Investigation on effect of process parameters on FDM fabricated specimen using natural composite feedstock material

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Abstract

Additive Manufacturing (AM), commonly known as 3D printing, has transformed the manufacturing industry by enabling the rapid production of intricate and customized parts. While AM has primarily utilized polymers and metals as printing materials, recent advancements have unveiled the potential of composite materials for additive manufacturing applications. Composites offer a unique combination of properties, including a high strength-to-weight ratio, excellent mechanical performance, and enhanced functionality, which make them highly appealing to various industries. However, there are challenges associated with composite additive manufacturing, such as material selection, process optimization, interfacial bonding, and post-processing techniques. This study aims to address these issues by introducing bagasse-fabricated composite feedstock in the extrusion-based AM process, specifically the Fused Deposition Modeling (FDM) process. The study investigates the influence of process parameters, such as fiber orientation and fiber weight in the feedstock material, on the FDM technique. The study encompasses the complete fabrication process of the feedstock material, starting from plate preparation to filament fabrication, while considering two crucial process parameters: fiber orientation and fiber weight. The results indicate that lower fiber orientation and higher fiber weight exhibit superior mechanical properties. The experimental findings are validated through thermal characterization using Differential Scanning Calorimetry (DSC). Furthermore, this work proposes the development of an expert system to assist future designers in the field. This system will provide valuable guidance and insights based on the knowledge and experience gained from this study. In conclusion, this study explores the utilization of composite materials in additive manufacturing, focusing on the FDM process. By introducing bagasse-fabricated composite feedstock and investigating the effects of fiber orientation and weight, the study offers valuable insights into optimizing the additive manufacturing process for composite materials. The experimental results, complemented by thermal characterization, demonstrate the potential of the proposed approach. The development of an expert system further extends the impact of this work, providing a valuable resource for future designers in the field of composite additive manufacturing.

Keywords: FDM; Composite Materials; Natural Fibre in AM; AM; FFF

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, has revolutionized the manufacturing industry by enabling the fabrication of complex geometries with high precision and customization [1-3]. While AM has primarily utilized polymers and metals, recent advancements have explored the incorporation of composite materials, offering enhanced properties and functionality [4-13]. The present section provides an overview of the utilization of composite materials in additive manufacturing processes, covering various aspects such as types of composites, additive manufacturing techniques, challenges, and applications [14-17]. The utilization of composite materials in AM has opened up new possibilities for advanced manufacturing processes. The application areas for composite materials in AM are extensive and diverse [18-21]. In aerospace industries, the lightweight and high-strength properties of composite materials offer opportunities for fabricating complex structural components [22]. In the biomedical field, biocompatible composites can be used to produce patient-specific implants with improved mechanical compatibility and biological functionality [23]. Moreover, composite materials have shown promise in the production of functional electronics, energy storage devices, and even architectural structures [24]. Composite materials, composed of two or more distinct constituents, offer superior mechanical, thermal, and electrical properties compared to traditional materials [25]. These properties make them highly attractive for a wide range of applications, including aerospace, automotive, and biomedical industries. Composite materials used in additive manufacturing encompass a range of configurations. Fiber-reinforced composites, such as carbon fiber-reinforced polymers (CFRP), provide high strength-to-weight ratios and excellent mechanical properties [26]. Particulate composites, incorporating fillers or reinforcements like ceramics or metal powders into a polymer matrix, offer enhanced thermal and electrical conductivity as fiber-reinforced composites, such as carbon fiber-reinforced polymers (CFRP), provide high strength-to-weight ratios and excellent mechanical properties [27]. Nano-composites, where nanoparticles are dispersed within a matrix, enable improvements in mechanical, thermal, and barrier properties [28]. Composite materials used in additive manufacturing encompass a range of configurations. Fiber placement techniques, such as automated fiber placement (AFP) and continuous fiber printing, allow for precise control over fiber orientation and volume fraction, resulting in improved mechanical performance [29]. Most of composites, incorporating fillers or reinforcements like ceramics or metal powders into a polymer matrix, offer enhanced thermal and electrical conductivity. Nano-composites, where nanoparticles are dispersed within a matrix, enable improvements in mechanical, thermal, and barrier properties. Several additive manufacturing techniques have been employed for fabricating composite parts. Composite materials used in AM exhibit a wide range of properties depending on the constituents and their distribution within the matrix. The mechanical properties, such as strength, stiffness, and toughness, can be tailored by adjusting the composition and orientation of the reinforcing fibers [30]. Fused Filament Fabrication (FFF) is commonly used, where continuous fibers or chopped fibers are embedded in a polymer matrix during the printing process [31]. Stereolithography (SLA) utilizes photopolymerization to create composites with precise details and smooth surfaces [32]. Selective Laser Sintering (SLS) allows for the fabrication of complex geometries by selectively melting polymer powders with embedded reinforcements [33]. Binder Jetting involves the deposition of powdered composite materials, followed by the application of a binder to bind the particles together [34]. Composite additive manufacturing presents certain challenges that need to be addressed for successful implementation. One crucial consideration is the interfacial bonding between the fibers and the matrix, as it influences the overall strength and performance of the composite [35]. Optimizing printing parameters, including layer thickness, infill density, and print speed, is essential to achieve desired mechanical properties and surface finish [36]. Post-processing techniques, such as heat treatment and surface finishing, play a vital role in enhancing the final properties and aesthetics of the composite parts [37]. Composite additive manufacturing has found applications in various industries. In the aerospace sector, lightweight and high-strength composite components are being produced for aircraft and spacecraft applications [38].

