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Smart UV-Sensing E-Textiles for Real-Time Sun Exposure Monitoring and Skin Cancer Prevention: Mechanisms, Challenges, and Industry 4.0 Prospects

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Abstract

Skin cancer is the most common and preventable of cancers in the world and is caused most frequently by excess ultraviolet (UV) radiation. Best preventive practices in the form of sunscreen, protective apparel, and changes in behavior are effective but are limited by their users' low commitment levels. The most recent innovation is UV sensors based on textile, which is a cutting-edge concept where the sensors are implemented on the textile itself so that the UV exposure can be sensed in real-time and non-invasively. The review summarizes the recent achievements in textile-based UV dosimetry, and the mechanisms, such as photochromic dyes, nanomaterials, printed electronics, and fiber-level functionalization, are outlined. Systems reported show high sensitivity to both UV-A and UV-B radiation, providing comfort, affordability, and wearability benefits over the traditional electronic dosimeters. Nevertheless, there are still issues with washability, calibration error, environmental stability, and compatibility issues at large-scale manufacturing. The potential uses are found in occupational safety, sports and recreational apparel, pediatric apparel, and consumer wellness products. Additionally, it can be incorporated into the Internet of Things (IoT) to provide population-level exposure analytics and predictive healthcare planning that adheres to Industry 4.0 paradigms. Sustainability considerations such as material choice, scale-up-able processing, and lifecycle analysis are also important in providing long-term commercial sustainability and environmental stewardship. The integration of UV-sensing technologies in the fabrics of common wearables would transform preventative health care and decrease the incidence of UV-related skin cancers by a long margin, and create an active paradigm in the management of personal health.

Keywords
Smart Textiles, UV Sensors, Preventive Healthcare, Internet of Things (IoT), Sustainable Manufacturing.

1. Introduction
Among the most common cancers in the world today is skin cancer (Tahseen and Nambudiri 2022). According to epidemiological research, skin cancer is an important public health concern, as it can affect anyone of any age group and regardless of gender, as the disease has steadily increased during the last several decades (Zou et al. 2020). It may cause permanent damage to our health and undermine the quality of our lives in general. Much attention is paid to the research, development, and improvement of protective garments, and their barrier properties, in particular (Periyasamy et al. 2020). The protective barriers are the ability of clothing or textiles to protect the wearer against the above-mentioned risky conditions, and whether this protection is only partial or limited by environmental factors as time passes (Minaoglou et al. 2024). This paper shall discuss textile-based UV sensors as a way of reducing the risk of skin

cancer. Skin cancer is a cancer that starts with the growth of skin cells (Ibrahim et al. 2025). These cells are able to advance and destroy normal body tissue (Gilaberte et al. 2022). In some cases, the cells become detached and spread to the other parts of the body (Fu et al. 2024). There are many types of skin cancer depicted in Figure 1. Basal cell carcinoma and squamous cell carcinoma are the most common kinds of skin cancer (Tahseen and Nambudiri 2022). Most of them (or the most common) are often curable. The highest risk type of cancer of the skin is melanoma (Dejene et al. 2025). Its greater transmissibility makes it hard to treat.

