

Microstructural and Elemental Characterization of TPU/Jute CNFs Nanocomposites via FESEM and EDX Analysis

Siti Syazwani Nordi ¹, Ervina Efzan Mhd Noor ^{1*}, Aeslina Binti Abdul Kadir ² ,
Mirza Farrukh Baig ¹

¹ Centre for Manufacturing and Environmental Sustainability (CMES), Faculty of Engineering and Technology, Multimedia University, Ayer Keroh, Melaka 75450, Malaysia.

² Faculty of Civil Engineering and Built Environment, University Tun Hussein Onn Malaysia, Batu Pahat 86400, Malaysia.

Abstract

This study aims to investigate the microstructural and elemental characteristics of thermoplastic polyurethane (TPU) nanocomposites reinforced with jute cellulose nanofibers (CNFs), with the objective of understanding the dispersion behavior and interfacial interactions within the polymer matrix. CNFs were extracted from jute fibers through a chemo-mechanical process involving alkaline treatment, acid hydrolysis, bleaching, and high-energy milling, followed by melt blending with TPU to fabricate nanocomposites at varying filler loadings (1–5 wt%). Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray (EDX) spectroscopy were employed to analyze the surface morphology and elemental distribution of the nanocomposites. The FESEM results revealed that uniform CNF dispersion was achieved up to 4 wt%, beyond which noticeable agglomeration occurred. EDX analysis confirmed the successful incorporation of CNFs and identified performance-enhancing elements such as Si, Ca, Na, and Al in the reinforcement phase. These findings suggest that CNF content strongly influences microstructure and bonding quality, which are key factors for mechanical performance. The novelty of this work lies in its exclusive focus on microstructural and elemental characterization—providing essential insight into filler distribution and matrix compatibility—offering a foundation for optimizing sustainable, high-performance TPU/CNF nanocomposites for advanced industrial applications.

Keywords:

Thermoplastic;
Polyurethane;
Nanocomposites;
Microstructural;
FESEM;
EDX.

Article History:

Received:	06	April	2025
Revised:	09	August	2025
Accepted:	17	August	2025
Published:	01	October	2025

1- Introduction

The development of polymer nanocomposites has gained significant momentum in recent years, driven by the growing demand for materials that offer enhanced mechanical, thermal, and functional properties while maintaining environmental sustainability. Among the widely used polymers, thermoplastic polyurethane (TPU) stands out due to its excellent flexibility, abrasion resistance, and chemical stability, making it a suitable candidate for a wide range of applications including automotive parts, medical devices, and protective coatings [1, 2]. To further improve the performance of TPU, reinforcement with cellulose nanofibers (CNFs) has emerged as a promising strategy [3–5]. CNFs, especially those derived from natural fibers such as jute, offer several advantages: high specific strength and stiffness, biodegradability, cost-effectiveness, and wide availability [6, 7]. Jute, a bast fiber extracted from *Corchorus* species, is abundantly produced and contains valuable structural elements including cellulose, hemicellulose, and lignin [8]. However, to use it effectively at the nanoscale, a thorough chemo-mechanical treatment is required to isolate high-purity CNFs [9].

* **CONTACT:** ervina.noor@mmu.edu.my

DOI: <http://dx.doi.org/10.28991/ESJ-2025-09-05-016>

© 2025 by the authors. Licensee ESJ, Italy. This is an open access article under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Recent studies have demonstrated the remarkable potential of jute-derived and CNFs in enhancing the performance of TPU nanocomposites. The incorporation of jute CNFs led to a 20.13% increase in hardness strength, confirming the effectiveness of natural fibers in reinforcing polymer matrices [3]. Surface modification of CNFs has also been shown to improve their compatibility with TPU, resulting in enhanced tensile modulus and ultimate tensile strength due to better dispersion and stronger interfacial interactions [4]. Even untreated CNFs, such as those derived from empty fruit bunches, significantly improved tensile strength and dynamic mechanical properties, suggesting great potential for flexible applications [5]. Supporting this, Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray (EDX) analyses confirmed improved interfacial bonding and the effective integration of nanofibers within the TPU matrix.

Innovative fabrication methods, including bead-milling and twin-screw extrusion, have enabled the solvent-free incorporation of cellulose nanocrystals (CNCs) into TPU, resulting in improved mechanical performance while retaining thermoplastic behavior [10]. Studies using low-toxicity solvents in scaffold fabrication further showed that CNFs enhance compressive properties, making them suitable for biomedical and structural applications [11]. Moreover, TPU/CNF composites exhibit superior thermal stability and reduced water absorption compared to pure TPU, which broadens their practical use [12]. Functionalized nanofillers such as glycidyloxypropyltrimethoxysilane-modified CNCs (GLCNCs) have achieved dramatic mechanical improvements, with tensile strain and toughness reaching 1740.42% and 90.01 MJ/m³, respectively—significantly outperforming unmodified TPU [13]. Other research has confirmed that CNCs enhance Young's modulus and tensile strength while acting as nucleation agents during matrix crystallization [14]. Additionally, FESEM analysis of CNF-reinforced TPU scaffolds revealed improved strength and durability, attributed to effective nanofiber absorption and surface interaction [15]. Recent work also shows that even small CNF loadings (e.g., 0.3 wt%) can result in substantial mechanical gains—for instance, increasing Young's modulus by 204.02%, indicating their value in developing high-performance composites [16]. Beyond mechanical reinforcement, CNFs have been integrated into flax fiber-reinforced epoxy systems to improve structural performance [17] and into conductive films with carbon nanotubes, creating flexible strain sensors with improved electrical conductivity and flexibility [18].

Previous studies have explored the chemical, thermal, and mechanical performance of TPU composites reinforced with CNFs, including our earlier work on thermal and morphological analysis [19]. However, the microstructural and elemental behavior of TPU/CNF nanocomposites has not been comprehensively examined—especially in relation to how nanofiber dispersion, agglomeration, and interfacial bonding affect composite performance. A deeper understanding of these features is essential to guide the optimization of filler loading and processing conditions.

