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Enhancing ECG Heart Rate Measurement Accuracy through Advanced Noise Cancellation Techniques

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Abstract

Proper monitoring of heart rate is important in the early diagnosis, the continued evaluation of patients, and the creation of wearable health care systems. Nevertheless, records of ECGs that are obtained on low-power portable devices are susceptible to motion artifact, baseline drift, muscle noise, and electromagnetic interference, leading to a considerable decrease in the reliability of measurements. This paper introduces a heart rate sensor based on noise-resilient noise cancellation algorithms for the ECG sensor, utilizing both hardware and digital noise cancellation methods. This system uses a high-gain instrumentation amplifier with a customized circuit to eliminate common-mode interference, which is then followed by analog bandpass filtering to eliminate baseline wander and high-frequency noise. The digitized signals are then further processed with an optimized digital pipeline, which consists of a 0.5-40 Hz bandpass filter. Experimental findings from the measured conditions of control in lab experiments and simulated motion conditions demonstrated that the proposed method is significantly more effective in terms of signal-to-noise ratio and reduces erroneous detections, providing more reliable and steady heart rate estimation. The suggested system shows high potential for application in low-cost wearable health-monitoring systems, remote patient-care technologies, and smart e-textile implementations where reliable physiological sensing is needed.

Keywords
Noise Cancellation, ECG (Electrocardiogram), Smart E-Textiles, Wearable health monitoring, Motion Artifacts.

1. Introduction
ECG is one of the most important physiological measurements used in assessing the rhythm, detecting abnormalities related to cardiac disorders, and monitoring patient health. The rapid advancements in wearable technologies have expanded ECG monitoring into consumer devices, home health systems, smart garments, and low-power ambulatory sensors. Despite these developments, accurately measuring heart rate using ECG remains a challenging task due to the presence of significant noise during real-world data acquisition. The amplitude of ECG signals ranges from millivolts, while the occupied bandwidth spans the low-frequency domain from 0.05 to 100 Hz, making it particularly susceptible to both external and physiological interferences. Noise contamination distorts QRS complexes, causing false R-peak detections and thus unreliable heart-rate calculations. ECG noise resilience would therefore be improved

toward achieving robust wearable and remote health-monitoring systems. This review outlines the state-of-the-art noise-cancellation strategies for improving the accuracy of ECG-based heart-rate measurements. It consolidates the hardware and digital methods developed so far, presents a critical assessment of their effectiveness, and emphasizes emerging opportunities for next-generation sensing technologies (Figure 1)

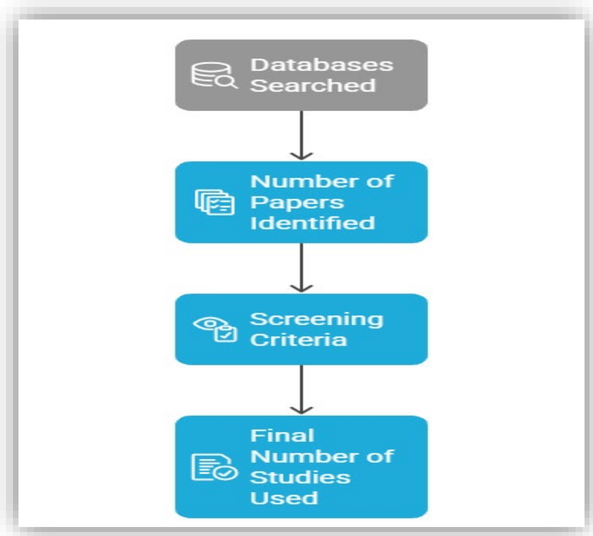

Figure 1. Overview of ECG Signal and Noise Sources

2. Literature Search Strategy

A comprehensive literature review was conducted to identify relevant research on noise cancellation techniques. The databases utilized included PubMed, Scopus, Web of Science, and Google Scholar. The search methodology involved using a combination of keywords such as ECG, monitor, signals, DSP, and public health. To ensure that only the most current and pertinent findings were included, the search was restricted to peer-reviewed publications from the past decade (2013-2025) (Figure 2).