The automotive industry is exploring the use of composites in printed car parts to achieve weight reduction and improve fuel efficiency [39]. The healthcare field is benefiting from composite-based medical devices with tailored properties and improved biocompatibility [40]. Additionally, consumer goods, sporting equipment, and architecture are other domains witnessing the integration of composite additive manufacturing. Accurate characterization of composite materials is crucial for evaluating their performance in AM. Various techniques, including scanning electron microscopy (SEM), X-ray diffraction (XRD), and mechanical testing, are commonly employed. SEM allows for the visualization of the composite microstructure, providing insights into the distribution and alignment of the reinforcing fibers [41]. XRD analysis helps identify the crystal structure and phase composition of the composite, aiding in understanding its thermal and mechanical behavior [42]. Mechanical testing, such as tensile and flexural tests, assesses the strength and deformation properties of the composite material [43-45].

The abovementioned literature study has highlighted the potential of composite materials in additive manufacturing processes. By incorporating different types of composites and utilizing appropriate additive manufacturing techniques, manufacturers can leverage the benefits of improved mechanical performance, lightweight designs, and functional versatility. However, challenges related to interfacial bonding, process optimization, and post-processing techniques need to be addressed to fully exploit the capabilities of composite additive manufacturing. Further research and advancements in materials, process parameters, and industrial applications are expected to drive the widespread adoption of composite materials in additive manufacturing. Hence the material selection is becoming a key instrument into the industries as polymer have longer degradation time and there is need to utilize more and more natural sources into the AM techniques. However, the major issues that application of natural composite in AM is not treated in much detail. As per author’s knowledge there is few studies are presented on investigation on the composite materials in AM and designing an expert system for developing a prediction model. To address the same, present work is carried out detailed study on effect of two process parameters i.e., Fibre orientation and Fibre weight on mechanical properties of feedstock material prepared for FDM technique.

2. Materials and Methods

2.1 Natural composite plate preparation

In the present work, Bagasse natural fibre is used for preparing a feedstock material for FDM process. As per mentioned in above literature review, for the present study the two process parameters i.e., fibre orientation and fibre weight are considered. For the plate preparation, Design of Experiment (DoE) method is considered for the present work. The parameter settings/ranges for the present work is as mentioned in Table 1.

FDM Process Parameters	**Units**	**Levels**		
		-1	**0**	**+1**
Fibre Orientation	°	0	45	90
Fibre Weights	Grams	10	55	100

Table 1. DOE factor levels and ranges of process parameters

For the plate preparation (as mentioned in Figure 1), The hand layup technique was employed to fabricate hybrid composite plates, utilizing E-glass/bagasse fibers as the reinforcement and unsaturated polyester resin GP-7150 as the matrix. Various mechanical tests were conducted to evaluate the properties of these plates. The composite material was prepared using bagasse fibers in random chopped form, both in dry and chemically treated states. Among the different chemical treatments, alkaline treatment was widely adopted, aiming to enhance surface roughness.

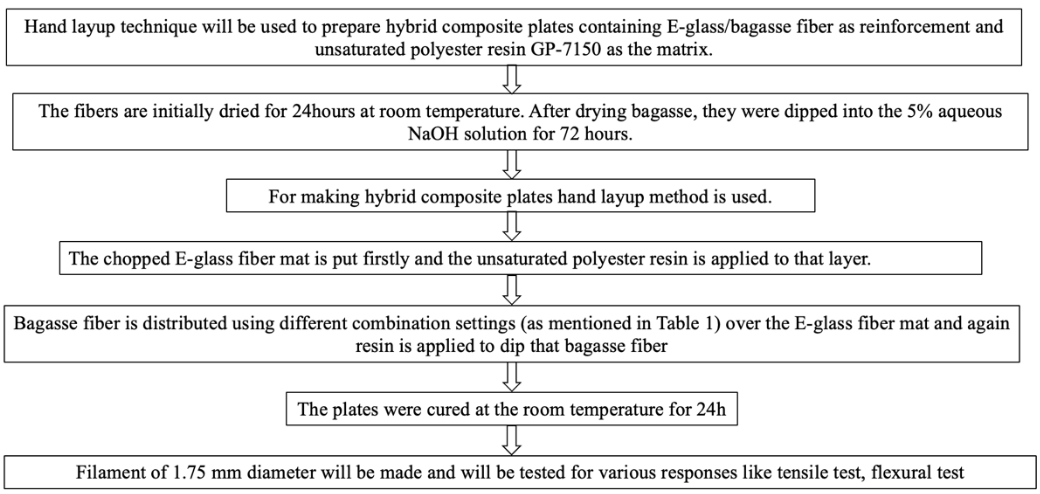


Fig. 1 Composite plate preparation steps for proposed work

In its natural form, bagasse contains wax, lignin, and oils on its outer surface, which hinder the bonding between the resin and the fiber. Alkaline treatment effectively removes a portion of these substances. To prepare the bagasse fibers for composite production, they underwent a drying process at room temperature for 24 hours. Subsequently, the dried bagasse fibers were immersed in a 5% aqueous NaOH solution for 72 hours to undergo chemical treatment. Add filler material if required to epoxy resin and mix it with the help of glass rod uniformly. Here 4 % of Titanium dioxide (TiO2) is added with respect to weight of epoxy resin. Now take 10 % of Hardener with respect to weight of epoxy taken. Hardener should be added after the addition of filler material in epoxy resin. The fabrication of hybrid composite plates will be carried out using the hand layup method. Initially, a layer of chopped E-glass fiber mat will be placed, followed by the application of unsaturated polyester resin. Subsequently, the bagasse fiber will be distributed and oriented at 0°, 45°, and 90° over the E-glass fiber mat, and resin will be applied to impregnate the bagasse fibers. Then, another layer of E-glass fiber mat will be placed on top of the bagasse layer, and resin will be applied once again. Following this process, the plates will be cured at room temperature for 24 hours. For this study, composite plates will be fabricated with different orientations of bagasse fiber, while maintaining a constant proportion of E-glass fiber and polyester resin, steps for the same are as illustrated in Figure 2.