Theoretically, the integration of CNFs into a polymer matrix affects the composite's behavior through interfacial adhesion, shear-lag mechanisms, and load transfer models, all of which depend on the dispersion quality and bonding efficiency at the matrix–filler interface. Poor dispersion or excessive agglomeration can lead to stress concentrations and reduced mechanical integrity. Therefore, the objective of this study is to perform an in-depth microstructural and elemental analysis of TPU/jute CNF nanocomposites using FESEM and EDX. By examining the surface morphology, nanofiber distribution, and elemental composition at various filler loadings (1–5 wt%), this work aims to identify the optimal CNF content for uniform dispersion and improved bonding—providing critical insights for the future design of high-performance, bio-based nanocomposites.

2- Material and Methods

In this study, thermoplastic polyurethane (TPU) was selected as the polymer matrix, while jute cellulose nanofibers (CNFs) served as the reinforcing material. The TPU, supplied in granular form, was procured from Mecha Solve Engineering Sdn. Bhd. Meanwhile, the raw jute fiber, obtained in rope hemp form, was sourced from Zhejiang Hailun Rope and Net Co., LTD (China), as illustrated in Figures 1-a and 1-b [19]. Jute is a natural bast fiber extracted from the main stem of *Corchorus* plants and is widely recognized as one of the most abundant and cost-effective natural fibers, produced on a large scale globally [3, 20]. Its biodegradability, availability, and mechanical integrity make it an ideal candidate for sustainable composite applications.

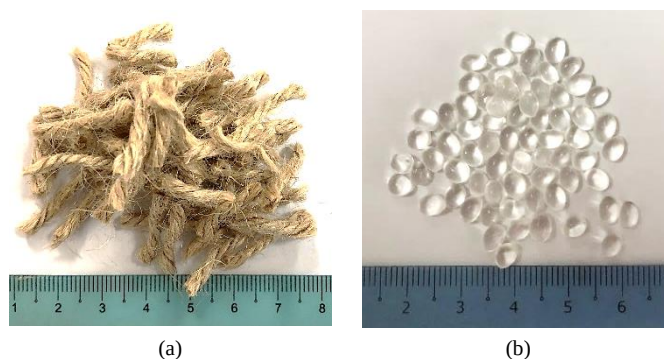


Figure 1. (a) Cut Jute rope hemp (b) Granulate TPU

2-1- Preparation of CNFs from Jute Fiber

CNFs were extracted from raw jute fibers using a comprehensive chemo-mechanical approach that combined sequential chemical treatments with high-energy mechanical milling. Initially, jute fibers were cut into 2–3 cm lengths and immersed in an 18% (w/v) sodium hydroxide (NaOH) solution for 2 hours at room temperature to induce swelling. This step effectively removed non-cellulosic components, including lignin, hemicellulose, waxes, and other impurities. After the treatment, fibers were thoroughly rinsed with distilled water to achieve neutralization and then air-dried. Subsequently, the fibers underwent acid hydrolysis using 2M sulfuric acid (H_2SO_4) at 80°C under continuous stirring for 3 hours. After hydrolysis, they were repeatedly washed with distilled water until a neutral pH was achieved. This was followed by a second alkaline treatment using 3% (w/v) NaOH at 80°C for 3 hours to further remove residual lignin. Again, the fibers were rinsed thoroughly and air-dried for 3 hours. To eliminate any remaining lignin and achieve fiber whitening, a bleaching process was performed using 2% (v/v) sodium chlorite (NaClO_2) at 50°C for 1 hour. This step was repeated two to three times until the fibers became visibly colorless. The bleached fibers were cooled, filtered, rinsed with distilled water, and air-dried to yield chemically treated, purified CNFs.

Mechanical treatment was then performed through a wet pulverization process using a high-energy planetary ball mill (Retsch PM-100). Deionized water and 10 mm zirconia balls (10:1 ball-to-water ratio) were added to an agate milling jar. The slurry was milled at 450 rpm for 6 hours at room temperature. The final slurry was collected and freeze-dried at –50°C for 8 hours to obtain high-purity, finely milled CNFs.

2-2- Preparation of TPU Nanocomposite

TPU/jute CNF nanocomposites were fabricated using a melt blending and compression molding process. Five compositions were prepared with varying CNF weight percentages: 1%, 2%, 3%, 4%, and 5%. Initially, TPU granules were preheated at 80°C for 6 hours to eliminate residual moisture. The pre-dried TPU and specified amounts of CNFs were compounded using a ThermoHAAKE PolyLab Rheomix internal mixer at 180°C with a rotor speed of 150 rpm. The blended materials were then subjected to hot compression molding at 180°C under a pressure of 5 MPa for 10 minutes to form square sheets (150 mm × 150 mm × 3 mm). After molding, the sheets were cooled to room temperature under constant pressure to ensure dimensional and structural uniformity. The resulting sheets were cut into cuboid specimens (1 cm × 1 cm × 0.3 cm) using a die cutter for microstructural and elemental characterization using Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray (EDX) analysis.

Figure 2 presents a comprehensive flowchart illustrating the sequential methodology used in this study. The flowchart is divided into two main pathways: Figure 2-a chemo-mechanical extraction of CNFs from jute fibers, and Figure 2-b fabrication of TPU/CNF nanocomposites via melt blending and compression molding. Each step—ranging from chemical treatments and mechanical milling to sample molding and preparation—is visually represented to facilitate better understanding of the overall workflow.