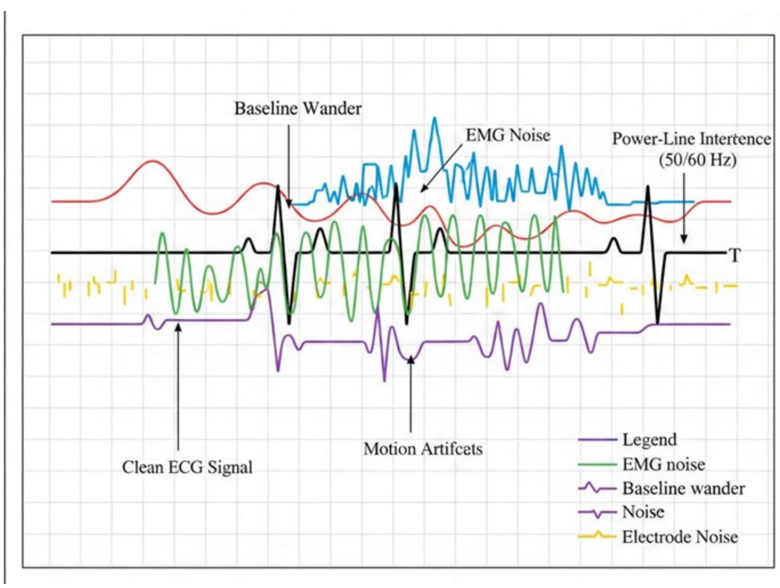

Figure 2. Systematic Review Process

3. Discussion

Improving accuracy for heart rate measurement within ECG signals requires an understanding of the contribution levels of various noise-canceling methods, either based on hardware or digital. Various methods have different benefits and challenges, making it necessary to combine them. At times, combining multiple methods might be more beneficial.

3.1 Role of Hardware-Based Noise-Cancellation Methods

Noise-cancellation methods based on hardware provide the basic layer of ECG signal conditioning. High-CMRR instrumentation amplifiers, such as INA128, AD620, and INA333, are crucial in the initial step of signal acquisition (Alsabah et al. 2025). Analog bandpass filtering usually follows (0.5-40 Hz), which, along with these front-end circuits, effectively removes baseline wander and high-frequency EMG noise. Power-line interference is further reduced by means of 50/60 Hz notch filters, while DRL circuits actively stabilize the body reference potential and further reduce common-mode noise (AlArnaout et al. 2025). However, electrode technologies also constitute an important part in this respect: conductive hydrogel, flexible polymer-based sensors, textile-integrated electrodes, and capacitive non-contact electrodes improve skin contact and reduce impedance fluctuations, thus minimizing motion-induced artifacts. Hardware filtering may significantly improve the baseline SNR; however, it cannot exclude non-stationary and movement-related disturbances, thus, advanced digital post-processing is inevitable (Ameen et al. 2024).

3.2 Digital Noise-Cancellation Techniques for Enhanced Signal Refinement

Digital noise cancellation methods further extend and refine the improvements obtained in hardware conditioning. FIR and IIR digital bandpass filters are very popular owing to their computational efficiency and stable performance in wearable devices (Balasubramanian and Naruka 2022). For dynamic noise conditions such as motion artifacts and fluctuating EMG interference, adaptive filtering techniques are of higher performance, specifically LMS and RLS, when reference inputs such as accelerometer data are available. Wavelet-transform-based denoising recently emerged as one of the powerful techniques for non-stationary noise, because it preserves QRS morphology but isolates signal components at different scales. Empirical Mode Decomposition (EMD) further improves low-frequency noise suppression but is computationally intensive; hence, its utility in a low-power wearable is limited (Bechinia et al. 2024). (Figure 3)

