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Evaluation of Mechanical, Water Uptake, and Soil Degradation Performance of Gamma-Irradiated Pineapple Leaf Fiber Reinforced Polypropylene Composites

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Abstract

This study examines the mechanical, water uptake, and soil degradation performance of pineapple leaf fiber (PALF) reinforced polypropylene (PP) composites subjected to gamma irradiation. Composites containing 40 wt.% PALF were fabricated through compression molding, and gamma doses ranging from 2.5 to 10 kGy were applied to evaluate radiation-induced modifications. Tensile, bending, and elongation properties were assessed using ASTM-standard procedures. Gamma irradiation influenced fiber–matrix interaction and produced noticeable variations in mechanical behavior. The tensile modulus improved at 7.5 kGy, whereas higher radiation levels caused a decline. Elongation at break showed a decreasing trend due to enhanced interfacial adhesion and restricted polymer mobility. Water absorption remained low (0.92–1.85%) since PP is hydrophobic, although minor uptake occurred through exposed fiber edges. Soil burial tests for four weeks demonstrated gradual weight loss (up to 8.12%), attributed to cellulose biodegradation, while PP exhibited limited deterioration. The composites preserved nearly half of their initial mechanical integrity after one month of soil exposure. The findings emphasize the future promise of PALF as an efficient reinforcement for PP and show that controlled gamma irradiation can fine-tune composite performance for sustainable engineering applications.

Keywords
Pineapple leaf fiber; Polypropylene composites; Gamma irradiation; Mechanical properties; Soil degradation.

1. Introduction
Composite materials consist of two or more distinct phases that unite to deliver performance that no single component can achieve alone. Their rapid use in structural and semi-structural applications reflects global interest in lightweight materials with acceptable mechanical strength, dimensional stability, and durability. Traditional composites reinforced with synthetic fibers such as glass, carbon, and aramid have supported various engineering sectors for many decades; however, these fibers originate from non-renewable resources and involve costly, high-energy manufacturing routes (Hoque et al. 2022), (Motaleb et al. 2018), (Soundhar et al. 2022), (Santos et al. 2024), (Khoshraftar 2025).

Their non-biodegradable character further restricts usage in environmentally responsible product design. These limitations encouraged researchers to move toward natural fibers as reinforcement in polymer matrices. Studies on jute, flax, kenaf, sisal, ramie, and PALF report that natural fibers can reduce composite weight, lower production cost, and improve energy efficiency. Their renewable origin, biodegradability, low density, and favorable specific strength position them as competitive alternatives for sustainable composite development (Maiti et al. 2022), (Prasad et al. 2024), (Makinde-Isola et al. 2024).

Among available lignocellulosic fibers, pineapple leaf fiber has received growing attention due to its high cellulose content and notable stiffness. PALF originates as an agricultural residue from pineapple cultivation, and this availability supports low-cost reinforcement for thermoplastic polymers (Hoque et al. 2018). Several investigations reported that PALF can improve the tensile and flexural behavior of PP composites because the fiber carries high axial strength and a relatively smooth microfibrillar structure. Reports on PALF/PP systems show improved modulus and strength at moderate fiber fractions, although limited adhesion at the hydrophobic PP interface continues to be a challenge. The non-polar nature of PP restricts interfacial bonding with the hydrophilic cellulose structure of PALF, and this mismatch has led many researchers to evaluate treatments that improve compatibility between both phases (Naushad et al. 2024), (Solaiman et al. 2020), (Hoque et al. 2018).

Gamma irradiation represents one promising route for interface modification. Ionizing radiation generates free radicals within polymer structures and promotes cross-link formation, which enhances fiber-matrix adhesion. Several studies on gamma-treated natural fiber composites indicate that controlled doses can improve tensile strength, modulus, and interfacial stability (M. B. Hoque et al. 2022). Research on jute/PP, flax/PP, and sisal-reinforced polymers showed that moderate radiation levels increase compatibility because cross-linking stabilizes the polymer network and anchors fiber surfaces more effectively. Yet high radiation doses may produce chain scission, oxidative reactions, and partial fiber degradation. This complex balance between interfacial improvement and structural damage highlights the need for a dose-dependent evaluation for each fiber–polymer system. PALF contains a highly crystalline cellulose structure, and its response to gamma irradiation may differ from jute or flax; therefore, a dedicated investigation is essential for accurate interpretation (Naikwadi et al. 2022), (Kabir et al. 2018).