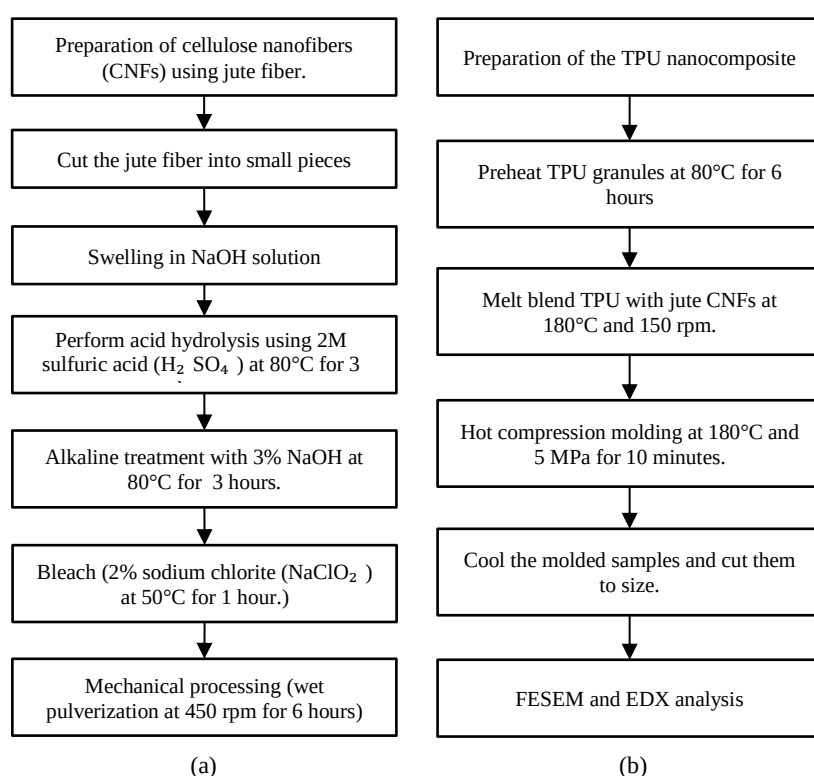


Figure 2. CNF Extraction from Jute Fiber (Chemo-Mechanical Process) (b) Fabrication of TPU/CNF Nanocomposites

2-3-Field Emission Scanning Electron Microscope (FESEM) and Energy Dispersive X-Ray (EDX)

The microstructural and elemental characterization of the fabricated TPU/jute CNF nanocomposites was conducted using Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray (EDX) spectroscopy. FESEM was employed to examine the surface topography and morphology of the nanocomposites after the incorporation of jute CNFs. Prior to imaging, all samples were coated with a thin layer of gold to improve surface conductivity and minimize charging effects during analysis. The surface features were analyzed using a Hitachi SU8010 FESEM at magnifications of 5,000 $\times$ (5kX) and 10,000 $\times$ (10kX), allowing detailed observation of nanofiber dispersion and interfacial interactions. In addition, EDX spectroscopy—integrated within the FESEM system—was used to determine the elemental composition of the nanocomposites and to verify the presence and distribution of elements associated with both TPU and jute-derived CNFs.

3- Results and Discussion

3-1-Microstructural Analysis of Neat TPU and TPU/ Jute CNFs Nanocomposites Using FESEM

Field Emission Scanning Electron Microscopy (FESEM) was employed to investigate the surface morphology, dispersion quality, and physical interactions between jute CNFs and the TPU matrix. Prior to imaging, the samples were sputter-coated with ~ 1 nm of gold to improve conductivity and prevent surface charging. Figures 3-a to 3-f and 4-a to 4-f present FESEM micrographs of neat TPU and TPU/jute CNF nanocomposites at 5k and 10k magnifications, respectively.

