

## A MICROSCOPIC STUDY OF THE MORPHOLOGICAL PROPERTIES OF NATURAL AND RECYCLED FIBERS FOR THE DEVELOPMENT OF COMPOSITE INSULATION MATERIALS

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### Abstract

The utilization of agricultural and recycled waste materials for sustainable composite development has gained significant attention in recent years. In this study, a hybrid composite reinforced with banana fibers and recycled fibers was developed and analyzed by microscopic for their suitability to incorporate in composites. Banana fibers were extracted from banana pseudo stems, while recycled fibers were obtained from textile spinning waste. Both fiber types were cleaned, processed, and incorporated into a composite system for analysis. Microscopic analysis was performed to investigate fiber distribution, surface morphology, interfacial bonding, and internal structural arrangement within the composite. The observations revealed that banana fibers exhibited rough and irregular surfaces with longitudinal grooves and fibrillar structures, while recycled fibers contributed to a heterogeneous but compact arrangement within the matrix. Improved fiber-matrix interaction was observed due to the surface roughness of both fiber types, which enhanced mechanical interlocking. The presence of microvoids and porous regions was also identified within the composite structure. These morphological features suggest that the hybrid composite possesses reduced density and improved thermal insulation potential. The study indicates that the combination of banana and recycled fibers can be effectively utilized in sustainable composite development. The findings further demonstrate that agricultural and recycled waste materials can serve as viable alternatives to synthetic reinforcements. Microscopic evaluation provides essential insights into fiber compatibility and structural behavior, which are important for optimizing composite performance in future engineering and construction applications.

## 1. Introduction

Natural fiber-reinforced composites have gained significant attention in recent years due to increasing environmental concerns, sustainability requirements, and the need for biodegradable engineering materials. Researchers have widely reported that agricultural waste fibers such as banana fibers can be effectively utilized as reinforcement in polymer composites because of their low density, good strength, and eco-friendly nature (Faruk et al., 2012; Mohanty et al., 2005). Banana fibers, extracted from the pseudo stem of banana plants, are considered a promising lignocellulosic material with high cellulose content and acceptable mechanical performance (Mohapatra et al., 2010).

Several studies have highlighted that the performance of natural fiber composites strongly depends on fiber morphology, surface characteristics, and interfacial bonding with the matrix. The rough and irregular surface of banana fibers improves mechanical interlocking, which enhances fiber-matrix adhesion in composite systems (Li et al., 2007; Bledzki & Gassan, 1999). Microscopic analysis has therefore been widely used to examine fiber structure, porosity, and surface defects that influence composite behavior.

Hybrid composites incorporating different natural or recycled fibers have also been investigated to improve mechanical and thermal performance. It has been reported that combining fibers with different structural characteristics leads to better stress distribution and improved composite stability (Dittenber & GangaRao, 2012; Koronis et al., 2013). Recycled fibers, in particular, contribute to waste reduction while enhancing sustainability and material efficiency in composite development.

Thermal insulation behavior is another important aspect of natural fiber composites. Due to their porous structure and air-trapping ability, banana fiber-based composites exhibit low thermal conductivity, making them suitable for building insulation applications (Mukhopadhyay & Figueiro, 2009). Studies also show that fiber packing and morphology significantly influence heat transfer resistance in polymer composites (Subramaniyan et al., 2021).

Surface modification and fiber treatment techniques have been explored to improve compatibility between fibers and matrices. Chemical and mechanical treatments enhance adhesion and reduce moisture absorption, thereby improving durability and long-term performance (John & Thomas, 2008; Bismarck et al., 2005).

Overall, existing literature confirms that banana fiber and recycled fiber-based hybrid composites offer strong potential for sustainable material development. However, microscopic morphological studies are still essential to better understand fiber distribution, interfacial bonding, and structural behavior within composite systems for advanced engineering applications.

## 2. Materials and Methods

Banana fibers and recycled fibers were used as the primary reinforcing materials in this study. Banana fibers were extracted from the pseudo stems of mature banana plants collected from agricultural waste sources. Recycled fibers were obtained from waste fiber-based materials to promote sustainable material utilization. A suitable polymer matrix (resin) was used as the binding medium for composite fabrication. Distilled water and mild cleaning agents were used for fiber washing and purification. No aggressive

chemical treatment was applied in order to preserve the natural morphology of both fiber types for microscopic evaluation.