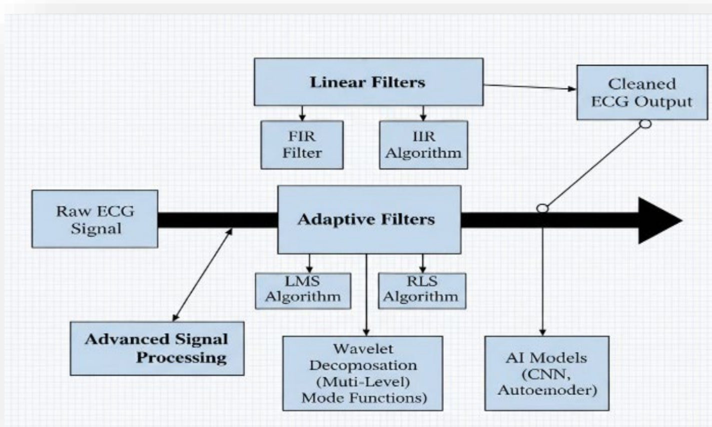

Figure 3. Digital Filtering Workflow

However, these methods are mostly demanding of higher processing power and more memory, requiring optimizations to be appropriate in real-time wearable applications. Accurate R-peak detection algorithms, such as those suggested by Pan–Tompkins, Hamilton–Tompkins, and derivative-based, remain central in reliable heart-rate extraction, particularly after noise suppression.

3.3 Comparative Performance and Trade-Off Analysis

A comparative review of these methods underlines the merits and trade-offs inherent in each class. Hardware filtering is power-efficient and indispensable for rejecting primary noise sources, but suffers from insufficiency against motion artifacts. Digital bandpass filtering provides simplicity but faces difficulties with non-stationary interferences (Figure 4)(Bondarenko et al. 2025). Adaptive filters ensure performance in dynamic conditions but rely on reference signals. Wavelet denoising ensures workability of complex signals at a moderate computational cost, while the EMD method provides good low-frequency noise suppression; however, it is not feasible for real-time processing due to large computational complexity (Chatterjee et al. 2020). AI-based approaches ensure the highest accuracy, which is conditioned by high power consumption and system complexity. Because of this, hybrid analog-digital architectures constantly outperform the pure methodology approaches by taking advantage of every stage:

