tiab] OR sunburn*[tiab] OR usability[tiab] OR "System Usability Scale"[tiab] OR SUS[tiab] OR economic*[tiab] OR cost[tiab] OR "cost-effect*"[tiab] OR efficiency[tiab] OR operational[tiab] OR workflow*[tiab] OR accuracy[tiab] OR calibration[tiab] OR "Bland-Altman"[tiab] OR MAE[tiab] OR RMSE[tiab] OR MAPE[tiab]) AND (human*[tiab] OR participant*[tiab] OR bench[tiab] OR laboratory[tiab])	07/09/2025
Scopus	TITLE-ABS-KEY ((wearable* OR "smart watch" OR smartwatch* OR wristband* OR (wrist W/1 band*) OR clip* OR badge* OR patch* OR "electronic skin"	**RQ 1:** (TITLE-ABS-KEY (wearable* W/3 (sensor* OR dosimeter* OR radiometer* OR photodiode* OR patch* OR clip* OR "electronic skin" OR textile*)) AND TITLE-ABS-KEY (ultraviolet OR "UV" OR UVA OR UVB OR "UV index") AND TITLE-ABS-KEY (human* OR participant* OR bench OR laboratory OR calibration)) AND (PUBYEAR>2020) AND (LANGUAGE(english))	07/09/2025

	OR (e W/1 skin) OR textile* OR (smart W/1 textile*)) AND (ultraviolet OR UV OR UVA OR UVB OR (UV W/1 INDEX)) AND (sensor* OR dosimeter* OR radiometer* OR photodiode* OR colorimetric OR photochromic OR (UV W/1 monitor*)) AND (human* OR participant* OR bench OR laboratory OR calibration OR accuracy OR (UV W/1 dose) OR sunburn* OR sunscreen* OR shade OR adherence OR usability OR (system W/1 usability W/1 scale) OR SUS OR efficiency OR operational OR cost*))	**RQ 2:** (TITLE-ABS-KEY (wearable* OR smartwatch* OR wristband* OR clip* OR patch* OR "electronic skin") AND TITLE-ABS-KEY (ultraviolet OR UV OR UVA OR UVB) AND TITLE-ABS-KEY (sensor* OR dosimeter* OR radiometer* OR photodiode*) AND TITLE-ABS-KEY (behaviour* OR behavior* OR sunburn* OR erythema OR "UV dose" OR exposure OR sunscreen* OR shade OR adherence OR compliance OR engagement OR "behavior change technique*" OR BCT OR JITAI OR "just-in-time" OR "goal setting" OR notification* OR alert* OR "text message*" OR SMS OR intervention* OR trial) AND TITLE-ABS-KEY (human* OR participant*)) **RQ 3:** (TITLE-ABS-KEY (wearable* OR smartwatch* OR wristband* OR clip* OR patch* OR "electronic skin") AND TITLE-ABS-KEY (ultraviolet OR UV OR UVA OR UVB) AND TITLE-ABS-KEY (sensor* OR dosimeter* OR radiometer* OR photodiode*) AND TITLE-ABS-KEY (effectiv* OR efficac* OR outcome* OR "UV dose" OR sunburn* OR usability OR "system usability scale" OR SUS OR economic* OR cost OR "cost-effect*" OR efficiency OR operational OR workflow* OR accuracy OR calibration OR "Bland-Altman" OR MAE OR RMSE OR MAPE) AND TITLE-ABS-KEY (human* OR participant* OR bench OR laboratory))

Appendix B: Scoping Review Tables

Table B1. Characteristics of articles included in the scoping review on wearable UV sensors (n = 29).

Author(s), year, and journal	Country	Study design	Participants [population; number of participants]	UV-sensor wearable and digital components	Primary objective
Chen et al. (2022). *Sensors & Actuators A: Physical*	China	Experimental study	No human participants reported.	Flexible photochromic polydimethylsiloxane wearable sensor, smartphone application utilising a convolutional neural network-based image evaluation.	To develop and validate a low-cost, power-free wearable photochromic UV sensor with smartphone-based quantification of solar intensity.
Chen et al. (2024). *Small*	China	Experimental study	No human participants reported.	Wearable band or polydimethylsiloxane-based sensing cell with CsPbCl3 perovskite nanocrystals, cumulative dose readout via fluorescence shift and colour change, multi-indicator array.	To develop an easily fabricated, low-cost wearable ultraviolet dosimeter with a visual cumulative-dose readout and multi-range quantification.
Chen et al. (2025). *Advanced Materials*	China	Experimental study	No human participants reported.	Flexible recyclable ultraviolet A monitor, Bluetooth communication, smartphone application showing ultraviolet intensity, cumulative dose, and personalised alerts based on skin type.	To develop a flexible, recyclable wearable ultraviolet A monitor for real-time dose monitoring under dynamic conditions with application-based feedback.
Dickey et al. (2024). *International Journal of Dermatology*	United States	Prospective observational pilot study	Erythropoietic protoporphyria patients; number of participants: 5.	Wireless light dosimeter worn as a wristband and locket, with continuous wavelength monitoring and smartphone connection via Bluetooth Low Energy.	To validate wearable measurements of UVA, blue, and red-light exposure in erythropoietic protoporphyria and correlate exposures with manifestations.
Dumont et al. (2024). *Frontiers in Medicine*	United States	Prospective randomised observer-blinded controlled clinical trial	Older adults with actinic keratoses; number of participants: 97.	Chest-worn Shade ultraviolet sensor with magnetic attachment, smartphone application (Apple and Android) connected via Bluetooth, real-time UVI and cumulative dose, exposure history, sunscreen logging, and notifications.	To evaluate clinical and behavioural effects of a wearable ultraviolet dosimeter and companion application, including lesion outcomes and quality-of-life measures.
Guo et al. (2021). *Materials Horizons*	China and Russia	Experimental study	No human participants reported.	Flexible ultraviolet organic photodetector integrated with a flexible organic light-emitting diode for visual intensity readout, with no smartphone component reported.	To develop visible-blind UV organic photodetectors and demonstrate a proof-of-concept wearable UV monitor with visual readout.
Han et al. (2024). *Macromolecular Rapid Communications*	China	Experimental study	No human participants reported.	Wearable UV detector fabric that converts UV illumination into electrical signals through an illumination-mechanical stress-electrical signal mechanism.	To create scalable, flexible, skin-compatible UV detector fabrics with UV-to-electrical signal conversion.

