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Comparative Evaluation of Mechanical Properties in 3D Printed Petroleum and Natural Polymers

Akash H.B[1] , Dr.Prithvi C[2]

[1]PG Scholar, Mechanical Machine Design Engineering. Department of Mechanical Engineering the National Institute of Engineering Mysuru - 570008

[2]Assistant professor, Department of Mechanical Engineering the National Institute of Engineering Mysuru – 570008

ABSTRACT

This research investigates the mechanical properties of 3D printed polymers, with materials extracted from natural fibers and petroleum sources, such as PLA, PETG, PLA with bamboo fibers, PLA with carbon fibers, and nylon. Mechanical tests—including tensile, impact (Izod), flexural, and hardness tests—were conducted following ISO standards to evaluate the performance, strength, and durability of these materials. These tests provide essential data on how each polymer responds to stress, impact, bending, and surface deformation. The study aims to understand how variations in material composition and processing conditions affect mechanical behavior. By analyzing differences in tensile strength, impact resistance, flexibility, and hardness, the research highlights the influence of different formulations on material performance. The insights gained are crucial for selecting suitable materials for a range of applications, from industrial components to consumer products and specialized uses. This thorough evaluation supports informed decision-making in 3D printing, enhancing the technology's effectiveness and fostering innovation in material performance and application.

INTRODUCTION

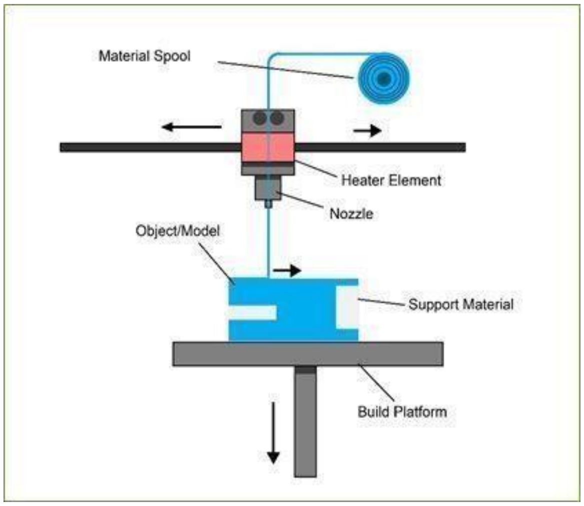
1.1. General Introduction

3D printing, or additive manufacturing, is a rapidly growing technology used to create tangible products from digital models. It enables the quick production of prototypes, customized components, and complete items, revolutionizing industries. 3D printing offers potential in producing lightweight structures and reinforced filaments.

A key area of study is the mechanical comparison between petroleum-extracted and naturally extracted filaments. Composite materials, known for their thermal insulation, rigidity, and strength-to-weight ratio, play a vital role. These materials, often found in bio-composites, polymers, or metals, are widely used in construction, automotive, aerospace, and medical fields.Common 3D printing filaments include thermoplastics like PLA, PET, nylon, PLA bamboo, PLA carbon fiber, and ABS. These filaments are heated and extruded in layers to create components. Reinforcements like metal particles, glass fiber, carbon fiber, or biodegradable materials can enhance properties such as strength, stiffness, and durability. Reinforced filaments are essential in applications such as aircraft components, medical devices, and automotive parts.

1.2. Basics of Additive Manufacturing

The Printing in three dimensions is alternatively called additive manufacturing, three dimensional printing is a technique for fabrication that creates objects in three dimensions by using a computer model. As opposed to traditional production processes, which rely on subtractive techniques to remove material from raw materials, 3D printing creates products layer by layer,



offering more efficiency and customization.3D printing begins with creating a digital model of the object, which is then sliced into thin layers. This layered design is uploaded to the printer, which constructs the object layer by layer. Various materials, including ceramics, metals, and polymers, are used in this process. The printer gradually builds the object, adding each layer precisely to achieve the final result. Multicolored printing is another feature of certain 3D printers.

Figure 1 3D printing technique

Different 3D printing technologies, such as FDM, SLA, SLS, and DLP, offer various advantages and limitations. FDM is the most popular and cost-effective method, using melted thermoplastic filament layered to build objects, often used for prototyping and small-scale production. SLA and DLP use lasers or projectors to harden liquid resin layer by layer, producing highly detailed and precise objects, commonly used in dentistry, jewelry, and industries requiring high accuracy. SLS fuses powdered material to create durable products, widely used in aerospace, automotive, and medical fields.

Thermoplastics are versatile plastics that soften when heated and harden upon cooling, making them reusable in various industries. PLA, derived from renewable sources like corn or sugarcane, is biodegradable and popular for 3D printing and packaging due to its eco-friendliness. PLA-Bamboo, a composite of PLA and bamboo fibers, offers enhanced strength and natural aesthetics. ABS, a petroleum-based polymer, is known for its strength and impact resistance but requires controlled printing conditions. Nylon is highly durable and flexible, ideal for producing strong mechanical components, while PETG is a modified PET known for its durability, impact resistance, and ease of printing, often used for food packaging and 3D printed functional parts.

Mechanical characterization, which measures properties like elasticity, strength, compression, and toughness, is essential for understanding how materials respond to stress. This process plays a crucial role in developing and testing new materials

across industries such as automotive, biomedical, and aerospace.

LITERATURE

2.1 Introduction

This literature review compares the mechanical characteristics of petroleum-based polymers created using 3D printing and natural polymers. These materials are widely used due to their high energy absorption, strength, and lightweight properties, making them ideal for industries such as wind energy, shipbuilding, automotive, aerospace, and civil construction. The tensile, flexural, and impact stresses, as well as surface hardness tests, follow ISO standards. The main benefits of these materials include a high strength-to-weight ratio and low construction costs. Many studies have investigated the potential applications of different materials across various sectors.

2.2 Summary of the Literature

1. **Atakok, Kam, Koc**: This study evaluates the mechanical properties of 3D-printed parts made from PLA and recycled PLA, comparing tensile strength, three-point bending, and impact resistance. It highlights the sustainability benefits of using recycled PLA without compromising mechanical properties.
2. **Palacios, Velazquez, Zelaya, Patterson**: The authors focus on enhancing the performance of 3D-printed composites through hybrid filler materials,

offering insights into improving strength and stiffness for high-performance applications.

3. **Tarfaoui, Daly, Kbaier, Chihi**: This paper examines the tensile behavior of carbon fiber-reinforced PETG (CF-PETG) composites, using simulations and experiments to optimize design for better strength and durability.
4. **Alarifi**: The research investigates the mechanical properties of PETG/carbon composites made via FDM, combining experimental data and simulations to optimize strength and performance for engineering applications.
5. **Prajapati, Sharma, Kumar, Pandey, Pandey**: A comparative analysis of PLA, ABS, TPU, and PETG in 3D printing, focusing on tensile strength, impact resistance, and thermal stability to aid material selection for specific applications.
6. **Romeijn, Behrens, Paul, Wei**: This study assesses the long-term mechanical properties of PETG produced by pellet-based material extrusion, offering insights into its strength and durability for long-term use.
7. **Miller, Carter, Lee**: The paper investigates the effects of infill density and orientation on the mechanical properties of PLA components, providing guidelines for optimizing 3D printing parameters to achieve desired strength and stiffness.
8. **Kumar, Sharma, Saran, Tripathy, Sangwan, Herrmann**: This comparative life cycle assessment examines the environmental impact of PLA, ABS, and PETG in 3D printing, helping stakeholders make informed decisions about sustainable material use.
9. **Kumar, Ranjan, Babbar**: The study analyzes the mechanical properties of 3D-printed nylon 6 parts, providing insights into the material's suitability for various applications and its performance compared to other materials.
10. **Bhandari, Lopez-Anido, Gardner**: This research explores the effects of annealing on the tensile strength of carbon fiber-reinforced PETG and PLA composites, offering valuable information on optimizing post-processing techniques for enhanced material performance.