Recent investigations continue to validate and enhance these modification methodologies, particularly through the use of ionizing radiation. Gamma and electron beam treatments are extensively investigated to generate functional groups and free radicals on the surface of lignocellulosic fibers, enhancing chemical bonding or grafting with matrix polymers (Parida et al. 2025), (Habib et al. 2025). Research on analogous systems, such as silk fiber-reinforced PP composites, demonstrates that gamma irradiation significantly improves mechanical characteristics by enhancing fiber-matrix adhesion and cross-linking inside the PP matrix (Shubhra et al. 2010), (Ahmed et al. 2024). A significant challenge persists in balancing advantageous cross-linking with harmful chain scission in the PP matrix. Recent literature indicates that polypropylene is particularly vulnerable to radiation-induced chain scission, attributable to the high reactivity of its tertiary carbon atoms, resulting in a substantial deterioration of properties such as tensile strength and elongation at break at elevated dose (Azevedo et al. 2025).

PP also responds sensitively to gamma exposure. Previous reports describe improved stiffness and reduced elongation at breaks under moderate doses, while excessive irradiation may lead to oxidation and a drop in mechanical integrity. Combined fiber-matrix effects therefore depend on both fiber behavior and PP chain stability. Despite expanding interest in natural fiber composites, limited research exists on PALF/PP systems exposed to gamma irradiation at high fiber fractions. Studies rarely consider water uptake and soil-degradation performance together with mechanical behavior, although these characteristics are essential for evaluating long-term environmental durability (Salim et al. 2025), (Shirvanimoghaddam et al. 2021).

The present work aims to examine how gamma irradiation affects the mechanical properties, water absorption, and soil degradation performance of PP composites reinforced with 40 wt.% PALF. The study investigates radiation doses in a systematic manner to identify a dose that supports favorable interfacial adhesion without causing excessive damage to the polymer or fiber. The novelty of this work lies in the application of a comparatively high fiber loading, the combined assessment of mechanical and environmental characteristics, and the establishment of a structure–property relationship for gamma-irradiated PALF/PP composites. This integrated analysis provides new insight into the development of sustainable, high-performance natural fiber composites for engineering applications.

2. Materials and Methods

2.1. Materials

The composite material employed PP granules as the polymer matrix, acquired from a designated manufacturer in Hatkhola, Dhaka, Bangladesh. The reinforcement comprised PALF obtained as raw fiber from Tangail, Bangladesh. Before the composite was manufactured, the raw PALF underwent critical pre-processing, which included comprehensive cleaning and drying, succeeded by trimming to an acceptable length.

2.2. Composite Preparation

Composites reinforced with PALF based on PP were produced employing compression molding procedure. PP sheets were created by placing PP granules between two metal plates in the heat press machine (Gangil et al. 2025). The heat press machine was utilized at an elevated temperature of 360°F for a duration of 5 minutes with a load weighing about 30 MPa to ensure proper melting and fusion of the polymer granules. The laminated materials are chilled in the heat press machine under pressure to solidify the sheets uniformly. Composites were created by placing pineapple filaments between two distinct films of PP. The composites were fabricated utilizing the technique outlined for PP sheets. The fiber concentration of the composite was maintained to constitute 40% by weight. Then the assembled laminates went under same pressure and temperature as PP sheets to acquire matrix consolidation and adequate fiber impregnation (Sayeed et al. 2023). Later the composites were cooled and enclosed in polyethylene containers for testing.

2.3. Gamma radiation (γ radiation)

The application of gamma irradiation was investigated to assess its effect on the mechanical attributes of the fabricated composites. Particular dimensions of 60 mm × 15 mm × 4 mm had been employed for cutting the composites, regardless of whether they were filled, and subsequently sealed in a polyethylene bag to preserve an airtight environment. Cobalt-60 (90 kCi) served as the gamma radiation source, operating under ambient conditions of room temperature at an exposure yield of 0.025 kGy/min. The specified dosage values were obtained only from the goal dose assessed using a basic Harwell Amber Perspex dosimeter, model 3042F. The skeletal characteristics of the composite materials were assessed following exposure to varying doses of gamma radiation (2.5 to 10 kGy).