Hong et al. (2024). *Science China Materials*	China	Experimental study	No human participants reported.	Stretchable hydrogel-based UV photoelectric sensors, a wireless UV alarm circuit board, and a sensor array for monitoring and imaging.	To develop stretchable, stable hydrogel-based UV photoelectric sensors and demonstrate a wearable wireless UV alarm system.
Jeong et al. (2024). *AIP Advances*	Republic of Korea	Experimental study	No human participants reported.	Wearable colourimetric UV fibre with naked-eye readout, no digital component reported.	To create robust UV photochromic fibres suitable for wearable colourimetric UV sensing.
Kim et al. (2023). *Advanced Optical Materials*	Republic of Korea	Experimental study	No human participants reported.	Wearable UV-detection patch integrating microphotodetectors and electrodes, with no smartphone component specified.	To demonstrate practical wearable UV-detection patches designed for long-term use in medical and clinical settings.
Kim et al. (2024). *IEEE Sensors Journal*	Republic of Korea	Experimental study	No human participants reported.	Transparent stretchable electronic-skin sensor combining strain sensing and UV sensing, with no digital component described.	To create a dual-function wearable sensor that integrates strain and UV sensing with enhanced sensitivity and stability.
Lawrynowicz et al. (2024). *Chemical Engineering Journal*	Finland and Denmark	Experimental study	No human participants reported.	Hackmanite-coated fabric UV sensor, Sensoglow smartphone application, estimating UVI from fabric colour saturation using image analysis.	To demonstrate hackmanite-coated textiles as wearable UV sensors and validate application-based UVI estimation.
Li et al. (2024). *Small*	China	Experimental study	Volunteers for biocompatibility testing; number of participants not reported.	Photochromic bacterial cellulose patches and textiles, photopatterned logos and quick response codes readable by smartphone camera.	To propose a biofabrication route for photochromic wearable textiles for UV monitoring and smartphone-readable photopatterning.
Lin et al. (2021) *ACS Applied Materials & Interfaces*	China and Germany	Experimental study	No human participants reported.	Wristband with ionic hydrogels embedded in a polyurethane band, visual colour changes indicating solar radiation dose, no smartphone component reported.	To enable solar dose monitoring using an easy-clean wearable band intended to support balancing sun exposure benefits and risks.
Lin et al. (2024) *IEEE 20th International Conference on Body Sensor Networks (BSN)*	United States	Experimental development and usability validation study	Adults; 11 participants recruited; 10 completed the study.	Self-sustaining wrist sensor with solar charging and Bluetooth communication, real-time feedback and personalised recommendations.	To develop and evaluate a continuously powered wearable UV sensor and assess its potential to influence sun-protection intentions.
Mahitha et al. (2025) *IEEE International Students' Conference on Electrical, Electronics, and Computer Science*	India	Developmental and proposal-based study	Not reported (target population described as outdoor workers).	Cap-based wearable concept, microcontroller with Bluetooth communication, and a mobile application for monitoring and alerts.	To provide continuous real-time UV monitoring and preventive feedback for outdoor populations using an energy-efficient wearable system.