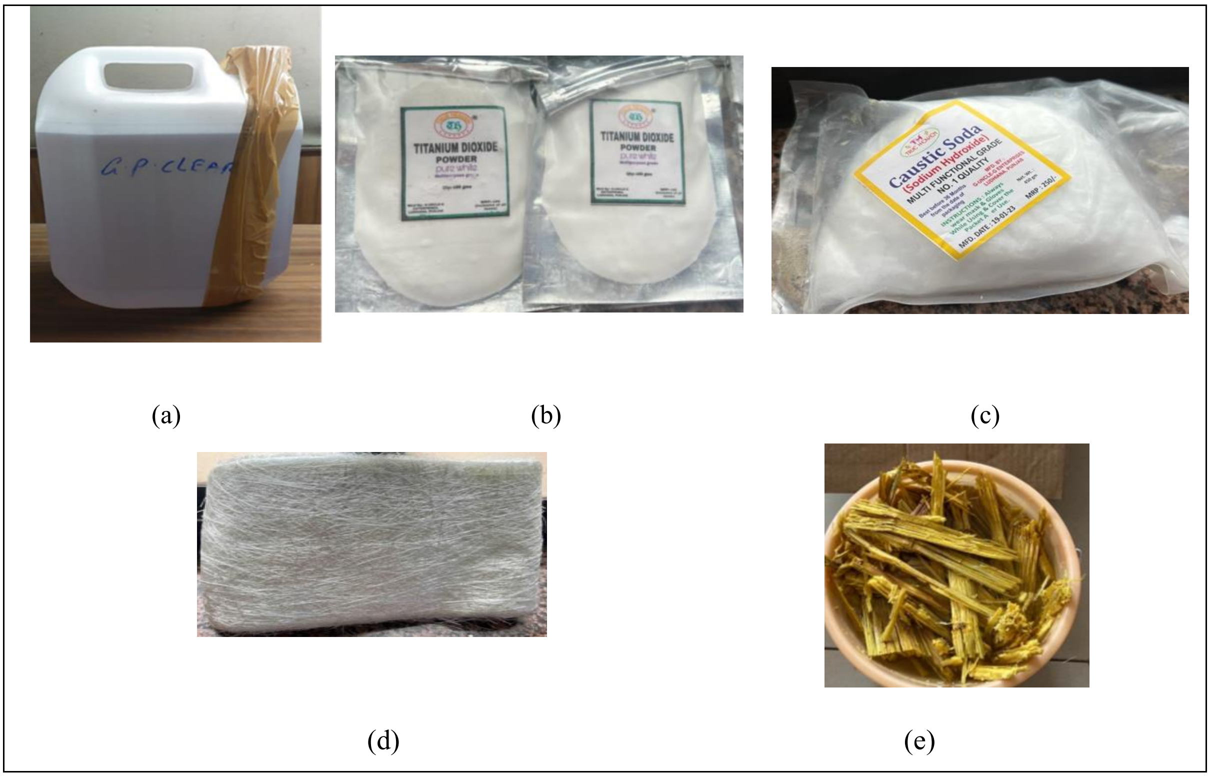


Fig. 2 Composite plate preparation chemicals: (a) GP Resin (b) Titanium Dioxide (c) Sodium Hydroxide (d) Fibre Plate or Fibre Glass (e) Socked in sodium hydroxide

2.2 *Natural composite feedstock preparation*

In the present work, the natural composite i.e., bagasse is used to fabricate the plates. For the fabrication of the feedstock material, there are steps in preparation of the feedstock preparation as mentioned below:

2.2.1. Preparation of the pellets: In the present work, the composite plate is crushed using plastic pelletizing process (the specification of the crusher is as mentioned in the Table 2). The Pellets is prepared by the size of 21-20 cm (as a granule diameter).

Granule Diameter (cm)	**Machine Dimensions (cm)**	**Machine Weight (kg)**	**Working Capacity (kg/Hr)**
21-20	70*45*115	250	30-40

Table 2. Plastic Pelletizing Machine Specification

2.2.2. Preparation for feedstock wire: As in FDM process, the melting temperature of the feedstock wire material plays an essential role hence to identify and evaluate the thermal characteristics of the bagasse composite material. Differential Scanning Calorimetry (DSC) is a widely used technique for analyzing the thermal behavior of materials. It provides valuable insights into the thermal transitions, such as melting, crystallization, glass transition, and thermal stability of various materials. DSC testing offers a wide range of applications in materials science, polymer research, pharmaceuticals, food science, and other fields. It provides valuable data for material characterization, quality control, and formulation development. Differential Scanning Calorimetry (DSC) is a thermal analysis technique that measures the heat flow into or out of a sample as a function of temperature or time. The principle behind DSC involves comparing the heat flow to a reference material, allowing the determination of endothermic or exothermic processes occurring within the sample. During a DSC test, the sample and reference material are subjected to controlled heating or cooling rates within a hermetically sealed chamber. As the temperature changes, the instrument measures the heat flow required to maintain the sample and reference at the same temperature. Any temperature difference between the sample and reference generates a signal, which is recorded and plotted as a DSC curve. DSC can provide valuable information about a material's thermal behavior. Some common applications of DSC include:

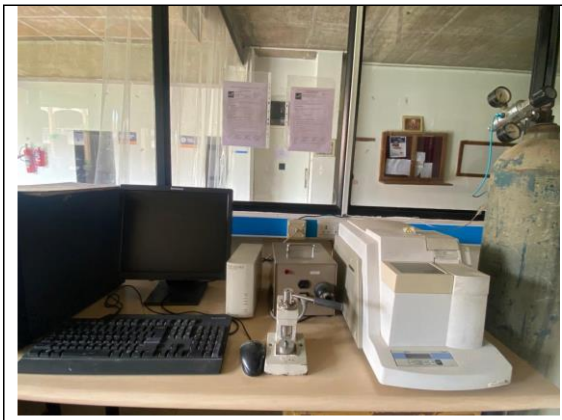
(a) Melting and Crystallization Behavior: DSC can determine the melting point and heat of fusion of a material, providing insights into its phase transitions and crystallinity. The onset and peak temperature of melting or crystallization can be determined from the DSC curve.