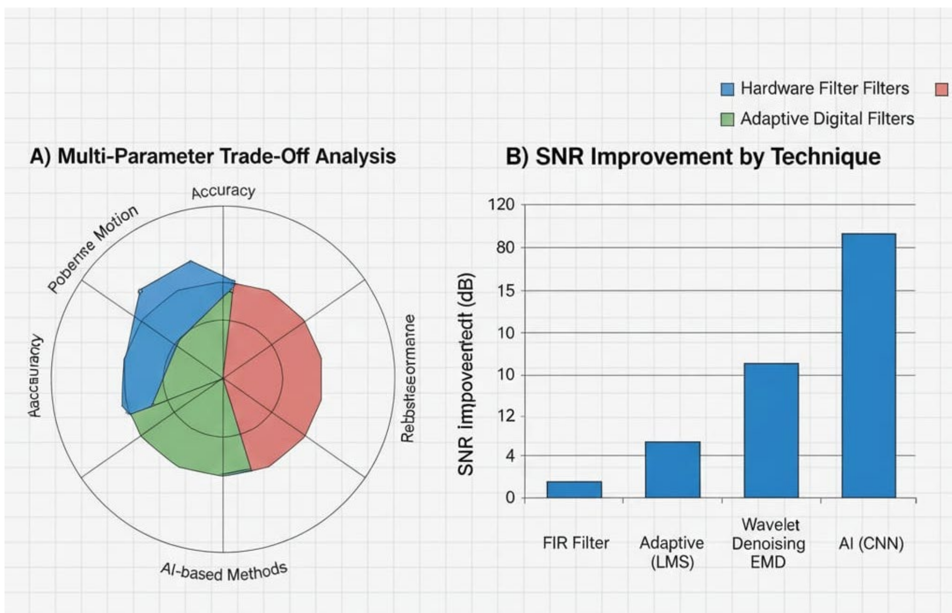

Figure 4. Comparative Analysis Chart

3.4 Importance of Hybrid Approaches for Wearable ECG Systems

What follows from the discussion is that no single technique is universally optimal; instead, the most reliable ECG heart-rate monitoring systems integrate multiple hardware and digital strategies optimized for the noise environment and device constraints at hand. Hybrid systems, which combine high-quality analog pre-processing with adaptive or wavelet-based digital filtering and intelligent algorithms for R-peak detection, represent the most viable solution up to date for wearable and smart health-monitoring technologies (Chen et al. 2024). An integrated approach thus assures that this is an accurate, robust strategy against real-world noise sources and suitable for low-power, mobile, and e-textile-based ECG systems.

4. Potential Applications in Healthcare

Advanced ECG noise cancellation forms an integral component in smartening the performance of wearable heart-monitoring devices like smartwatches, chest straps, and textile-integrated garments, some of which are shown in Figure 5. The systems, by improving motion-related signal clarity, track heart rates continuously and reliably during daily activities, exercise, and sleep. Such devices facilitate early detection of arrhythmias, better long-term cardiac assessment, and accurate health analytics for clinical and consumer applications.

Figure 5. Potential Application in Healthcare

4.1 Remote Patient Monitoring and Telehealth

In turn, high-quality ECG signals are necessary in remote healthcare settings for timely medical decision-making. Enhanced denoising methods also mean that patients, especially those with chronic cardiac conditions, can be monitored from home with clinical-level accuracy (Ding et al. 2024). It cuts down on frequent hospital visits, which ensures early intervention and enhances patient outcomes while lowering healthcare costs. Integration with telehealth platforms further enables real-time physician supervision and automated alerts for abnormal heart activity.

4.2 Intensive Care and Emergency Medicine

In critical care, ECG signals are generally noised by motion, electrical interference, and the instability of the patient (Fahoum 2023). Advanced analog-digital noise reduction architectures enhance the robustness of ECG systems for use in ICUs, emergency departments, and ambulances. Accurate R-peak and rhythm detection helps clinicians rapidly diagnose arrhythmias, ischemic events, and heart-rate variability abnormalities during acute conditions where immediate decisions are essential (Gaoudam et al. 2025).

4.3 Rehabilitation and Exercise Physiology

ECG signals are very often disturbed by muscle activity and motion artifacts during physical rehabilitation or exercise testing. Advanced filtering and adaptive denoising techniques allow physicians and sports scientists to monitor cardiac performance more precisely during stress tests, physiotherapy sessions, and athletic training (Hussein et al. 2022). This enables detailed analyses of cardiovascular functions, ensures patient safety during supervised activities, and is helpful in personalized rehabilitation planning.

4.4 Mobile Health (mHealth) and Personalized Wellness Technologies

For mobile health platforms, integrated low-power intelligent filtering techniques will enable personalized wellness applications (Khalili et al. 2024). With the help of smartphones and connected sensors, users can monitor heart-rate trends, stress levels, and sleep quality more precisely (Kim et al. 2024). More so, AI-enhanced ECG processing is supportive of delivering personalized health insights for proactive lifestyle adjustments, inclusive of long-term cardiovascular wellness monitoring.

4.5 Early Detection of Cardiovascular Diseases

This acts to improve ECG signal quality, thereby providing automated detection systems with greater diagnostic capability for early signs of cardiac abnormalities such as atrial fibrillation, ventricular hypertrophy, ischemia, and conduction disorders (Hussein et al. 2025). Algorithms resistant to noise allow clinicians to identify tiny changes in

ECG wave morphologies, which can facilitate early interventions that reduce disease progression and, eventually, lead to improved cardiac health across populations (Joseph Michael Jerard et al. 2021).

