# Preparation of Activated Carbon from Pine Wood and Fabrication of Polylactic Acid based Bio-composites

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## GRAPHICAL ABSTRACT

# Preparation of Activated Carbon from Pine Wood and Fabrication of Polylactic Acid based Bio-composites

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A novel method for forming composite materials was investigated by incorporating activated carbon powder (ACP) as a reinforcing agent within a polylactic acid (PLA) matrix, utilizing the hand layup fabrication technique. The composite materials were synthesized by varying the weight percentages of the matrix and reinforcements, encompassing pure PLA as well as ratios of 90:10, 80:20, 70:30, 60:40, and 50:50. PLA is recognized for its biocompatibility and favorable thermomechanical properties, similar to conventional plastics. The incorporation of activated carbon powder, known for its remarkable aspect ratio, proved highly advantageous, yielding exceptional mechanical properties. Analysis revealed that the composite with a ratio of 90:10 wt% of carbon powder to PLA demonstrated significant improvements in tensile strength (26.8%), flexural strength (26.37%), impact strength (61.1%), compression strength (25%), and hardness (45.8%). Additionally, thermal analysis showed that the 90:10 wt% composite exhibited minimal weight loss and maximum heat flow sustainability at approximately 600 °C compared to other composite combinations. Morphological examination using field emission scanning electron microscopy unveiled a uniform distribution of activated carbon powder reinforcement within the matrix, actively contributing to the enhanced mechanical properties of the composite.

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*Keywords: Poly lactic acid; Activated carbon powder; Composite; Characterizations; FE-SEM*

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## INTRODUCTION

The booming social and economic landscape has fueled significant advancements in polymer research and development (Bajpai *et al*. 2012). In the realm of biopolymers, polylactic acid (PLA) is a rising star, showcasing the wide possibilities of sustainable materials (Kalsoom *et al*. 2016). PLA's claim to fame lies in its sustainable production from renewable sources such as corn and sugarcane, yielding a biocompatible, biodegradable, and surprisingly sturdy material ideal for biomedical applications (Farah *et al*. 2016). Beyond its biocompatibility, PLA boasts a significantly lower environmental footprint. It requires 25% to 55% less energy for production compared to traditional petroleum-based plastics, and its degradation products are non-toxic as well (DeStefano *et al*. 2020). Lactic acid, the building block of PLA, is easily fermented from renewable sugars, making it an eco-friendly choice with features perfectly suited for use within the human body. Commercial biodegradable bone screws degrade more quickly than biodegradable bone screws made of PLA. (Ismail *et al*. 2023).

Fortunately, blending PLA with other polymers offers a useful workaround, allowing tailor-made materials with precisely targeted properties (Zhang *et al*. 2012). This opens doors to biomedical applications, including drug delivery, implants, sutures, and cell seeding matrices. The success of these medical breakthroughs lies in the delicate interplay between PLA's inherent properties, the chosen manufacturing processes, and the desired final product characteristics (Pawar *et al*. 2014). Cellulose fillers, as an economical and environmental-friendly alternative as reinforcement material, yields good mechanical properties due to enhanced adhesion with the biodegradable matrix (Lucas Polo Fonseca *et al*. 2021). Acrylonitrile-butadiene-styrene (ABS) on incorporating with 20% cellulose possess better tensile strength of 37.8% higher than pure ABS (Ponsuriyaprakash *et al*. 2020).

Wood-PLA composites have been chosen as insulators in the building sector. Wood-PLA material has both structural stability and insulating functions (Bahar *et al*. 2023). Incorporating jute fibers enhances the tensile strength and modulus of elasticity of the jute fiber reinforced PLA composite (Ruksakulpiwat *et al*. 2010). It was suggested that among PLA composites, kenaf and hemp excel in stiffness and strength, while cotton shines in impact resistance. Lyocell stands out as a well-rounded option, offering both high tensile strength and stiffness along with good impact properties (Graupner *et al*. 2009). Battegazzore *et al*. (2018) focused on the use of agricultural wastes as inexpensive and abundant fillers. Hemp hurds showed the highest calculated modulus and best filler-matrix interaction. Zhang *et al*. (2012) implied that adding modified coconut fibers significantly increased the strength and heat resistance of PLA while achieving the best bonding between the fiber and PLA matrix. Filler materials influence wear mechanisms and reduce friction coefficients. Composite materials prepared with different proportions of fillers have more wear resistant potential for industrial and biomedical applications (Boparai *et al*. 2015).

Addition of carbon fiber (CF) in polymer matrix improves tensile properties with proper parameters (Magri *et al*. 2019). Adding CF to PLA resulted in a slight density increase of 1.3%, but significantly improved wear resistance. Tests showed a remarkable 70% reduction in wear rate when incorporating CF, especially under applied load (Suresha *et al*. 2022). Adding nanodiamonds and CF makes PLA stiffer, stronger, and harder. Carbon fibers are a proven approach. Additive manufacturing techniques have great potential for composite materials. Fillers are required to improve the mechanical properties of polymers (Mansour *et al*. 2023).

Maqsood and Rimašauskas (2021) revealed a trade-off between strength and flexibility. As the amount of fiber reinforcement increased, Young's modulus improved (increased stiffness) but ductility (flexibility) decreased. Furthermore, PLA-continuous carbon fiber specimens displayed the greatest bending strength (flexural stress). Similarly, increasing fiber contents in new honeycomb designs ($2^{nd}$ order PLAuD) further improve strength and stiffness. The adopted recycling method has been shown to be a feasible process for recycling CF-waste and uncured Carbon Fibre Reinforced Polymers (CFRP). The combination of CF-waste and waste PLA can be used to produce composite materials. CF-PLA composites possess better mechanical behaviour than recycled PLA. CF-PLA composite at 20 has higher modulus of elasticity compared to CFRP at 20. The experiment provides a low-cost method for producing aesthetically good physical forms of components made from waste prepreg (Alzahmi *et al*. 2022). Valvez *et al*. (2020) concluded that for a significant boost in the mechanical performance of PLA composites, continuous carbon fibers content led to a stiffer composite (higher flexural modulus). Kargar and Ghasemi-Ghalebahman (2023) examined how CF improves the fatigue resistance (life under repeated stress) and tensile strength (resistance to pulling forces) of PLA composites made using fused deposition modeling (FDM).

Addition of $CaCO_3$ fillers increased water absorption of PLA composites. Despite the decrease in tensile strength with higher filler content, the research suggests white eggshells (WES) can be a viable and potentially eco-friendly alternative as a filler for PLA composites, especially when considering smaller particle sizes and their impact on other properties (Betancourt *et al*. 2017). Incorporating recycled CF dust into polypropylene granulate led to improved material properties (Uhlmann and Meier 2017). Specifically, the resulting composite exhibited increased rigidity and tensile strength compared to standard, non-reinforced polypropylene plastics (Boparai *et al*. 2015). Compression molding benefits the base PLA material (without jute fibers), whereas injection molding is more effective for creating PLA-jute composites with enhanced properties (DeStefano *et al*. 2020). Ponsuriyaprakash *et al*. (2020) suggested that hand lay-up shines for its simplicity in crafting polymer composites. The selection of a material for a specific application hinges critically on its thermomechanical properties. Thermal analysis techniques, such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), are indispensable tools in the development of novel materials, as they provide crucial insights into a material's thermal behavior and stability (Krishnasamy *et al*. 2019).

This study presents a novel composite material of PLA polymer reinforced with activated carbon powder fabricated by the technique of hand lay-up. The mechanical (tensile, flexural, impact, compression strength, and hardness) and thermal (TGA, DSC) characterizations were accomplished by varying weight percentages of matrix and reinforcement materials as 0, 10, 20, 30, 40, and 50 wt%. Also, the microstructure of polymer matrix composite (PMC) was examined by field emission scanning electron microscopy (FESEM).