(b) Glass Transition Temperature (T_g): DSC is widely used to measure the Tg of polymers and other amorphous materials. The T_g represents the transition from a glassy state to a rubbery or viscous state, and it affects material properties like flexibility, brittleness, and processing conditions.

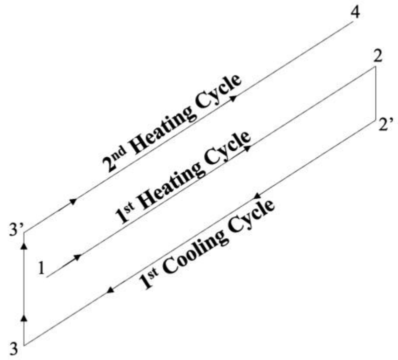
(c) Chemical Reactions and Curing: DSC can detect exothermic or endothermic reactions, such as polymerization, curing, or decomposition. The heat flow associated with these reactions provides information about reaction kinetics, curing time, and reaction enthalpy.

(d) Thermal Stability and Oxidation: DSC can evaluate the thermal stability of materials by measuring the temperature at which decomposition or oxidation occurs. This information is crucial for assessing the suitability of materials in high-temperature applications.

In the present work, Differential Scanning Calorimetry (DSC) technique is used to study the thermal characterization of the proposed natural composite material. The DSC setup and working cycle for the proposed work is as mentioned in the Figure 3.



(a)



(b)

Fig. 3 (a) DSC setup (b)DSC cycle for thermal characterization

2.3 Expert system designing using neural network approach

Neural networks have been applied in additive manufacturing for process modeling, including predicting process parameters, optimizing build orientations, and simulating thermal behavior. By training neural networks on historical process data, accurate models can be developed to optimize process parameters and improve part quality (Jin et al., 2021). Neural networks are used for predicting part quality based on process parameters, material properties, and design characteristics. By leveraging historical data, neural networks can estimate the likelihood of defects, warpage, and mechanical properties, enabling proactive quality assurance (Zhang et al., 2020).

Neural networks are powerful tools in the field of machine learning, enabling us to solve complex problems and make accurate predictions. In the present work, MATLAB is used for creating ANN based expert system. MATLAB provides a user-friendly environment for developing and implementing neural networks. There are followed mentioned steps are used for building a neural network in MATLAB:

(i) Data Preparation:

To start, we need to prepare the training data. Consider an example where we have input data X and corresponding target outputs Y. X represents the input features, and Y represents the desired output for each input sample.

(ii) Neural Network Architecture:

Next, we define the architecture of our neural network. In MATLAB, we typically create a feedforward neural network with an input layer, one or more hidden layers, and an output layer. The number of neurons in each layer depends on the problem at hand. For simplicity, let's create a neural network with one hidden layer.

(iii) Initialization of Network Parameters:

Once the architecture is defined, we initialize the network parameters. This involves randomly initializing the weights and biases of the neural network. The weights determine the strength of connections between neurons, and the biases provide an offset to the neuron activations.

(iv) Training the Neural Network:

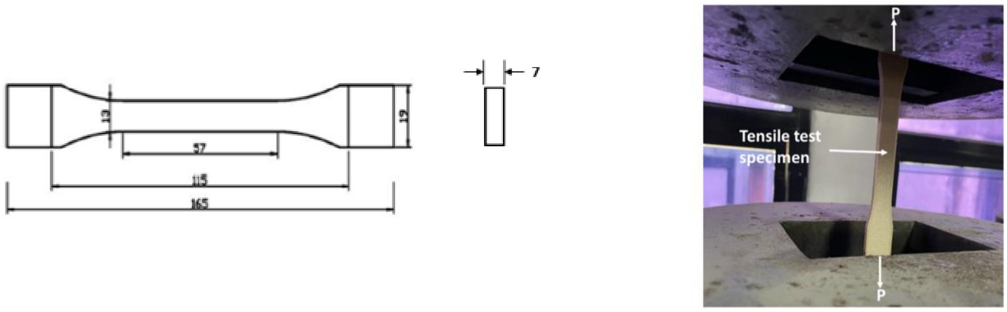
In MATLAB, we can use various optimization algorithms, such as stochastic gradient descent (SGD) or Adam, to train the neural network. During training, we iteratively adjust the network parameters to minimize the difference between the predicted output and the desired output. This process involves forward propagation, where the input data is passed through the network, and backpropagation, where the gradients are calculated and used to update the parameters.

(v) Testing and Evaluation:

Once the neural network is trained, we evaluate its performance on unseen data. We provide test inputs to the network and compare the predicted outputs with the actual outputs. Performance metrics such as accuracy, precision, and recall can be calculated to assess the network's effectiveness.

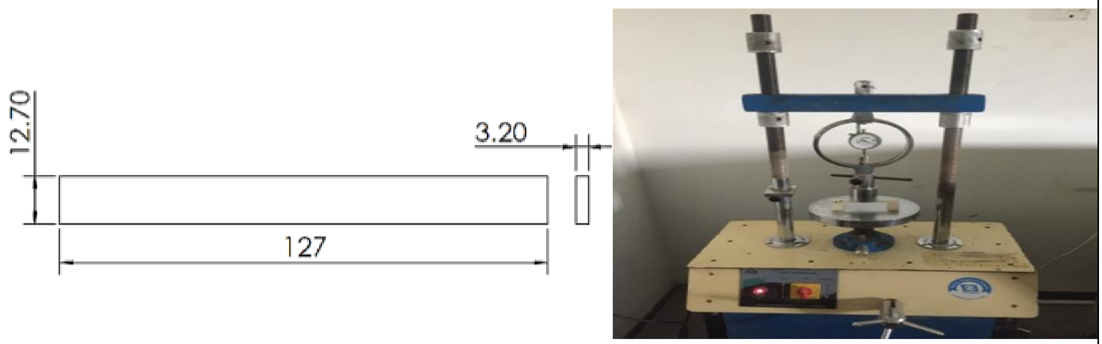
(vi) Deployment and Application:

After thorough testing and evaluation, the trained neural network can be deployed for real-world applications. MATLAB provides tools to integrate the neural network into larger systems, making it usable in various domains such as image classification, speech recognition, or time series prediction.