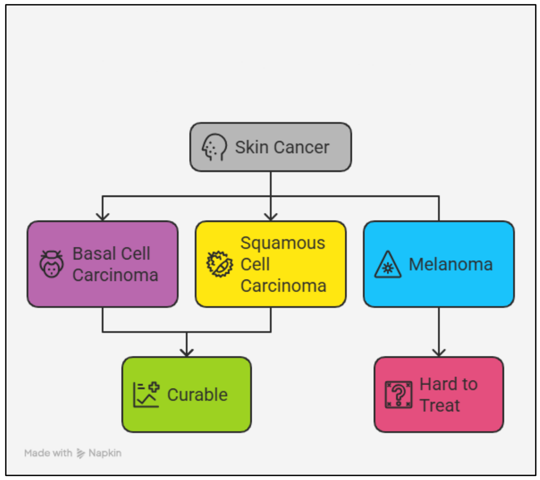

Figure 1. Some Types of Skin Cancer

Most of the skin cancers develop in locations of the skin that are highly exposed to the sun (Choi et al. 2022). It is assumed that the major cause of the majority of skin cancers is sun radiation (Aguilera et al. 2024). The most secure way is to protect your skin by dressing or putting sunscreen on to shield your skin against sunlight exposure to avoid skin cancer (Adeleke, n.d.). Preventive strategies are effective, but much relies on personal compliance and education (Abtew et al. 2025). Portable UV dosimeters have in recent years, emerged as a useful weapon that can scientifically be used to assess the dose of UV to people (Arab Hassani et al. 2020) (Ascierto and Schadendorf 2022). These devices have several benefits: they provide real-time, numerical feedback of total UV exposure, can be paired with smartphone applications to provide actionable feedback, and, in some research, have been successful at promoting sun protection behavior (Basit et al. 2025). However, modern dosimeter jewels also have significant limitations. They might depend on their location and orientation to the body and require battery power or wireless communication (Chen et al. 2022). Furthermore, their cost and size restrict the popularity and use in everyday settings, particularly in more general settings, such as schools, workplaces, or outdoor careers (Choudhry, n.d.).

2. Literature Search Strategy

An extensive literature review was conducted to find the relevant research on skin cancer prevention. The databases used included PubMed, Scopus, Web of Science, and Google Scholar. The search methodology involved a mixture of words such as skin cancer, malignancy, melanoma, non-melanoma, prevention, and public health. To ensure that the most up-to-date and relevant findings are included, the search was limited to peer-reviewed publications published within the past 10 years (2013-2025).

3. Discussions

A study on textile-built UV sensors has shown that it is highly sensitive to UV-A and UV-B light (Li and Chai 2021). Prototype systems are often shown to exhibit a measurable change in electrical resistance, optical absorption, or colorimetric response with increasing UV intensity (Adeleke, n.d.). The expected results include an almost linear response curve of the ultraviolet in calibration systems with reversible changes in materials such as photochromic dyes or functionalized nanomaterials. However, reversibility and long-term stability are inconsistent in the documented prototypes, with Some models showing a progressive depletion following repeated exposure cycles, illustrated in Figure 2.

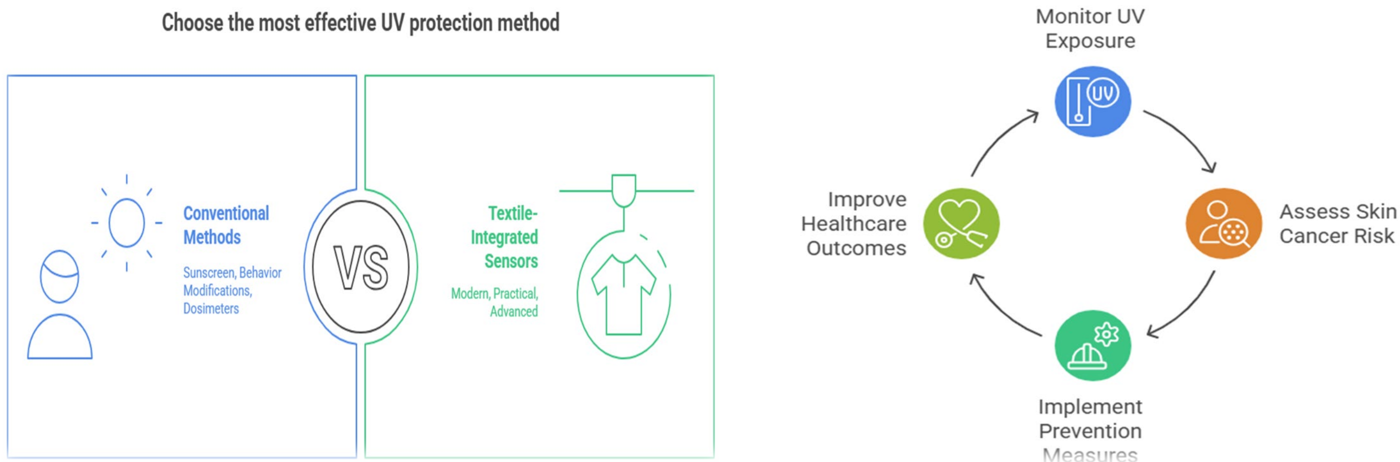

Figure 1: Closed-loop approach to reducing UV-induced skin cancer risks through monitoring, assessment, prevention, and outcome evaluation.