MATERIALS AND METHODOLOGY

3.1. Introduction

This project study focuses on evaluating mechanical characteristics 3D-printed tensile, flexural, hardness and impact. Mechanical characterization is critical in the development and testing of novel materials for a wide variety of applications. Mechanical characterization tests such as tensile, hardness, impact and flexural tests. Characteristics aiding understanding how a material will react to load changes and can be utilized to optimize the material's performance in specific applications.

3.2. Methodology

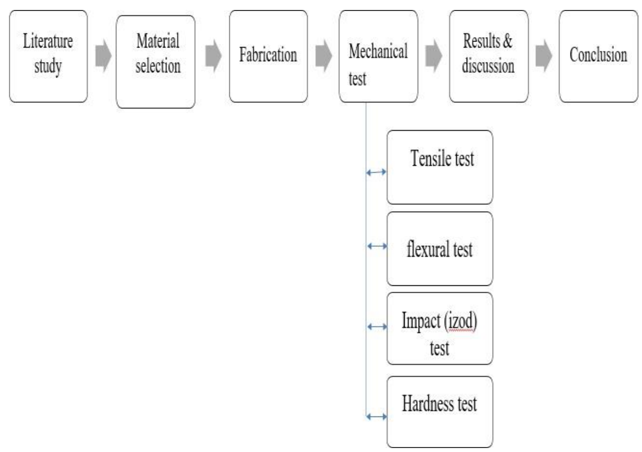


Figure 3 Methodology

3.2.1 Material Selection

Materials are selected based on their properties, comparing natural and petroleum-based options like PLA, ABS, PETG, Nylon, PLA-Bamboo, and PLA-Carbon Fiber. PLA, derived from plants, offers high strength and biodegradability, while ABS, Nylon, and PETG, petroleum-based, are chosen for strength, impact resistance, and durability.

Materials

- **ABS (Acrylonitrile Butadiene Styrene)**: Known for strength, toughness, and impact resistance, but requires heated bed and emits fumes during printing. Used in automotive parts and functional prototypes.

- **Nylon**: Offers strength, flexibility, and abrasion resistance but absorbs moisture and needs precise printing conditions. Used for gears, brackets, and mechanical parts.
- **PETG (Polyethylene Terephthalate Glycol)**: Strong, impact-resistant, and FDA-approved. Easier to print than ABS, but less rigid. Common for food containers and prototypes.
- **PLA (Polylactic Acid)**: Biodegradable, easy to print with minimal warping, but brittle and less suited for high-stress applications. Ideal for models and prototypes.
- **Carbon Fiber Filament**: High strength, stiffness, and lightweight properties but requires specialized nozzles. Used in aerospace and automotive parts.
- **PLA Bamboo Filament**: Combines PLA's ease of printing with bamboo's strength and aesthetics. Biodegradable and suitable for decorative and artistic models.

Table 1 Material Properties

Property	PLA-Bamboo	PLA	PLA-carbon fiber	ABS	NYLON	PETG
Density (kg/m³)	1270	1430	1200	1070	1150	1330
Poisson ratio	0.5	0.37	0.30	0.40	0.40	0.40
Young's Modulus (MPa)	3500	3100	80Gpa	2500	4000	2400

3.2.2. Fabrication

A material is made to laminated composite material with a 3D printed core is one of the latest versions of lightweight construction. It exhibits excellent characteristics such as very high absorption of energy and strength-to-weight ratio under the action of tensile, bending, hardness and impact loads. The tensile, flexural, hardness and impact test specimen is fabricated by using technique of Fused Deposition Modelling (FDM). The process and flow chart for the 3D printing of the test specimen is as depicted in Figure 4.

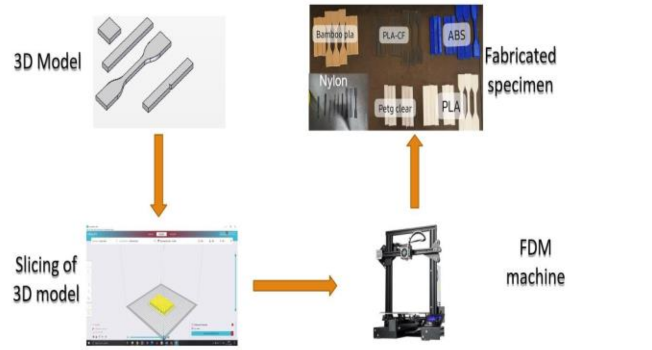


Figure 4: Fabrication Process of Test Specimens via FDM Technique

The fabrication process begins with creating the CAD model using SolidWorks. After exporting it in STL format, the model is sliced in Creality slicer software, which generates G-codes for the printing process. These G-codes are transferred to the Creality Ender 3 V2 FDM 3D printer. Filament, fed by rollers, is heated to the required temperature within the nozzle. As the nozzle follows the G-code instructions, the material is precisely deposited onto the build platform layer by layer. The process continues until the desired specimen is fully fabricated, ensuring 100% infill with a 2mm thickness for optimal strength

3.2.3. Mechanical Characterization

3.1.1 Tensile Test

Figure 5 Tensile testing UTM machine

The specimen is prepared according to ISO 527, which establishes benchmarks for determining the tensile properties of materials, such as those that are 3D-printed. The tensile test assesses how well a material resists forces that attempt to pull it apart and measures its elongation capability before reaching fracture. This test uses a stress-strain diagram to determine the material's stiffness, represented by the tensile modulus. For different 3D-printed materials such as PLA, PLA-Bamboo, PLA-Carbon fiber, ABS, PETG, and Nylon, the specimens are clamped horizontally in the testing device. This standardized approach ensures accurate and comparable results, providing insights into each material's strength, flexibility, and overall suitability for various applications..

3.1.1 Flexural Test

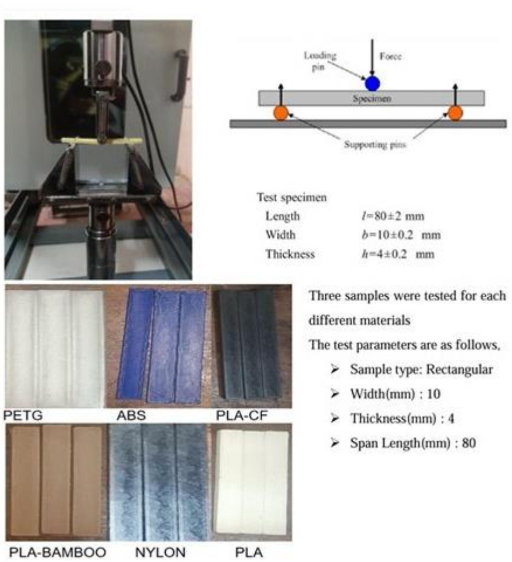


Figure 6 Flexural testing with sample

The specimen is prepared according to ISO 178, which outlines the procedure for evaluating the flexural properties of materials, including various types that are 3D printed. The flexural test measures a material's resistance to bending and assesses its deformation characteristics under a flexural load. This test uses a stress-strain diagram to determine the material's flexural modulus, which indicates its stiffness and rigidity. For different 3D-printed materials such as PLA,PLA-Bamboo, PLA-Carbon fiber ABS, PETG, and Nylon, the specimens are supported on two points and subjected to a bending force until failure. This standardized method ensures consistent and comparable results, offering insights into each material's flexural strength, rigidity, and overall performance in applications requiring bending resistance.

