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Eco-friendly ABS composites with pistachio shell powder reinforcement: mechanical and microstructural evaluation

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Abstract

Acrylonitrile Butadiene-Styrene (ABS) composites are being used for various engineering applications due to their higher toughness, strength, and lightweight. The properties of ABS reinforced with pistachio shell powder (PSP) have been investigated. PSP was incorporated into the ABS matrix at varying weight fractions (0%, 1%, 3%, and 5%), and composite filaments were fabricated via single screw extrusion. The experiments are conducted as per the Taguchi L16 method to analyse parameters: layer thickness (LT), infill density (ID), nozzle temperature (NT), PSP content, and infill pattern (IP) on mechanical properties. Standardized testing, in accordance with American Society for Testing and Materials (ASTM) D638, D790, D695, and D256, was conducted to evaluate tensile, flexural, compressive, and impact behaviour. The results revealed that a 3% PSP composition, coupled with an LT 0.4 mm, and ID 65–80%, yielded optimal tensile and flexural performance. The maximum tensile strength is found to be 33 MPa and modulus of 457 MPa, while the highest compressive strength reached 71 MPa at 5% PSP. Analysis of variance (ANOVA) identified PSP composition and infill density as the most significant contributors to mechanical enhancement. The findings confirm the viability of PSP as a sustainable, cost-effective reinforcement for ABS in FDM-based applications, with promising implications for eco-friendly composite manufacturing.

Keywords ABS, PSP, Mechanical properties, FDM, 3D printing

Introduction

Engineered composite materials that meet desired performance requirements have attracted massive attention due to excellent strength-to-weight ratios and stiffness, excellent wear resistance, and high corrosion resistance characteristics of the composite material [1]. Fused Deposition Modeling (FDM) is recently emerging as a highly potent method that synthesizes composite substances by incorporating reinforcing fibers, or fillers, within the thermoplastic matrices [2]. In FDM, the molten polymer is extruded by a nozzle and solidifies by cooling to create a 3-dimensional object layer by layer. An important review of 2025 presents the results in the continuous fiber-reinforced polymer

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systems and evaluates carbon-, glass-, and natural-fiber based-composites, and describes the essential role of the FDM processing parameters, including fiber orientation, volume fraction, and toolpath design, on such mechanical performance and FDM enabling aerospace and automotive applications [3, 4]. Recently, numerous interest in reinforcing Acrylonitrile butadiene styrene (ABS) composite with natural fiber reinforcement, with the rising mandate for eco-friendly composite materials. The natural fiber, including jute, kenaf, hemp, flax, coconut shell, bamboo, wood flour, and agricultural wastes like rice husk, wheat straw, and pistachio shell powder, has been investigated as a prospective [4–6].

ABS is a thermoplastic polymer known for its moderate stiffness, toughness and energy absorption properties [2]. Of relevance in improving stiffness, strength, and eco-friendliness, the reinforced ABS with natural fiber, Kenaf, jute, hemp, bamboo, or flax, has drawn a lot of attention. As an illustration, kenaf fiber ABS composites produced through the use of fused deposition modeling showed tensile strengths that ranged between ~ 11.5 MPa, at low fiber loading levels (5 wt%), to a level of ~ 18.6 MPa, at 10 wt%. Tensile modulus also increased at ~ 184 MPa, at 5 wt% and subsequently 276 MPa at 10 wt%, though lower than the neat ABS, these tensile values can provide more stiffness than the Young's modulus of ABS (~ 2.3 GPa) with the use of natural fiber when surface treatments and loadings are optimized [3].

Hybrid-type combinations (ex., jute with crab shell powders or carbon fibre in polyester matrices) have been cited as showing significant increases in tensile, impact and flexural strength but not directly comparable with ABS composites unless the same type of matrices are employed [4]. More precisely, jute fiber polymer composite experiments showed tensile strengths of 42.9 MPa and a tensile/bending strength, ~ 69.3/MPa [5]. Even bamboo-fiber-reinforced polyester/epoxy composites provide similar tensile strengths of 234 MPa and flexural moduli of 14 GPa again in a thermoset matrix-but showing the potential of the fiber [6].