3.1 Durability and Wearability

Sturdiness is a critical requirement of textile applications. It has been shown in the literature that although sol-gel coatings and grafted polymer films may enhance photostability, washability remains a major limitation (Du et al. 2023). Printed electronic circuits often crack or delaminate after laundering, and fiber-level embedding provides a higher endurance, but at a higher cost of manufacture. Abrasion resistance, exposure to perspiration, and UV-aging experiments indicate significant deterioration of performance in many prototypes, and it is important to develop improved methods of encapsulation.

3.2 Benchmarking Against Existing Wearables

Textile-integrated systems are expected to offer more comfort and flexibility in wear and also integration in everyday clothing, compared to commercial electronic UV dosimeters (Eagleton et al. 2023). Although dosimeters are accurate, giving quantitative data, they tend to be bulky and very costly (Firmanda et al. 2022). Conversely, solutions based on textiles are less expensive and more wearable, but at present lack calibration accuracy, long-term stability, and standardized performance validation (Gao et al. 2025).

3.3 Engineering Challenges

There are several engineering barriers in the process of transforming laboratory prototypes to market-ready products. The accuracy is also determined by factors in the environment, including temperature, humidity, and light angularity. Electronic textiles have power issues, with energy-harvesting and passive sensing methods under investigation.

3.4 Public Health Perspective

Textile-built UV sensors have a great potential in promoting sun-safety behaviors from a public health perspective (Hua et al. 2025). They are capable of continuous, non-invasive monitoring of daily outdoor activities, unlike the stand-alone devices, which enhance adherence to the user. These systems may aid in customized UV exposure warning systems and promote re-application of sunscreens, and minimize the chances of cumulative overexposure, especially useful in areas with high UV indices (Ianculescu et al., n.d.). Nonetheless, to be successful in translation, it must be clinically validated, user-centrically designed, and affordable on a large scale so that it can be made equally accessible.

4. Potential Applications in Industry and Healthcare

UV sensors built into textiles are not just confined to lab experiments and have a huge potential to be applied in many practical uses (Joutsen et al. 2024), some of them is depicted in Figure 3. These systems can also help wearable technology close the divide between proactive health measures and the technology worn every day by integrating UV-sensing applications into regular clothing, ensuring easy and efficient sun protection (Juan et al. 2025).

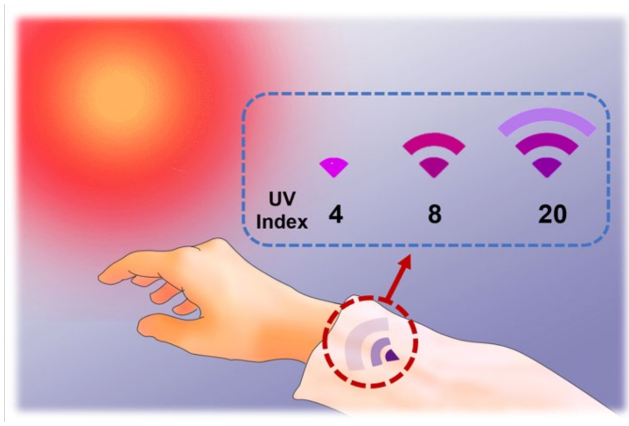

Figure 2. Schematic overview of textile-integrated UV sensor application

4.1 Outdoor Workers

Construction laborers, farm workers, and fisheries workers are occupational groups whose exposure to the sun is prolonged and in some instances greater than the recommended daily UV dose limit (Li et al. 2024). Real-time avoidance (for example, shade breaks, reapplication of sunscreen, or use of head protection) can be attained by integrating UV sensors into attire (Figure 4). These applications may greatly lower occupational skin cancer risk, particularly in places with elevated ambient UV index.