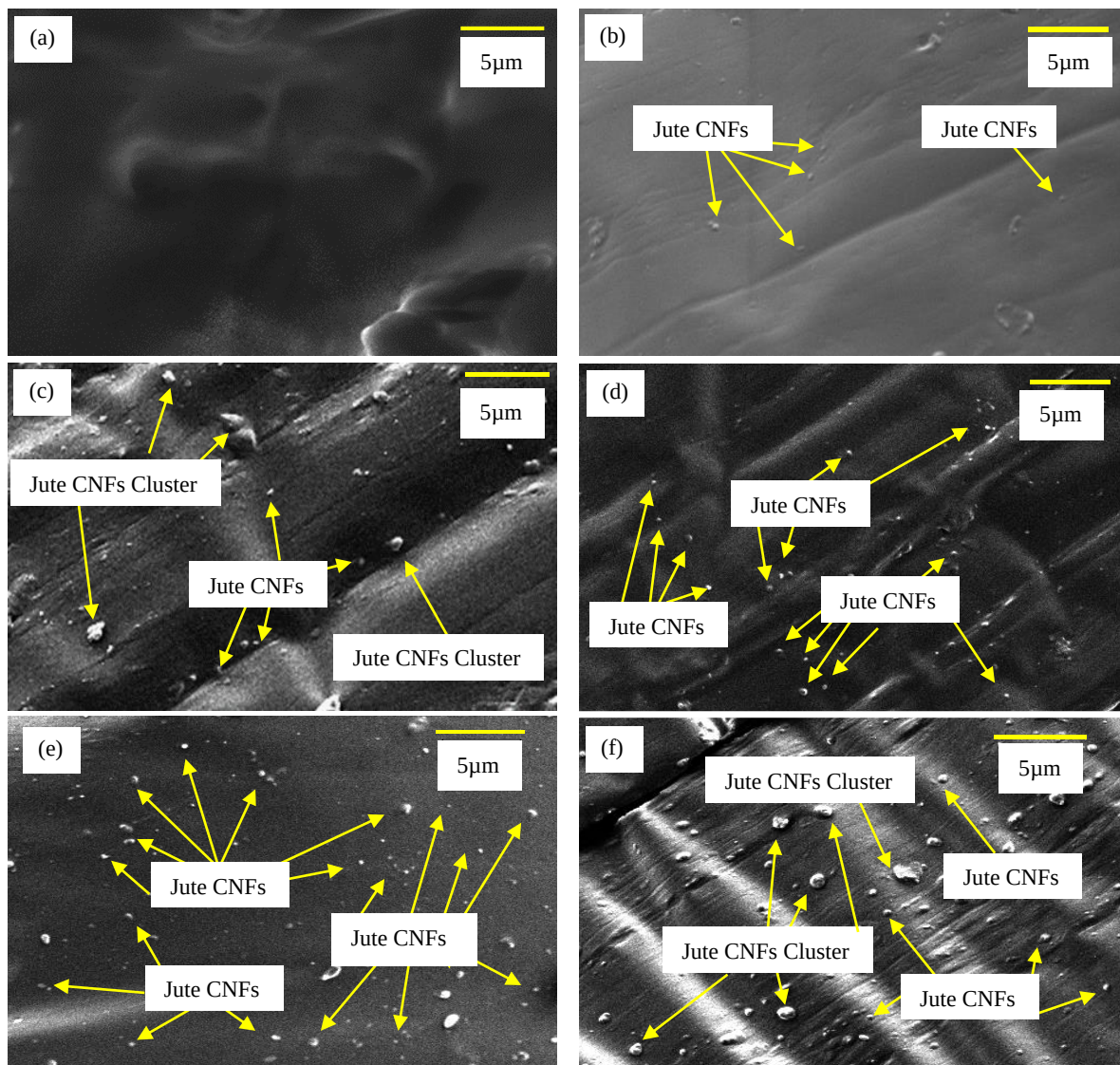
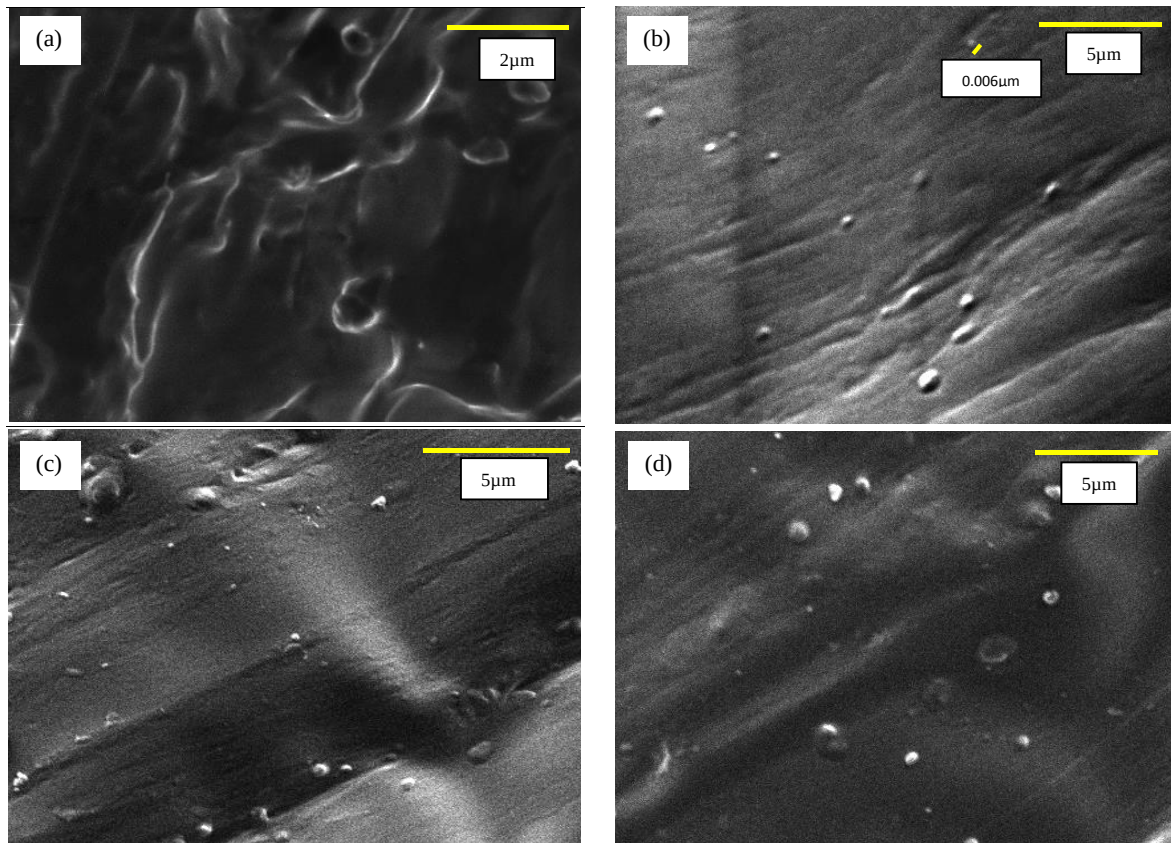


Figure 3. FESEM Micrographs at 5k Magnification (a) Neat TPU (b) TPU/1 wt% Jute CNFs Nanocomposites; (c) TPU/2 wt% Jute CNFs Nanocomposites (d) TPU/3 wt% Jute CNFs Nanocomposites (e) TPU/4 wt% Jute CNFs Nanocomposites (f) TPU/5 wt% Jute CNFs Nanocomposites.

Figure 3-a shows that neat TPU exhibits a smooth and defect-free surface with no visible porosity or voids, indicating high-quality melt blending and complete polymerization. However, the homogeneity also reveals an absence of internal reinforcement structures, which theoretically results in limited crack resistance and poor load dissipation—typical weaknesses in unreinforced elastomers. In contrast, the incorporation of 1 wt% jute CNFs (Figure 3-b) introduces visible surface texture and uniformly distributed nanoscale dots. These features correspond to well-dispersed CNFs embedded within the TPU matrix, forming an early-stage fiber network. According to classical composite theory, even low concentrations of high-aspect-ratio fillers can enhance stress transfer and create tortuous paths that deflect crack propagation. The rougher texture observed here also supports the hypothesis that CNFs contribute to energy dissipation and mechanical toughening through increased interfacial surface area [21]. At 2 wt% CNFs (Figure 3-c), the number of visible CNFs increases, and initial signs of clustering appear. This suggests that the composite is approaching the percolation threshold, beyond which the filler begins forming continuous networks. While some CNF clusters are observed, the dispersion remains relatively uniform, enabling effective interfacial bonding and mechanical reinforcement. The formation of these nano-networks aligns with shear-lag theory, which predicts improved load-bearing capacity when well-dispersed fillers bridge the matrix.

Figures 3-d and 3-e (3–4 wt%) further confirm the homogeneous dispersion of CNFs without noticeable agglomeration. The micrographs show finer, evenly spaced CNFs integrated throughout the TPU matrix. At 4 wt%, the dispersion appears optimal, suggesting strong Van der Waals interactions balanced with sufficient shear mixing energy to prevent clustering [22, 23]. This condition promotes maximum surface contact between the matrix and CNFs, enhancing load transfer and crack arrest mechanisms—key for mechanical integrity. However, at 5 wt% CNFs (Figure 3-f), the morphology deteriorates, revealing multiple clusters and dense CNF aggregations. This behavior is attributed to excessive filler-filler interactions and insufficient matrix content to encapsulate and separate the fibers. The agglomerates reduce effective surface area for bonding and introduce potential voids or stress concentrators—limiting mechanical enhancement. Similar trends are well-documented in high-aspect-ratio fillers where exceeding the percolation limit compromises dispersion and results in reduced composite performance [23].