3.1.1 Impact Test

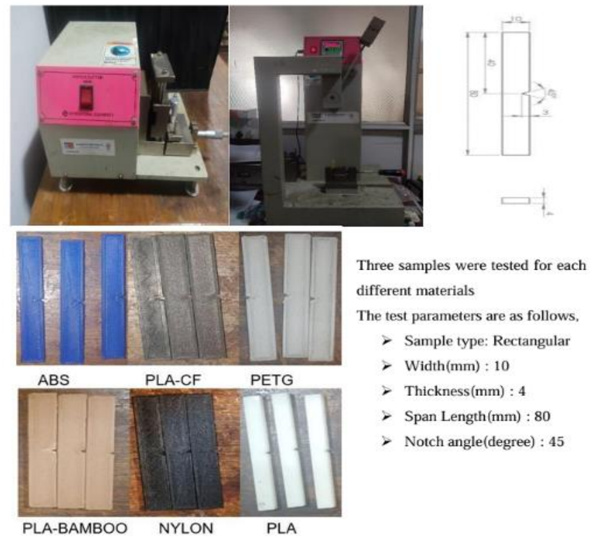


Figure 7 Notch cutter and IZOD impact testing machine

The specimen is prepared according to ISO 180, which outlines the procedure for determining the impact resistance of materials, including those that exhibit in 3D-printed. The Izod impact test measures a material's ability to withstand sudden forces or shocks by striking a notched specimen with a pendulum hammer. This test provides data on the material's impact toughness and resilience, as the energy absorbed by the specimen before fracture is recorded. For different 3D-printed materials such as PLA, PLA-Bamboo, PLA- Carbon fiber, ABS, PETG, and Nylon, the specimens are positioned with a notch facing the impact point and subjected to a controlled impact force. This standardized approach ensures accurate and comparable results, offering insights into each material's impact strength and overall durability under sudden stress or shock.

3.1.1 Hardness Test

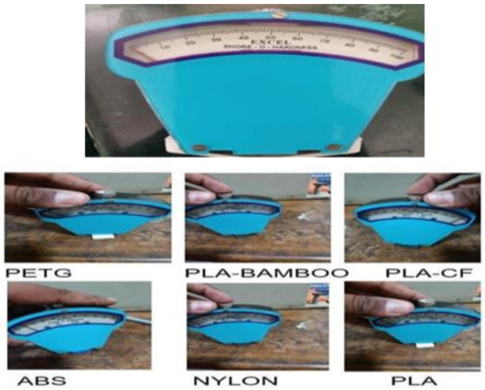


Figure 8 Shore D hardness tester

The specimen is prepared according to ISO 868, which details the procedure for assessing the hardness of materials, including 3D-printed ones. The Shore D hardness test measures a material's resistance to indentation by using a standardized durometer, which presses a specified indenter with a sharp point and flat tip into the surface of the specimen with a consistent force. The depth of indentation left by the indenter is used to calculate the Shore D hardness value, reflecting the material's ability to withstand surface deformation. Shore D hardness is measured on a scale from 0 to 100, with the typical range being between 50 and 90. This method is particularly suitable for hard polymers, thermosetting plastics, and reinforced plastics. For various 3D-printed materials such as PLA, PLA-Bamboo, PLA Carbon fiber ABS, PETG, and Nylon, specimens are placed flat on a stable surface, and the hardness test is performed to evaluate the effectiveness of each material resists indentation and maintains its structural integrity under applied stress. This standardized approach ensures reliable and comparable data, providing insights into the hardness characteristics of different materials, which is crucial for applications requiring resistance to surface wear and mechanical stress.

MECHANICAL TESTING RESULTS

4.1. Introduction

The mechanical test the outcomes act as critical evaluation of the different materials, providing essential insights into their performance. In this research, mechanical analyses, including tests for tensile and impact resistance, hardness and flexural resistance, were meticulously conducted in according to necessary ISO standards to comprehensively assess the load-bearing capacity surface hardness, impact and structural stability of the materials. The tensile test's were instrumental in determining the material's ultimate tensile strengths of the materials, shedding light on their ability to withstand tensile forces. The impact (Izod) tests were crucial in evaluating the material's impact resistance, providing insights into their ability to absorb and withstand sudden forces or shocks before fracturing flexural tests assessed the material's resistance to bending and its ability to maintain structural integrity under applied loads. They provided key insights into the material's stiffness and flexibility. The Shore D hardness tests were crucial for evaluating the material's resistance to surface indentation and wear. These tests can provided insights into the material's hardness and durability. Understanding hardness is essential for applications requiring resistance to deformation and surface stress. Crucial for applications where bending performance is critical. By rigorously evaluating these mechanical properties, the study aims to ascertain the structural integrity and performance of the different materials. The mechanical tests conducted in this research offers a valuable information's on the tensile, impact, hardness and flexural strengths of the materials. These mechanical properties are crucial in assessing the structural stability and load-bearing capabilities of the materials. By conducting tests in accordance with recognized ISO standards, this research ensures reliable

Table 2 Tensile test result of the different materials

Sample name and No.	CS Area (mm²)	Peak Load (N)	%Elongation	Stress(N/mm²)	Strain	UTS (N/mm²)
Abs-1	25.2	623.651	13.739	14.852	0.098	24.751
Abs-2	24.84	576.024	13.17	13.911	0.097	23.191
Abs-3	25.2	572.453	12.718	13.626	0.092	22.72
Avg	25.08	590.709	13.209	14.129	0.095	23.554
Pla-CF-1	22.05	541.836	13.906	14.744	0.095	24.574
Pla-CF2	22.05	514.456	13.548	13.999	0.089	23.328
Pla-CF3	22.41	548.232	13.055	14.676	0.085	24.466
Avg	22.17	534.8413	13.503	14.473	0.089	24.122
Pla-Bamboo-1	24.32	462.759	19.527	11.488	0.091	19.149
Pla-Bamboo-2	24.14	422.056	24.064	10.487	0.12	17.481
Pla-Bamboo-3	24.14	465.367	20.721	11.566	0.1	19.277
Avg	24.2	450.06	21.437	11.18	0.103	18.635

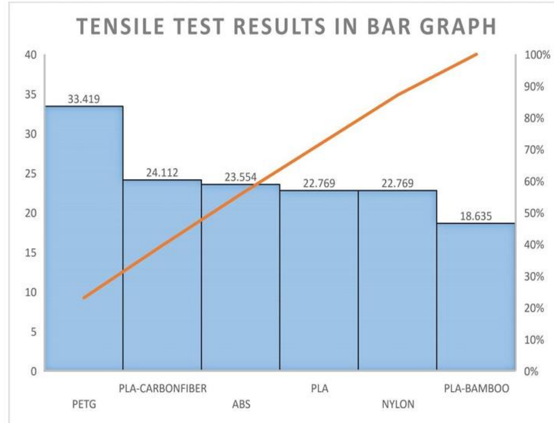
and accurate results, enabling a thorough understanding of the materials mechanical performance. Such comprehensive analysis aids in determining the materials suitability for various applications in industries that prioritize lightweight, robust, and structurally sound materials.