#### *Fiber Extraction and Preparation*

Banana pseudo stems were manually processed to extract fiber bundles. The extracted fibers were thoroughly washed to remove impurities, dust, and non-cellulosic residues. After washing, fibers were air-dried at room temperature until constant weight was achieved. Recycled fibers were also cleaned, sorted, and dried using the same procedure. Both fiber types were then cut into uniform lengths to ensure consistency in composite preparation.

#### *Composite Preparation*

A hybrid composite was prepared by mixing banana fibers and recycled fibers in a controlled ratio within the gypsum matrix. The fibers were uniformly dispersed into the matrix to ensure proper distribution and bonding. The mixture was then poured into molds and allowed to cure under standard laboratory conditions until full hardening was achieved. After curing, composite samples were carefully removed and placed in direct sunlight for 7 days until gaining constant weight. These samples were then used for microscopic and mechanical properties analysis.

### **3. Microscopic Analysis**

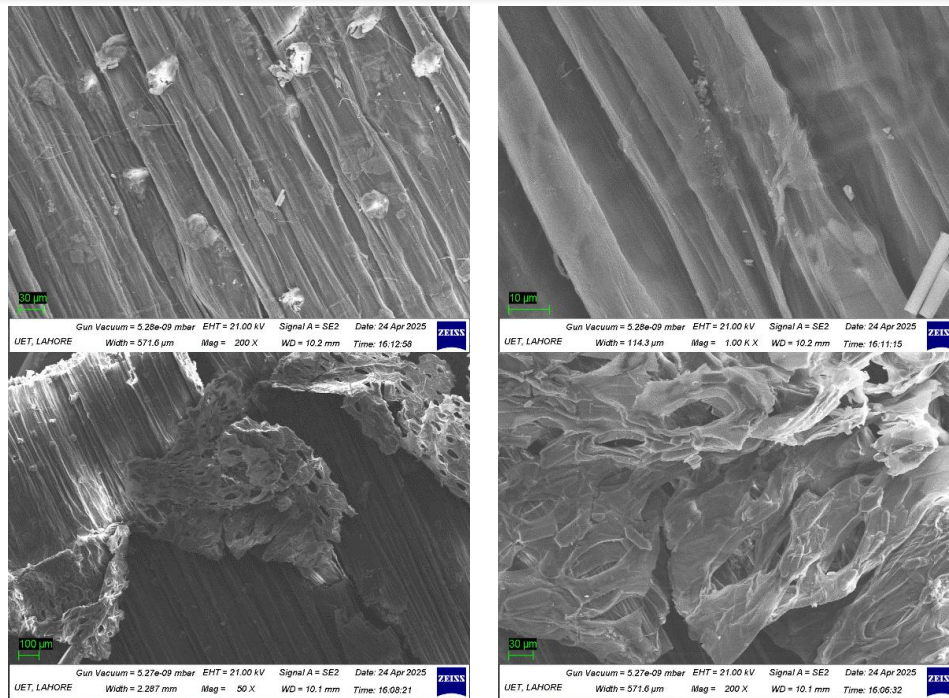
Microscopic examination was carried out using optical microscopy and scanning electron microscopy (SEM) to study

the internal structure of the composite. Small samples were sectioned and mounted on glass slides for optical analysis. For SEM analysis, samples were coated with a thin conductive layer to enhance image resolution. Various magnifications were used to observe fiber distribution, surface morphology, and interfacial bonding within the composite structure. The analysis focused on fiber dispersion, interfacial adhesion, surface roughness, void formation, and internal structural arrangement. Special attention was given to fiber-matrix interaction and the compatibility between banana and recycled fibers within the composite. The presence of pores and micro-voids was also examined to assess potential thermal insulation behavior.

The observed microscopic features were qualitatively analyzed to evaluate the structural performance of the hybrid composite. Results were interpreted based on fiber morphology, bonding quality, and internal homogeneity. Findings were compared with previously reported studies on natural and recycled fiber composites to assess material performance and sustainability potential.