Ponnambalam et al. (2025) *6th International Conference on Intelligent Communication Technologies and Virtual Mobile Networks*	India	Experimental study	No human participants reported.	UV sensors integrated with a microcontroller and display, a mobile application with push notifications, a dashboard, and digital logging are described.	To enable low-cost personalised UV exposure tracking and alerts, supported by mobile notifications and a monitoring dashboard.
Robinson et al. (2021). *Archives of Dermatological Research*	United States	Randomised controlled trial (mixed-methods)	Melanoma survivors; number of participants: 60.	Battery-free wrist-worn UV A sensor, Android application synchronised using near-field communication, and daily short message service messages.	To assess short-term UV exposure changes using a wearable sensor with real-time exposure feedback and daily message-based goal prompts.
Stump et al. (2023). *International Journal of Environmental Research and Public Health*	United States	Observational study	Parent-child dyads; number of dyads: 97.	Shade UV monitoring device with Bluetooth connection to the Shade application, automated dose logging, and data accessible via a Health Insurance Portability and Accountability Act-compliant cloud-based server.	To assess correlations between quantitatively measured UV exposure and documented sunburn incidence in parent-child dyads.
Vieira et al. (2022). *Sensors & Actuators A: Physical*	Brazil	Experimental study	No human participants reported.	A transparent, printed ZnO-based photodetector transistor employing a cellulose-based hydrogel electrolyte, laboratory evaluation of UV response metrics, with no smartphone components reported.	To measure how UV radiation influences transistor characteristics and photodetector efficacy indices.
Vogel et al. (2023). *PLOS ONE*	United States	Randomised controlled trial	Melanoma survivors; number of participants: 386.	Second-generation Shade UV wrist wearable, intervention application with daily exposure limits and sunscreen notifications, and a control application that records exposure without feedback.	To test whether a wearable UV sensor and application promote sun-protective behaviours and reduce sunburns among melanoma survivors.
Wu et al. (2024). *Chinese Journal of Polymer Science*	China	Experimental study	No human participants reported.	Reusable wearable textile for UV monitoring and shielding, no digital component required.	To develop a ready-to-use, reusable, inexpensive wearable textile for UV monitoring and shielding.
Yang & Ju (2022). *RSC Advances*	Republic of Korea	Experimental study	No human participants reported.	Textile-based colourimetric sensors using thermochromic and UV photochromic fibres, colour analysis performed using red-green-blue and CIE Lab colour space in Adobe Photoshop CS4.	To develop washable, flexible fibrous sensors that visually signify alterations in thermal conditions and UV radiation intensity.
Yang et al. (2023) *Advanced Materials Technologies*	Australia	Experimental study	Human participants: population characteristics not reported.	Soft epidermal UV sensor with layered design enabling naked-eye quasi-quantitative monitoring, designed to avoid interference from skin colour, no auxiliary digital equipment required.	To develop a skin-compatible epidermal UV sensor enabling rapid, naked-eye quasi-quantitative monitoring with durability over repeated exposure cycles.
Yu et al. (2022).	Republic of Korea	Experimental study	Human demonstrations:	Flexible platform integrating strain sensing and UV sensing, UV indication can be transmitted to	To demonstrate integrated wearable strain and UV sensing,

ACS Applied Materials & Interfaces			number of participants not reported.	smartphones when combined with commercial signal-emitting devices.	including outdoor UV intensity monitoring and demonstration with human activity monitoring.
Zhang et al. (2021). *Optics Express*	China	Experimental study	No human participants reported.	Flexible zinc oxide microwire and polyaniline UV photodetector, no smartphone component reported.	To develop an affordable, flexible UV photodetector for wearable optoelectronic uses.
Zhang et al. (2024). *Nano Energy*	China	Experimental study	No human participants reported.	Wristband with film-based tunnelling UV sensor and flexible printed circuit board, Android application enabling real-time monitoring, Bluetooth communication, and battery-powered system.	To build a wrist-worn system that enables real-time, continuous solar UV monitoring, supported by an Android application.
Zhao et al. (2022). *ACS Applied Nano Materials*	China	Experimental study	No human participants reported.	Wristband with paper-based colour-switching film and reference colour band for visual comparison, no smartphone component required.	To enable a reusable, power-free, low-cost wrist-worn solar UV monitor with naked-eye intensity estimation.
Zhou et al. (2022). *Nano Energy*	China	Experimental study	Not specified.	Flexible wristband with self-powered perovskite photodetector, microcontroller-based signal acquisition and Bluetooth communication, Android application for real-time UVI visualisation and cloud upload, and additional environmental sensors reported.	To create a wristband for real-time UV monitoring using a self-powered, flexible photodetector with smartphone-based visualisation integration.

Table B2. Classification of UV-sensor wearables (n = 22).

Article	Form factor	Technological framework	UV spectral coverage	Application functionalities
Chen et al., 2022	Flexible, lightweight, power-free wearable photochromic sensor in PDMS; portable "gingerbread man" design.	Passive photochromic PDMS sensor coupled to a deep learning convolutional neural network for automated colour-to-intensity quantification; deployed as a mobile application.	Not specified; Inferred UV intensity based on colour change.	The mobile application provides real-time UV intensity estimation, convolutional neural networks for image processing to minimise ambient light interference, and provides solar-protection alerts on Android and Raspberry Pi.
Chen et al., 2024	Flexible wearable UV dosimeter (bracelet) based on PDMS; optional multi-indicator array.	Photochromic perovskite nanocrystals in dibromomethane as the sensing material; fluorescence colour shift via anion exchange.	Not fully specified.	The visualised fluorescence colour change enables real-time monitoring of cumulative solar UV dose. A multi-indicator array supports multi-range quantification (up to 1200 J/m²) and helps distinguish between safe and harmful exposure thresholds