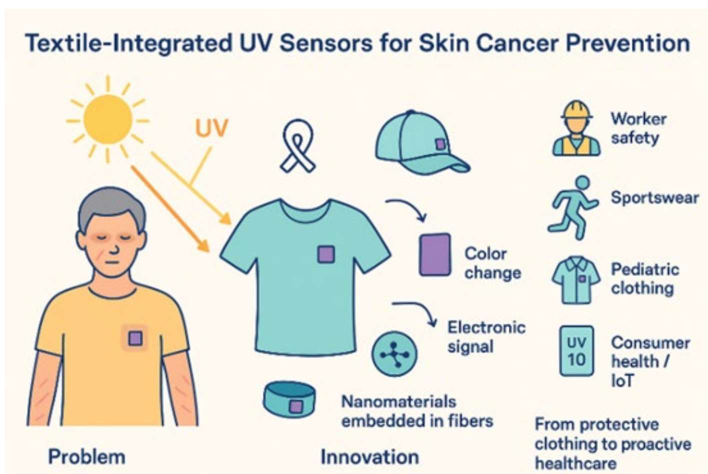

Figure 3. Illustration of a wearable UV sensor embedded in clothing, displaying real-time UV index levels through variable signal intensity corresponding to different exposure levels.

4.2 Sports and Recreational Wear

Sport athletes, runners, cyclists, and outdoor recreationists are also at risk for UV overexposure based on time spent outside (Li and Chai 2021). Sensors integrated into fabric elements of sport clothing or accessories (e.g., headbands, wristbands) might provide dynamic exposure feedback without impacting performance. Its breathable, flexible, and lightweight design makes it comfortable and promotes safer recreational practices (Liu et al. 2022).

4.3 Pediatric Applications

Kids are also the most exposed to the effect of UV on the skin as they spend a lot of time outside, and their skin is sensitive [1]. School uniforms with UV sensors would be beneficial in two ways: creating awareness among parents and teachers, along with teaching sun-safe behaviors at an early age. Simple, non-digital tools, such as the use of colorimetric indicators in the clothing of children, can also be used to notify the caregivers that there is a high UV exposure (Lugoda, n.d.).

4.4 Consumer Health and Wellness Products.

The health-wise wearable market is growing at a very fast rate. The possibilities of UV-sensing textiles include embedding them into daily clothing, accessories, or lifestyle items, and allowing the user to track their personal sun exposure (Mi et al. 2025). A smartphone platform would enable integration to enable its users to monitor cumulative UV dose, get behavioral suggestions, and share data with the dermatologist to maintain primary healthcare (Milone et al. 2023).

4.5 Incorporation in Industry 4.0 and IoT-Based health monitoring systems

Smart textiles Future is connectivity. UV sensors based on textiles would add to real-time exposure databases on a large scale when combined with IoT platforms (Fu et al. 2024). Such integration would make it possible to predictively analyze public health planning, employer-initiated occupational safety surveillance, as well as wellness programs, which are often tied to insurance (Piao et al. 2025). These systems correspond to Industry 4.0 paradigms, with information-driven decision-making increasing personal safety and health management of the entire population (Ping et al. 2023).

5. Sustainability and Considerations in Manufacturing

The introduction of UV-dosimeter features in the textile world is a major concern of sustainability and manufacturing, especially in terms of material choice, processing pathway, and end-of-use.