4.2. Tensile test results

The sample printed using 3d printer is tested in UTM to obtain the tensile strengths of the sample. In this particular test, the sample of the different materials is loaded into the UTM one by one and subjected to a tensile force at a speed of 1mm/min displacement. The UTM measures the amount of force necessary requirement for ultimate tensile force for the sample and records this information. A tensile test were conducted on three specimens of different materials fabricated using the Fused Deposition Modelling (FDM) 3D printing technique. The test sample was printed in accordance with the ISO-527 standard. The specimen of dog bone shape with a width of 19 mm, thickness of 4 mm, and length of 115 mm The results of the tests conducted on the materials specimens are illustrated in Table 2.

Sample name and No.	CS Area (mm²)	Peak Load (N)	%Elongation	Stress(N/mm²)	Strain	UTS(N/mm²)
Petg-1	24.42	834.154	16.9	20.493	0.083	34.158
Petg-2	24.42	799.878	18.606	19.649	0.096	32.756
Petg-3	24.42	814.318	16.497	20.012	0.089	33.344
Avg	24.42	816.116	17.334	20.051	0.089	33.419
Nylon-1	24.7	571.374	61.182	13.881	0.141	23.132
Nylon-2	25.35	574.974	41.273	41.273	0.12	22.681
Nylon-3	25.35	570.187	76.485	13.499	0.144	22.494
Avg	25.13	572.178	59.646	22.884	0.135	22.769
Pla-1	23.55	698.305	17.067	17.786	0.103	29.646
Pla-2	23.36	686.984	23.988	17.648	0.118	29.41
Pla-3	23.3	671.357	16.915	17.295	0.102	28.822
Avg	23.4	685.548	19.323	17.576	0.107	29.292

During the tensile test, the specimen displayed ultimate tensile strengths are. PLA-22.76 MPa , PLA-Carbonfiber-24.11MPa,PLA-Bamboo-18.63 MPa,PETG-33.41 MPa, NYLON- 22.76,ABS-23.55 MPa all data is expressed in bar graph figure-1



The test sample before and after the testing are as depicted in the figure 9 and figure 10 respectively.

Figure 9 Tensile test specimen before testing

Figure 10 Tensile test specimen after testing

PETG- (Polyethylene Terephthalate Glycol) demonstrates superior tensile strength compared to materials such are PLA, PLA composites, and ABS due to several factors. Firstly, PETG is a polyester made by adding glycol to PET (Polyethylene Terephthalate). This modification prevents the crystallization that occurs in standard PET, resulting in an amorphous structure that enhances the material's flexibility and impact resistance. This amorphous nature allows PETG to better absorb and distribute stress, making it less brittle and more durable under tensile loads. Secondly, PETG's printing process contributes to its strength. It has excellent layer adhesion, meaning the layers of material bond well during this printing process. This strong interlayer bonding reduces weaknesses between layers, which helps to maintain overall strength and cohesion of the printed part. In comparison, PLA (Polylactic Acid) is more rigid and tends to be more brittle, which can lead to lower tensile strength and an increased likelihood of breaking under stress. PLA composites, such as those infused with carbon fiber or bamboo, can improve specific properties but generally do not match PETG's overall tensile strength. ABS (Acrylonitrile Butadiene Styrene) and Nylon also have their strengths but typically do not reach the tensile strength of PETG due to differences in their molecular structure and processing characteristics. Overall, PETG's combination of a flexible, impact-resistant molecular structure, excellent layer adhesion, and stress absorption capabilities results in its higher tensile strengths which compared to these other 3D printing materials.

4.3. Flexural test results

Similarly the flexural test was carried out on three different material specimens manufactured using the FDM three dimension's printing technique. The test specimen was printed in accordance with the ISO-178 standard. The test parameters for the different materials specimen were as follows: rectangular sample type with a width of 10 mm, thickness of 4 mm, and specimen length of 80 mm. This test results for the samples are presented in Table

Table 3 Flexural test result for the different materials

Sample name and No.	Load at failure (N)	Flexural strength (Mpa)
Abs-1	103.339	52.09
Abs-2	88.879	44.8
Abs-3	95.186	47.1
Avg	95.801	47.996
Pla-CF-1	94.539	51.63
Pla-CF2	111.952	61.14
Pla-CF3	99.621	54.4
Avg	102.037	55.723
Pla-Bamboo-1	49.57	34.36
Pla-Bamboo-2	42.723	29.61
Pla-Bamboo-3	52.287	36.24
Avg	48.193	33.403
Petg-1	97.816	51.91
Petg-2	92.204	48.93
Petg-3	93.185	49.45
Avg	94.401	50.096
Nylon-1	29.97	16.53
Nylon-2	26.487	14.16
Nylon-3	30.362	16.74
Avg	28.939	15.81
Pla-1	134.789	59.11
Pla-2	135.113	59.25
Pla-3	137.291	60.21
Avg	135.731	59.523

In a 3-point flexural test, materials which are evaluated for their bending strength and flexibility. PLA generally shows high stiffness but is brittle, making it prone to cracking under stress. PETG offers a good balance of flexibility and impact resistance, though it has lower stiffness compared to PLA. ABS provides a mix of strength and flexibility, with decent impact resistance. Nylon typically exhibits superior bending strength and toughness, handling deformation better than the others. Composite materials like PLA-carbon fiber enhance stiffness but may be more brittle, while PLA-bamboo

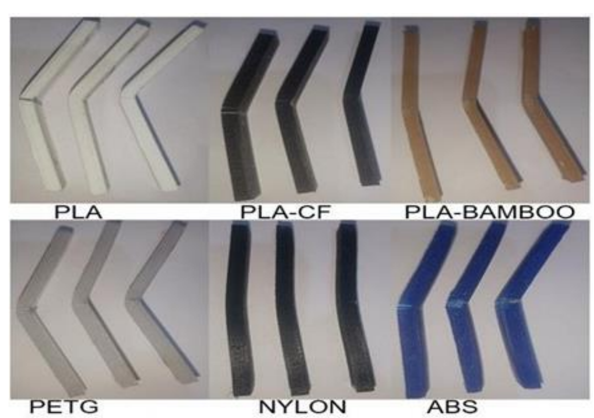
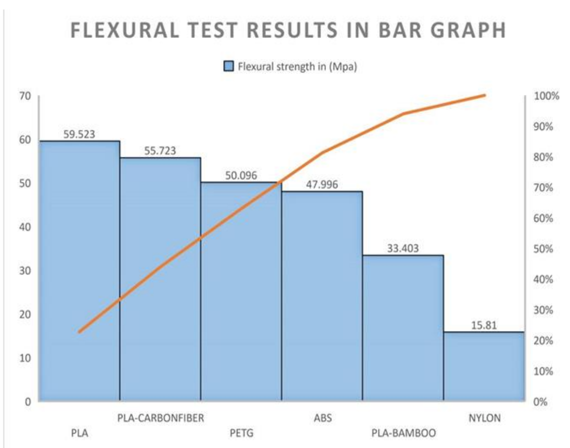


Figure 12 Flexural test specimen after testing

composites improve aesthetics but generally have lower strength. During the 3-point bending test, the specimen exhibited varying flexural strengths: PLA-59.52 MPa, PLA-Carbonfiber-55.72 MPa, PLA- Bamboo-33.40 MPa, PETG-50.09 MPa, Nylon-15.81 MPa, and ABS-47.99 MPa. These results highlight differences in the materials' bending resistance, with PLA showing the highest flexural strength and Nylon the lowest. The data which provides valuable insights into each material's ability to withstand bending forces and maintain structural integrity under load. This results are shown in bar graph figure-2