(a) (b)

Fig. 4 (a) Tensile test specimen as per ASTM D638 type I (b) Specimen in Tensile test apparatus



(a) (b)

Fig. 5 (a) Flexural test specimen as per ASTM D790 type I (b) Specimen in Flexural test apparatus

In the present work, two input nodes are considered i.e., fibre orientation and fibre weight and two output nodes i.e., tensile strength and flexural strength for sample as shown in Figure 4 and Figure 5. The ANN architecture used for the present work is considered as 2:8:4:2 (Figure 6). The experimental results achieved are used to train the ANN model and design to predict the future results.

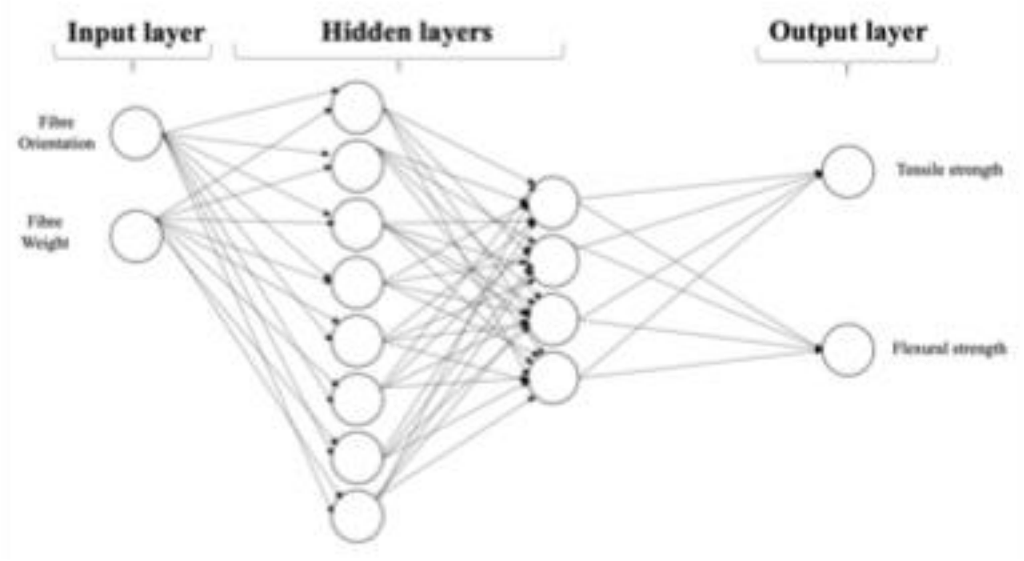


Fig. 6 ANN Architecture (2:8:4:2)

3. Results and Discussion

In the present work the material is prepared using bagasse fibre and feedstock material for FDM process is manufactured. For processing any new material into FDM as a feedstock material, it is essential to evaluate the thermal properties of that material. Hence the thermal properties of the prepared pellets are measured using Differential Scanning Calorimetry (DSC) method.

Run	Fibre orientation (°)	Weight of fibre (grams)	Melting Point (°C)
1	90	100	210
2	90	55	208
3	45	10	205
4	45	55	215
5	90	10	200
7	0	10	220
8	0	55	212
9	45	55	216
10	45	100	218

13	0	100	235

Table 3. FCCCD Schema for mechanical properties measurement

The melting temperature of the plates are evaluated using the DSC testing. The DSC curves are mentioned into Fig. 8 for the non-centric runs of FCCCD schema. DSC curves shows the melting temperature and glass transition temperature for each non-centric run of FCCCD schema table. Table 3 represents the melting point for each combination of proposed FCCCD schema that temperature used to extruded and produce wire filaments (as a feedstock material) using Filabot extruder machine. The filaments requirement for producing tensile specimen (as per ASTMD638) and flexural specimen (as per ASTMD790) is measured using commercially available slicing software CURA® as mentioned into Table 4. Hence the Filabot extruder is used to extrude the wire filaments of respective length. Using the extruded filament, the specimens are manufactured as per proposed schema and the mechanical properties are evaluated as mentioned into Table 5. The results shows that higher mechanical properties (tensile strength and flexural strength) are achieved at lower part orientation (0°) and higher fibre weight (100 grams).

Tensile Strength (meter)	**Flexural Strength (meter)**
1.65	1.45

Table 4. Feedstock requirement for tensile and flexural specimen

The possible reason for the same is the bonding between the strands during FDM process.

Run	**Fibre orientation (°)**	**Weight of fibre (grams)**	**Tensile strength (MPa)**	**Flexural strength (MPa)**
1	90	100	16.4552	15.13878
2	90	55	13.7015	12.60538
3	45	10	18.6059	17.11743
4	45	55	20.7566	19.09607
5	90	10	9.7485	8.96862
6	45	55	24.1066	22.17807
7	0	10	23.2155	21.35826
8	0	55	26.0496	23.96563

9	45	55	24.6426	22.67119
10	45	100	26.1233	24.03344
11	45	55	23.9659	22.04863
12	45	55	24.4885	22.52942
13	0	100	32.5285	29.92622

Table 5. FCCCD Schema for Mechanical Properties (Tensile Strength & Flexural Strength) measurement

The statistical stability of the obtained results is also studied with Analysis of Variance (ANOVA). Table 6 and Table 7 mentioned the ANOVA for Tensile and Flexural strength respectively. As shown in Table 6 for tensile strength ANOVA, 112.55 F-value obtained from the analysis indicates that the model is statistically significant. The actual R2 value of 97.40% suggests that the model explains 97.40% of the total variation in the data. The adjusted R2 value, which is 96.54%, indicates that 96.54% of the total variability is accounted for by the model, considering the number of variables and samples. The predicted R2 value of 93.30% suggests that 93.30% of the variability is expected to be explained by the model when applied to future data. The small difference between the actual R2 (0.9740) and the predicted R2 (0.9330) or adjusted R2 (0.9654), which is less than 0.3, indicates that the model is capable of representing the larger population.