5.1 Fiber level versus Coating Methods

There are two main strategies that are used: fiber-level functionalization and post-processing coating (Pupeikė 2025). A better solution is fiber-level incorporation, when the UV-sensitive materials are incorporated in the way of fiber spinning or polymer modification, and normally offers better durability, wash resistance, and long-term functionality (Qiu, n.d.). These processes are, however, usually complex in the way that they require intricate synthesis mechanisms, a high energy input, and possibly non-renewable feedstocks (Rai et al., n.d.). Conversely, more convenient techniques to coat the surfaces, including dip-coating, spray application, or screen-printing, are easier and more scalable. However, they often utilize solvent-based systems, have shorter functional lifetimes, and become a source of more chemical waste and microplastic discharge through surface wear (Ramasamy, n.d.).

5.2 Scalability and Factory Production

Changing the prototypical models from the laboratory scale to the industrial scale is a significant obstacle (Ronghan et al. 2025). The processes involving coating are more scaling-friendly in nature and use the pre-existing infrastructure of textile finishing. However, the prediction of uniform deposition, functionality of the deposition after repeated laundering, and performance variability throughout large fabric lots are still challenged (Saty et al. 2024). Fiber-level processes, which have potential in the area of durability, need special extrusion or spin-on composites equipment, which incurs increased capital expenditures and is unable to fit with existing large-scale systems of production. Therefore, the development in the future should deal with the trade-offs of durability, cost-effectiveness, and production feasibility (Wagih et al. 2023).

5.3 Lifecycle Assessment (LCA)

There should be a lifecycle approach to gauge the environmental impact of UV-dosimeter textiles (Figure 5). Among the key parameters are the energy requirements in the process of polymer production, the nanomaterials preparation, or finishing operations (Yildirim et al. 2018). Generation of wastes, especially the effluents and solvents used in coating processes. Recyclability (usually compromised in coated textiles by using multi-material layers, which are harder to recycle) can be achieved on the fibre level by mono-material system design, although it is seldom done so. Product lifespan, as long life cycles of products decrease the total replacement rate, and as a result, decrease cumulative resource consumption (Ronghan et al. 2025). New approaches to minimizing environmental impact involve the use of bio-based or biodegradable polymers, solvent-free or waterless processing methods, and a combination of environmentally friendly photochromic or thermochromic dyes (Yildirim et al. 2018).

Figure 4. Lifecycle Approach

6. Conclusion and Future Work

UV dosimeter textiles offer a promising future of wearable health monitoring, providing a more convenient and practical platform to monitor continuous exposures. These systems open up the possibility of real-time non-invasive monitoring by implementing UV-sensitive properties to fabric, which can be easily fitted into everyday life. These innovations help solve a major health issue in the public, as over-exposure to UV is still one of the leading causes of skin cancer in the world. Although there are welcome improvements, there are still various constraints. The main challenge that current research has been facing is proof-of-concept demonstrations with washability, durability, and calibration under varying environmental conditions remaining to be a major challenge. To guarantee sensor stability in the repeated laundering process, and guarantee consistent performance of sensitivity in various skin shades, weather, and usage behavior, this should be considered significant in the area of future research. In order to make the process of bringing laboratory prototypes into real-life applications faster, there are several research domains that should be given priority. To begin with, it will be necessary to conduct clinical validation and real-life testing; randomized controlled trials (RCTs) will have to be carried out to prove the clinical viability of textile-based UV dosimeters in reducing the harmful exposure, as well as enhancing health outcomes. Second, pilot-scale production and process optimization should be implemented to determine large-scale manufacturing viability so that researchers and industry can determine the scalability, cost-effectiveness, and compatibility of a new technology with current textile manufacturing systems. Lastly, some standardization of testing procedures is essential to create a set of common standards of UV sensitivity, wash resistance, and operating life, which would allow comparison of the outcomes of each study with others in a single study and make regulatory approval possible. Finally, the introduction of UV dosimeter technologies in the textile industry might become a radical change in preventive medicine. With these innovations making UV exposure easily monitored, continuously, and without facing the user, there is a great possibility to greatly decrease rates of UV-related skin cancer and allow individuals to take their own health more seriously.