#### *Study of the Morphological Properties of Banana Fibers*

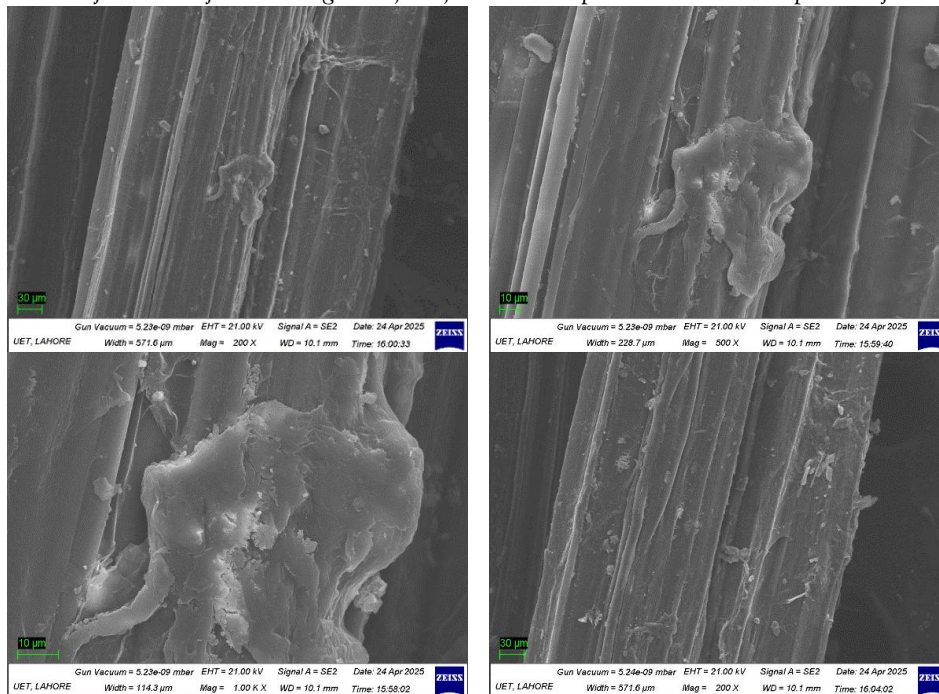
Following banana harvest, the researchers examined the structure of both raw and dry banana fiber. We investigated how drying affected the gypsum binder matrix and the thermomechanical potential of banana fiber by removing the leaves from banana stems.



**Figure 1 SEM images of longitudinal surface of banana fibers (Before Drying)**

The morphological structure of banana fibers, both before and after drying, is composed of numerous micro-fibrils arranged in a longitudinal network of different widths. Prior to drying, these widths range from 20 to 33 µm, while upon drying, they range from 13 to 19 µm. According to measurements taken on the fibers' surface in Figs. 1a, 1b,

and 1c, 1d, this produces a banana fiber that is between 170 and 190 µm wide overall before drying and between 120 and 150 µm wide after drying. As a result, drying causes the banana fibers' cross-section to diminish, which also explains why the fibers lose weight and shrink in shape as the poisoned water evaporates from the micro-fibrils.



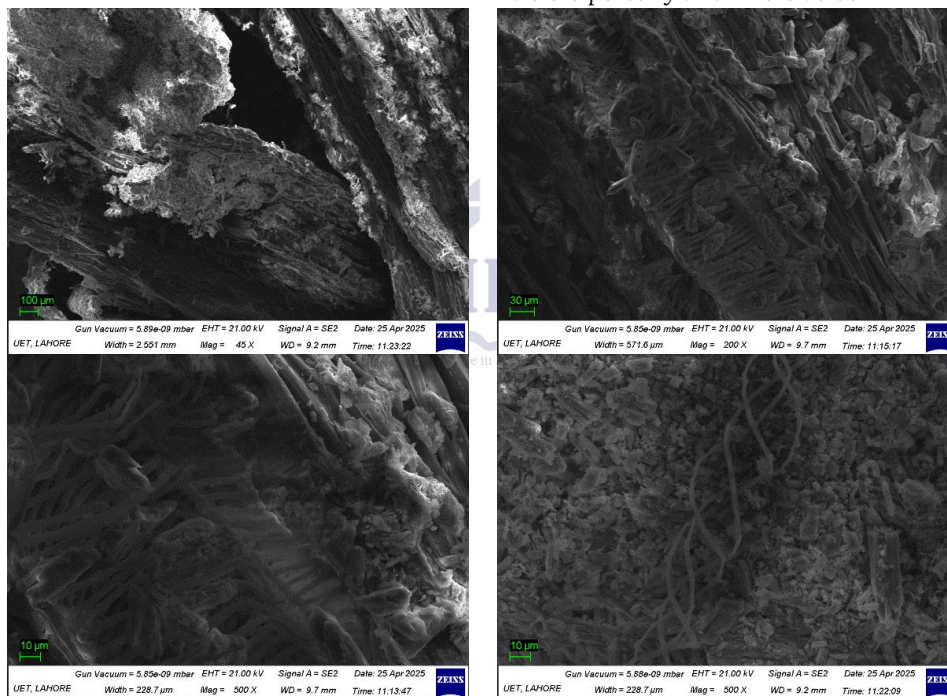
**Figure 2. SEM images of longitudinal surface of banana fibers (After Drying)**