				(including Minimum Erythema Dose).
Chen et al., 2025	Intrinsically flexible electrospun composite-fabric device; lightweight, stretchable, and durable (approximately 40 µm Az-TPU/P(VDF-TrFE) film; 150 µm conductive tape).	Azobenzene-thermoplastic polyurethane elastomers (Az-TPU) and piezoelectric poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] nanogenerators. Under UVA irradiation, trans–cis azobenzene isomerisation generates internal stress that induces dipoles in P(VDF-TrFE), producing electrical signals; Bluetooth enables real-time transmission to a mobile application.	Refined for UVA observation with elevated spectral specificity; negligible reaction to UVB owing to diminished azobenzene absorption.	Real-time UVA intensity and accumulated dose. The mobile application displays intensity and dose and provides personalised alerts based on the user-selected skin type, including a calculated maximum daily permissible UVA exposure and threshold alerts indicating the percentage of the daily limit reached.
Dumont et al., 2024	Chest-worn Shade UV dosimeter with magnetic attachment and companion application.	Measures erythemally weighted UV exposure every second and aggregates cumulative UV dose every 6 minutes; companion application via Bluetooth Low Energy.	Erythemal weighted UV (UVA and UVB).	Real-time UVI and cumulative exposure with exposure history. Users can set and adjust a daily UV exposure limit; notifications are provided. Sunscreen use can be logged, with SPF-based adjustment.
Guo et al., 2021	Flexible UV monitor integrating a visible-blind UV photodetector (PM-type OPD) and flexible OLED; built on a PET substrate with ITO electrodes.	Visible-blind photomultiplication-class organic photodetector (PM-class OPD) incorporating a TAPC: C60 (50:1) active stratum.	Narrowband response approximately 300–370 nm (cutoff approximately 370 nm).	Measures UV intensity and converts it to a visual OLED signal. Visible-blind operation reduces interference from visible light and other wavelengths.
Han et al., 2024	Flexible, skin-friendly electrospun (AzNPs-IL)/PVA fabric UV detector.	Poly(vinyl alcohol) (PVA) substrate with azobenzene-containing polymer nanoparticles (AzNPs) as UV-responsive units and a water-soluble ionic liquid ([BMIM][BF4]) as the conductive medium; illuminance–mechanical stress–electrical signal conversion.	Responsive at 365 nm (UVA).	Quantitative UV illuminance detection (10–150 mW/cm^2). Flexible and breathable, with potential integration into the Internet of Things and smart devices.
Hong et al., 2024	Stretchable, flexible hydrogel-based UV photoelectric sensor with a CuO/carbon-hydrogel-ZnO/carbon structure.	Strain-isolated CuO/carbon-hydrogel-ZnO/carbon heterojunction with p–n-junction-like electrodes bridged by ion-conductive hydrogel (I−/I3− redox); integrated with a circuit board for wireless alerting.	The highest response occurs at 395 nm (UVA); UVB coverage not reported.	Real-time UV intensity monitoring to protect patients with skin diseases; Bluetooth transmission to a smartphone and threshold-based alerts.

Jeong et al., 2024	Hydrophobic, stretchable UV-photochromic textile with photochromic fibers embedded in elastic spandex for garment integration.	Hydrophobic photochromic fibre design enabling reversible colourimetric sensing under mechanical deformation.	UV-responsive; UVA/UVB coverage not reported.	Power-free visual UV monitoring; consistent under stretching and exposure to aqueous environments, perspiration, and cleansing agents.
Kim et al., 2023	Skin-attached three-dimensional porous PDMS patch integrating InGaN/GaN microphotodetectors.	InGaN/GaN Schottky-diode microphotodetectors incorporated into a porous patch; rapid reaction and minimal-energy functionality.	Engineered for UVA (315–400 nm), optimised near 393 nm.	Long-term UVA monitoring for medical and clinical applications; designed for long-term usability with sweat and skin by-product removal.
Kim et al., 2024	Transparent, stretchable dumbbell-shaped sensor on a single PDMS substrate with soft and hard PDMS layers.	PANI nanofibres for strain sensing and ZnO nanorods for UV sensing (microwave-assisted hydrothermal growth).	Peak sensitivity at approximately 340 nm (near the UVA–UVB boundary).	Combined strain (deformation) and UV sensing for wearable and healthcare applications.
Lawrynowicz et al., 2024	Hackmanite-coated textiles and prints, including caps, are reported to resist washing and flexing.	Hackmanite ($Na_8Al_6Si_6O_{24}(Cl, S)_2$) is a photochromic mineral with reversible white-to-purple colouration; application-based analysis (Sensoglow).	UVA and UVB.	The application supported UVI estimation. The textile transitions from white to purple within 15 seconds of UV exposure and reverts to white in about 50 minutes under white light. Integration into wearable items (such as caps) has also been reported.
Li et al., 2024	Photochromic bacterial cellulose films or textiles are flexible and breathable.	In situ microbial fermentation using Gluconacetobacter xylinus with photochromic dyes; dye integration into bacterial cellulose nanonetworks to support uniform distribution and enhanced fastness.	UVA activation at 365 nm.	Daily sunlight UV monitoring and early warning for skin protection; supports multicolour switching and patterning.
Lin et al., 2021	Polyurethane wristband integrating an ionic hydrogel colourimetric sensor; shape-tunable.	Acrylamide polymerisation with TEMEDA to form an ionic hydrogel network; photoinduced oxidation of dyes (MB and NR) by TEMEDA.	Reported 190–280 nm.	MB discolouration indicates a sufficient dose of vitamin D; NR discolouration indicates sunburn risk. A thermoresponsive coating supports easy cleaning.
Lin et al., 2024	Self-sustaining wearable UV sensor featuring configurations for the wrist, hat, arm, and chest.	Solar energy harvesting using ETFE-based solar panels; includes Bluetooth Low Energy for real-time feedback.	UVA and UVB, with UVC capability through an AS7331 sensor.	Real-time UV data transmission. Personalised recommendations are provided to incorporate user inputs, such as sunscreen and clothing.
Mahitha et al., 2025	Proposed lightweight wearable cap with an embedded UV sensor and microcontroller for outdoor activities.	GUVA-S12SD UV sensor with an ESP32 microcontroller; mobile	Detection range reported as 240–370 nm (UVA and UVB).	Real-time dashboard with configurable exposure thresholds