Source	**Sum of Squares**	**df**	**Mean Square**	**F-Value**	**P-value**		**Contribution (%)**
Model	617.26	3	205.75	112.54	< 0.0001	significant	
A-Fibre Orientation	572.04	1	572.04	312.90	< 0.0001		90. 26
B-Fibre Weight	34.54	1	34.54	18.89	0.0019		5.45
AB	10.68	1	10.68	5.84	0.0388		1.685
Residual	16.45	9	1.83				
Lack of Fit	13.18	5	2.64	3.22	0.1399	not significant	
R- Squared				0.9740			
Adj R- Squared				0.9654			
Pred R- Squared				0.9330			

Table 6. ANOVA table for Tensile Strength

Source	Sum of Squares	df	Mean Square	F-Value	P-value		Contribution (%)
Model	1154.40	3	166.66	105.16	< 0.0001	significant	
A-Fibre Orientation	933.79	1	463.35	170.12	< 0.0001		77.21
B-Fibre Weight	220.60	1	27.98	40.19	0.0019		18.24
Residual	1154.40	9	1.48				
Lack of Fit	933.79	5	2.14	3.22	0.1399	not significant	
R- Squared				0.9516			
Adj R- Squared				0.9455			
Pred R- Squared				0.9061			

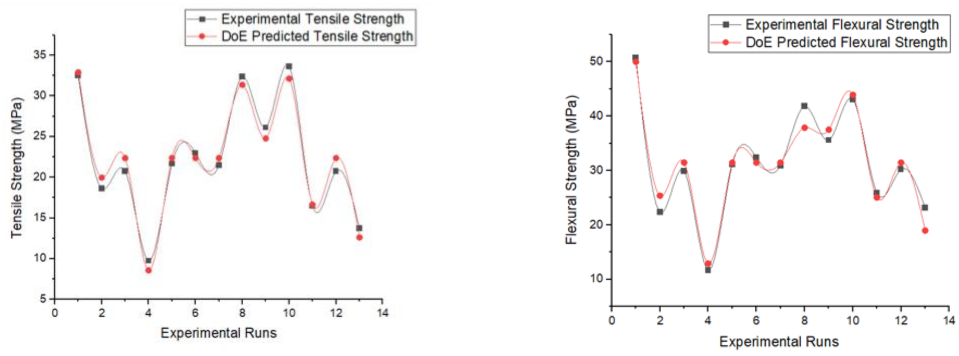
Table 7. ANOVA table for Flexural Strength

This suggests that the model is reliable and can be generalized beyond the specific data used for its development. Furthermore, the lack of fit value (0.1399) is not statistically significant, indicating that the proposed model fits the experimental data well. This implies that the parameters included in the model have a substantial impact on the response variable, providing meaningful insights into the relationship between the variables. The obtained experimental results are further used to design an expert system using Artificial Neural Network (ANN) approach. The Back Propagation Neural Network (BPNN) is considered for the present work.

Run	Fibre orientation (°)	Weight of fibre (grams)	Experimental Values		ANN Values	
			Tensile strength (MPa)	Flexural strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)
1	90	100	16.4552	15.13878	15.5432	15.02878
2	90	55	13.7015	12.60538	12.7895	12.49538
3	45	10	18.6059	17.11743	17.6939	17.00743
4	45	55	20.7566	19.09607	19.8446	18.98607
5	90	10	9.7485	8.96862	8.8365	8.85862

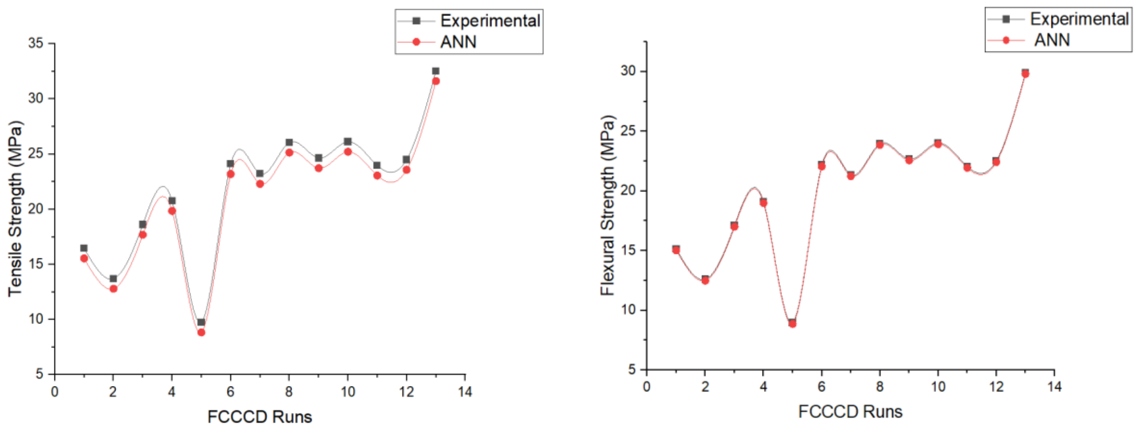
6	45	55	24.1066	22.17807	23.1946	22.06807
7	0	10	23.2155	21.35826	22.3035	21.24826
8	0	55	26.0496	23.96563	25.1376	23.85563
9	45	55	24.6426	22.67119	23.7306	22.56119
10	45	100	26.1233	24.03344	25.2113	23.92344
11	45	55	23.9659	22.04863	23.0539	21.93863
12	45	55	24.4885	22.52942	23.5765	22.41942
13	0	100	32.5285	29.92622	31.6165	29.81622