Figures 4-a to 4-f present FESEM micrographs at 10k magnification, offering more precise insight into CNF size, dispersion quality, and interfacial interactions. Neat TPU (Figure 4-a) again shows a smooth, featureless matrix, affirming its homogeneity but also its vulnerability to crack initiation. At 1–4 wt% CNF loadings (Figures 4-b to 4-e), CNFs are observed with average diameters between 60–140 nm. These nanofibers are evenly distributed throughout the matrix and appear well-integrated, suggesting strong physical entanglement and potential for mechanical interlocking. The absence of large voids or surface cracks in these images implies excellent adhesion and dispersion—conditions required for optimal matrix-to-fiber stress transfer, as predicted by micromechanical composite models.



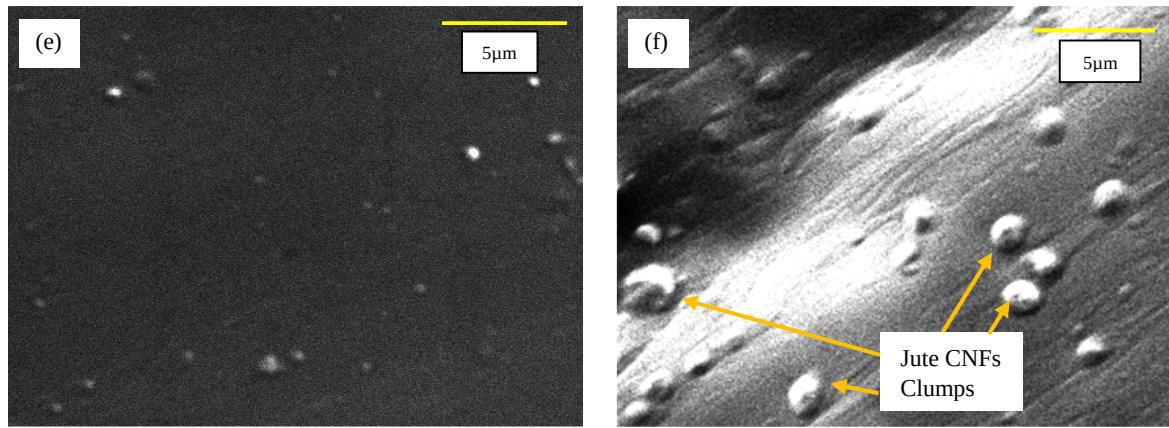
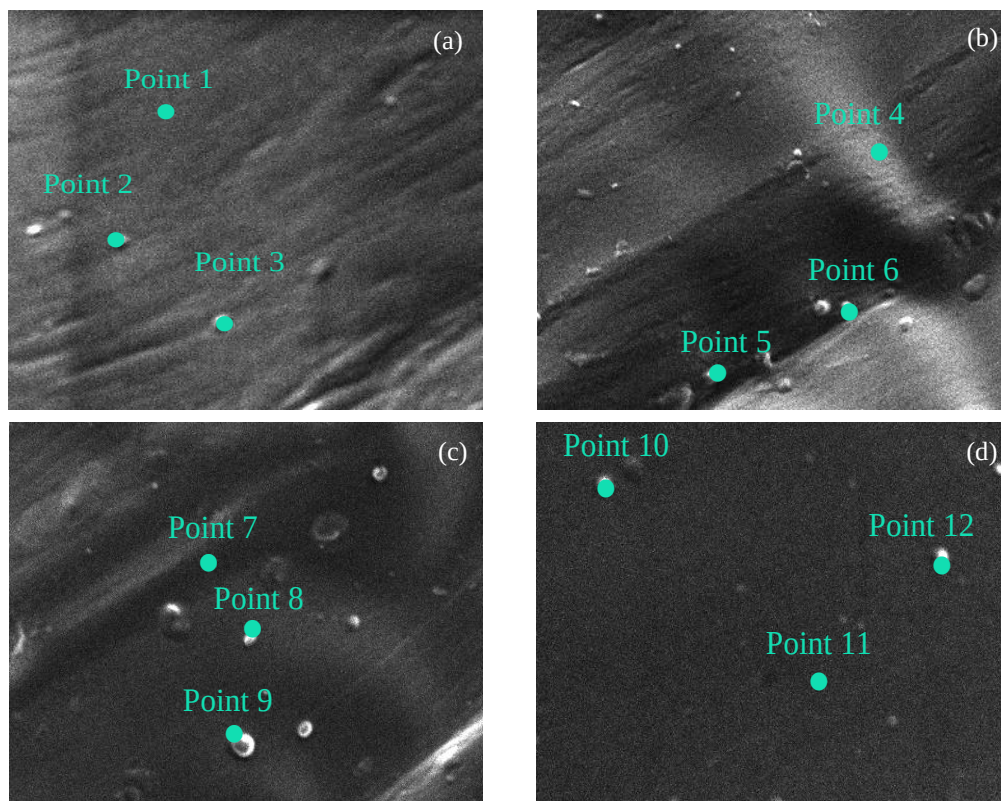


Figure 4. FESEM Micrographs at 10k Magnification (a) Neat TPU (b) TPU/1 wt% Jute CNFs Nanocomposites (c) TPU/2 wt% Jute CNFs Nanocomposites (d) TPU/3 wt% Jute CNFs Nanocomposites (e) TPU/4 wt% Jute CNFs Nanocomposites (f) TPU/5 wt% Jute CNFs Nanocomposites.