Though in most applications natural-fiber-based reinforced ABS composites do not achieve the same levels of tensile strength as neat ABS without careful optimization, well-designed natural fiber composites can enhance stiffness and impact behaviour with proper fiber type, loading and treatment. Hybrids or high-fiber fractions can meet or even surpass the base ABS, which stretches tensile strength into 60 MPa and flexural modulus into several GPa or even exceed former levels of treated ABS in certain qualities [7, 8]. The mechanical properties of different natural fibres have been investigated by various researchers [4, 7–11].

Printing parameters also influence the mechanical strength and stiffness of FDM-developed ABS composites. In a study, carbon-fiber reinforced ABS printed with 80% honeycomb infill demonstrated major gains in mechanical properties. Tensile and flexural modulus increased by over 200% compared to lower densities (20%, 40%) [9]. In another study, ABS parts printed with concentric infill at 80% density and 0.1 mm layer thickness exhibited increased tensile strength of 123% and impact strength of 168% more than line or triangle patterns [12]. In a study, it is reported that slower printing speed allows proper melt flow index and interlayer fusion for improving the tensile strength [13].

Talking about Pistachio shell, we deal with a lignocellulosic agro-waste produced in considerable amounts, specifically, in key producing nations such as the U.S., Turkey,

and Iran, which produce hundreds of thousands of tonnes each year [13]. Instead of being thrown away or burned, these shells can be reconditioned as low-cost, eco-friendly bio filler. PSP consists of cellulose (25–30%), lignin (30–40%) and remaining hemicellulose, which gives it rigidity and hardness. This geometry added stiffness and wear resistance when it is embedded in a polymer matrix [14]. This study has indicated that epoxy composites in the case of low to moderate content of PSP (e.g. 5–10 wt %) show significant improvements in tensile (~ 56 wt %), flexural (~ 87 wt %) and impact (~ 75 wt %) strength, when there are smaller size particles (< 63 μm) [10]. More recent study on epoxy with 12 wt per cent PSP carried out in 2024 also showed an improvement of tensile and bending strength of approximately 815 per cent and a hardness of about 815 per cent and a rise in density with 1715 per cent difference [15, 16]. It is revealed use of PSP improved sliding wear resistance by up to 62%, and scrtch performance was superior compared to walnut shell hybrids [7].

The current study investigates the impact of adding pistachio shell powder to ABS polymer to examine mechanical properties. The effect of FDM process parameters on the strength of printed parts has been investigated. Also it is very important further to validate the result with recent studies demonstrate that finite element analysis (FEA) reliably supports mechanical testing of polymer and composite materials. Ganeshkumar et al. (2022) validated tensile behaviour of 3D-printed PLA using ANSYS simulations [8]. while Li et al. (2025) reported close agreement between experimental and numerical tensile responses of FDM-ABS parts [11]. Similarly, Behseresht and Park (2024) applied thermomechanical FEA to composite polymers and confirmed strong correlation with material performance [17]. Flexural behaviour of fibre-reinforced polymer composites has also been accurately captured through FEA, as demonstrated by under bending loads [18]. These works collectively show that integrating simulation enhances accuracy, supports trend validation, and provides deeper insight into stress distribution and failure mechanisms, justifying the inclusion of FEA in the future study.

Materials and methods

Materials

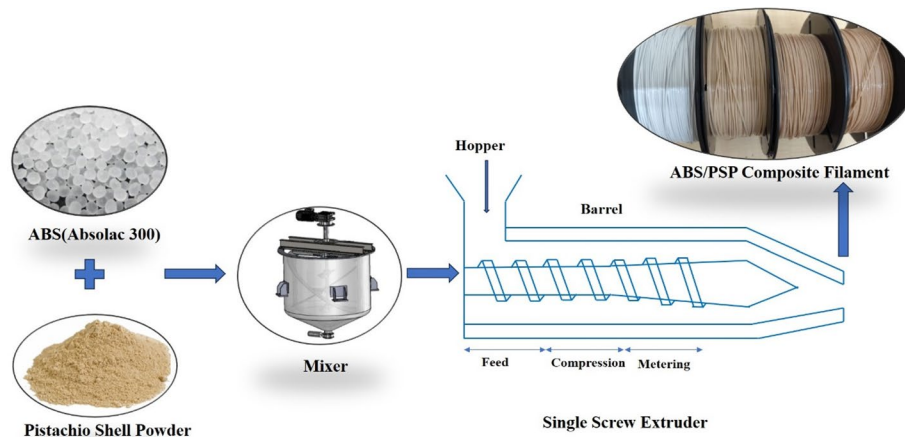
Pistachio shell powder is procured from Mangalam Agro, Nagpur, India. The powder has been dried in normal sunlight for 24 h to suit the purpose of the mixture of powder with ABS (Absolac 300) granules. Figure 1 (a, b) shows pistachio shell powder and Absoac 300, and Table 1 represents the properties of ABS.