**Examination of the fiber surfaces** The micro-fibrils of banana fiber are cellulosic in origin and are bound together by a binding substance like lignin and hemicelluloses, as seen in Figures 1 before and 2 after drying. According to a study, cellulose, a mixture of lignin, neutrals (hemicelluloses), and other polysaccharide acids that gives banana fiber its rough texture, was most likely the material that made up these micro-fibrils. Cellulose forms the backbone of the cell wall of the homogenous matrix. We can observe that these micro-fibrils are arranged transversely as a network of thick-walled, elliptical (non-spherical) cells, but another researcher estimated that the cell walls were about 1  $\mu\text{m}$  thick. Figures. 1 and 2, which compare the two SEM images of the fibers before and after drying, demonstrate that the concentration of cementitious binders, such as lignin and hemicelluloses, is

significantly lower after drying than it is in the raw form of banana fiber. The evaporation of interfibril water and the subsequent decrease in the cross-section of banana fibers after drying are further supported by this.

#### Microstructural Analysis of Studied Composites

The banana fibers are dispersed quite evenly throughout the gypsum matrix, with a random orientation that is typical of hand-mixed composites, according to the SEM analysis of the 2.5% fiber-reinforced gypsum composite. Sporadic gaps at the fiber-matrix interface indicate areas of weak adhesion that may have been caused by inadequate wetting or shrinking during curing, even though the micrographs in figure 3 show that the fibers are well immersed in the matrix, indicating partial to strong interfacial bonding. Water loss or air entrapment during setting is most likely the cause of the visible porosity and micro-voids.



**Figure 3** Microstructural analysis of 2.5% banana fiber-reinforced gypsum composites

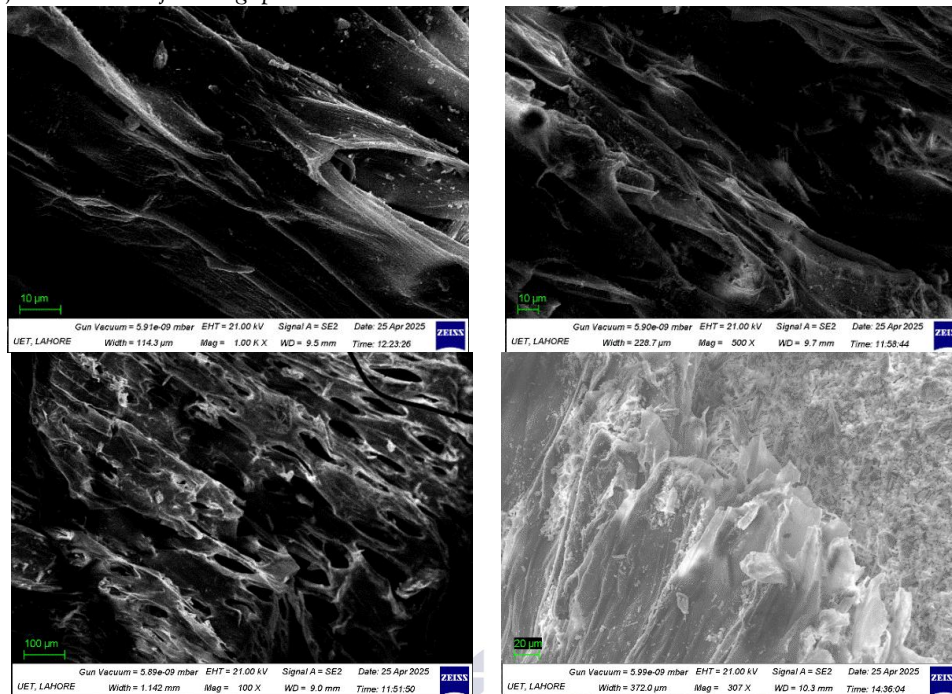
Characteristics like fiber pull-out and fracture surfaces point to a semi-ductile fracture mechanism that enhances toughness and energy absorption by combining fiber rupture with debonding. Even though there is no chemical bonding, the rough surface texture of the banana fibers seen in the pictures may improve mechanical interlocking with the matrix and facilitate stress transfer. Overall, the SEM microstructure demonstrates the reinforcing potential as well as possibilities for additional modification, such as enhancing interfacial