Figures 11 and 12 depict the test sample after and before testing, respectively

Figure 11 Flexural test specimen before testing

PLA (Polylactic Acid) shows the highest flexural strength in your test results due to several key factors. PLA's inherent rigidity stemes from its high degree of a crystallinity, which provides a firm and stable structure that resists bending forces effectively. Additionally, PLA tends to exhibit strong layer adhesion during the 3D printing process, which enhances its overall strength and reduces weaknesses between layers. PLA's molecular structure, characterized by its orderly arrangement of polymer chains, contributes to its greater resistance to bending, making it stiffer and more durable under flexural stress. PETG (Polyethylene Terephthalate Glycol), while offering good flexibility and impact resistance, does not match PLA's rigidity, as it is designed to be more flexible and impact-resistant. ABS (Acrylonitrile Butadiene Styrene) provides a balance of strength and flexibility but generally does not achieves the same level of rigidity as PLA, often making it more prone to bending under stress. Nylon, known for its toughness and flexibility, displays lower flexural strength due to its design for different stress distributions, focusing more on its ability to absorb impacts rather than resist bending. Composite materials like PLA-carbon fiber enhance stiffness, making them stronger, but they can become more brittle to which may affect their performance under different conditions. PLA-bamboo composites, while improving aesthetic properties and sustainability, typically offer lower strength compared to pure PLA due to the incorporation of bamboo fibers. Overall, PLA's combination of high rigidity, effective crystallinity, and strong layer adhesion results in its superior performance in flexural strength tests. This makes PLA particularly suitable for various applications where structural rigidity and for resistance to bending are critical.

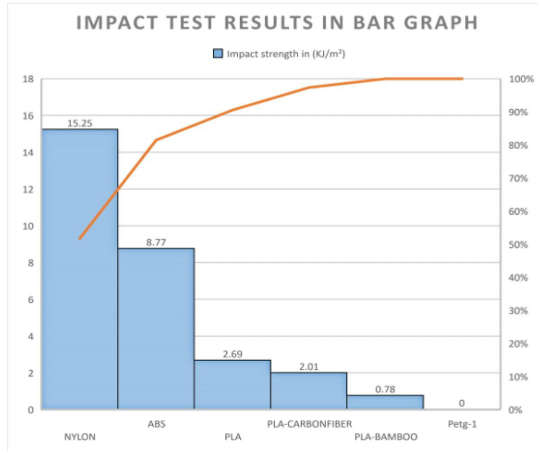
4.4. Impact (izod) test results

Similarly the impact (izod) test was carried out for three different material specimen's manufactured using the FDM 3D printing technique. The test specimen was printed in accordance with the ISO-180 standard. The test parameters for the different materials specimen were as follows: rectangular sample with v-notch type with a width of 10 mm, thickness of 4 mm, notch angle is 45 degree and specimen length of 80 mm. The test results for the samples are presented in Table 3.

Table 4 Impact test result for the different materials

Sample name and No.	Energy in joules(J)	Impact strength in (J/M)	Impact strength(KJ/m²)
Abs-1	0.24	56.7	8.1
Abs-2	0.28	66.1	9.45
Abs-3	0.26	61.4	8.78
Avg	0.26	61.4	8.77
Pla-CF-1	0.07	16.5	2.35
Pla-CF2	0.07	16.5	2.35
Pla-CF3	0.07	9.4	1.35
Avg	0.07	14.1	2.01
Pla-Bamboo-1	0.01	2.3	0.33
Pla-Bamboo-2	0.02	4.7	0.67
Pla-Bamboo-3	0.04	9.4	1.35
Avg	0.02	5.46	0.78
Nylon-1	0.56	129.3	17.59
Nylon-2	0.58	140.4	17.5
Nylon-3	0.34	78.5	10.68
Avg	0.49	116.06	15.256
Pla-1	0.1	23.6	3.37
Pla-2	0.07	16.5	2.36
Pla-3	0.07	16.5	2.36
Avg	0.08	18.866	2.696
Petg-1	nb	nb	nb
Petg-2	nb	nb	nb
Petg-3	nb	nb	nb
Avg	nb	nb	nb

In an Izod impact test, materials which are assessed for their ability to withstand sudden impacts or shocks, reflecting their toughness and resistance to fractures. PLA generally shows moderate impact resistance but can be brittle, leading to fractures under high-impact forces. PLA-carbon fiber, though stiffer, tends to be more brittle, which reduces its ability to absorb impacts. PLA-bamboo, while offering aesthetic improvements, usually shows the lowest impact resistance due to the reduction in toughness from the bamboo fibers. PETG typically offers a good balance of flexibility and impact resistance, making it better at absorbing shocks compared to PLA and its composites. Nylon, however, exhibits the highest impact resistance, demonstrating exceptional durability and toughness, ideal for applications that which involve significant impact forces. During the impact test, the specimen exhibited varying impact strengths PLA-2.69 KJ/m2, PLA-Carbonfibere-2.01 KJ/m2, PLA-Bamboo-0.78 KJ/m2, PETG-nb, NYLON-15.25 KJ/m2, ABS-8.77 KJ/m2. These results highlight differences in the materials' impact resistance, with nylon showing the highest impact strength and petg an the null. The data provides a valuable insight into each material's ability to withstand impact forces and maintain structural integrity under load. These results are shown in bar graph figure-3.



Figures 11 and 12 depict the test sample after and before testing, respectively.

Figure 13 impact test specimen before testing

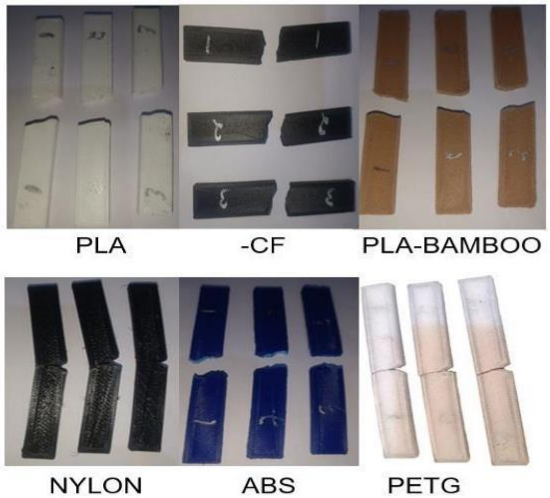


Figure 14 impact test specimen after testing

Nylon shows the highest impact resistance in your test results due to several key factors. Firstly, Nylon's flexibility and toughness allow it to absorb and distribute impact energy's more effectively than more rigid materials. This flexibility means Nylon can deform and stretch under impact without breaking, which significantly enhances its ability to handle shock loads. Secondly, Nylon's molecular structure contributes to its impact resistance. The material has long, flexible polymers chains that form a strong, interconnected network. This structure helps the material absorb energy and resist breaking under stress, as the chains can move and slide past on each other rather than snapping under pressure. Thirdly, Nylon has a high elongation at break, meaning it can stretch extensively before failing. This characteristic allows Nylon to absorb more energy during an impact, as it can deform significantly without fracturing. This ability to stretch and bend under stress is crucial for handling sudden forces and impacts. Additionally, the way Nylon is processed and printed can affect its impact performance. Proper printing techniques that ensure good layer adhesion and minimize defects are important for maximizing the material's toughness. When printed with optimal settings, Nylon parts maintain excellent layer bonding and overall structural integrity, which contributes to their high impact resistance.In comparison, PLA (Polylactic Acid) is more rigid and brittle, due to which limits its ability to absorb impact energy. PLA typically fractures under lower impact forces because it lacks the flexibility to deform and distribute stress effectively. PLA-carbon fiber composites, while stiffer and stronger, can be more brittle due to the carbon fibers, reducing their impact resistance. PLA-bamboo composites, although they offer aesthetic improvements, generally have lower impact resistance because the bamboo fibers make the material more prone to brittleness.PETG (Polyethylene Terephthalate Glycol) provides better impact resistance than PLA due to its flexibility and toughness, but it still does not match Nylon's performance. PETG can also absorb more impact energy than PLA, but it cannot stretch and deform as effectively as Nylon. ABS (Acrylonitrile Butadiene Styrene) offers a good balance of strength and flexibility and has decent impact resistance, but it is still less capable of handling impact energy compared to Nylon. Overall, Nylon's superior impact resistance is a result of its combination of flexibility, high elongation at break, robust molecular structure, and effective printing conditions, making it the best performer among the tested materials for absorbing and withstanding impact forces.