Fig. 1 (a) Pista Shell Powder, (b) Absoac 300

Table 1 Properties of ABS material

Matrix	Melt Flow index (g/10min)	Density (g/cc)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Elongation at yield (%)
ABS (Absolac 300)	35	1.04	75	2700	5–6

**Fig. 2** Manufacturing of filament**Table 2** The printing parameters

Process Parameters	Settings
Printing Speed	120 mm/s
Raster Angle	45
Bed Temperature	110 °C
Extruder Nozzle	0.4
Build Orientation	Flat

Manufacturing of filament for FDM

The composite filament manufacturing process involves three batches as follows: in the first batch, the ABS granules are mixed with 1% of PSP fibres, in the second and third batches, the ABS with 3 and 5% of PSP fibres, respectively, are mixed, and the batches are mixed using batch mixture to get a uniform composition of the mixture.

Processing of ABS/PSP filament was done using the extruder in suitable parameters of temperature between 230 °C and 245 °C with a screw speed of 25–35 rpm and die pressure of 45–80 bar. The extruder barrel was then used to melt, mix and heat the batches. The extrusion of molten ABS composite was in the form of a die that would give them a continuous form of 1.75 mm diameter filament. Figure 2 shows the detailed process of manufacturing ABS/PSP filament.

Process parameters for FDM

The process parameters NT, LT, ID, raster angle, and print speed on the strength of 3D-printed ABS have been considered and these are selected based on the literature [3–5, 9, 15, 16, 19]. Table 2 shows printing parameters, and Table 3 represents the selected parameters for the current investigation.

Table 3 Range of process parameters and levels

Parameters	Level 1	Level 2	Level 3	Level 4
PSP composition	0	1	3	5
LT (mm)	0.1	0.2	0.3	0.4
IL	35	50	65	80
NT	245	255	265	275
IP	Line	Triangle	Tri Hexagonal	Honeycomb

Table 4 Design of experiment, Taguchi L₁₆ orthogonal array

Run	Composition	Extruder Temperature (°C)	Layer Thickness	Infill Density (%)	Infill Parent
1	0	245	0.1	35	Line
2	0	255	0.2	50	Honeycomb
3	0	265	0.3	65	Tri-Hexagonal
4	0	275	0.4	80	Octet
5	1	245	0.2	65	Octet
6	1	255	0.1	80	Tri-Hexagonal
7	1	265	0.4	35	Honeycomb
8	1	275	0.3	50	Line
9	3	245	0.3	80	Honeycomb
10	3	255	0.4	65	Line
11	3	265	0.1	50	Octet
12	3	275	0.2	35	Tri-Hexagonal
13	5	245	0.4	50	Tri-Hexagonal
14	5	255	0.3	35	Octet
15	5	265	0.2	80	Line
16	5	275	0.1	65	Honeycomb