## EXPERIMENTAL

### Materials

*Polylactic acid*

Polylactic acid (PLA) is a bioplastic isolated from renewable resources such as plant starch (Farah *et al*. 2016). Lactic acid and lactide as its key building blocks, PLA's journey began in 1932 with the synthesis of low-molecular-weight forms (DeStefano *et al*. 2020). DuPont, in 1952, took it a step further, paving the way for high-molecular-weight PLA, the robust material we know today. Beyond its eco-friendly nature, PLA stands out with its ease of printing and significantly lower energy requirements compared to its petroleum-based plastic counterparts. This versatile engineering plastic has a density of just 1.24 g/cm$^3$. Its high melting point of 170 °C confers heat resistance (Bajpai *et al*. 2012). With a tensile strength of 60 MPa, PLA can withstand significant pulling forces. Its moderate elongation at break of 9% allows for some flexibility before reaching its limit. And finally, its flexural strength of 108 MPa makes it a viable opponent against bending and warping (Farah *et al*. 2016).

PLA may provide options for a more sustainable future (Kalsoom *et al*. 2016). This bioplastic holds potential for a wide range of industries and applications (Singhvi *et al*. 2019). PLA in its pellet form was purchased from Green Dot Biopak, Ahmedabad, Gujarat for this study. Figure 1 shows the process flow of converting raw corn to PLA pallets.

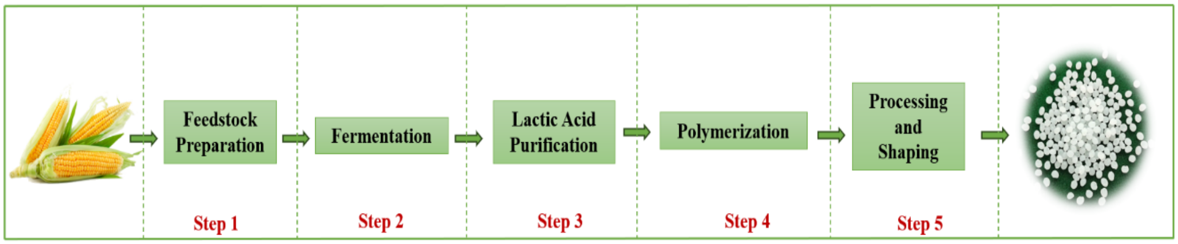


**Fig. 1.** PLA extraction from corn

*Pine wood activated carbon powder*

Pine wood activated carbon powder can be used to reinforce polymers, making them stronger, more durable, and fit for a wider range of applications (Uhlmann and Meier 2017).

*Properties of pine wood activated carbon powder*

*High surface area:* This means each tiny particle has a large amount of surface for interacting with polymer chains. The microscopic hooks grab onto long polymer strands, anchoring them together and creating a stronger, more cohesive network (Kargar and Ghasemi-Ghalebahman 2023).

*Electrical conductivity:* Carbon powder conducts electricity, which helps dissipate heat generated during stress or use in the polymer. This reduces thermal degradation and extends the lifespan of the material (Betancourt *et al*. 2017).

*Fillers:* Carbon particles act as fillers within the polymer, reducing shrinkage and improving dimensional stability. This is particularly important for precise manufacturing processes (Januszewicz *et al*. 2020).

*The benefits of reinforcement*

By incorporating activated carbon powder, polymer manufacturers achieve significant improvements such as increased tensile strength, enhanced abrasion resistance, improved tear resistance, and higher thermal stability. Activated carbon powder, once just a black dust, has become a cornerstone of modern technology. Its ability to transform polymers into stronger, more durable materials makes it an essential ingredient in our everyday lives.

*Preparation of activated carbon powder*

As research progresses and new applications emerge, the future of carbon powder in polymer reinforcement looks bright, paving the way for even more innovative and sustainable materials (Januszewicz *et al*. 2020). Figure 2 shows the preparation methodology of activated carbon powder from pine wood pulp.

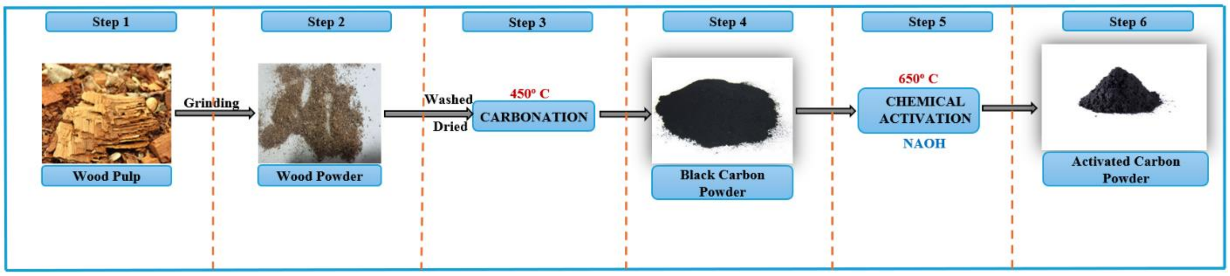


**Fig. 2.** Activated carbon powder preparation from pine wood pulp

*Dichloromethane*

This study utilized dichloromethane, a colorless liquid with a characteristic odor, to create a workable solution from PLA. Dichloromethane, obtained from Sisco Research Lab in Maharashtra, India, was chosen due to its exceptional dissolving power for PLA: At 25 °C, it can dissolve 17.5 g of PLA/L, making it ideal for transforming solid PLA granules into a liquid state. It is found that the ratio of PLA to dichloromethane affected the resulting mixture's viscosity. By adjusting this ratio, it could achieve the specific consistency needed for the experiments.

## Methods

*Fabrication methodology of PLA/ activated carbon powder composites*

This study examined how adding different amounts of activated carbon powder affects PLA composites. To achieve this, PLA pellets were first transformed into a slurry.

*Slurry Preparation:* PLA pellets were weighed out in various ratios according to Table 1. These ratios were chosen to investigate the effects of different activated carbon powder contents.

*Mixing:* The PLA and chosen amount of activated carbon powder were then manually mixed using a stir stick following the hand lay-up technique. This mixing continued until a visually uniform distribution (slurry) was achieved.

*Molding and sample fabrication:* As shown in Fig.3, the resulting mixtures were then poured into designated glass molds according to standard ASTM dimensions. After 24 hrs. of drying period in room temperature, the samples were removed using sharp plate.

*X-ray diffraction analysis*

The crystalline structure of PLA matrix reinforced with activated carbon powder, and their composites (containing 0-50 wt% activated carbon) was investigated using X-ray diffraction (XRD) with an advanced analytical Xpert Pro diffractometer. Samples were scanned in the $2\theta$ range of 10° to 80° with a scan rate of 4° $min^{-1}$.

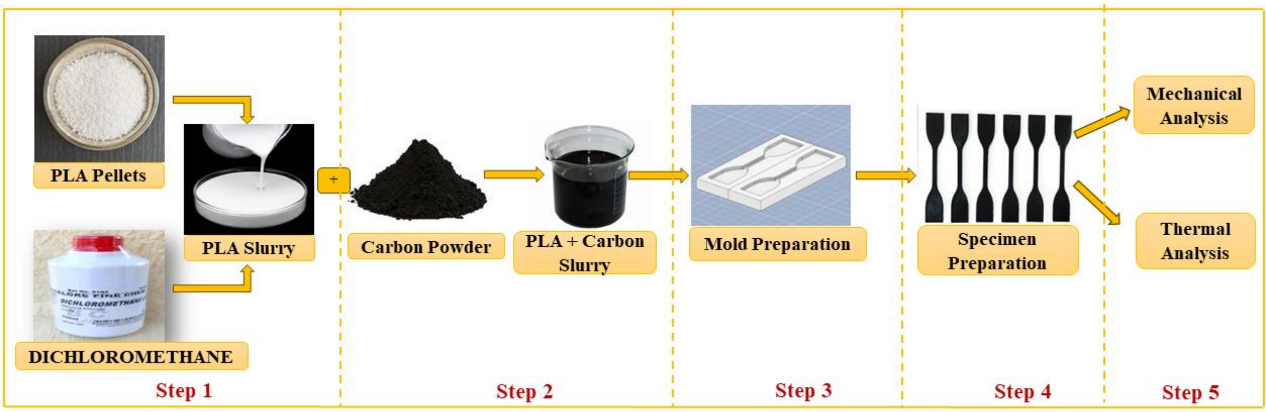


**Fig. 3.** Fabrication methodology

*Fracture surface morphology*

The morphology of the fractured surfaces of the composites was examined by field emission scanning electron microscopy (FE-SEM) using a Quanta FEG-250 SEM instrument. This instrument is equipped with energy-dispersive X-ray spectroscopy (EDS) for elemental analysis.