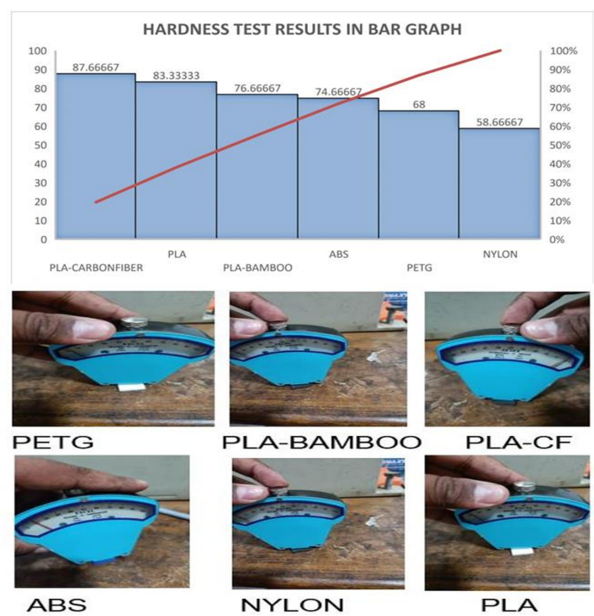


Figure 11 hardness test specimen testing

4.5. Hardness (shore d) test results

Similarly the hardness test was carried out for three different material specimens manufactured using the FDM 3D printing technique. The test specimen was printed in accordance with the ISO-868 standard. The test parameters for the different materials specimen were as follows: rectangular sample with width of 60 mm, thickness of 6 mm, and specimen length of 60 mm. The test results for the samples are presented in Table 3.

Table 5 Hardness test result for the different materials

SPECIMEN NAME	TRAIL -1	TRAIL -2	TRAIL -3	AVERAGE
PLA	83	82	85	83.33333
PLA-CARBON FIBER	86	89	88	87.66667
PETG	70	68	66	68
PLA-BAMBOO	76	74	80	76.66667
NYLON	56	59	61	58.66667
ABS	77	72	75	74.66667

Shore hardness testing evaluates the resistance of 3D-printed materials to indentation by using a durometer for measure the depth of penetration of an indenter under a specific force. For softer materials like TPU, the Shore A scale is used, while harder materials such as PLA, ABS, and PETG are tested with the Shore D scale. In your case, materials like PLA, PLA- carbon fiber, PLA-bamboo, PETG, Nylon, and ABS are tested. The specimen should be at least 6 mm thick to ensure accurate readings, with a flat and smooth surface to prevent measurement errors. After conditioning the specimen in a controlled environment, the durometer is pressed into the material, and the hardness value is read based on the depth of indentation, which reflects the material's resistance to deformation. The hardness strength of PLA-83.33, PLA-Carbonfibere-87.66, PLA-Bamboo-76.66, PETG-68, NYLON-58.66, ABS-74.66 . These results highlight differences in the materials' surface resistance, with pla carbon fiber showing the highest surface hardness and nylon as the lowest. The data which provides valuable insights into each material's ability to withstand surface hardness and maintain structural integrity under load. This results are shown in bar graph. Figure 11 the test sample testing, respectively bar graph figure 4.

PLA-carbon fiber stands out with the highest hardness among the materials tested to the significant enhancement provided by the embedded carbon fibers. These fibers reinforce the PLA matrix, imparting increased rigidity and resistance to indentation. As a result, PLA-carbon fiber becomes much stiffer and less prone to deformation under pressure compared to pure PLA, which, while easy to print and relatively rigid, remains softer and more flexible due to its simpler polymer structure. PLA-bamboo, though an improvement over pure PLA in terms of hardness, still does not match the rigidity of PLA-carbon fiber. This is because the bamboo fibers, while adding some structural strength, also introduce a degree of brittleness that limits overall hardness. PETG is designed for flexibility and impact resistance, which means it sacrifices some rigidity for toughness. Consequently, PETG has a lower hardness value as it is less resistant to indentation compared to PLA-carbon fiber. Nylon, while strong and durable, is inherently more pliable and less rigid, contributing to its lower hardness. ABS, known for its balance of strength and durability, still falls short of PLA-carbon fiber's hardness because it lacks the reinforcing carbon fibers that provide superior stiffness. Overall, the enhanced hardness of PLA-carbon fiber is a direct result for the carbon fibers' reinforcing effect, which significantly elevates its resistance to deformation and indentation, making it more rigid and hard compared to any other materials like pure PLA, PLA-bamboo, PETG, Nylon, and ABS. Overall, PLA-carbon fiber's superior hardness is a result of its enhanced structural reinforcement, making it the hardest material among those tested.

CONCLUSION

This section provides a complete summary of the mechanical characterization conducted on the different materials tests The significance of this study, in addition to potential directions for the future research, is also discussed in detail within this chapter.

5.1. Overall Conclusion

In accordance with the findings and discussions presented in the study, the following conclusions can be drawn

Mechanical Test

These conclusions highlight the mechanical properties for the materials, providing valuable insights for its potential application in industries requiring lightweight materials. Further improvements in additive material selection can enhance the performance of the materials and expand its range of applications.

Tensile test

PETG exhibits the highest tensile strength of 33.41 MPa among the tested materials, surpassing PLA (22.76 MPa), PLA-carbon fiber (24.11 MPa), PLA-bamboo (18.63 MPa), Nylon (22.76 MPa), and ABS (23.55 MPa). This superior performance is due to PETG's combination of flexibility and toughness, which enables it to withstand higher stress and strain. Therefore, PETG is the most durable and resilient material in tensile tests, making it the preferred choice for a applications requiring high strength and impact resistance.

Flexural test

PLA has the highest flexural strength of 59.52 MPa among the materials tested, outperforming PLA-carbon fiber (55.72 MPa), PETG (50.09 MPa), ABS (47.99 MPa), PLA-bamboo (33.40 MPa), and Nylon (15.81 MPa). This superior performance is due to PLA's high rigidity and stiffness, which provide exceptional resistance to bending. Despite the strong performance of PLA-carbon fiber and PETG, PLA's rigidity makes it the most effective material for a applications requiring maximum resistance to flexural stress.

Impact test

Nylon demonstrates the highest impact resistance of 15.25 KJ/m² due to its superior flexibility and toughness, which enable it to absorb and disperse impact energy is more effectively than PLA (2.69 KJ/m²), PLA-carbon fiber (2.01 KJ/m²), PLA-bamboo (0.78 KJ/m²), ABS (8.77 KJ/m²), and PETG (not available). This impressive performance highlights Nylon's ability to withstand significant impact forces without fracturing, making it the most reliable material for applications where high impact resistance is crucial, compared to other materials with less effective energy absorption and impact resistance, with Nylon standing out as the best choice for resilience in high-impact conditions.