2.4. Mechanical Characteristics of the Composites

The tensile properties of the PALF-reinforced polypropylene composites, with and without filler, were evaluated to determine their mechanical performance under uniaxial loading. Tensile tests were conducted using a universal testing machine (H10KS) following the ASTM D638-01 standard. The tests were conducted with a gauge length of 20 mm and a cross-head speed of 1 mm/s to maintain controlled deformation during loading. All specimens were prepared in a uniform size of 60 mm × 15 mm × 4 mm to minimize dimensional influence on mechanical response. In addition to tensile behavior, the bending performance of the composites was examined using the same universal testing machine. Bending strength and bending modulus were measured under identical test settings to assess the composites' resistance to flexural deformation (Dağlı 2025) (Ng et al.2024).

2.5. Water Absorption of the Composites

Composite specimens were immersed in a glass vessel containing 100 ml of distilled water at ambient temperature (25°C) for a short duration. Initially, the weight of the samples was recorded; subsequently, at a designated interval, they were collected from the vessel and dried using paper towels. Their weight was documented again. The total weight acquired, namely the water absorption of the examined samples, has been calculated by subtracting the starting weight from the net weight at the end. A water absorption inspection was conducted on 3 specimens, each possessing a distinct weight of the composite material.

3. Results and Discussions

3.1. Mechanical characteristics of composites

The tensile and bending properties of the PALF/PP composites at 40 wt.% fiber and gamma doses of 2.5, 5, 7.5, and 10 kGy are presented in Figure 1. Before irradiation, the composites showed a TS of 80 MPa, a TM of 1.3 GPa, and an EB% of 10%. Gamma exposure altered these properties, as 2.5 kGy produced 64.2 MPa, 3.8 GPa, and 7.5%, while 5 kGy yielded 62 MPa, 3.85 GPa, and 6.5%. At 7.5 kGy, the values reached peak irradiated values of 66.5 MPa, 4 GPa, and 6%, followed by a decrease to 60.7 MPa, 3.3 GPa, and 6.4% at 10 kGy. TM at 7.5 kGy suggests an optimal level of radiation-induced crosslinking, which enhances the fiber–matrix interfacial adhesion. In contrast, the reduction of TS from 80 MPa to 66.5 MPa shows a detrimental effect that dominated the cross-linking effects on the TS. The decline at 10 kGy may be attributed to chain scission and fiber degradation, which weaken structural integrity. This trend aligns with previous studies reporting that moderate gamma doses enhance compatibility and stiffness in natural fiber composites, whereas excessive irradiation reduces mechanical strength due to polymer degradation. Similar behavior has been noted in gamma-treated jute/PP and flax/PP systems, where improved adhesion is observed up to a threshold dose, followed by property deterioration at higher irradiation levels.