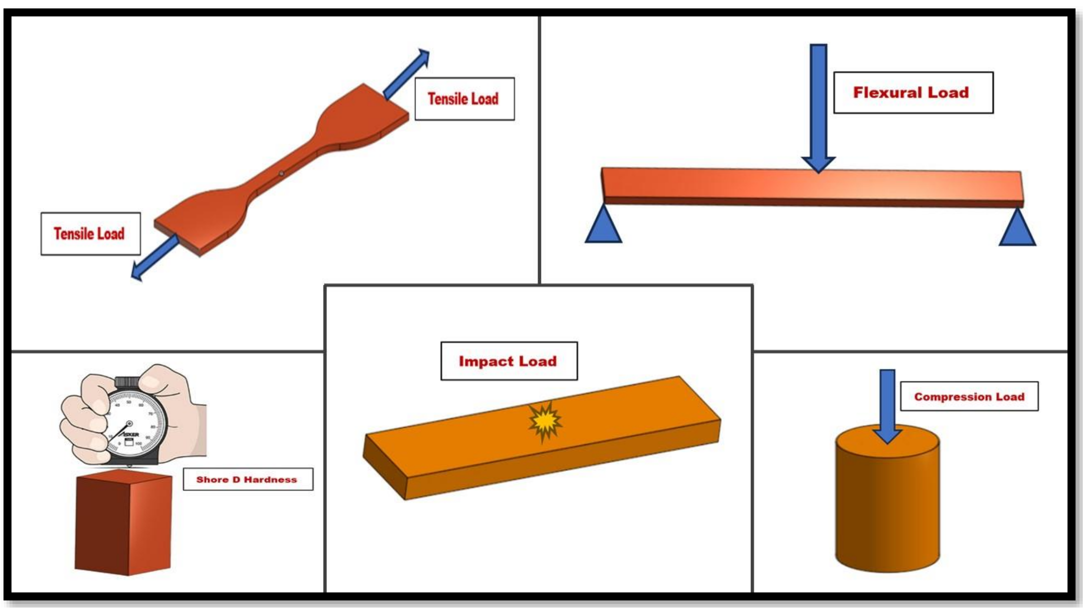


**Fig. 4.** Mechanical testing of fabricated composites

*Tensile test*

PLA and activated carbon powder reinforced composite materials were shaped into specimens with specific dimensions using a glass mold, following ASTM D638 (Ponsuriyaprakash *et al.*2020) guidelines, as shown in Fig. 5. These specimens were then subjected to tensile testing on an Instron servo-hydraulic machine with the load capacity of 50 kN. The specimens were firmly gripped by precision wedges while a controlled load was steadily applied to a velocity of 5 mm/min. The motion was continued until the specimens fractured, providing valuable data regarding the material's ultimate tensile strength. To ensure accurate measurements, the gauge length was set to 150 mm, as mandated by the standard.

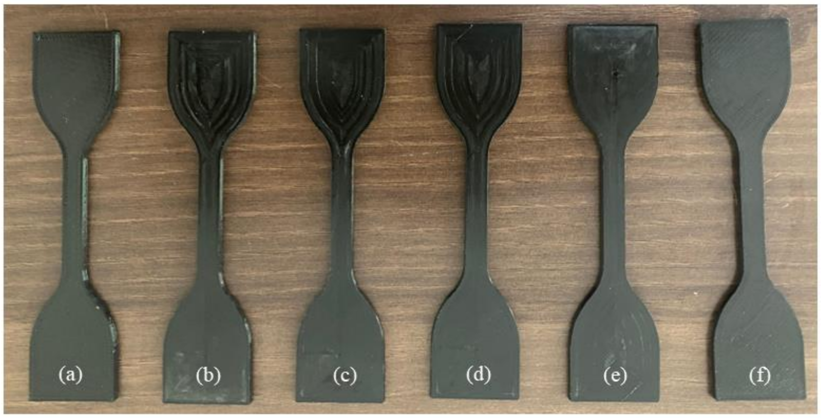


**Fig. 5.** Mechanical testing of fabricated composites tensile test specimen (a) 0% reinforcement, (b) 10% reinforcement, (c) 20% reinforcement, (d) 30% reinforcement, (e) 40% reinforcement, (f) 50% reinforcement

*Flexural test*

PLA and activated carbon powder reinforced specimens underwent evaluation using a standardized three-point bending test (ASTM D790-Ponsuriyaprakash *et al*. 2022) in a designated UTM named 'Generic Flexure 3PT' with the maximum loading capacity of 10 kN, as shown in Fig. 6. The test, conducted at a controlled strain rate of 5 mm/min, offered valuable information regarding the material's resistance to bending forces. The consistent flexural strength values across the tested composites indicate a well-balanced performance. This suggests they could be suitable for applications requiring both strength and flexibility.

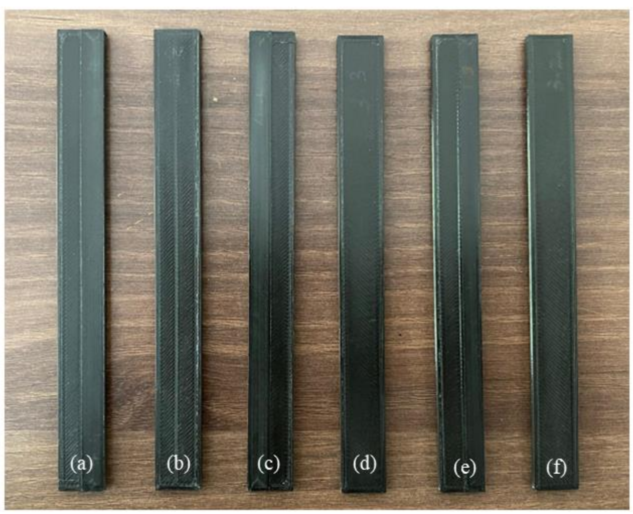


**Fig. 6.** Flexural test specimen (a) 0% reinforcement, (b) 10% reinforcement, (c) 20% reinforcement, (d) 30% reinforcement, (e) 40% reinforcement, and (f) 50% reinforcement

*Impact test*

Researchers employed the Izod impact test (ASTM D256-07-Ponsuriyaprakash *et al*. 2022) to evaluate the impact toughness of PLA-based composites reinforced with activated carbon powder. As shown in Fig. 7, six specimens, each with the standardized dimensions of 63.5 mm × 12.5 mm × 3 mm, underwent testing on a standard hammer type pendulum machine. The test utilized a controlled speed of 3.55 m/s, delivering 12.5 J energy over a 615 mm distance. The consistent performance of the composites, reflected in the reported average impact strength, suggests their potential applicability in situations demanding resistance to sudden forceful impacts.