5. Current Challenges

Wearable ECGs are faced with various interlocking problems that greatly affect wearable ECG accuracy, functionality, and practicability (Kumari et al. 2025). The first and most visible challenge faced by wearable ECGs is the dominance of motion artifacts (Figure 6). These artifacts arise from walking, running, stretching, or even slight changes in clothing position, causing considerable noise sources within the ECG signal (Lee et al. 2023). These noise sources substantially hide the actual ECG signal associated with the heart rate and rhythm. As wearable ECGs are designed for prolonged observation, addressing motion artifacts can be considered the most challenging task while developing useful ECG systems (Lu et al. 2024). A third challenge can be identified as an issue with processing capabilities. ECGs are wearable devices that rely on microcontrollers with low consumption rates. These microcontrollers consume low energy and are most useful due to prolonged observation. Due to these limitations, microcontrollers do not efficiently process algorithms with high complexity. It becomes difficult for microcontrollers to calculate adaptive filters, wavelet denoising, and noise cancellation algorithms driven by machine learning concepts. Electrode variability becomes an added complexity. ECGs with textile and dry electrodes are very user-friendly and efficient for prolonged observations. However, ECG electrodes with textile and dry electrodes demonstrate inefficiencies due to inconsistencies under constant skin-electrode contact. Moreover, factors like sweating, dryness of skin, movement, and variability among human physiologies complicate ECG signals (Mahim et al. 2024). Electrode variability leads to gaps, variability, and instability within the measurement. Finally, energy consumption becomes a strict constraint on ECG designs. ECGs should be capable of operating for prolonged times without needing extra charging. Moreover, sensing, processing, and wireless ECG data communications consume considerable energy (Malekifar et al. 2025). Energy efficiency with long life poses an extreme challenge. All these complexities state that it is necessary to improve ECG wearable devices based on advancements made with materials and materials science research.

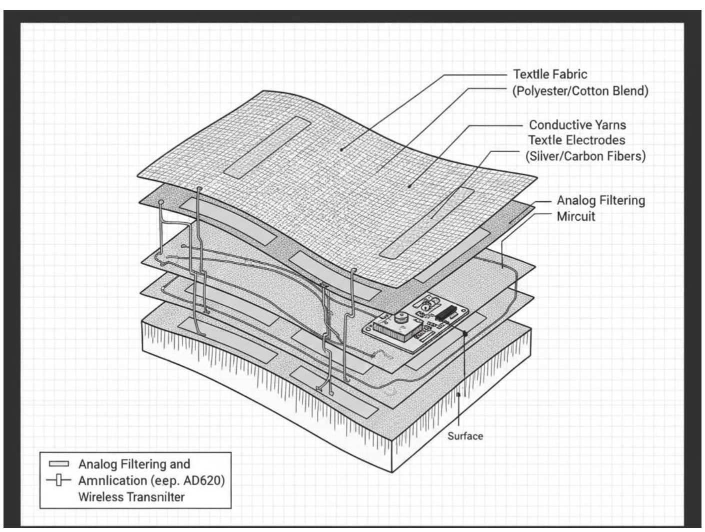

Figure 6. Motion Artifact Variability in Wearables

6. Future Research Directions

Sensor fusion uses the collective information gathered from ECG sensors, accelerometers, and gyroscopes. It more effectively models and eliminates motion noise. By correlating limb movement, acceleration, and rotational activity with ECG noise, it becomes easier for the system to separate ECG signals from motion noise. Smarter algorithms like Kalman filters, adaptive filters, or machine learning-based fusion algorithms will be able to intelligently estimate noise patterns and eliminate ECG signal noise adaptively (Malekifar et al. 2025). It presents a better solution to wearable environments, as unexpected limb movement cannot be avoided.

6.1. Low-Power AI-on-Edge ECG Denoising

The low-power AI on edge solutions concentrate on optimizing and applying neural networks like low CNNs, auto-encoders, or models like MobileNet on microcontrollers (Uwaechia and Ramli 2021). These models are designed to be executed efficiently within tight constraints on memory, latency, and power (Marnani et al. 2024). The use of methods like quantification, pruning, and distillation reduces computation while still having accuracy. Denoising on an edge reduces cloud dependence and leads to better user privacy, and also facilitates continuous monitoring even with an offline network (Tran et al. 2025).