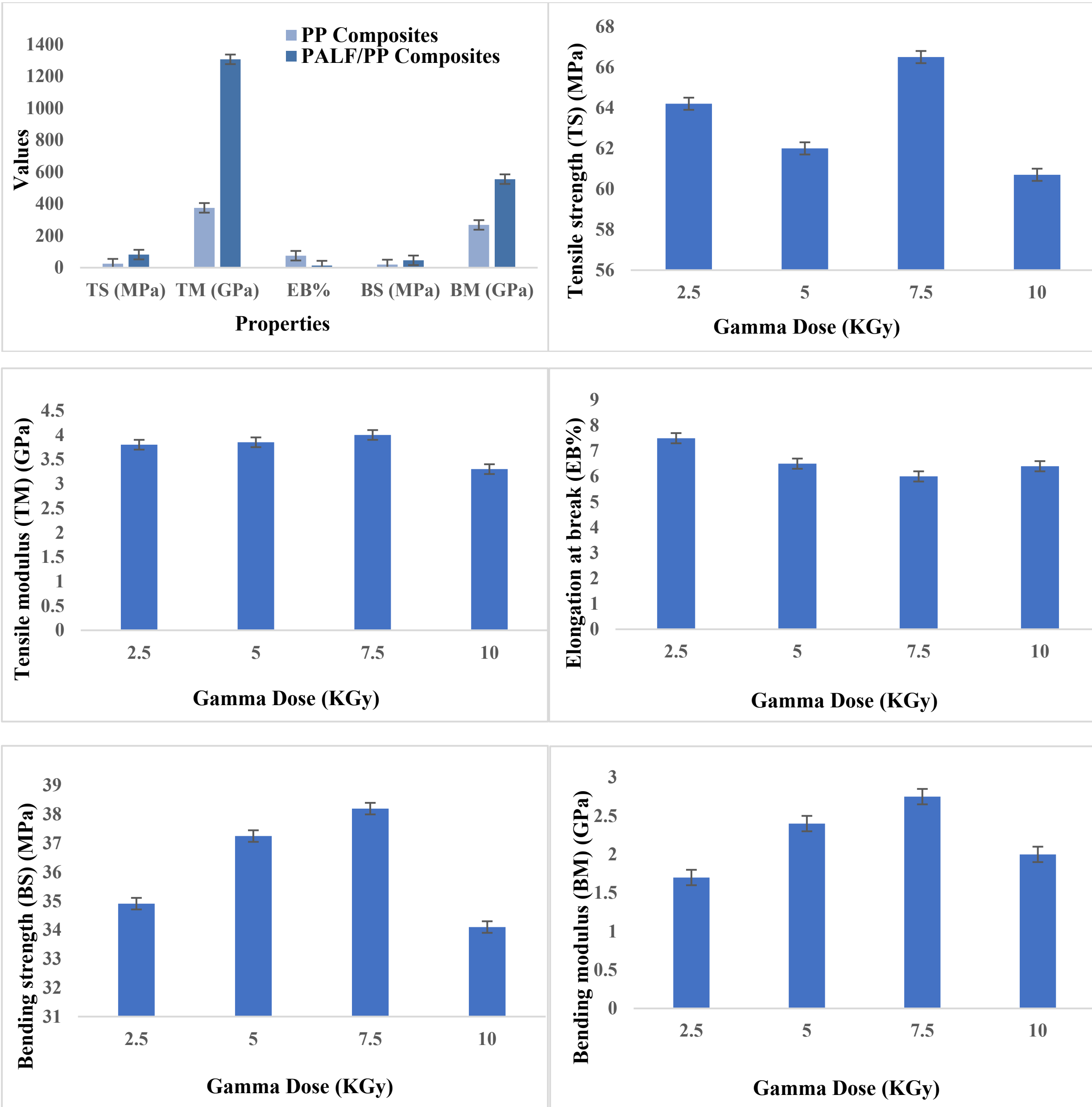

Figure 1. Effect of Gamma Irradiation Dose on Mechanical Performance of PALF/PP Composites (40 wt% fiber).

3.2. Water uptake (%) profile of composites

A water-absorption test was performed to determine the water uptake of the PALF/PP composites. Figure 2 presents the water uptake behavior of samples containing 40 wt.% PALF at different gamma irradiation doses. The overall water absorption remained low. At 2.5 kGy, the composites absorbed 1.07% water, and at 5 kGy the value increased slightly to 1.25%. The highest uptake, 1.85%, was recorded at 7.5 kGy, whereas the lowest value, 0.92%, appeared at 10 kGy. These small variations indicate that gamma irradiation modifies the fiber-matrix interface and the accessibility of hydrophilic sites, yet the bulk hydrophobic character of the composite remains dominant.