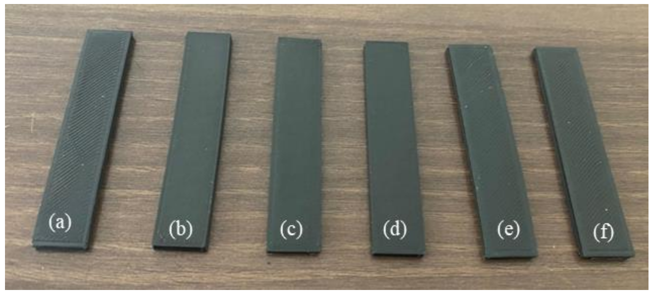


**Fig. 7.** Impact test specimen (a) 0% reinforcement, (b) 10% reinforcement, (c) 20% reinforcement, (d) 30% reinforcement, (e) 40% reinforcement, and (f) 50% reinforcement

*Hardness test*

The hardness, a crucial indicator of a polymer composite's resistance to deformation, was evaluated using the Shore D-scale durometer by following (ASTM D2240 standards-Ponsuriyaprakash *et al*. 2022) dimensions, as shown in Fig. 8. The hardness measurements were taken on standardized samples from each composite formulation, with the test conducted at a controlled temperature of 25 °C. This approach, utilizing a reliable Fasne Test Equipment Pvt. Ltd. durometer, revealed key mechanisms behind the mechanical behavior of the composites.

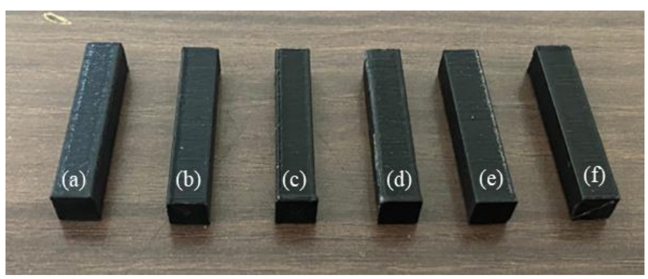


**Fig. 8.** Hardness test specimen (a) 0% reinforcement, (b) 10% reinforcement, (c) 20% reinforcement, (d) 30% reinforcement, (e) 40% reinforcement, and (f) 50% reinforcement

*Compression test*

The compressive strengths of activated carbon powder reinforced PLA composites using the ultimate compression strength (UCS) test, adhering to ASTM D695 standards. A UTM (Universal Testing Machine) was used to evaluate the properties of six standardized samples for compression at a predetermined load of 50 kN and a controlled deformation rate of 5 mm/min, as shown in Fig. 9. The resulting average UCS value demonstrates the composites' exceptional ability to resist compressive forces, making them suitable for applications demanding structural integrity.

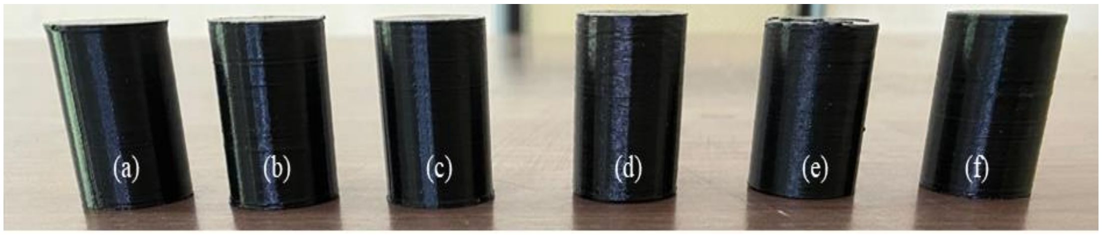


**Fig. 9.** Compression Test Specimen (a) 0% reinforcement, (b) 10% reinforcement, (c) 20% reinforcement, (d) 30% reinforcement, (e) 40% reinforcement, and (f) 50% reinforcement

*TGA and DSC analysis*

A thermogravimetric analysis (TGA) and differential scanning calorimetric (DSC) analysis was employed to explore the weight loss behaviour and heat flow behaviour of PLA and activated carbon powder composites. Specimens weighing between 10 and 15 mg were analyzed in platinum TGA pans under a nitrogen atmosphere. After drying, the specimens underwent a heating ramp of 10 °C/min from 30 to 900 °C. The instrument records the heat flow associated with thermal events occurring in the sample compared to an inert reference.

## RESULTS AND DISCUSSION

### X- ray Diffraction

X-ray diffraction was employed to confirm the formation of PLA matrix composites reinforced with activated carbon powder. The XRD patterns of pristine PLA matrix and activated carbon powder are presented in Fig.10, respectively.

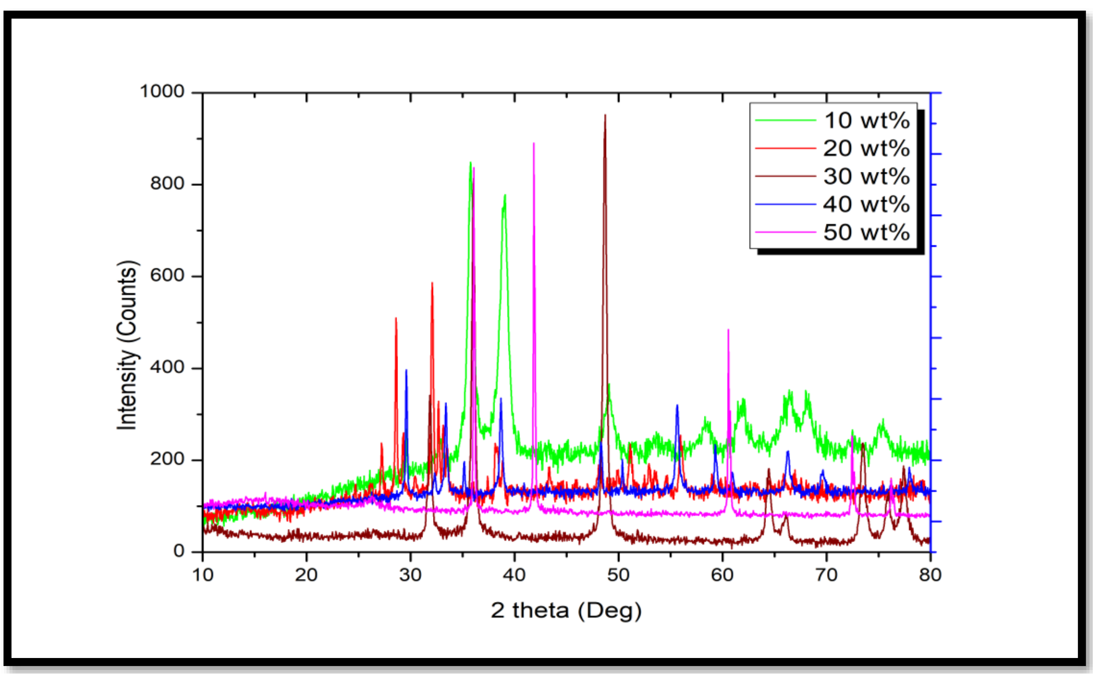


**Fig. 10.** XRD analysis of PLA/Activated carbon powder reinforced composites

A distinct peak at $2\theta$ = 47.5° in the spectrum signifies the presence of activated carbon powder reinforcement within the PLA matrix material, as corroborated by its intensity (Chen and Hsu 2007). This peak also indicates the homogeneous dispersion of carbon powder throughout the PMC composites, as illustrated in Fig. 10. The most intense peak corresponds to the PLA matrix material, whereas the weakest peak pertains to the activated carbon powder reinforcement.

## Field Emission Scanning Electron Microscope (FESEM)

During FESEM analysis, 5 to 15 kV of accelerating voltage, 10 to 100 µm of working range, and 20 to 100 µm scale bar were used to observe how the variation in carbon powder content influences the surface morphology of the PLA matrix. As the weight percentage (wt%) of carbon powder was increased (from 10% to 50%), the surface became rougher. At a high reinforcement content (50 wt%) showed uneven fiber distribution, suggesting potential for clustering and fracture. These observations suggest that the amount of carbon powder can influence how the composite absorbs and distributes external loads. Different magnification scales were used in the FESEM analysis because identifying the bonding interface between the PLA matrix and carbon powder can be challenging at various fiber content ratios.