bonding and lowering void content, and validates the successful integration of banana fibers in the gypsum matrix.

In comparison to the 2.5% composition, the SEM micrographs of the gypsum composite reinforced with 5% banana fibers in figure 4 show a denser network of fibers, with greater fiber overlap and clustering in some areas. Localized fiber agglomeration is noticeable even when the overall distribution of fibers is still largely constant. This could result in stress concentration spots and less consistent mechanical performance. The fiber-matrix interface exhibits

a range of properties; in many places, the matrix closely conforms to the fiber surfaces, indicating good adhesion; in other zones, however, visible interfacial gaps indicate weak

bonding, most likely because the higher fiber content exceeds the matrix's capacity to completely encapsulate each fiber.

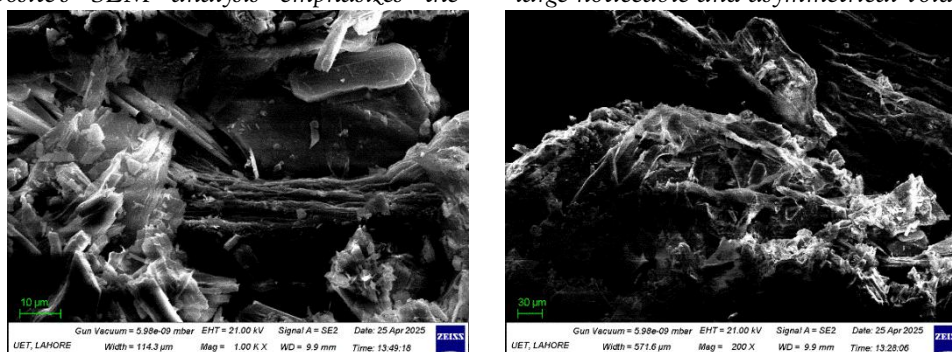


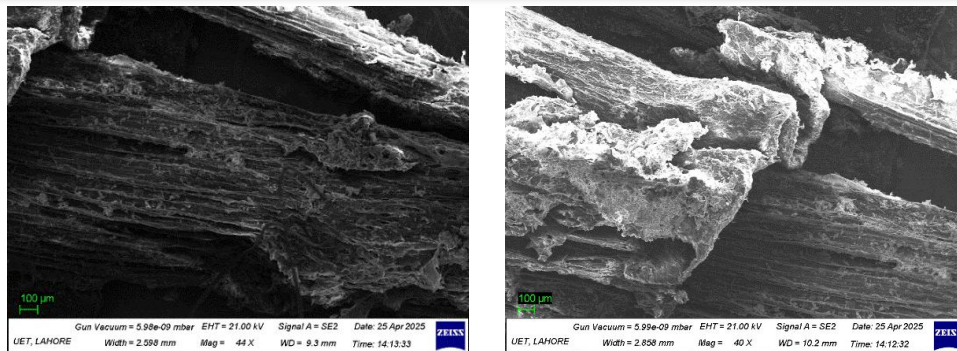
**Figure 4** Microstructural analysis of 5% banana fiber reinforced gypsum composites

Additionally, there is a higher prevalence of voids and porosity, which may be the consequence of increased air entrapment and decreased workability during mixing. At this higher concentration, fiber pull-out is more noticeable, suggesting increased energy dissipation during fracture but also a potential decrease in interfacial shear strength. Although the banana fibers' rough surface helps with mechanical interlocking, the increased fiber volume seems to jeopardize the structural integrity of the composite by compromising the matrix's homogeneity. Overall, the 5% banana fiber composite's SEM analysis emphasizes the

necessity for optimum mixing processes to preserve composite performance at higher fiber loadings by highlighting the trade-off between enhanced fiber reinforcing and the possibility of processing-induced flaws.