6.2 Smart E-Textile ECG Integration

Smart e-textile technologies include incorporating electrodes, conductive paths, micro-circuits, and analog filtering modules into textile fibers, shown in Figure 7(N et al. 2024). Smart e-textile technologies make it easier for signals to be obtained with high precision. Technologies such as flexible PCBs, conductive threads, and breathable electrode materials improve signal acquisition (Pradipta et al. 2025). Smart textiles enable on-body signal processing, making it easier for filters and smoothing functions to be performed before signals are sent to the main device.

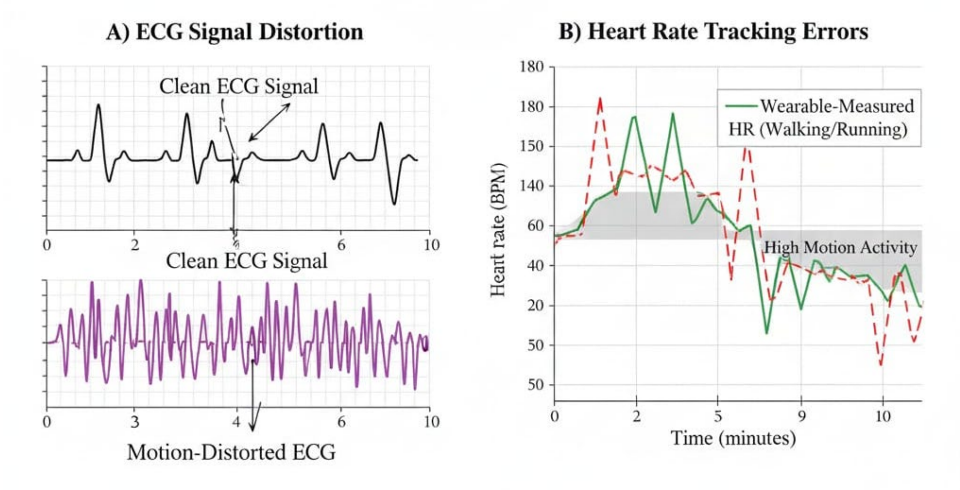

Figure 7. Smart E-textile ECG Structure

6.3 Adaptive Hybrid Architectures

It uses various modes of filters, like adaptive, Wavelet, and AI filters, and changes between these modes as per the detection of noise. Also, if there are heavy motions detected, it uses sensor fusion or AI filters, but once it becomes stable, it changes to simpler algorithms, thus being energy efficient (Sumalatha et al. 2024). By doing so, it enhances signal quality and reduces energy consumption. It uses intelligent allocation and boosts reliability for low and high movement (Talukder et al. 2024).

6.4 Cloud-Assisted ECG Processing

Cloud-based processing makes it possible for wearable systems to employ algorithm offloading and transfer computationally expensive operations like arrhythmia diagnosis, trend analysis, and denoising via deep learning on cloud servers (Ramco Institute of Technology, India and S 2024). Additionally, cloud platforms are capable of handling large volumes of data, which makes it possible for wearable systems to receive updates on diagnosis as per the processed data. Moreover, cloud-based processing allows for low-power designs for wearable devices (Tran et al. 2025).

7. Conclusion

It reviews advanced noise-cancellation techniques to improve ECG heart-rate measurement accuracy, especially in modern wearable and mobile health-care systems. Hardware-based techniques include high-CMRR amplifiers, DRL circuits, and optimized electrode materials, all of which provide the basis for interference minimization at the baseline and improvement of the quality of the original signal. Digital processing further refines the signal through adaptive filtering, wavelet analysis, EMD, and, most recently, using AI-driven denoising models that can handle complex and non-stationary patterns of noise. Comparative insight into these methods clearly shows that there is no globally optimum approach, but that hybrid analog-digital architectures have provided the best and most robust performance in various operating environments. Ultra-low-power AI-on-edge models, multimodal sensor fusion, and adaptive hybrid filtering are some of the emerging research directions wherein the hybrid system updates itself in real time based on the changes in noise conditions. Innovations in smart e-textile integration and cloud-assisted ECG processing promise to enhance comfort, scalability, and clinical utility. In all, these will drive the next generation of ECG wearables toward higher accuracy, energy efficiency, and user friendliness, thus supporting continuous monitoring, early disease detection, and improved patient outcomes. Addressing the current challenges and leveraging the upcoming technologies, future ECG systems can provide reliable real-time cardiac health insights into clinical and day-to-day applications.