**Table 1.** Physical Properties of Carbon Powder Reinforced PLA Polymer Matrix Composites

| **Matrix** | **PLA** | **Matrix and Reinforcement Composition (%)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **100** | **90** | **80** | **70** | **60** | **50** |
| **Reinforcement** | **Activated carbon powder** | **0** | **10** | **20** | **30** | **40** | **50** |
| Mechanical Behaviour | Tensile Strength (MPa) | 56 | 71 | 69 | 64 | 59 | 53 |
| | Flexural Strength (MPa) | 91 | 115 | 109 | 102 | 93 | 89 |
| | Impact Strength (KJ/m$^2$) | 18 | 29 | 26 | 21 | 19 | 15 |
| | Compression Strength (MPa) | 72 | 90 | 86 | 81 | 75 | 69 |
| | Hardness (Shore D) | 83 | 89 | 97 | 106 | 112 | 121 |

## Tensile Behaviour

The key to maximizing the tensile strength of these composites lies in finding the optimal carbon content. Data from a universal testing machine (Fig. 11) revealed a remarkable increase in strength with increasing carbon content, peaking at 10 wt%. However, exceeding this threshold led to a significant drop in strength, possibly due to limitations like low strain, structural inconsistencies, and potential flaws. This knowledge is instrumental in tailoring carbon reinforcement strategies for similar composites to achieve peak tensile performance.

A study investigating the reinforcement of polymer fiber composites with carbon powder found a significant increase in tensile strength when 10% carbon powder (by weight) was added, as shown in Fig. 11(a). Figure 11(b) shows the stress strain curve of different wt% of PLA and AC powder. This improvement enhanced the interfacial bonding between the carbon powder and the PLA. Microstructural analysis of Fig. 12 (a-b) using FE-SEM confirms this improved bonding and revealed a uniform distribution of the carbon powder throughout the PLA matrix.

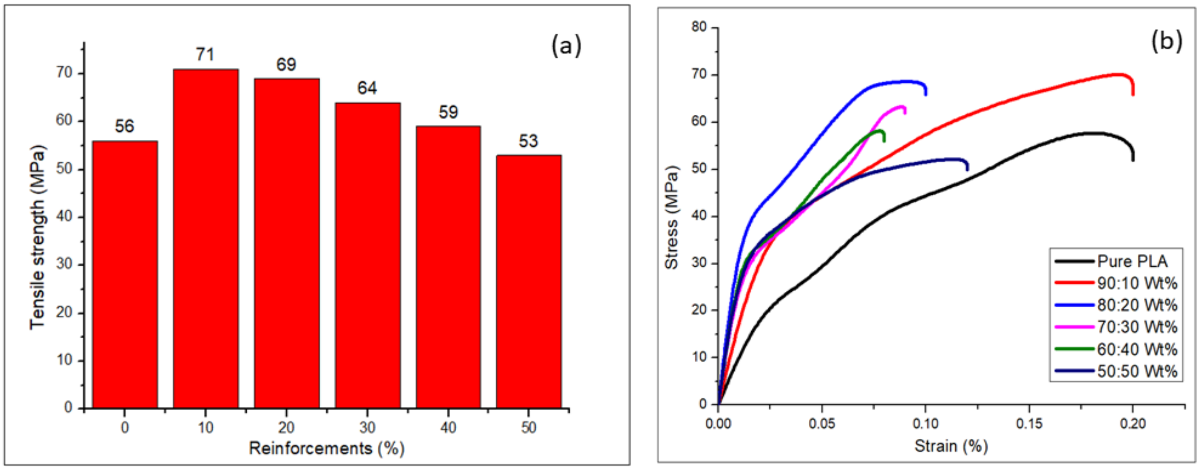


**Fig. 11 (a).** Tensile behavior of PLA and activated carbon reinforced composites, **(b)** Load *vs.* displacement graph of tensile tested composites samples

Figure 12 shows the fractured surface (fracture) of a composite material (PMC) containing 10% activated carbon powder and 90% PLA matrix, analyzed after a tensile strength test. This analysis, called fractography, revealed strong interfacial bonding between the PLA matrix and the reinforcing carbon powder particles. This improved bonding facilitated better transfer of load throughout the composite material, which resulted in a substantial improvement in the material's ability to withstand pulling forces (tensile strength). The FESEM images provided compelling visual proof of enhanced bonding between the PLA matrix and the carbon powder, along with its even distribution throughout the material.

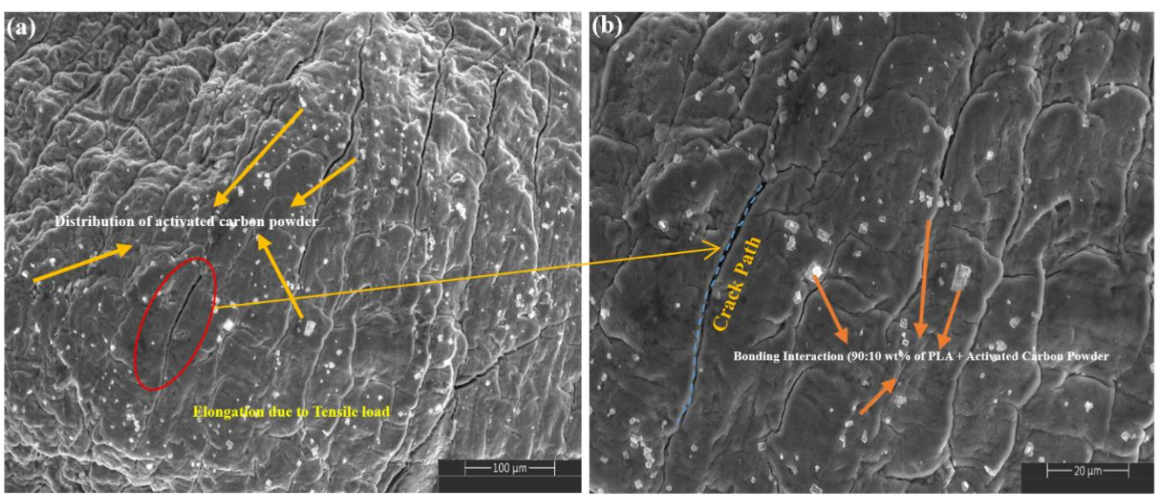


**Fig. 12.** FESEM of post tensile tested 90:10 PLA/activated carbon powder reinforced composite sample: (a) Distribution of activated carbon power in PLA matrix; and (b) Bonding interaction of PLA/activated carbon powder

## Flexural Behaviour

The key to achieving optimal bending strength in PLA/carbon composites lies in optimizing the activated carbon powder content, as shown in Fig. 13 (a). Compared to unfilled PLA, these composites demonstrated significant improvements in both strength and stiffness due to activated carbon powder reinforcement. The data showed a remarkable increase in flexural strength for PLA composites reinforced with 10 wt% activated carbon powder. However, using more than this amount can be counterproductive, making the material more brittle and reducing its performance under bending loads. These findings provide valuable insights for designing and engineering PLA-based composites with a balance of strength and functionality. Figure 13. (b) shows the force vs displacement curve of different wt % of PLA and AC powder for the flexural behaviour.