		application via Bluetooth Low Energy.		and alerts; data logging for longer-term exposure insights.
Robinson et al., 2021	Battery-free mini wireless wrist UV dosimeter with a photodiode positioned on the dorsal wrist; synchronised to a smartphone.	Supercapacitor stores charge generated by photocurrent; wireless readout via near-field communication to a smartphone application. The application displays real-time UVA exposure and cumulative daily UVB exposure.	Real-time UVA exposure and cumulative daily UVB exposure (via application).	Real-time UVA display and cumulative daily UVB summary. Daily text messages provide behavioural facilitation, outcome expectancies, self-efficacy, and self-regulation strategies; continuous feedback supports behaviour change towards reduced sun exposure.
Vieira et al., 2022	Transparent ZnO electrolyte-gated transistor suitable for flexible PET and paper substrates.	ZnO semiconducting layer fabricated by spray pyrolysis; cellulose-based hydrogel electrolyte (CHE) and an ITO/ZnO/electrolyte/ITO structure with ITO source, drain, and gate electrodes; spray-coating system based on an airbrush spray nozzle adapted to a three-dimensional printer framework.	UVA sensing range reported as 320–400 nm.	A multiparametric UV photodetector that shows how the threshold voltage, subthreshold swing, transconductance, and saturation mobility vary with changes in UV light intensity. Documented application domains include optical communication, environmental surveillance, biomedical imaging, video imaging, dosimeters, security frameworks, and wearable electronic devices.
Wu et al., 2024	A textile-based sensor that is flexible, breathable, and durable, made by electrospinning a spiropyran derivative (SP-TPE) with polyurethane (PU).	SP-TPE undergoes reversible isomerisation between closed-ring (colourless) and open-ring (blue) forms under UV exposure; visible light or heat supports reversal. The loose, porous textile maintains photochromic properties after repeated bending, curling, twisting, 1000 folds, 3 hours of water immersion, and storage for 15 months at room temperature.	Not specified.	The chromatic change from white to blue indicates that the entity has been exposed to UVR, and the phenomenon can be reversed for retesting. The textile provides UV shielding and is reported to be resistant to mechanical stress and water immersion; application to cotton, nylon, spandex, and polyester textiles is described.
Yang et al., 2023	An epidermal wearable sticker comprising four 25 µm layers—skin-specific, UV-absorptive, UV-photochromic, and a white background) applied using medical adhesives.	Photochromic and UV-absorptive materials integrated into PDMS using screen printing and lamination. Photochromic materials (SINO, TPSO, and DNP) change colour under UV exposure, and the absorptive layer tunes the	Detection across UVA (365 nm), UVB (310 nm), and UVC (254 nm), with wavelength selectivity via the photoswitchable materials (SINO, TPSO, and DNP).	Visual discrimination of UVI levels 3–9 without auxiliary equipment. Customisation for skin types I–VI is achieved by adjusting the absorptive-layer concentration. Colour change and recovery occur within 30 seconds, and performance

		UV intensity reaching the photochromic layer.		is maintained for over 30 exposure cycles. Soft, stretchable mechanics are reported (Young's modulus comparable to human skin). The sensor is characterised as facilitating the observation of the application and removal of sunscreen.
Zhang et al., 2024	CsPbCl3 film-based tunnelling UV sensor wired to a flexible printed circuit board through conductive silver paint and encapsulated in a wristband; polymer battery embedded in a watch buckle.	Photo-induced tunnelling mechanism (CTUS) integrated with a compact, flexible printed circuit board (70 × 25 mm^2; 4.59 g) for signal processing and wireless communication; an Android application enables real-time, continuous monitoring via Bluetooth. The device's documented characteristics include an exceptionally low dark current (100 pA), notable responsivity (285 mA/W), a linear dynamic range of 95 dB, a short response time of 2.1 µs, and a low-light detection threshold of 150 nW.	Not specified.	Real-time UV intensity and UVI display on a smartphone.
Zhou et al., 2022	A flexible wristband features a UV photodetector incorporated.	Methylammonium lead chloride ($MAPbCl_3$) perovskite films are produced through solution-assisted halide exchange; Bluetooth 5 communication with an Android app, optional cloud uploading, and integrated temperature and relative humidity sensing.	Response is reported to be approximately 300–420 nm, with a 420 nm cutoff indicating it is visible-blind.	Indoor and outdoor real-time UV monitoring with smartphone visualisation and data recording, and integration into items such as caps, clothes, umbrellas, and robots, are described.
Zhao et al., 2022	Paper-based colour-switching film is used as a wrist-type UV monitor.	Titania/hydrated tungsten oxide (THTO) heteronanoparticles integrated into sticker paper; photo-driven redox colouration from colourless to blue.	Broad UV sensitivity reported as 200–400 nm (UVA and UVB).	Photoreversible switching enables multiple monitoring cycles; supports naked-eye monitoring of real-time personal solar UV intensity without external power (sunlight-activated).

Table B3. Intervention characteristics, empirical effects on behaviours and compliance (n = 5).