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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. She served as a Research Fellow at the Atomic Energy Research

Establishment (AERE), Bangladesh Atomic Energy Commission. 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.

Protik Barua is a Lecturer in the Department of Mechatronics Engineering at the World University of Bangladesh (WUB), Dhaka. He received his B.Sc. in Mechatronics and Industrial Engineering from Chittagong University of Engineering and Technology (CUET) in 2023 and is currently pursuing an M.Sc. in Robotics and Mechatronics Engineering at the University of Dhaka, where he has completed all coursework and is working on his thesis. His research interests include robotics, mechatronic system design, Internet of Things (IoT), artificial intelligence, machine learning, and digital twin technologies, particularly with applications in healthcare, manufacturing, and predictive maintenance. He has contributed to multiple conference papers and book chapters, focusing on machine learning–based maintenance prediction, multi-modal deep learning frameworks for disaster response, and emerging trends in mechatronics. Before joining academia, he gained industry experience as an Android App Developer at AI4SEE Pvt. Ltd. and also completed an internship at Transcom Beverage Ltd. Mr. Barua is committed to advancing research in intelligent systems and aims to pursue doctoral studies in robotics and machine learning in the near future.

Md. Sohan Sheikh is a highly motivated undergraduate student pursuing a Bachelor of Science (BSc) in Textile Engineering at the Faculty of Science and Engineering, World University of Bangladesh. He is actively involved in academic leadership, research, and professional development alongside his studies. He is currently serving as the Vice President of the Industrial Engineering and Operations Management (IEOM) Society, World University of Bangladesh Chapter (June 2024–Present). In addition, he holds the position of Research and Extension Secretary of the Textile Club, World University of Bangladesh (January 2024–Present). Previously, he served as the Head of Executives of the Textile Club from January 2022 to December 2023, where he played a key role in organizing academic and research-oriented activities. Md. Sohan Sheikh has also been working as an Affiliate Campus Ambassador since June 2022, contributing to student engagement and outreach initiatives. In 2023, he successfully completed a workshop on Public Speaking at the World University of Bangladesh, enhancing his communication and presentation skills. He demonstrated his academic competence by participating in the Textile Olympiad held at Bangladesh University of Textiles, where he achieved an impressive 5th position. Additionally, he served as a Research Fellow at the Atomic Energy Research Establishment (AERE), Bangladesh Atomic Energy Commission, and gaining valuable hands-on research experience in advanced scientific environments. Currently, he is actively involved in five technical projects, reflecting his strong commitment to research and innovation. His research interests include composite materials, smart textiles, piezoelectric materials, flexible electronics, and environmental science, with a particular focus on sustainable and next-generation textile-based technologies.

MD Imran Hosen 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. His involvement in these activities reflects his commitment to promoting research engagement and practical applications of textile engineering concepts. Through his work, MD Imran Hosen 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.

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.

Ifthekhar Hussain is a dedicated engineering graduate from Chittagong University of Engineering and Technology (CUET), where he built a strong academic foundation in electrical and computational technologies. He is highly enthusiastic about research, particularly in the rapidly evolving domains of Machine Learning and Artificial Intelligence. His interests center on developing intelligent systems, data-driven solutions, and algorithmic approaches that address real-world challenges across engineering and technology. With a growing passion for innovation, he continues to expand his expertise through independent research, academic collaborations, and exploration of emerging trends in AI-driven automation, predictive modeling, and intelligent decision-making systems.