In Figure 4-f, corresponding to 5 wt% CNF, larger clumps are evident, with some agglomerates reaching sizes of approximately 430 nm. These clusters confirm the earlier hypothesis that increasing CNF content raises the surface energy of the system, promoting fiber self-aggregation as a means of minimizing free energy. Such agglomeration disrupts interfacial continuity, impedes uniform stress transfer, and introduces weak points that can trigger premature mechanical failure—emphasizing the critical need to optimize filler loading for consistent nanocomposite performance. In this study, microstructural analysis revealed that uniform dispersion of jute CNFs within the TPU matrix was effectively maintained up to 4 wt%, beyond which agglomeration and clustering became prominent. This trend not only explains the observed microstructural degradation but is also consistent with previous studies [24], which identified 4 wt% CNF loading as optimal due to its balance of mechanical enhancement and structural integrity. These findings collectively underscore the importance of identifying a threshold concentration that maximizes reinforcement benefits while minimizing the drawbacks of nanoparticle crowding.

3-2-Microstructural Analysis of Neat TPU and TPU/ Jute CNFs Nanocomposites Using EDX

Energy Dispersive X-ray (EDX) spectroscopy was used to analyze the elemental distribution within the TPU/jute CNF nanocomposites. Figures 5-a to 5-e shows the point analysis locations at 10k magnification for samples containing 1–5 wt% CNFs. The corresponding spectra and elemental compositions are summarized in Table 1.



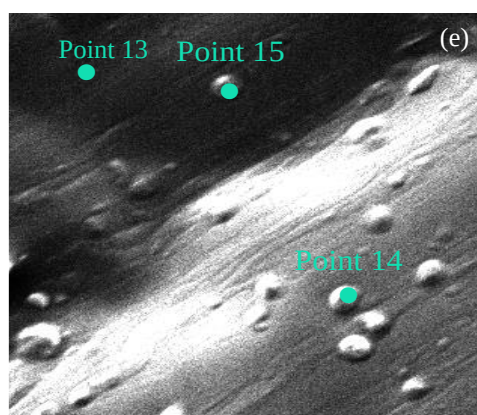


Figure 5. EDX point analysis of (a) TPU/1 wt% Jute CNFs Nanocomposites (b) TPU/2 wt% Jute CNFs Nanocomposites (c) TPU/3 wt% Jute CNFs Nanocomposites (d) TPU/4 wt% Jute CNFs Nano-composites (e) TPU/5 wt% Jute CNFs Nanocomposites, all captured at 10k magnification.

Table 1. EDX analysis of TPU/Jute CNFs nanocomposites at varying concentrations: (a) 1 wt% (b) 2 wt%, (c) 3 wt% (d) 4 wt%, and (e) 5 wt% Jute CNFs

Spectrum/ Point	Element (%)									
	Ca	C	O	P	K	Si	Na	Al	S	Y
Point 1	0.8	76.96	17.44	-	0.8	2.7	1.5	-	0.7	0.1
Point 2	3.4	46.3	11.2	2.1	3.5	5.1	14.5	2.7	3.9	3.7
Point 3	2.6	51.1	14.2	1.6	1.7	6.3	16.7	2.3	2.9	3.9
Point 4	0.9	76.86	15.44	-	0.5	3.7	1.8	-	0.7	0.1
Point 5	4.1	48.3	12.2	2.3	2.5	5.6	15.5	2.4	3.5	4.3
Point 6	3.9	49.1	11.2	1.6	1.8	6.8	15.7	2.8	3.6	3.5
Point 7	1.8	74.7	13.9	2.1	0.9	3.9	1.8	-	0.4	0.5
Point 8	3.1	48.9	11.1	2.5	2.8	5.6	15.5	2.8	3.7	3.11
Point 9	3.7	49.1	11.2	2.2	2.5	6.7	17.8	3.1	4.3	3.8
Point 10	3.9	44.7	13.7	3.1	4.8	10.3	19.1	4.4	1.9	4.1
Point 11	2.1	72.4	13.1	2.4	0.9	4.2	1.9	0.4	0.6	0.7
Point 12	4.0	41.1	10.6	2.6	2.7	6.7	19.8	4.4	4.3	4.1
Point 13	1.9	69.8	18.3	2.1	1.1	4.2	1.9	0.2	0.4	0.7
Point 14	3.1	32.9	8.5	3.5	3.9	15.5	18.1	5.9	5.2	3.4
Point 15	3.4	33.3	10.4	3.2	3.4	14.6	17.4	5.7	4.9	3.7

The EDX analysis reveals two distinct phases across the samples: a dark phase, which corresponds to the TPU matrix, and a bright phase, representing the jute CNF reinforcements. The TPU-rich regions consistently show high concentrations of carbon (C) and oxygen (O) (e.g., Points 1, 4, 7, 11, and 13), typical of organic polyurethane backbones. These areas also contain minor traces of silicon (Si) and sodium (Na), likely attributed to background contamination or limited CNF presence. In contrast, the bright-phase regions (e.g., Points 2, 3, 5, 6, 8–10, 12, 14, 15) exhibit elevated levels of inorganic elements characteristic of jute-derived CNFs, such as calcium (Ca), sodium (Na), silicon (Si), aluminum (Al), phosphorus (P), potassium (K), and yttrium (Y). These findings confirm the successful incorporation and distribution of jute CNFs within the TPU matrix [25].

The elemental composition observed in CNF-rich regions is consistent with the known profile of plant-based natural fibers and plays a significant role in influencing the properties of the TPU nanocomposites. Among the elements detected, silicon (Si) was present in concentrations ranging from 5.1% to 19.8%, contributing to thermal reinforcement by acting as a barrier against thermal degradation and improving dimensional stability at elevated temperatures. From a polymer composite perspective, Si's polar nature also facilitates better matrix-fiber bonding. Sodium (Na) and potassium (K), both present in substantial amounts, enhance ionic conductivity and promote crystallinity in the semi-crystalline TPU matrix, with sodium—measured between 15.5% and 19.1%—playing a key role in improving polymer chain alignment, thereby enabling more efficient stress transfer. Calcium (Ca), present up to 4.1%, is known to increase rigidity and stiffness, effectively enhancing the material's modulus and resistance to deformation. Trace elements like aluminum (Al) and phosphorus (P) contribute additional functionality, including flame retardancy, interfacial compatibility, and crosslinking potential, particularly in their oxidized forms. Yttrium (Y), although uncommon in natural fibers, may

derive from residual minerals and is believed to influence UV stability and surface energy, potentially improving CNF-matrix adhesion. Theoretically, these elemental contributions are supported by multiple composite models. According to interfacial adhesion theory, the polar and metallic elements increase surface energy, promoting stronger hydrogen bonding and van der Waals interactions with TPU's urethane groups. Micromechanical theories suggest that improved filler dispersion and bonding lead to more uniform load distribution, thereby minimizing local stress concentrations. Finally, the rule of mixtures and hybrid reinforcement theory predict that such elemental enrichment at the matrix–filler interface enhances the overall mechanical synergy, particularly in terms of tensile strength and elastic modulus.