Author(s) and year	Behavioural targets and outcomes assessed	Effects on sun-protection behaviours (sunscreen, shade, protective clothing)	Compliance with wearable and application use
Dumont et al., 2024	Behavioural targets: Monitor and manage UV exposure using real-time data and personalised alerts; promote adherence to sunscreen use, protective clothing, and shade seeking. Outcomes assessed: Incidence of actinic keratoses; incidence of non-melanoma skin cancers; self-reported ability to participate in social activities; anxiety and depression (NIH PROMIS surveys); UV exposure behaviour (daily exposure dose and time spent outdoors).	Sunscreen: Low use (typically once or twice weekly). Shade: Not assessed. Protective clothing: Not assessed.	Wearable use: Compliance exceeded 75% in the summer and fell below 50% after November. Application use: Participants engaged with the application weekly, set daily exposure-dose thresholds, and received notifications about exposure.
Lin et al., 2024	Behavioural targets: Assess baseline sun-protection habits, post-study intentions, and UV awareness (usability study). Outcomes assessed: Baseline sun-protection habits; post-study intentions; UV awareness.	Sunscreen: Baseline, 18.2% reported consistent sunscreen use, and 36.4% reported never using sunscreen; post-study, 70% intended to increase sunscreen use. Shade: Baseline, 63.6% reported seeking shade. Protective clothing: Baseline, 18.2% reported consistently wearing protective clothing; after the research was completed, 90% stated they would wear protective clothing more often.	Wearable use: Participants wore the wrist sensor throughout the experiment and used the device's functions (high protocol adherence). Application use: Not reported; a companion application for personalised monitoring was proposed. Engagement and acceptability: Post-experiment feedback indicated perceived effectiveness and a higher likelihood of using sun-protection methods.
Robinson et al., 2021	Behavioural targets: Support self-management through goal setting and daily text messages, including reflection on personal UV exposure; prevent sunburn. Outcomes assessed: UV exposure and sunburn during the 21-day intervention.	Sunscreen: Promoted through daily messaging. Shade: Promoted through daily messaging. Protective clothing: Promoted through daily messaging.	Wearable use: Wearable sensor worn daily for 21 days (06:00-18:00) and synced to a smartphone for real-time exposure reporting. Application use: Participants reported that real-time exposure data helped them adjust outdoor activities to stay below their maximum tolerated exposure dose. Engagement and acceptability: Many participants expressed a desire to retain the sensor and application, as well as daily text messages and goal setting.
Vogel et al., 2023	Behavioural targets: Improve sun-protection behaviours (sunscreen use, shade seeking, protective clothing, shirts with sleeves, wide-brim hats, sunglasses) and reduce time spent in the sun to get a tan.	Sunscreen: No significant between-group differences were observed. Shade: No notable inter-group modifications were detected.	Wearable use: Approximately 75% reported wearing the device continuously for at least 5 days per week; compliance was similar across groups. Application use: Most participants downloaded the mobile application and provided exposure data (92.1% overall; 90.0% in the intervention and 94.1% in the

	Outcomes assessed: The primary outcome was a composite sun habit score averaging six behaviours (sunscreen, shirt with sleeves, sunglasses, shade, time in the sun to get a tan [reverse-coded], and hat). Secondary outcomes included self-reported sunburns, UV exposure (self-reported and objectively measured with the Shade device), physical activity, depression, and anxiety.	Protective clothing: No significant between-group differences were observed for shirts with sleeves and wide-brimmed hats. Other: Participants in the intervention group paid more attention to the device and its application, which affected sun-related behaviours (for example, sunscreen application) more than in the control group.	control); four control participants used the intervention application. Technical issues: About 40% experienced device issues (for example, broken straps or malfunctioning devices), resulting in 5-10-day delays in device use for some participants; damaged devices were replaced promptly.
Yang et al., 2023	Behavioural targets: Encourage adoption of sun-protection behaviours by providing real-time, skin-specific UV exposure monitoring. Outcomes assessed: Skin-tone-specific tolerance thresholds; user-reported wearability and skin reactions.	Sunscreen: Real-time feedback was intended to cue sunscreen use; sunscreen could be applied directly over the sensor. Shade: Not reported. Protective clothing: Not reported.	Wearable use: Volunteers reported that the sensor was barely noticeable during daily activities (walking, reading, and exercising). Adverse events: No adverse skin reactions were observed after wearing the sensor for a day.

Table B4. Evidence on the effects of UV-sensor wearables on individual UV dose and sunburn (n = 3).

Author(s) and year	**Study design and comparator**	**Relevant UV-related endpoint(s)**	**Effect on individual UV dose**	**Effect on sunburn incidence**	**Summary of reported findings**
Dumont et al., 2024	Prospective, randomised, observer-blinded controlled trial in an older population with actinic keratosis over six months (for one summer). Intervention group: UV dosimeter wearable device (Shade UV sensor) added to standard UV protection counselling. Control group: standard UV protection counselling alone.	Primary outcome: incidence rate of actinic keratosis at disenrolment in relation to the intermediary visit. Secondary outcomes: incidence rate of non-melanoma skin cancer at disenrolment in relation to the intermediary visit; UV exposure measured in Standard Erythemal Dose (SED).	A between-group change in mean UV dose was not described. In August-September, subjects with > 1 actinic keratosis at disenrolment had a greater mean daily exposure to UV radiation compared with those with 0 or 1 lesion (0.60 versus 0.33 SED; p = 0.0354).	Sunburns experienced by participants were not evaluated.	The actinic keratosis incidence rate ratio was 20% lower in the device group than the control group (p = 0.44). The non-melanoma skin cancer incidence rate ratio was 95% lower in the device group than the control group (p = 0.024).
Robinson et al., 2021	In a randomised trial conducted for a period of 21 days among 60 survivors of melanoma, both groups relied on a wearable UV sensor connected to a mobile application along with text messages. For this study, structured goal achievement was compared to unstructured goal achievement.	Primary outcome: reduction of UV exposure from Days 1-10 to Days 11-21 with a goal of minimising exposure to less than each participant's maximum tolerated dose.	The results showed a significant change in UV exposure, with the effects of the structured goal-setting procedure being more effective in reducing UV exposure than the unstructured goal-setting procedure.	There were no reports of sunburn during the intervention.	Short-term changes in UV exposure and the maintenance of such changes were higher in the goal-setting arm. The intervention package, consisting of the wearable sensor, smartphone app, daily texts, and goal-setting tasks, was found to be acceptable to the