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Biographies

Tanzim Hossain Oyshi is a 4th-year undergraduate student in the Department of Textile Engineering at the World University of Bangladesh (WUB), where she maintains an excellent academic record. Her primary research interests include functional textiles, sustainable materials, natural fiber composites, and the environmental impacts of textile processing. She previously served as a Research Fellow under the Ministry of Science and Technology, contributing to the project titled "Development and Characterization of Locally Available Natural Fiber Reinforced Polypropylene (PP) Matrix Based Partially Degradable Composites for Civil Construction*."* In this role, she was actively involved in experimental analysis, fiber–matrix characterization, mechanical testing, and material evaluation, supporting the development of eco-friendly composite materials. Oyshi has authored multiple publications covering diverse yet impactful areas, including taro fiber properties, eco-friendly material development, environmental consequences of textile dyes, and the psychological effects of the COVID-19 pandemic. Her work reflects a strong commitment to sustainability-driven innovation and interdisciplinary research. Beyond academics and research, she is deeply engaged in leadership and extracurricular activities. She currently serves as the President of the IEOM Society WUB Student Chapter and the Organizing Secretary of the WUB Textile Club, along with contributing as a Campus Ambassador for various textile and engineering platforms. Throughout her journey, she has also actively participated in volunteering initiatives, especially in projects supporting underprivileged street children. Passionate about research, sustainability, and community impact, Oyshi aims to continue advancing environmentally responsible textile solutions and contribute to research-driven innovations that address global challenges.

Mohammad Bellal Hoque is a dedicated academic and researcher specializing in Textile Engineering. Since September 2023, he has served as a Senior Lecturer in the Department of Textile Engineering, following previous roles as an Assistant Professor (2022-2023) and Lecturer (2018-2022). His earlier professional experience includes teaching Apparel Manufacturing & Technology (2017-2018) and roles in the textile industry (2016-2017). He is currently pursuing a PhD in Textile Engineering at Dhaka University of Engineering & Technology (DUET), where he previously completed his M.Sc. in Textile Engineering (2022), having earned his B.Sc. in Textile Engineering from World University of Bangladesh (2016). Mr. Hoque possesses extensive laboratory skills, including UV-Visible and FTIR spectroscopy, mechanical testing, and composite fabrication (hand lay-up/compression molding). He is proficient in data analysis (Origin) and reference management (Zotero). His research is focused on natural fiber-reinforced composites, natural dyeing and finishing, sustainable textiles, and functional materials. He has contributed significantly to research at institutions like AERE, BCSIR, and DUET. His scholarly output includes 27 peer-reviewed publications (two book chapters, two conference papers). He is also an Associate Investigator on a MOST-funded project (2024–2025) focused on developing partially degradable, natural fiber-reinforced polypropylene composites for civil construction.

Mr. Md. Mostafizur Rahman currently serves as Associate Professor and Head of the Department of Textile Engineering and Fashion Design at the World University of Bangladesh (WUB), where he also leads the Curriculum Committee. He is presently pursuing his Ph.D. in Textile Engineering at the Dhaka University of Engineering and Technology (DUET). Mr. Rahman previously served as Chairman of the Program Self-Assessment Committee (2017–2018) under the Higher Education Quality Enhancement Project (HEQEP) of the University Grants Commission

(UGC). He has extensive experience in designing and reviewing Outcome-Based Education (OBE) curricula, developing course profiles and assessment strategies, and overseeing faculty professional development initiatives. He has authored 29 peer-reviewed journal articles and multiple book chapters published by Wiley–Scrivener and Springer Nature. His research interests include smart textiles, wearable electronics, medicinal and antimicrobial textiles, ultraviolet protection coatings, and natural polymer-based composites. In his professional affiliations, Mr. Rahman is a member of both the Institute of Engineers, Bangladesh (IEB) and the Institute of Textile Engineers and Technologists (ITET). He began his career in 2008 as a senior executive in the Research and Development Department of Interstoff Apparels Ltd., Gazipur, before joining WUB as a Lecturer in 2010.