Table 8. ANN and Experimental values of Tensile and Flexural Strength comparison



(a) (b)

Fig. 10 Comparison Graph between (a) Experimental Tensile Strength vs. Actual Tensile Strength (b) Experimental Flexural Strength vs. Actual Flexural Strength



(a) (b)

Fig. 11 Comparison Graph between (a) Experimental Tensile Strength vs. ANN Tensile Strength (b) Experimental Flexural Strength vs. ANN Flexural Strength

Table 8 illustrates the ANN values for various combinations of FCCCD schema. As mentioned into Figure 7 and Figure 8, the results obtained from ANN are in efficient agreement with experimental values of Tensile strength and Flexural strength.

4. Conclusion

The present study has explored the significant role of composite materials in additive manufacturing, highlighting their immense potential for revolutionizing various industries. By combining the advantages of both composites and additive manufacturing, new possibilities for designing and fabricating complex structures with enhanced properties have emerged. Through an analysis of the existing literature and case studies, it is evident that composite materials offer numerous advantages in additive manufacturing processes. The present work comprises of evolution of the effect of fibre orientation and fibre weight on mechanical properties i.e., Tensile strength and Flexural strength. The study also utilizes thermal characterization technique i.e., Differential Scanning Calorimetry (DSC) for identify the thermal properties of newly developed material using bagasse composite material. Using the DSC results, the feedstock wire for FDM is utilized for manufacturing the specimen as per ASTM standards for tensile strength and flexural strength. The experimental results shows that lower fibre orientation and higher fibre weight results in higher mechanical properties. The experimental results are further used to design an expert system using Artificial Neural Network (ANN) approach. The results obtained from ANN are in good agreement with the experimental results. However, challenges remain in the widespread adoption of composite materials in additive manufacturing. Issues such as material compatibility, process optimization, and post-processing techniques need to be addressed to ensure consistent and reliable fabrication of composite-based components.

Funding and/or Conflicts of interests/Competing interests

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

[1] Rane, K., Strano, M. A comprehensive review of extrusion-based additive manufacturing processes for rapid production of metallic and ceramic parts. *Adv. Manuf.* **7**, 155–173 (2019). https://doi.org/10.1007/s40436-019-00253-6

[2] Gonzalez-Gutierrez J, Cano S, Schuschnigg S et al (2018) Additive manufacturing of metallic and ceramic components by the material extrusion of highly-filled polymers: a review and future perspectives. Materials 11(5):840. https://doi.org/10.3390/ma11050840

[3] Stavropoulos P, Foteinopoulos P (2018) Modelling of additive manufacturing processes: a review and classification. Manuf Rev 5(2):1–26

[4] Chia, H. N., & Wu, B. M. (2015). Recent advances in 3D printing of biomaterials. Journal of Biological Engineering, 9(1), 4. doi: 10.1186/s13036-015-0001-4

[5] Yadroitsev, I., Gusarov, A., Yadroitsava, I., & Smurov, I. (2010). Single track formation in selective laser melting of metal powders. Journal of Materials Processing Technology, 210(12), 1624-1631. doi: 10.1016/j.jmatprotec.2010.05.010

[6] Song, X., & Liu, L. (2019). Ceramic additive manufacturing: Developments and prospects. Engineering, 5(4), 589-601. doi: 10.1016/j.eng.2019.03.011

[7] Zhang, D., & Zeng, X. (2018). Additive manufacturing of polymer composites: Processing, morphologies, properties and applications. Materials Science and Engineering: R: Reports, 132, 1-27. doi: 10.1016/j.mser.2018.07.001

[8] Ventola, C. L. (2014). Medical applications for 3D printing: Current and projected uses. P&T, 39(10), 704-711.

[9] Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., & Gibb, A. G. (2012). Developments in construction-scale additive manufacturing processes. Automation in Construction, 21, 262-268. doi: 10.1016/j.autcon.2011.06.005

[10] Gibson, I., Rosen, D. W., & Stucker, B. (2014). Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer.

[11] Huang, Y., Leu, M. C., & Mazumder, J. (2015). Additive manufacturing: current state, future potential, gaps and needs, and recommendations. Journal of Manufacturing Science and Engineering, 137(1), 014001.

[12] Melchels, F. P., Domingos, M. A., Klein, T. J., Malda, J., Bartolo, P. J., & Hutmacher, D. W. (2012). Additive manufacturing of tissues and organs. Progress in Polymer Science, 37(8), 1079-1104.

[13] Jia, Z., Li, D., Jiang, W., & Zhang, Y. (2017). Additive manufacturing of fiber reinforced polymer composite materials: status, opportunities, and challenges. Composites Part B: Engineering, 110, 442-458.

[14] Bai, S., & Sun, C. (2018). Composite materials for 3D printing. MRS Bulletin, 43(9), 689-697.

[15] Wang, C., Gardner, D. J., & Kim, B. J. (2018). Reinforcement materials for 3D printing: state of the art and future outlook. Journal of Materials Science, 53(16), 11985-12007.

[16] Bellini, A., & Güçeri, S. I. (2019). Composite materials for additive manufacturing. In Additive Manufacturing: Materials, Processes, Quantifications, and Applications (pp. 333-363). Springer.

[17] Garcia, E. J., & Medina, F. (2021). Additive manufacturing of continuous fiber-reinforced polymer composites. Materials Today, 45, 86-102.

[18] Campbell, I., Bourell, D., & Gibson, I. (2012). Additive manufacturing: rapid prototyping comes of age. Rapid Prototyping Journal, 18(4), 255-258.