					individuals. Long-term maintenance of changes outside the trial was not ascertained.
Vogel et al., 2023	The RCT lasted for 12 weeks and targeted melanoma survivors. It took place online during the two waves of the summer situations in the years 2020 and 2021. The intervention had the Shade (2nd generation) wearable device along with an app for mobile phones that enabled the users to access real-time information about UV radiation exposure, in addition to push notifications, as well as the sunscreen alarm feature.	Primary outcome measure: A composite measure of sun habits at week 12, including sunscreen, long-sleeved shirt, sunglasses, seeking shade, duration of sun exposure for purposes of tanning (reverse coded), and wearing a hat.	No statistically significant between-group differences were observed in objective UV exposure during peak hours or across full days. A UVR exposure time affected by the measure of the Sun Protection Factor in intervention participants using the sunscreen feature differed from the objective UV radiation exposure (median of 63 vs 87 J/m²). Objective UV radiation exposure for the sunscreen feature users was higher than for the non-users (median of 87 vs 56 J/m²; p = 0.03).	Sunburn prevalence was similar between the two groups (control 14.4% vs intervention 12.7%, p = 0.75). In the intervention, the prevalence of self-reported sunburn remained below 15%, compared with the pre-intervention value of 30%.	No significant inter-group improvements in sun-protection practices, UV radiation exposure, or sunburn. The limitations included device-related factors, a high level of baseline sun protection practices, and limited sun protection information in the application of the intervention.

Appendix C: Survey Questionnaire

Wearable UV Sensor Devices for Skin Cancer Prevention

You are invited to take part in a research study about sun exposure and attitudes towards wearable UV sensor devices for skin cancer prevention. This study is conducted as part of a Master's Thesis on Digital Transformation in the Healthcare Sector (ManagiDiTH) at ISCTE – University Institute of Lisbon.

The aim of this study is to explore how adults are exposed to the sun, how they protect their skin, and how they perceive wearable UV sensor devices for skin cancer prevention, including their interest and intention to use such devices in the future.

The survey is anonymous and takes about 5-10 minutes to complete. No information that could directly identify you will be collected.
Your participation is voluntary, and you may withdraw at any time without any consequences.

Consent

Q1. By selecting "I agree" and continuing, you confirm that you are at least 18 years old, have read the information above, and voluntarily agree to participate.

Response type: single choice

( ) I agree
( ) I do not agree

Section A - Demographic and health background

A1. Age

Response type: single choice

( ) 18–24
( ) 25–34
( ) 35–44
( ) 45–54
( ) 55 or above

A2. Gender

Response type: single choice

( ) Female
( ) Male
( ) Other
( ) Prefer not to say

A3. Country of residence

Response type: single choice

( ) Albania ( ) Andorra ( ) Armenia ( ) Austria ( ) Azerbaijan ( ) Belarus ( ) Belgium ( ) Bosnia and Herzegovina ( ) Bulgaria ( ) Croatia ( ) Cyprus ( ) Czech Republic (Czechia) ( ) Denmark ( ) Estonia ( ) Finland ( ) France ( ) Georgia ( ) Germany ( ) Greece ( ) Hungary ( ) Iceland ( ) Ireland ( ) Italy ( ) Kazakhstan (partly in Europe) ( ) Kosovo ( ) Latvia ( ) Liechtenstein ( ) Lithuania ( ) Luxembourg ( ) Malta ( ) Moldova ( ) Monaco ( ) Montenegro ( ) Netherlands ( ) North Macedonia ( ) Norway ( ) Poland ( ) Portugal ( ) Romania ( ) Russia ( ) San Marino ( ) Serbia ( ) Slovakia ( ) Slovenia ( ) Spain ( ) Sweden ( ) Switzerland ( ) Turkey (partly in Europe) ( ) Ukraine ( ) United Kingdom ( ) Vatican City

A4. Educational level

Response type: single choice

( ) Primary education
( ) Secondary education
( ) Bachelor's degree
( ) Master's degree
( ) Doctoral degree
( ) Other

A5. Main current occupation

Response type: single choice

( ) Student
( ) Employed
( ) Self-employed / freelancer
( ) Unemployed
( ) Retired
( ) Other

A6. Skin type (self-perception)

Response type: single choice

( ) Very fair / pale white skin, always burns, never tans
( ) Fair / light skin, burns easily, tans very little
( ) Light-to-medium skin, sometimes burns, tans gradually
( ) Light-brown / olive skin, rarely burns, tans easily
( ) Dark brown / moderately pigmented skin, rarely burns, tans deeply
( ) Very dark / black skin, deeply pigmented, never burns, always deeply tans
( ) I don't know / Prefer not to say

A7. Have you ever been diagnosed with skin cancer?

Response type: single choice

( ) Yes
( ) No
( ) Prefer not to say

A8. Do you have close relatives (parents, siblings, children) who have been diagnosed with skin cancer?

Response type: single choice

( ) Yes
( ) No
( ) I don't know / Prefer not to say

Section B - Sun exposure and protection behaviours

B1. On a typical weekday in spring/summer/autumn, how much time do you spend outdoors?

Response type: single choice

( ) Less than 30 minutes ( ) 30-60 minutes
( ) 1-2 hours ( ) 2-4 hours
( ) More than 4 hours

B2. How often do you get sunburnt? (strong redness that may hurt or peel)

Response type: single choice

( ) Never
( ) Less than once a year ( ) 1-2 times per year
( ) 3-4 times per year
( ) 5 or more times per year
( ) I don't know / can't remember

B3. How often do you use sunscreen (SPF 30 or higher) when you are in the sun at the beach or pool?