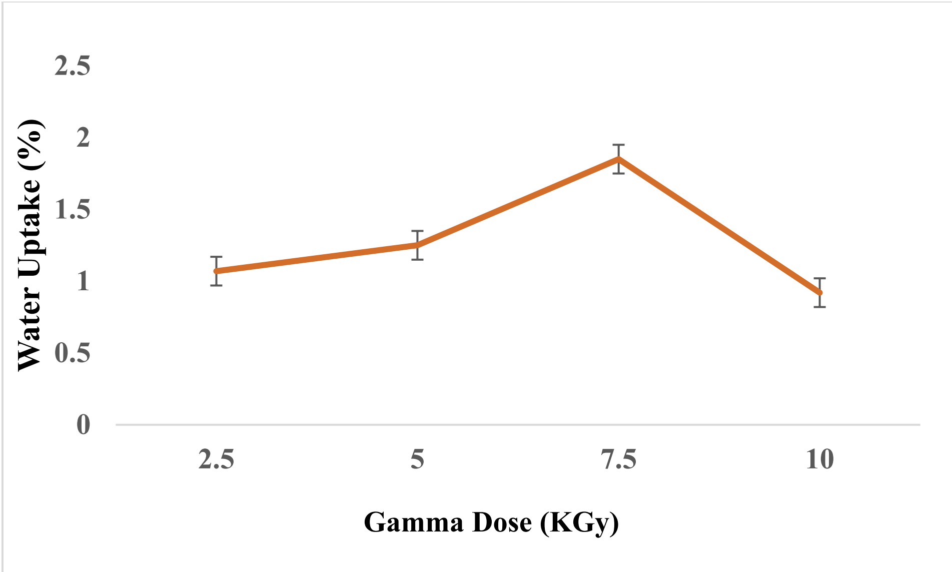

Figure 2. Effect of Gamma Irradiation on Water Uptake (%) of PALF/PP Composites (40 wt% Fiber)

The limited water uptake can be attributed to the continuous PP matrix, which creates a barrier to water diffusion and surrounds the PALF. PP is intrinsically hydrophobic, so water can enter the composite mainly through exposed fiber ends and microvoids created during grinding of the specimens. PALF contains cellulose with hydroxyl (-OH) groups that attract water molecules, so some moisture absorption is expected. Even so, the encapsulation of fibers inside the PP matrix restricts direct contact between water and cellulose, so the measured absorption stays below 2%. Similar low levels of water uptake have been reported for other natural fiber–reinforced PP systems, where the hydrophobic matrix governs the overall sorption behavior and restricts moisture penetration despite the presence of hydrophilic lignocellulosic fibers. This agreement with existing literature confirms that PALF/PP composites can maintain relatively low water absorption even at high fiber loading, which is advantageous for dimensional stability in service.

3.3. Soil Degradation Test of the Composites

Figure 3 presents the soil degradation results of the PALF/PP composites over a 4-week burial period at room temperature. The weight of the samples decreased gradually with prolonged exposure to soil. After the first week, the composites showed a 4% weight loss, followed by 6.5% after two weeks. The degradation progressed to 7.25% in the third week and reached 8.12% by the fourth week. This steady decline reflects the biodegradation of the natural PALF component, while the PP matrix contributed minimal mass loss due to its inherent stability.

The observed behavior aligns with the known characteristics of lignocellulosic fibers such as pineapple leaf, cotton, and jute, which exhibit hydrophilic surfaces and biodegrade readily in soil because of their cellulose-rich structure. Cellulose is susceptible to microbial attack and enzymatic breakdown, which accelerates mass loss when the composite is buried. In contrast, PP is hydrophobic and resistant to microbial degradation, allowing the matrix to retain its structure. During the test, moisture penetration occurred primarily through exposed edges generated during specimen preparation, enabling water to access and degrade the PALF regions. Similar trends have been reported in other natural fiber–reinforced composites, where soil exposure leads to selective decomposition of cellulose while the polymer matrix remains comparatively unaffected. The moderate weight loss in this study therefore confirms that PALF contributes to biodegradability without causing excessive structural breakdown of the composite within the early weeks of soil contact.