The data also reveals an important trend: as CNF content increases, elemental diversity and concentration in bright phases increase—up to an optimal range. However, at 5 wt% CNFs (Points 13–15), although elemental richness is evident, the micrographs (Figure 5-e) show clustered areas, which may result in localized overloading and compromised interfacial integrity.

This finding aligns with percolation theory, which states that after reaching a critical filler concentration, further addition leads to agglomeration rather than reinforcement. These clusters reduce the efficiency of stress transfer and can serve as failure initiation sites under mechanical loading.

4- Conclusion

This study demonstrated the successful development and characterization of thermoplastic polyurethane (TPU) nanocomposites reinforced with jute cellulose nanofibers (CNFs), focusing on their microstructural and elemental behavior. Through detailed FESEM and EDX analyses, it was observed that the optimal dispersion of CNFs within the TPU matrix occurred at a concentration of 4 wt%, where the nanofibers were uniformly distributed without significant agglomeration. The integration of jute CNFs notably modified the TPU surface morphology, introducing nanoscale reinforcement that improved interfacial bonding and load transfer. The elemental mapping confirmed the presence of reinforcing minerals—such as silicon, calcium, sodium, and aluminum—within the CNFs, which contributed to thermal stability, rigidity, and crystallinity. These enhancements are theoretically supported by interfacial adhesion theory, percolation theory, and micromechanical composite models, affirming the beneficial role of CNF dispersion on composite performance.

The combined effects of improved microstructure and elemental synergy resulted in enhanced tensile strength, modulus, impact resistance, and thermal properties, while reducing overall material weight. The findings validate the potential of TPU/jute CNF nanocomposites as sustainable, high-performance alternatives to conventional synthetic composites. These bio-based materials offer a promising pathway for application in structural components across automotive, aerospace, and consumer product industries. Future studies should aim to optimize processing conditions further, assess the long-term mechanical durability and environmental aging behavior, and explore additional functional enhancements, such as electrical conductivity or flame resistance. Expanding these nanocomposites into multifunctional platforms will support their scalability and integration into advanced material systems for real-world engineering challenges.

5- Declarations

5-1- Author Contributions

Conceptualization, E.E.M.N. and S.S.N.; methodology, E.E.M.N. and S.S.N.; software, S.S.N.; validation, E.E.M.N. and A.B.A.K.; formal analysis, S.S.N.; investigation, S.S.N.; resources, E.E.M.N. and A.B.A.K.; data curation, S.S.N.; writing—original draft preparation, S.S.N.; writing—review and editing, E.E.M.N. and M.F.B.; visualization, E.E.M.N., S.S.N. and M.F.B.; supervision, E.E.M.N.; project administration, E.E.M.N.; funding acquisition, E.E.M.N. All authors have read and agreed to the published version of the manuscript.

5-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5-3- Funding

The project described was funded by the Multimedia University (MMU) Internal Research Grant [Project No: MMUI180001.02].

5-4- Institutional Review Board Statement

Not applicable.

5-5- Informed Consent Statement

Not applicable.