[19] Dickens, P. M., Dapino, M. J., & Singh, C. V. (2020). Additive manufacturing in the automotive industry. In Additive Manufacturing for the Aerospace Industry (pp. 175-194). Elsevier.

[20] Sniderman, Z., & Narayan, R. (2016). Additive manufacturing in aerospace: examples and research outlook. Journal of Manufacturing Science and Engineering, 138(8), 081002.

[21] Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., ... & Wang, C. C. (2015). The status, challenges, and future of additive manufacturing in engineering. Computer-Aided Design, 69, 65-89.

[22] Vilar R (2014) Laser powder deposition. comprehensive materials processing 2014. Adv Addit Manuf Tooling 10:163–216.

[23] Zhang, X., Zhang, L., Chen, J., & Li, D. (2021). Progress in 3D-printing for biomedical applications. J. Mater. Res. Technol, 14, 1430-1450.

[24] Singh, R., Yadav, A., Kumar, A., & Kumar, D. (2023). An overview of 3D-printing: Materials, methods, and applications. Materials Today: Proceedings, 57, 619-625.

[25] Huang, Y., Leu, M. C., & Mazumder, J. (2018). Additive manufacturing: Current state, future potential, gaps and needs, and recommendations. Journal of Manufacturing Science and Engineering, 140(8), 1-19.

[26] Chen, Z., Huang, Y., Wang, W., Ma, X., Wang, D., & Shi, Y. (2017). Mechanical behavior of carbon fiber-reinforced polymer composites prepared by additive manufacturing. Materials & Design, 120, 263-273.

[27] Bikas, H., Stavropoulos, P., & Chryssolouris, G. (2016). Additive manufacturing methods and modeling approaches: A critical review. International Journal of Advanced Manufacturing Technology, 83(1-4), 389-405.

[28] Zhang, W., Wang, L., Huang, Y., Zhang, Y., & Zhang, L. (2018). Additive manufacturing of ceramic matrix composites: A review. Journal of the European Ceramic Society, 38(6), 2065-2087.

[29] Matriz, B., García, E., & Rodriguez, P. (2020). Fiber reinforced composites produced by additive manufacturing: Challenges and opportunities. Composites Part B: Engineering, 192, 108024.

[30] Hofstätter, T., Grasl, C., & Stampfl, J. (2021). 3D-printing of fiber reinforced composites: A review on the process, materials, and mechanical properties. Composites Part B: Engineering, 208, 108618.

[31] Vaezi, M., Seitz, H., & Yang, S. (2013). A review on 3D micro-additive manufacturing technologies. The International Journal of Advanced Manufacturing Technology, 67(5-8), 1721-1754.

[32] Domingo-Espin, M., Puigoriol-Forcada, J. M., & Garcia-Granada, A. A. (2017). Stereolithography as an alternative to manufacture composite parts with complex shapes. Composites Part B: Engineering, 128, 162-169.

[33] Ma, Z., Wang, D., Yin, Z., Li, S., & Yan, Y. (2018). Review on 3D printing of polymer matrix composites. Composites Part B: Engineering, 137, 260-276.

[34] Sun, Q., Riemer, B., & Savalani, M. M. (2019). Binder jetting additive manufacturing: A review on process, materials, and properties. Advanced Engineering Materials, 21(6), 1800719.

[35] Yu, X., Zhang, J., Jiao, T., & Zhu, Y. (2020). Recent advances on the fabrication and properties of fiber reinforced polymer composites for additive manufacturing. Composites Part B: Engineering, 189, 107904.

[36] Liu, Y., Zhao, C., Zhang, D., Guo, Y., Huang, W., & Liu, C. (2019). Research on the influence of printing parameters on the mechanical properties of 3D printed PEEK composites. Materials, 12(22), 3664.

[37] Wang, Z., Liu, J., Wang, C., & Liu, Y. (2021). A review of additive manufacturing of thermosetting polymer composites. Composites Part B: Engineering, 218, 108949.

[38] Sarkar, S., Das, S., & Das, A. (2020). Additive manufacturing of polymer-based composites in aerospace applications: a review. Virtual and Physical Prototyping, 15(1), 3-31.

[39] Gebhardt, A., Krutzsch, S., Pankalla, L., & Vielhaber, M. (2018). Additive manufacturing of continuous fiber reinforced thermoplastic composites using fused layer modeling. Materials Today Communications, 14, 194-202.

[40] Patel, R. N., Barakh Ali, S. F., Panda, S. K., Balani, K., & Naskar, A. K. (2019). Recent developments in additive manufacturing of natural fiber reinforced polymer composites. Composites Science and Technology, 174, 157-169.

[41] Yang, Q., Xu, Y., Chen, Y., & Yan, X. (2020). The research progress of carbon fiber-reinforced polymer composites in additive manufacturing: A review. Polymer Composites, 41(7), 2686-2699.

[42] Sanchez-Salcedo, S., Montes, R., Guiberteau, F., & Higuera, M. P. (2019). A review of additive manufacturing of composites: In-situ polymerization and ex-situ reinforced fillers. Materials & Design, 181, 108064.

[43] Huang, W., Zhang, Z., Wang, C., Du, P., Li, H., & Liao, W. (2021). Additive manufacturing of continuous carbon fiber-reinforced thermoplastic composites: Process, properties, and applications. Materials Today Advances, 12, 100150.

[44] Montes, R., Higuera, M. P., Benítez, A. N., Guiberteau, F., & Sánchez-Sáez, S. (2018). Review of composites manufacturing processes: Additive manufacturing, injection molding, compression molding, and forming. Materials, 11(8), 1431.

[45] Wang, F., Xiong, Z., Wang, C., & Zhang, Q. (2022). A review of fiber-reinforced polymer composites for aerospace applications: State of the art, emerging challenges, and future opportunities. Progress in Aerospace Sciences, 125, 100702.