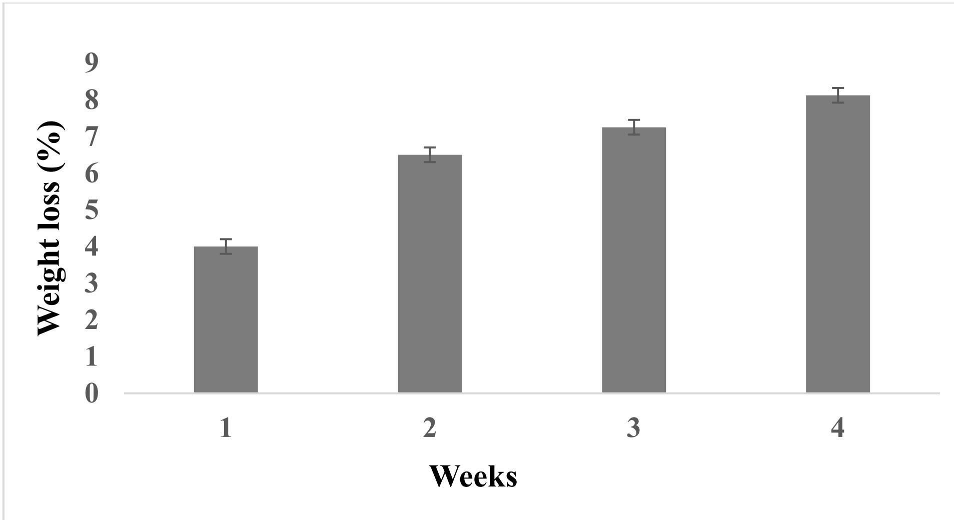

Figure 3. Weight Loss (%) of the PALF/PP Composites (40 wt% fiber) Soil Degradation Test.

4. Conclusions

This study evaluated the influence of gamma irradiation on the mechanical performance, water uptake, and soil-degradation behavior of PP composites reinforced with 40 wt.% PALF. The results showed that gamma exposure modified the interaction between PALF and PP. TM increased at 7.5 kGy, which indicated an improvement in interfacial adhesion due to radiation-induced cross-linking. A decline in mechanical properties at 10 kGy suggested the onset of polymer chain scission and partial fiber damage at higher doses. The bending results followed a similar pattern, which confirmed that an optimum radiation level exists for PALF/PP systems. Water uptake remained low for all samples because the hydrophobic PP matrix acted as a barrier to moisture. Minor variations across the radiation doses reflected changes in exposed fiber sites and microvoid distribution. The soil-burial test showed gradual weight loss over four weeks, which occurred because the cellulose-rich PALF supported microbial degradation while the PP matrix remained largely intact. The composite retained a substantial portion of its mechanical integrity after one month of soil exposure, which demonstrates acceptable environmental durability for short-term applications. Overall, the study confirms that controlled gamma irradiation can enhance the performance of PALF-reinforced PP composites and supports the use of agricultural waste fibers in sustainable material systems. The identification of an optimal dose adds value to the processing of natural fiber composites. These advanced composites are ideally suited for short-cycle industrial applications that prioritize stiffness and reduced weight, including automotive interior components such as door panels, headliners, and non-load-bearing construction elements, capitalizing on the material's advantageous balance of strength and sustainability. A significant limitation is the trade-off between biodegradability and long-term durability, as PALF renders the material prone to degradation over prolonged periods, thereby constraining its applicability in long-service-life contexts. The expenses and intricacies of gamma processing require meticulous management in high-volume production. Therefore, further studies may explore long-term degradation behavior, hybrid fiber system, or compatibiliser-assisted systems to expand the application potential of PALF/PP composites.

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Biographies

Masuma Jahan Tanjila is an undergraduate 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.

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.

Imran Hosan is an undergraduate 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 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.

Tanzim Hossain Oyshi is a 4th-year undergraduate in the Department of Textile Engineering at the World University of Bangladesh, maintaining a strong academic record. Her research interests include functional textiles, sustainable materials, natural fiber composites, and environmental impacts of textile processing. She served as a research fellow under the Ministry of Science and Technology on the project "Development and Characterization of Locally Available Natural Fiber Reinforced Polypropylene (PP) Matrix Based Partially Degradable Composites for Civil Construction," where she contributed to experimental analysis and material characterization. She has authored multiple publications covering topics such as taro fiber properties, eco-friendly material development, environmental impacts of textile dyes, and the psychological dimensions of the COVID-19 pandemic. Beyond her academic and research work, Oyshi is actively engaged in leadership and extracurricular roles. She currently serves as the President of the IEOM Society WUB Student Chapter and the Organizing Secretary of WUB Textile Club, while also working as a campus ambassador for several textile-focused platforms. Her passion lies in advancing sustainable textile solutions and contributing to research-driven innovations that address global environmental challenges.