Masuma Jahan Tanjila is an undergraduate student in the Department of Textile Engineering at the World University of Bangladesh, where she is currently in her third year of study with a strong academic record. Her research interests center on natural fibers, polymer composites, sustainable materials, and emerging textile technologies. She worked as a research fellow under the Ministry of Science and Technology on the project (2024–2025) titled "Development and Characterization of Locally Available Natural Fiber Reinforced Polypropylene (PP) Matrix Based Partially Degradable Composites for Civil Construction," contributing to material characterization and data analysis. She has authored and co-authored publications on topics such as taro fiber properties, extraction techniques, applications, and the health and environmental aspects of plant-based tannins. Beyond her academic work, she is actively involved in extracurricular and organizational activities, serving as the Vice President of Research at the IEOM Society WUB Student Chapter and the Research and Extension Secretary at WUB Textile Club. Through these roles, she promotes research engagement, student participation, and academic development within her institution. Her long-term goal is to pursue advanced research and contribute to sustainable innovations within the textile and materials engineering sectors.

Imran Hosan is an undergraduate student in the Department of Textile Engineering at the World University of Bangladesh, currently in his third year of study. His research focuses on natural fiber-reinforced polymer composites, with an emphasis on mechanical performance, water absorption behavior, and biodegradability of sustainable materials. He is actively engaged in the Ministry of Science and Technology (MOST)–funded project "Development and Characterization of Locally Available Natural Fiber Reinforced Polypropylene (PP) Matrix Based Partially Degradable Composites for Civil Construction," where he contributes to experimental design, material characterization, performance evaluation, and data analysis. Imran has also contributed to scientific literature on natural fiber properties, extraction methods, and their potential industrial applications. His academic interests include smart textiles, sustainable material development, medical textiles, and advanced composite technologies, which he intends to explore in future research initiatives. Beyond his research activities, Imran participates in student-led organizations and initiatives aimed at fostering academic collaboration, knowledge dissemination, and professional development among peers. Through his work, Imran Hosan seeks to contribute to the development of high-performance, eco-friendly materials, advancing the integration of sustainability and innovation within textile and materials engineering disciplines.

Umme Ayman is an undergraduate student in the Department of Textile Engineering at the World University of Bangladesh, currently in her third year. She has established a strong academic foundation complemented by active participation in research and technical initiatives. Her research interests include smart textile innovations, sustainable textile practices, coloration science, and medical textile applications, which she aims to explore further in her future work. She has contributed to several scientific review publications covering tannin extraction methods, industrial applications of natural polyphenols, and the processing and utilization of taro fibers. She is also involved in a Ministry of Science and Technology–funded project titled "Development and Characterization of Locally Available Natural Fiber Reinforced Polypropylene (PP) Matrix Based Partially Degradable Composites for Civil Construction," focusing on experimental evaluation, material characterization, and data analysis. In addition to her research, Umme Ayman serves as the Vice President of Activities of the Industrial Engineering and Operations Management (IEOM) Society – WUB Student Chapter, coordinating academic events and fostering student engagement. She aspires to advance sustainable innovations in textile and composite materials through further studies and research.

Rajib Hasan is a Mechatronics Engineering student at the World University of Bangladesh, specializing in embedded systems, firmware development, IoT technologies, and modern software development. He has strong skills in STM32, ESP32, and Arduino microcontrollers and is proficient in PCB design using Altium Designer, EasyEDA, and Proteus. In addition to hardware engineering, Rajib is a Flutter app developer and a MERN stack developer, enabling him to create mobile and full-stack web applications that integrate seamlessly with hardware systems. He has 2 years of job experience at THINK Lab as an Embedded System Developer, where he contributed to STM32-based solutions, automation systems, and various embedded firmware applications. At his university, Rajib is actively involved in research on embedded systems, robotics, IoT, wearable technology, e-textiles and smart textiles, image processing, and Flutter-based application development. His research focuses on designing intelligent, user-centric, and innovative systems that blend hardware and software for practical real-world applications.