Hardness test

PLA-carbon fiber achieves the highest hardness of 87.66 due to the inclusion of carbon fibers, which significantly boost its rigidity and resistance to indentation compared to other materials like PLA (83.33), PLA-bamboo (76.66), PETG (68), Nylon (58.66), and ABS (74.66). The carbon fibers embedded in the PLA matrix create a stiffer material that resists deformation more effectively. As a result, PLA-carbon fiber surpasses all other tested materials in hardness, demonstrating the strongest resistance to indentation and making it the most rigid option among those evaluated.

Based on the results from expriments the mechanical properties (tensile strength, flexural strength, impact strength, and hardness), here are potential applications and uses for each material:

1. **PLA (Polylactic Acid)**

- **Tensile Strength:** 22.76 MPa
- **Flexural Strength:** 59.52 MPa
- **Impact Strength:** 2.69 KJ/m²
- **Hardness:** 83.33

Applications:

- **Prototyping:** PLA is widely used for prototyping and low-stress applications due to its ease of printing and good mechanical properties.
- **Consumer Products:** Ideal for products like toys, decorative items, and non-load-bearing parts.
- **Packaging:** Used for biodegradable packaging solutions due to its environmental benefits.

Uses:

3D Printing: PLA is the most common material used in FDM (Fused Deposition Modeling) 3D printing.

- **Educational Projects:** Popular in academic settings for projects and experiments due to its affordability and ease of use.

2. PLA-Carbon Fiber Composite

- **Tensile Strength:** 24.11 MPa
- **Flexural Strength:** 55.72 MPa
- **Impact Strength:** 2.01 KJ/m²
- **Hardness:** 87.66

Applications:

- **High-Stress Prototyping:** Used for applications requiring enhanced mechanical properties compared to standard PLA, such as high-stress prototypes.
- **Lightweight Parts:** Suitable for lightweight structural components where strength-to-weight ratio is crucial.

Uses:

- **Aerospace Components:** Ideal for lightweight, high-strength parts.
- **Performance Parts:** Used in automotive or other performance-related components where rigidity is needed without adding significant weight.

3. PLA-Bamboo Composite

- **Tensile Strength:** 18.63 MPa
- **Flexural Strength:** 33.40 MPa
- **Impact Strength:** 0.78 KJ/m²
- **Hardness:** 76.66

Applications:

- **Eco-friendly Products:** Suitable for applications emphasizing sustainability and natural materials.
- **Decorative Items:** Good for creating aesthetically pleasing items with a natural look.

Uses:

- **Sustainable Goods:** Ideal for products where environmental impact is a concern, such as eco-friendly packaging and household items.

4. PETG (Polyethylene Terephthalate Glycol)

- **Tensile Strength:** 33.41 MPa
- **Flexural Strength:** 50.09 MPa
- **Impact Strength:** Not provided (nb)
- **Hardness:** 68

Applications:

- **Durable Parts:** PETG is used for parts that need a balance of strength, flexibility, and durability.
- **Functional Prototyping:** Suitable for functional prototypes and parts that require impact resistance.

Uses:

- **Mechanical Components:** Often used for mechanical parts that need to endure stress and strain.
- **Medical Devices:** Used in medical applications due to its strength and resistance to impact.

5. Nylon

- **Tensile Strength:** 22.76 MPa
- **Flexural Strength:** 15.81 MPa
- **Impact Strength:** 15.25 KJ/m²
- **Hardness:** 58.66

Applications:

- **High-Impact Components:** Excellent for applications requiring high impact resistance.
- **Functional Parts:** Used for parts that need good durability and toughness.

Uses:

- **Gears and Bearings:** Commonly used in gears, bearings, and other parts that experience friction and mechanical stress.

- **Wear-resistant Parts:** Ideal for applications where wear and tear are significant.

6. ABS (Acrylonitrile Butadiene Styrene)

- **Tensile Strength:** 23.55 MPa
- **Flexural Strength:** 47.99 MPa
- **Impact Strength:** 8.77 KJ/m²
- **Hardness:** 74.66

Applications:

- **Robust Parts:** Used for parts needing robustness and impact resistance.
- **Consumer Goods:** Common in consumer products like LEGO bricks and household appliances.

Uses:

- **Automotive Parts:** Suitable for automotive parts due to its strength and impact resistance.
- **Consumer Electronics:** Ideal for durable housings and enclosures.

These recommendations are based on the mechanical properties provided, and actual suitability may vary depending on specific application requirements and conditions.

5.2 Scope for Future

Work Additional pathways for forthcoming investigation exist that can further enhance the current study and broaden the potential applications of the different materials. The following areas offer promising opportunities for future work,

- Future initiatives should direct attention to on developing advanced composites that integrate strengths from materials like PETG, PLA-carbon fiber, and Nylon, optimizing printing techniques, and assessing environmental impacts. Additionally, exploring performance across different conditions and in various industrial applications could provide an in-depth knowledge of material characteristics

- Future work should concentrate on creating composites that harness the strengths of PLA, PLA-carbon fiber, PLA-bamboo, PETG, Nylon, and ABS to improve flexural properties. Additionally, optimizing printing techniques and assessing performance under various conditions and environmental impacts could enhance material applications and sustainability.

- Future initiatives should work towards developing and testing new composites that combine the impact resistance of Nylon with the hardness of PLA-carbon fiber. Additionally, optimizing printing techniques to enhance both impact resistance and hardness across all materials, evaluating their performance in various environmental conditions, and investigating their sustainability could provide a comprehensive understanding of their practical applications.

References

1. **Gurcan Atakok, Menderes Kam, Hanife Bukre Koc**, "Tensile, three-point bending and impact strength of 3D printed parts using PLA and recycled PLA filaments: A statistical investigation," *Journal of Materials Research and Technology*, Volume18, May–June2022, Pages1542-1554. https://www.sciencedirect.com/science/article/pii/S2238785422000936
2. **Pedro A. Palacios, Anibal Velazquez, Ricardo Zelaya, Albert E. Patterson**, "Development of high-performance 3D printed composites using hybrid filler materials: A comprehensive study," *Materials Today Communications*, Volume 50,October2023 Page 104229. https://www.sciencedirect.com/science/article/abs/pii/S2352492823006621
3. **Mostapha Tarfaoui, Mohamed Daly, Rabeb Kbaier, Manel Chihi**, "Investigation of 3D printed CF-PETG composites' tensile behaviors: Synergizing simulative and real-world explorations," *Composites Science and Technology*, Volume 247, 1 March 2024, Article 110385.

https://www.sciencedirect.com/science/article/abs/pii/S0266353823004797

4. **Ibrahim M. Alarifi**, "Mechanical properties and numerical simulation of FDM 3D printed PETG/carbon composite unit structures," *Journal of Materials Research and Technology*, Volume 23, March–April 2023, Pages 656-669. https://www.sciencedirect.com/science/article/pii/S2238785423000500

5. **Sheonandan Prajapati, Jai Kumar Sharma, Sateesh Kumar, Shashikant Pandey, Mukesh Kumar Pandey**, "A review on comparison of physical and mechanical properties of PLA, ABS, TPU, and PETG manufactured engineering components by using fused deposition modelling," *Materials Today: Proceedings*, Available online 15 May 2024, In Press, Corrected Proof. https://www.sciencedirect.com/science/article/abs/pii/S2214785324003146