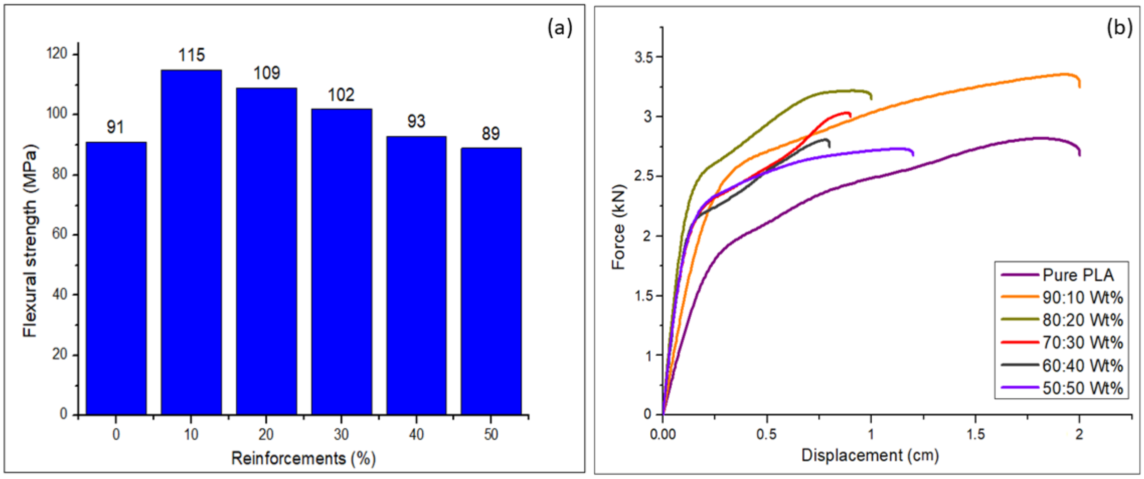


**Fig. 13 (a).** Flexural behavior of PLA and activated carbon powder reinforced composites, **(b)** Force *vs.* displacement graph of flexural tested composites samples

Figure 14 shows stronger interfacial bonding between the activated carbon powder and PLA matrix in the best optimized composite sample. This improved bonding, as observed through FE-SEM imaging, and it facilitated better load transfer within the material. The study confirmed that incorporating activated carbon powder at the optimal level significantly strengthens polymer fiber composites.

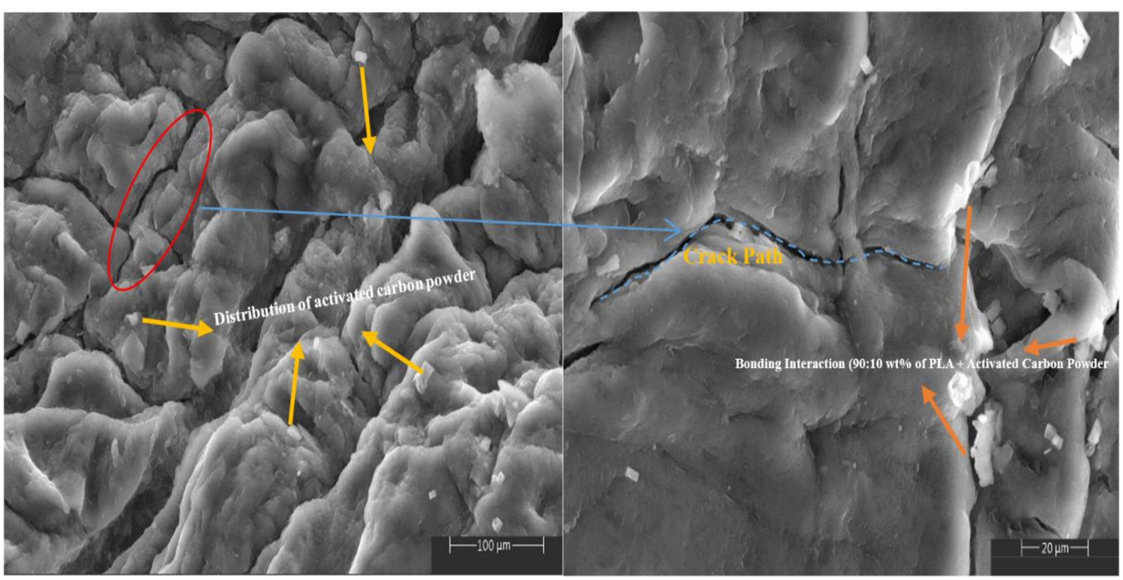


**Fig. 14.** FESEM of post flexural tested 90:10 PLA/Activated carbon powder reinforced composite sample (a) Distribution of activated carbon power in PLA matrix; and (b) Bonding interaction of PLA/Activated carbon powder

## Impact Behaviour

The highest impact strength, reaching 29 MPa, was observed in the composite containing 10 wt% activated carbon powder. This signifies a significantly improved interfacial bond between the fibers and the PLA polymer matrix. The even distribution of the reinforcement further contributed to this enhanced performance. The strong interface effectively hindered crack propagation, allowing the material to absorb impact energy more readily, thereby maximizing impact strength. However, as shown in Fig. 15, exceeding 10 wt% activated carbon powder reinforcement led to a gradual deterioration in impact strength. This is attributed to the substantial increase in brittleness of the composite material with a growing amount of activated carbon. As the material becomes stiffer, it loses its ability to absorb impact effectively, resulting in a decrease in overall strength.

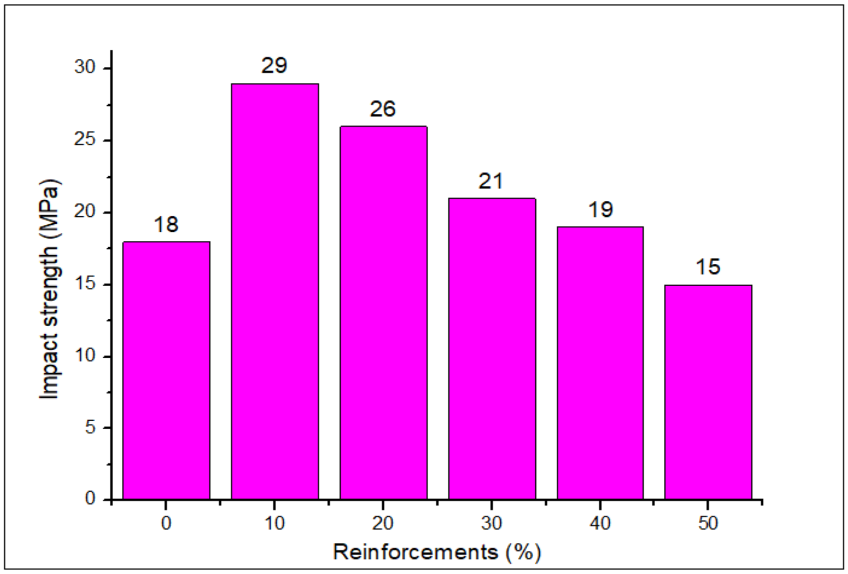


**Fig. 15.** Impact Behaviour of PLA and activated carbon powder reinforced composites

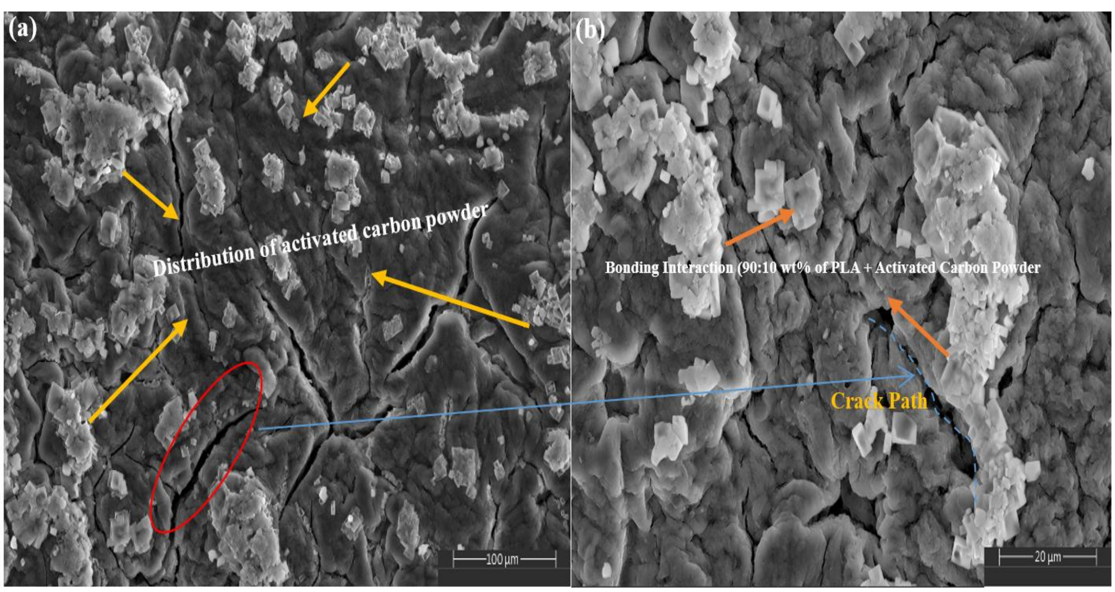


**Fig. 16.** FESEM of post impact tested 90:10 PLA/Activated carbon powder reinforced composite sample: (a) Distribution of activated carbon power in PLA matrix; and (b) Bonding interaction of PLA/activated carbon powder

Figure 16 presents fractographic analysis of the impact test for a composite containing 10% activated carbon powder and 90% PLA matrix. The analysis revealed improved interfacial bonding between the matrix and activated carbon powder that increased the impact strength of the polymer fiber composites studied. Furthermore, FE-SEM images confirmed this finding by visualizing the improved interfacial bonding and the uniform distribution of carbon throughout the PLA matrix.