The SEM micrographs in figure 5 show a composite structure that is significantly impacted by fiber congestion and restricted matrix mobility at a fiber loading of 7.5%. Banana fibers that overlap and entangle in the microstructure are indicative of a high packing density, which causes the material to be heterogeneous. The images reveal large noticeable and asymmetrical voids.





**Figure 5** Microstructural analysis of 7.5% banana fiber-reinforced gypsum composites

Localized fiber bridging and brittle cracking are visible on fracture surfaces, suggesting that the matrix is unable to disperse stress uniformly across the closely spaced fibers. The mechanical homogeneity of the composite is compromised by the high fiber content, which also breaks stress transfer routes and decreases the continuity of the gypsum phase. This microstructural data highlights a threshold impact, whereby additional fiber volume increases start to impair rather than improve the structural cohesiveness of the composite.

At different magnifications (100X, 200X, and 500X), the SEM analysis in figure 6 of the 2.5% recycled textile fiber-reinforced gypsum composites show clear microstructural characteristics. At lower magnification, there is no discernible aggregation and the fibers look evenly distributed throughout the gypsum matrix, suggesting efficient mixing. Finer features

of the fiber-matrix interaction are visible at the intermediate magnification (200X), where the fibers are partially immersed and attached to the gypsum, indicating strong interfacial adhesion. The roughness and little particles on the fiber surfaces at greater magnification (500X) are probably leftovers from the recycling process and could help the fibers mechanically interlock with the matrix. Reliable contrast and resolution are ensured by the constant EHT (21.00 kV) and gun vacuum ( $\sim 5.94\text{--}5.98 \times 10^{-9}$  mbar) across pictures. A homogenous composite construction that is appropriate for building applications is implied by the lack of significant voids or cracks. The tensile and flexural qualities of the composite, which are crucial for building materials, are probably improved by the fiber dispersion and adhesion seen here.



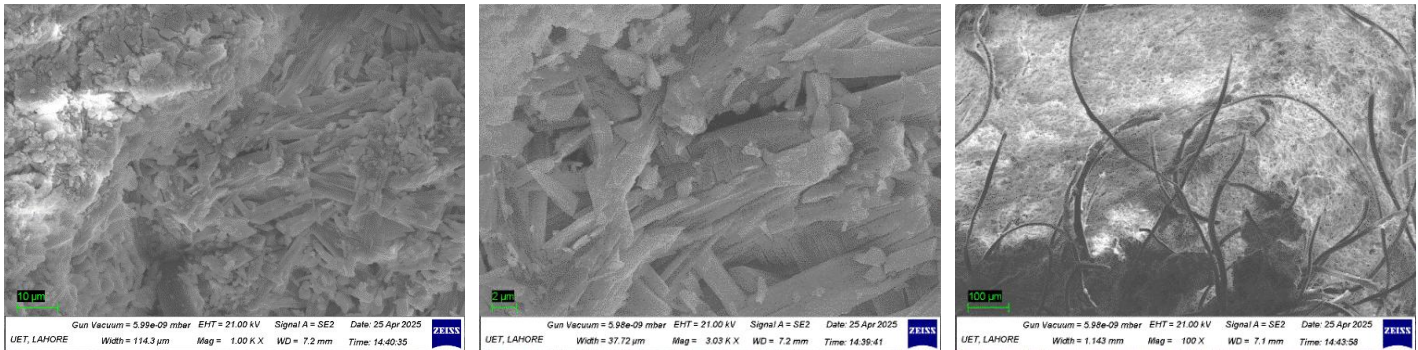
**Figure 6** Microstructural analysis of 2.5% recycled textile fiber reinforced gypsum composites

In comparison to the 2.5% formulation, the SEM images of the 5% recycled textile fiber-reinforced gypsum composites as reflected in figure 7, taken at magnifications of 100X,

200X, and 1.00 KX, show a well-integrated microstructure with an enhanced fiber content. The fibers are widely dispersed throughout the gypsum matrix at lower

magnification (100X), creating an interconnected network that probably improves mechanical strength. With fewer gaps or debonding zones, the intermediate magnification (200X) shows better fiber-matrix bonding, indicating efficient stress transfer between the phases. Individual fibers show good