Response type: single choice (Likert)

( ) 1 - Never
( ) 2 - Rarely
( ) 3 - Occasionally
( ) 4 - Often
( ) 5 - Very frequently

B4. How often do you use the following forms of sun protection?

Response type: matrix (Likert)

	1 Never	**2 Rarely**	**3 Occasionally**	**4 Often**	**5 Very frequently**
Hat or cap	[ ]	[ ]	[ ]	[ ]	[ ]
Covering clothing (shoulders/arms)	[ ]	[ ]	[ ]	[ ]	[ ]
Sunglasses	[ ]	[ ]	[ ]	[ ]	[ ]
Seek shade at peak hours (11-17h)	[ ]	[ ]	[ ]	[ ]	[ ]

B5. To what extent do you agree with the following statements?

Response type: matrix (Likert)

	1 Strongly disagree	**2 Disagree**	**3 Neutral**	**4 Agree**	**5 Strongly agree**
I like having a suntan.	[ ]	[ ]	[ ]	[ ]	[ ]
I think the sun in my country is dangerous for the skin.	[ ]	[ ]	[ ]	[ ]	[ ]
I am worried about the risk of developing skin cancer.	[ ]	[ ]	[ ]	[ ]	[ ]
I feel I have enough information about sun protection.	[ ]	[ ]	[ ]	[ ]	[ ]

Section C - Use of technology and wearables

C1. Do you currently use any wearable device? (for example, smartwatch, fitness band, sports watch)

Response type: single choice

( ) Yes, every day
( ) Yes, occasionally
( ) No, but I used to
( ) No, I have never used a wearable

If you answered "No, but I used to" or "No, I have never used a wearable", skip to C3.

C2. If you answered "Yes", which type(s) of wearable do you use?

Response type: multiple choice

[ ] Smartwatch
[ ] Fitness band / activity tracker
[ ] Sports watch
[ ] Other: _____

C3. Do you use health-related apps on your smartphone? (for example, step counter, sleep tracker, heart-rate monitor)

Response type: single choice

( ) Yes, several apps
( ) Yes, one or two apps
( ) No

Section D - Awareness of UV monitoring wearables

D1. Before this survey, had you ever heard about wearable devices that measure UV exposure?

Response type: single choice

( ) Yes
( ) No
( ) I am not sure

D2. Have you ever used a device or app specifically to monitor sun exposure or UV levels?

Response type: single choice

( ) Yes, I currently use one
( ) I used one in the past
( ) No, never

If you answered, "I used one in the past" or "No, never", skip to Section E.

D3. If you answered "Yes", which device or app did you use?

Response type: short answer

_____

Section E - Attitudes and intention to use UV wearables

Please imagine a wearable device with a UV sensor that connects to your smartphone and sends alerts when your sun exposure is high.

E1-E10. Indicate your level of agreement with the statements below.

Response type: matrix (Likert)

	1 Strongly disagree	**2 Disagree**	**3 Neutral**	**4 Agree**	**5 Strongly agree**
E1. I believe a wearable UV sensor could help me avoid sunburn.	[ ]	[ ]	[ ]	[ ]	[ ]
E2. A wearable UV sensor could help prevent skin cancer.	[ ]	[ ]	[ ]	[ ]	[ ]
E3. I would use a wearable UV sensor if it were easy to use in daily life.	[ ]	[ ]	[ ]	[ ]	[ ]
E4. I would use a wearable UV sensor if it were discreet or aesthetically pleasing.	[ ]	[ ]	[ ]	[ ]	[ ]
E5. I would be willing to receive notifications on my phone about my sun exposure.	[ ]	[ ]	[ ]	[ ]	[ ]
E6. I am concerned about data privacy if I use a wearable UV sensor.	[ ]	[ ]	[ ]	[ ]	[ ]
E7. I am concerned about the reliability/accuracy of UV measurements.	[ ]	[ ]	[ ]	[ ]	[ ]
E8. Price would be an important barrier for me to use this type of device.	[ ]	[ ]	[ ]	[ ]	[ ]
E9. I would recommend a wearable UV sensor to friends or family with sensitive skin or a history of skin cancer.	[ ]	[ ]	[ ]	[ ]	[ ]
E10. I see value in integrating UV wearable data with other health data (for example, physical activity, sleep).	[ ]	[ ]	[ ]	[ ]	[ ]

E11. If a wearable UV sensor cost around 30-50 EUR, how likely would you be to consider buying one?

Response type: single choice

( ) 1 - Very unlikely
( ) 2 - Unlikely
( ) 3 - Neither unlikely nor likely
( ) 4 - Likely
( ) 5 - Very likely

Section F - Device design preferences

F1. Which format of wearable UV sensor would you prefer?

Response type: single choice

( ) Wristband
( ) Watch
( ) Skin patch / sticker
( ) Clip for clothing
( ) Glasses / other accessory
( ) I would not use any of these

F2. Which types of alerts would you find most useful?

Response type: multiple choice

[ ] Notification on the smartphone
[ ] Vibration of the device
[ ] Change of colour / light on the device
[ ] Sound alerts

F3. In which situations do you think you would use a wearable UV sensor more often?

Response type: single choice

( ) Beach / swimming pool
( ) Outdoor sports or exercise
( ) Outdoor work
( ) Weekend outdoor activities
( ) Everyday activities (walking, running, etc.)
( ) I do not see myself using this type of device

Thank you for your participation.