5-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

6- References

- [1] Martin, D. J., Osman, A. F., Andriani, Y., & Edwards, G. A. (2012). Thermoplastic polyurethane (TPU)-based polymer nanocomposites. *Advances in Polymer Nanocomposites*, 321–350, Woodhead Publishing, Sawston, United Kingdom. doi:10.1533/9780857096241.2.321.
- [2] Behera, P. K., Dhamaniya, S., Mohanty, S., & Gupta, V. (2024). Advances in thermoplastic polyurethane elastomers. *Advances in Thermoplastic Elastomers*, Elsevier, Amsterdam, Netherlands. doi:10.1016/b978-0-323-91758-2.00014-3.
- [3] Siti Syazwani, N., Ervina Efzan, M. N., Kok, C. K., Aeslina, A. K., & Sivaraman, V. (2021). Microstructure and Mechanical Properties of Thermoplastic Polyurethane/Jute Cellulose Nanofibers (CNFs) Nanocomposites. *Recent Trends in Manufacturing and Materials Towards Industry 4.0*, 805–816. doi:10.1007/978-981-15-9505-9_71.
- [4] Kim, Y., Huh, P. H., & Yoo, S. Il. (2023). Mechanical Reinforcement of Thermoplastic Polyurethane Nanocomposites by Surface-Modified Nanocellulose. *Macromolecular Chemistry and Physics*, 224(4), 202200383. doi:10.1002/macp.202200383.
- [5] Azzra, N. A., Atiqah, A., Fadhlina, H., Jalar, A., Bakar, M. A., Ismail, A. G., & Supian, A. B. M. (2024). Effect of nanofibril cellulose empty fruit bunch-reinforced thermoplastic polyurethane nanocomposites on tensile and dynamic mechanical properties for flexible substrates. *Polymer Composites*, 45(16), 14633–14643. doi:10.1002/pc.28788.
- [6] Ervina Efzan, M. N., & Siti Syazwani, N. (2018). A Review on Effect of Nanoreinforcement on Mechanical Properties of Polymer Nanocomposites. *Solid State Phenomena*, 280, 284–293. doi:10.4028/www.scientific.net/ssp.280.284.
- [7] Barik, B., Maji, B., Sarkar, D., Mishra, A. K., & Dash, P. (2022). Cellulose-based nanomaterials for textile applications. *Bio-Based Nanomaterials*, Elsevier, Amsterdam, Netherlands. doi:10.1016/b978-0-323-85148-0.00009-9.
- [8] Yu, L., Lin, J., Tian, F., Li, X., Bian, F., & Wang, J. (2014). Cellulose nanofibrils generated from jute fibers with tunable polymorphs and crystallinity. *Journal of Materials Chemistry A*, 2(18), 6402. doi:10.1039/c4ta00004h.
- [9] Efzan, E., Kok, C. K., & Nurhidayatullaili, M. J. (2024). Synthesis of cellulose nanofibers from jute fiber by using chemomechanical method. *F1000Research*, 13, 40. doi:10.12688/f1000research.138665.1.
- [10] Mohd Amin, K. N., Chaleat, C., Edwards, G., Martin, D. J., & Annamalai, P. K. (2022). A cleaner processing approach for cellulose reinforced thermoplastic polyurethane nanocomposites. *Polymer Engineering and Science*, 62(3), 949–961. doi:10.1002/pen.25899.
- [11] Mi, H. Y., Jing, X., Salick, M. R., Cordie, T. M., & Turng, L. S. (2016). Carbon nanotube (CNT) and nanofibrillated cellulose (NFC) reinforcement effect on thermoplastic polyurethane (TPU) scaffolds fabricated via phase separation using dimethyl sulfoxide (DMSO) as solvent. *Journal of the Mechanical Behavior of Biomedical Materials*, 62, 417–427. doi:10.1016/j.jmbbm.2016.05.026.
- [12] Li, X., Li, J., Wang, J., Yuan, J., Jiang, F., Yu, X., & Xiao, F. (2021). Recent applications and developments of Polyurethane materials in pavement engineering. *Construction and Building Materials*, 304, 124639. doi:10.1016/j.conbuildmat.2021.124639.
- [13] Sun, X., Yang, X., Zhang, J., Shang, B., Lyu, P., Zhang, C., Liu, X., & Xia, L. (2023). Fabrication of Silane-Grafted Cellulose Nanocrystals and Their Effects on the Structural, Thermal, Mechanical, and Hysteretic Behavior of Thermoplastic Polyurethane. *International Journal of Molecular Sciences*, 24(5), 5036. doi:10.3390/ijms24055036.
- [14] Fortunati, E., Luzi, F., Janke, A., Häußler, L., Pionteck, J., Kenny, J. M., & Torre, L. (2017). Reinforcement effect of cellulose nanocrystals in thermoplastic polyurethane matrices characterized by different soft/hard segment ratio. *Polymer Engineering & Science*, 57(6), 521–530. doi:10.1002/pen.24532.
- [15] Ye, J., Si, J., Cui, Z., Wang, Q., Peng, K., Chen, W., Peng, X., & Chen, S. (2017). Surface Modification of Electrospun TPU Nanofiber Scaffold with CNF Particles by Ultrasound- Assisted Technique for Tissue Engineering. *Macromolecular Materials and Engineering*, 302(11). doi:10.1002/mame.201700277.
- [16] Yu, R., M.N., P., Feng, J., Yang, Y., Hong, S. H., & Song, J. il. (2025). Enhancing the mechanical properties of flax fiber-reinforced epoxy composites through cellulose nanofiber incorporation. *Industrial Crops and Products*, 223. doi:10.1016/j.indcrop.2024.120113.
- [17] Ci, Y., Lv, D., Yang, X., Du, H., & Tang, Y. (2024). High-performance cellulose/thermoplastic polyurethane composites enabled by interaction-modulated cellulose regeneration. *Carbohydrate Polymers*, 346, 122611. doi:10.1016/j.carbpol.2024.122611.

- [18] Mei, S., Xu, B., Wan, J., & Chen, J. (2024). Preparation of CNT/CNF/PDMS/TPU Nanofiber-Based Conductive Films Based on Centrifugal Spinning Method for Strain Sensors. *Sensors*, 24(12), 4026. doi:10.3390/s24124026.
- [19] Nordin, S. S., Noor, E. E. M., Kok, C. K., Julkapli, N. M., & Baig, M. F. (2025). Phase, Chemical, Thermal, and Morphological Analyses of Thermoplastic Polyurethane (TPU) Nanocomposites Reinforced with Jute Cellulose Nanofibers (CNFs). *Polymers*, 17(7). doi:10.3390/polym17070899.
- [20] Ahuja, D., Kumar, L., Jain, S., Nahak, B., & Kaushik, A. (2025). Transforming jute waste into high-performance biodegradable polyurethane bionanocomposites. *Cellulose*, 1-20. doi:10.1007/s10570-025-06653-1.
- [21] Pedrazzoli, D., & Manas-Zloczower, I. (2016). Understanding phase separation and morphology in thermoplastic polyurethanes nanocomposites. *Polymer*, 90, 256–263. doi:10.1016/j.polymer.2016.03.022.
- [22] Collado, I., Jiménez-Suárez, A., Vázquez-López, A., del Rosario, G., & Prolongo, S. G. (2024). Ultrasonication Influence on the Morphological Characteristics of Graphene Nanoplatelet Nanocomposites and Their Electrical and Electromagnetic Interference Shielding Behavior. *Polymers*, 16(8), 1068. doi:10.3390/polym16081068.
- [23] Rahmati, A., Balouch Sirgani, A., Molaei, M., & Karimipour, M. (2014). Cu-doped ZnO nanoparticles synthesized by simple co-precipitation route. *The European Physical Journal Plus*, 129(11), 250. doi:10.1140/epjp/i2014-14250-8.
- [24] Nordin, S. S., Mhd Noor, E. E., Muhd Julkapli, N., & Abdul Kadir, A. (2024). Study on the Effect of Jute CNFs Addition on the Water Absorption and Mechanical Properties of Geopolymer Concrete. *Buildings*, 14(11), 3444. doi:10.3390/buildings14113444.
- [25] Siti Syazwani, N., Ervina Efan, M. N., Kok, C. K., & Nurhidayatullaili, M. J. (2022). Analysis on extracted jute cellulose nanofibers by Fourier transform infrared and X-Ray diffraction. *Journal of Building Engineering*, 48. doi:10.1016/j.jobbe.2021.103744.