## Hardness Behavior

The hand lay-up process proved to be an effective method for producing high-quality activated carbon powder reinforced PLA composites, as evidenced by the hardness data in Table 1 and Fig. 17. A consistent increase in hardness was observed with increasing carbon content, from 10 wt% to 50 wt%. This trend not only highlights the strengthening effect of CF but also suggests successful composite creation with minimal pores and uniform fiber distribution, likely facilitated by the hand layup technique. Notably, the 50 wt% composite boasts an impressive 121 Shore D hardness, a 45.8% improvement over pure PLA. This significant enhancement demonstrates the hand layup method's potential for producing robust and high-performance composites.

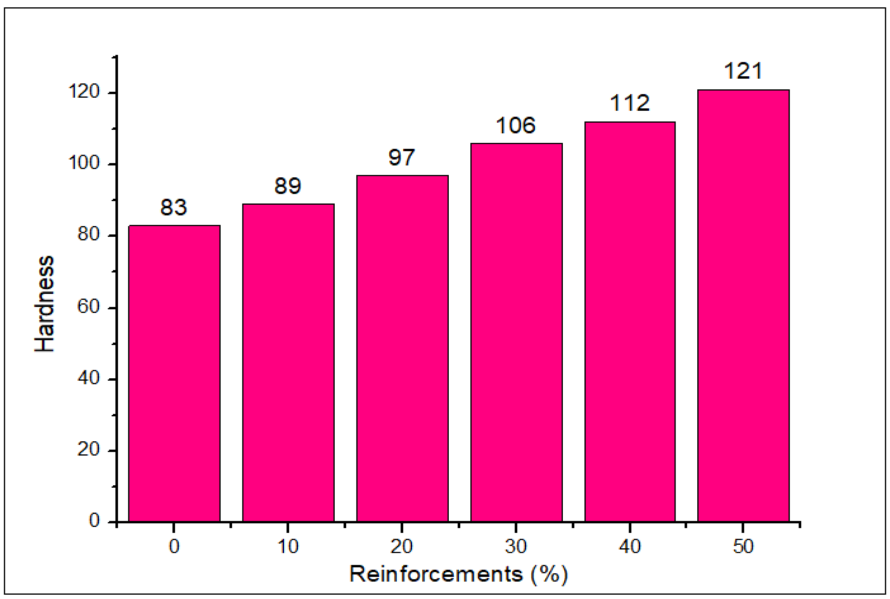


**Fig. 17.** Hardness behavior of PLA and Activated carbon powder reinforced composites

## Compression Test Analysis

Data presented in Fig. 18a illustrates a compelling correlation between the inclusion level of activated carbon powder and the compressive strengths of the resulting PLA composites. Adding up to 10 wt% carbon powder significantly strengthened the composite, as shown by a 25% increase in ultimate compression strength compared to pure PLA (72 MPa to 90 MPa). This improvement is likely due to enhanced interfacial bonding between the PLA and the carbon powder. However, in Fig.18 b, exceeding 10 wt% carbon powder content appeared to be detrimental, owing to minimal ductile property of stiffer material, the development of propagation of crack while compressive load on the composite materials leads to increased deformation.

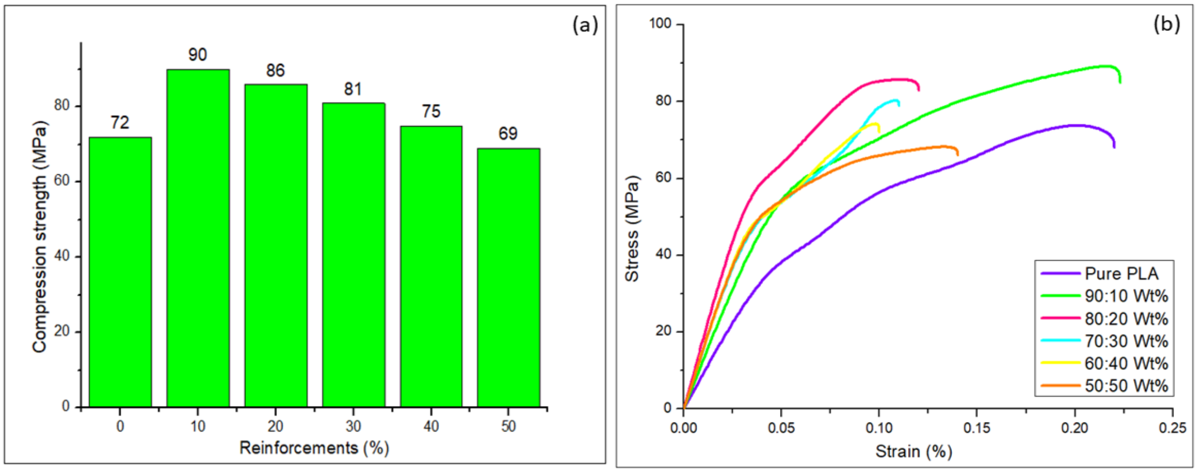


**Fig. 18 (a).** Compression behavior of PLA and activated carbon powder reinforced composites**, (b).** Stress-strain behavior of compression tested composite samples

By combining microstructural analysis and FE-SEM imaging, this study provides compelling evidence that incorporating activated carbon powder at an optimal ratio significantly strengthens PLA composites. This breakthrough paves the way for the development of next-generation materials with superior mechanical properties, opening doors for a wider range of applications.

Figure 19 shows the results of a fractographic analysis performed after a compression test on a composite material containing 10% activated carbon powder and 90% PLA matrix. This analysis examines the broken surfaces of the material to understand how it fractured. The analysis showed good adhesion between the PLA matrix and the activated carbon powder, which is crucial for effective reinforcement.

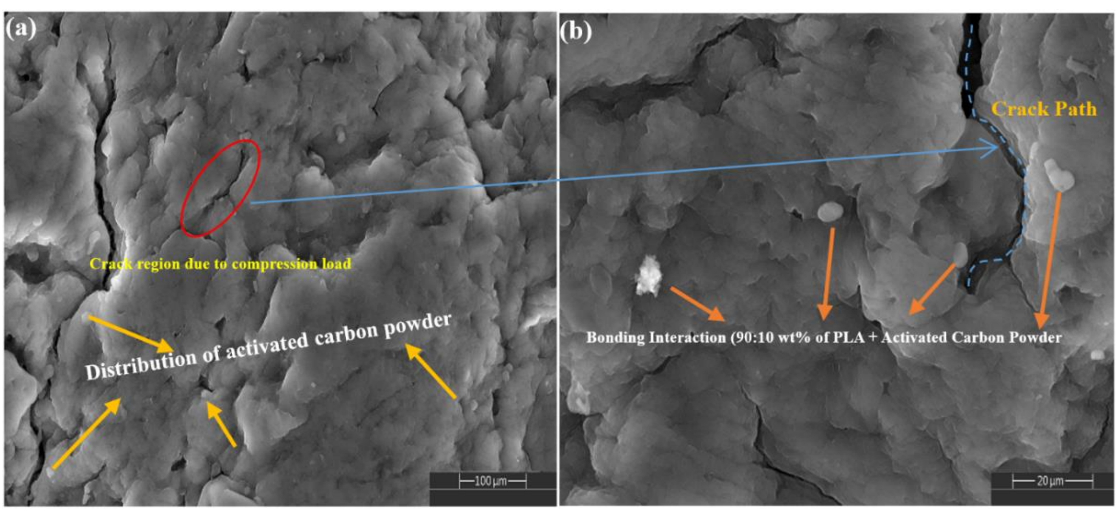


**Fig. 19.** FESEM of post compression tested 90:10 PLA/Activated carbon powder reinforced composite sample: (a) Distribution of activated carbon power in PLA matrix; and (b) Bonding interaction of PLA/activated carbon powder

## Thermo Gravimetric Analysis

Figure 20 represents the weight loss data (TGA curves) for all composite samples. A key objective of adding carbon powder to PLA was to improve its thermal stability. The data shows that the 90:10 wt% PLA/carbon powder composite with the optimal reinforcement content exhibited the lowest weight loss by withstanding the temperature about to 700 °C. This significant improvement compared to pure PLA suggests that the carbon powder has a stabilizing effect, likely due to strong interactions between the carbon fiber reinforcement and PLA matrix.