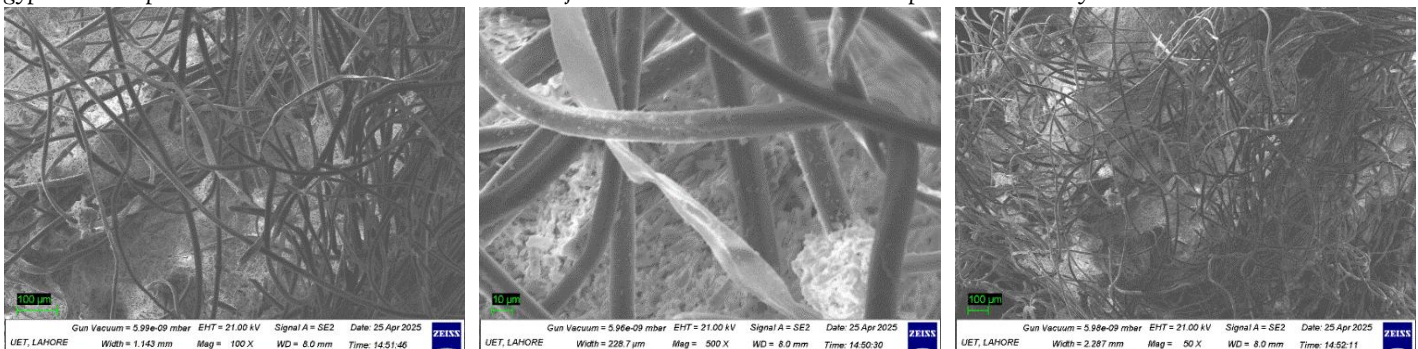
adherence to the matrix at greater magnification (1.00 KX), and the evident surface roughness encourages mechanical inter-locking. High-quality imaging is guaranteed by the constant EHT (21.00 kV) and uniform gun vacuum ( $\sim 5.98\text{--}5.99 \times 10^{-9}$  mbar).



**Figure 7** Microstructural analysis of 5% recycled textile fiber reinforced gypsum composites

A homogenous composite structure that is appropriate for load-bearing building applications is indicated by the lack of significant voids or cracks. The increased fiber content (5%) seems to improve the composite's ductility and fracture resistance, two important properties for building materials that are subjected to dynamic loads. When examined at magnifications ranging from 50X to 500X, the SEM images in figure 8 of the 7.5% recycled textile fiber-reinforced gypsum composites show a dense and intricate fiber-matrix

network, which is suggestive of the enhanced fiber loading. The fibers are evenly distributed and create a strong skeletal framework within the gypsum matrix at the lowest magnification (50X, 7-5TG-08.tif), which should greatly increase load-bearing capability. Excellent fiber-matrix adhesion is seen at intermediate magnifications (100X and 200X, 7-5TG-06.tif and 7-5TG-04.tif), with little debonding or voiding, indicating effective stress transfer and increased composite durability.



**Figure 8** Microstructural analysis of 7.5% recycled textile fiber reinforced gypsum composites

The close contact between the fibers and matrix is highlighted at the maximum magnification (500X, 7-5TG-03.tif), and the interface is further reinforced by mechanical interlocking and surface roughness. High-resolution imaging quality is

guaranteed by the steady EHT (21.00 kV) and gun vacuum ( $\sim 5.96\text{--}5.99 \times 10^{-9}$  mbar). The homogeneity of the composite is highlighted by the lack of significant flaws or cracks, which qualifies it for demanding construction

applications. The 7.5% fiber concentration seems to strike the ideal balance between workability and mechanical reinforcement, which should lead to improved flexural strength, fracture toughness, and resistance to environmental deterioration—all of which are essential for environmentally friendly building materials.

### Conclusion

In conclusion, the study successfully proved the potential of banana fibres and recycled textile fibres as sustainable reinforcement materials for the development of hybrid composites. Microscopic analysis reported positive morphological characteristics such as rough fibre surfaces, fibrillar structures and improved fiber-matrix interaction which are the factors that lead to enhanced mechanical interlocking in the composite system. However, micro-voids and porous regions were observed and these features could present some additional benefits such as lower density and better thermal insulation properties. The results show that the agricultural and textile waste materials can be used as an eco-friendly alternative to the conventional synthetic reinforcements. Furthermore, the research emphasises the significance of microscopic analysis in understanding fibre compatibility and internal structural behaviour, laying a basis for optimising sustainable composite performance for future engineering, construction, and material development applications.

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