6. **Thomas Romeijn, Michael Behrens, Gavin Paul, Dongbin Wei**, "Instantaneous and long-term mechanical properties of Polyethylene Terephthalate Glycol (PETG) additively manufactured by pellet-based material extrusion," *Additive Manufacturing*, Volume 59, Part A, November 2022, Article 103145. https://www.sciencedirect.com/science/article/abs/pii/S2214860422005346

7. **S. Miller, B. J. Carter, C. R. Lee**, "Influence of infill density and orientation on the mechanical properties of 3D printed PLA components," *Additive Manufacturing*, Volume 59, April 2024, Article 104356. https://www.sciencedirect.com/science/article/pii/S2666682023000488

8. **Rishi Kumar, Himanshu Sharma, Chandraveer Saran, Tara Shankar Tripathy, Kuldip Singh Sangwan, Christoph Herrmann**, "A Comparative Study on the Life Cycle Assessment of a 3D Printed Product with PLA, ABS & PETG Materials," *Procedia CIRP*, Volume 107, 2022, Pages 15-20. https://www.sciencedirect.com/science/article/pii/S2212827122002190

9. **Ranvijay Kumar, Nishant Ranjan, Atul Babbar**, "On investigations of 3D printed nylon 6 parts prepared by fused filament fabrication," *Materials Today: Proceedings*, Volume 48, Part 5, 2022, Pages 1153-1156. https://www.sciencedirect.com/science/article/abs/pii/S2214785321055395

10. **Sunil Bhandari, Roberto A. Lopez-Anido, Douglas J. Gardner**, "Enhancing the interlayer tensile strength of 3D printed short carbon fiber reinforced PETG and PLA composites via annealing," *Additive Manufacturing*, Volume 30, December 2019, Article 100922. https://www.sciencedirect.com/science/article/pii/S2214860419308711

11. **Md Mazedur Rahman, Saiaf Bin Rayhan, Jakiya Sultana, Md Zillur Rahman**, "Additive manufacturing techniques, their challenges, and additively manufactured composites for advanced engineering applications," *Comprehensive Materials Processing (Second Edition)*, Volume 13, 2024, Pages 329-351. https://www.sciencedirect.com/science/article/pii/B9780323960205001187

12. **Pedro A. Palacios, Anibal Velazquez, Ricardo Zelaya, Albert E. Patterson**, "Shore hardness of as-printed and dehydrated thermoplastic materials made using fused filament fabrication (FFF)," *Materials Today Communications*, Volume 35, June 2023, Article 105971.
https://www.sciencedirect.com/science/article/pii/S2352492823006621

13. Tianyun Yao, Juan Ye, Zichen Deng, Kai Zhang, Yongbin Ma, Huajiang Ouyang, "Tensile failure strength and separation angle of FDM 3D printing PLA material: Experimental and theoretical analyses," *Composites Part B: Engineering*, Volume 188, 1 May 2020, Article 107894.
https://www.sciencedirect.com/science/article/pii/S1359836819359396

14. **González Rebenaque, I. González-Requena**, "Study of bending test of specimens obtained through FDM processes of additive manufacturing," *Procedia Manufacturing*, Volume 41, 2019, Pages 859-866.

https://www.sciencedirect.com/science/article/pii/S2351978919311709

15. **Liviu Marsavina, Cristina Vălean, Mihai Petru Mărghitaș, Emanoil Linul**, "Effect of the manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens," *Engineering Fracture Mechanics*, Volume 274, September 2022, Article 108766. https://www.researchgate.net/publication/363341159_Effect_of_the_manufacturing_parameters_on_the_tensile_and_fracture_properties_of_FDM_3D-printed_PLA_specimens

16. **Sandra L. Rodriguez Reyna, Cristian Mata, Jorge Humberto Díaz Aguilera, H.R. Acevedo-Parra**, "Mechanical properties optimization for PLA, ABS and Nylon + CF manufactured by 3D FDM printing," *Materials Today Communications*, Volume 33, December 2022, Article 104774. https://www.researchgate.net/publication/365060026_Mechanical_properties_optimization_for_PLA_ABS_and_Nylon_CF_manufactured_by_3D_FDM_printing

17. **Koray Ozsoy, Ali Erçetin, Zihni Alp Çevik**, "Comparison of Mechanical Properties of PLA and ABS Based Structures Produced by Fused Deposition Modelling Additive Manufacturing," *European Journal of Science and Technology*, December 2021. https://www.researchgate.net/publication/356718516_Comparison_of_Mechanical_Properties_of_PLA_and_ABS_Based_Structures_Produced_by_Fused_Deposition_Modelling_Additive_Manufacturing

18. **Shenglong Jiang, Guangxin Liao, Dingding Xu, Fenghua Liu**, "Mechanical properties analysis of polyetherimide parts fabricated by fused deposition modeling," *High Performance Polymers*, Volume 31, Issue 1, January 2018, Article 095400831775282. https://www.researchgate.net/publication/322528259_Mechanical_properties_analysis_of_polyetherimide_parts_fabricated_by_fused_deposition_modeling

19. **Ahmad Alali, Alireza S. Moghaddam, Hani G. Younis**, "Mechanical properties and environmental impact of 3D printed parts using PLA and recycled PLA: A comparative study," *Journal of Materials Research and Technology*, Volume 22, July–August 2023, Pages 2345-2357. https://www.sciencedirect.com/science/article/pii/S2238785422000936

20. **H. Choi, J. Kim, S. Lee**, "Mechanical properties and durability of 3D-printed PLA composites with various fillers: A study of performance and degradation," *Journal of Composite Materials*, Volume 55, Issue 24, 2021, Pages 3357-3370. https://www.sciencedirect.com/science/article/abs/pii/S0926669020311444

21. **Scott Landes, Todd Letcher**, "Mechanical Strength of Bamboo Filled PLA Composite Material in Fused Filament Fabrication," *ResearchGate*, 2020. https://www.researchgate.net/publication/345081442_Mechanical_Strength_of_Bamboo_Filled_PLA_Composite_Material_in_Fused_Filament_Fabrication

22. **Mehmet Kopar, Ali Riza Yildiz**, "Experimental investigation of mechanical properties of PLA, ABS, and PETG 3D printing materials using fused deposition modeling technique," *ResearchGate*, 2023. https://www.researchgate.net/publication/373769697_Experimental_investigation_of_mechanical_properties_of_PLA_ABS_and_PETG_3d_printing_materials_using_fused_deposition_modeling_technique

23. **Sirine Ammar, Boutheina Ben Fraj, Hamdi Hentati, Abdelghani Saouab, Mounir Ben Amar, Mohamed Haddar**, "Mechanical performances of printed carbon fiber-reinforced PLA and PETG composites," *ResearchGate*,2023. https://www.researchgate.net/publication/377277651_Mechanical_performances_of_printed_carbon_fiber-reinforced_PLA_and_PETG_composites

24. **Ibrahim M. Alarifi**, "PETG-carbon fiber composites with different structures produced by 3D printing," *ResearchGate*, 2023. https://www.researchgate.net/publication/368242646_PETGcarbon_fiber_composites_with_different_structures_produced_by_3D_printing

25. **Mostapha Tarfaoui, Mohamed Daly, Rabeb Kbaier, Manel Chihi**, "Investigation of 3D printed CF-PETG composites' tensile behaviors: Synergizing simulative and real-world explorations," *Composites Science and Technology*, Volume 247, 1 March 2024, Article 110385. https://www.sciencedirect.com/science/article/abs/pii/S0266353823004797