Notably, higher carbon powder (50%) content led to a faster weight loss due to its default ash content. This suggests that the carbon powder itself starts degrading at higher temperatures than PLA, possibly because it is shielded by the more thermally stable PLA distributed around it. The enhanced thermal resistivity of 90:10 wt% composite could be attributed to two factors: (i) Activated carbon powder may act as a shield, capturing harmful free radicals generated during PLA degradation, and (ii) the fiber network may hinder the escape of volatile degradation products.

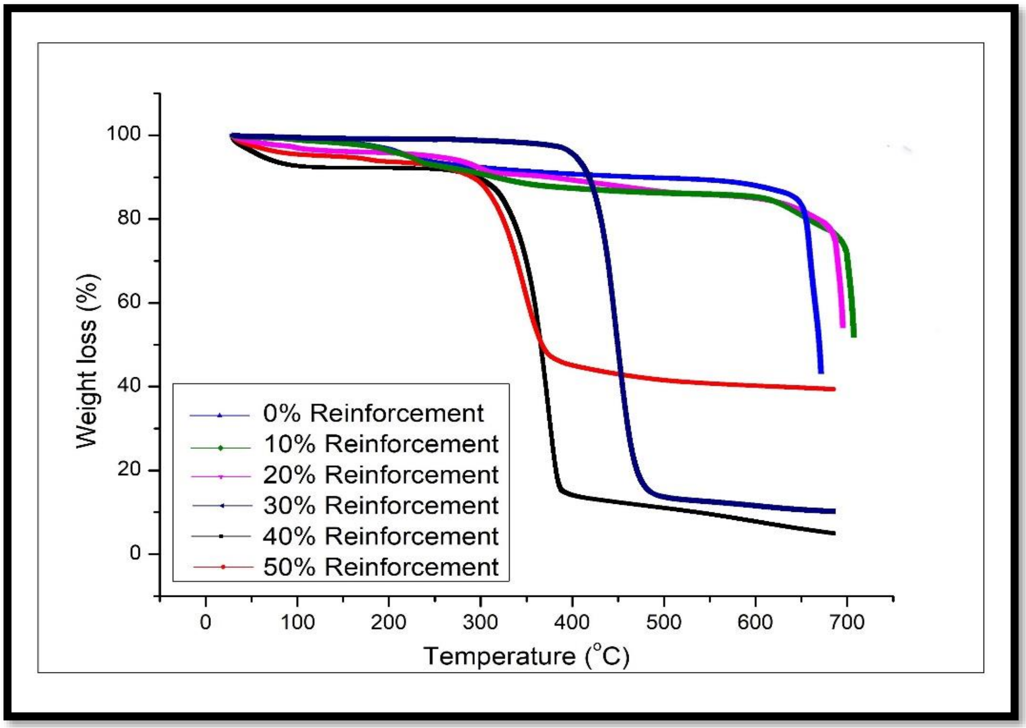


**Fig. 20.** TGA Analysis of PLA/activated carbon powder reinforced composites

## DSC Analysis

The DSC curves of the pure PLA and the activated carbon powder are shown in Figs. 21. The $T_g$ of pure PLA was observed at 250.4 °C. All the DSC curves of PLA and activated carbon powder composites systems had a single glass transition temperature in the experimental temperature range. Obviously, the presence of a single $T_g$ value indicates that ring open reactions occurred between the PLA and activated carbon powder composites. In that, 10% of activated carbon powder reinforced PLA composites exhibited a higher withstanding Tg temperature of above 600 °C compared to all composites including pure PLA. The temperature tolerance increased with increment of reinforcement and decrement after addition of reinforcement due to the excessive addition of fibers in polymer.

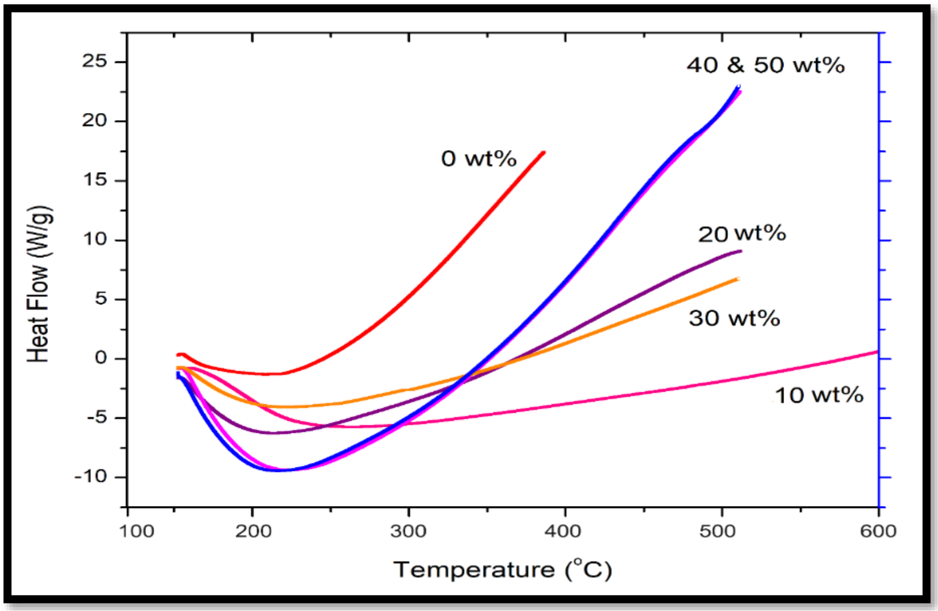


**Fig. 21.** DSC Analysis of PLA/activated carbon powder reinforced composites

## CONCLUSION

This study investigated the effects of adding activated carbon powder as reinforcement to a poly(lactic acid) (PLA) matrix. The traditional hand layup technique was used to create composite specimens with varying weight percentages of activated carbon. The key findings of this research are summarized in the following sections.

1. Tensile strength reached its peak by 71 MPa from 90 wt% PLA with 10 wt% activated carbon powder content in the composite sample. Hence, an increase of tensile strength by 26.8% was achieved compared to the neat PLA sample.
2. A composite containing 90% PLA by weight and 10% carbon powder by weight exhibited improvements in flexural strength by 26.4%, impact strength by 61.1%, and compression strength by 25% compared to a pure PLA sample (without the carbon powder reinforcement).
3. Field emission scanning electron microscopy (FESEM) analysis, performed on the composite material after each mechanical tests, revealed the microstructure, including the distribution of activated carbon powder particles within the PLA matrix and the bonding between them.
4. While adding activated carbon powder improved hardness, it came at the cost of reduced strength. The hardness increased significantly by 45.8%, from 7.23 Shore D (83 Shore D) to 121 Shore D.
5. Thermogravimetric analysis and differential scanning calorimetry revealed that the 90:10 wt% composite displayed superior thermal stability compared to other compositions. This was evident by minimal weight loss and sustained heat flow at approximately 600 °C.

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