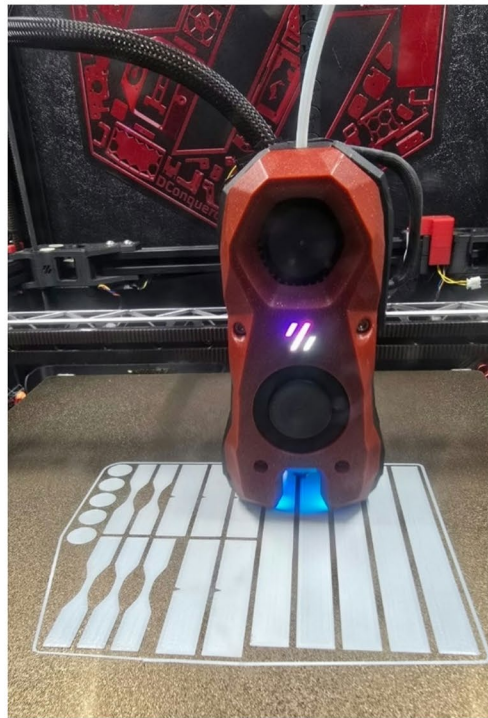
PSP composition was varied at 0%, 1%, 3%, and 5% by weight to examine how increasing lignocellulosic filler content affects matrix-filler adhesion, mechanical reinforcement, and warpage behaviour. The layer thickness was adjusted between 0.1 mm and 0.4 mm, as lower thicknesses typically improve surface finish and interlayer bonding but increase build time. Infill density was set at 35%, 50%, 65%, and 80% and printing time. Nozzle temperature was varied from 245 °C to 275 °C. Four types of infill patterns, as Line, Triangle, Tri-hexagonal, and Honeycomb, were selected to assess their influence on internal load distribution, print stability, and energy absorption capacity.

Design of experiment

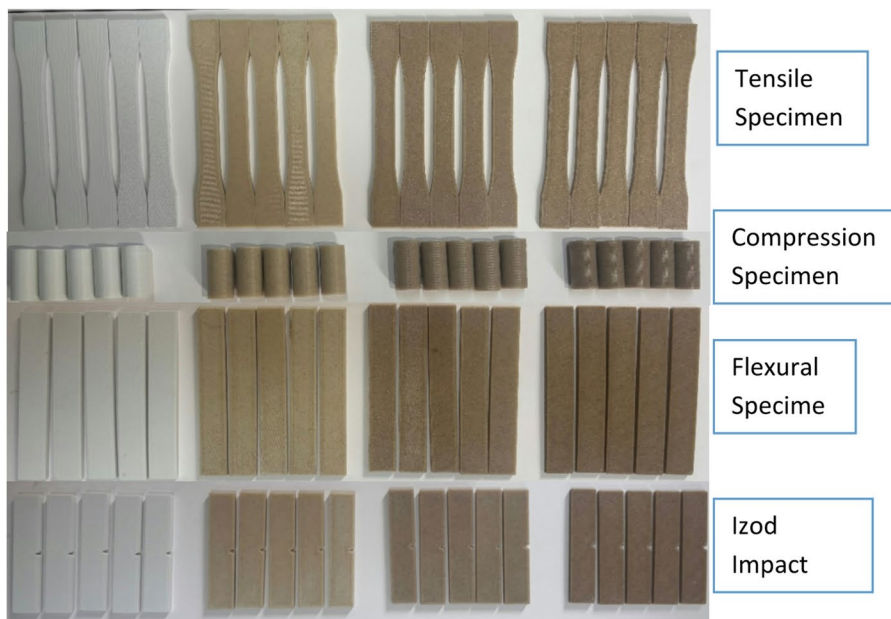
In order to get strong and trustworthy results and to cut down on experimental time and expense, the Taguchi L₁₆ method is implemented. Four-level factors for the process parameters are considered, as indicated in Table 3. Minitab software is used for statistical analysis. Table 4 displays the arrangement in which the ABS/PSP composite specimens were printed.

Manufacturing of composite specimen

A 3D CAD model of the specimen was developed, and for FDM-based 3D printing, an STL file was exported. G-code for exported CAD models was generated using orca slicer software, and all ABD/PSP specimens were manufactured using a core XY FDM printer Voron 2.4, as shown in Fig. 3 (a). All specimens were developed as per ASTM standard (Fig. 3(b)).



(a)



(b)

Fig. 3 (a) 3D printing machine, (b) 3D Printed ABS/PSP Specimen as per ASTM standard

Testing of composite specimen

Tensile test

The overall length of the specimen was 165 mm with a 50 mm gauge length. The central narrow portion has a width of 13 mm and 57 mm in length, with an end of 19 mm wide, which facilitates secure gripping during testing. The tensile tests were conducted

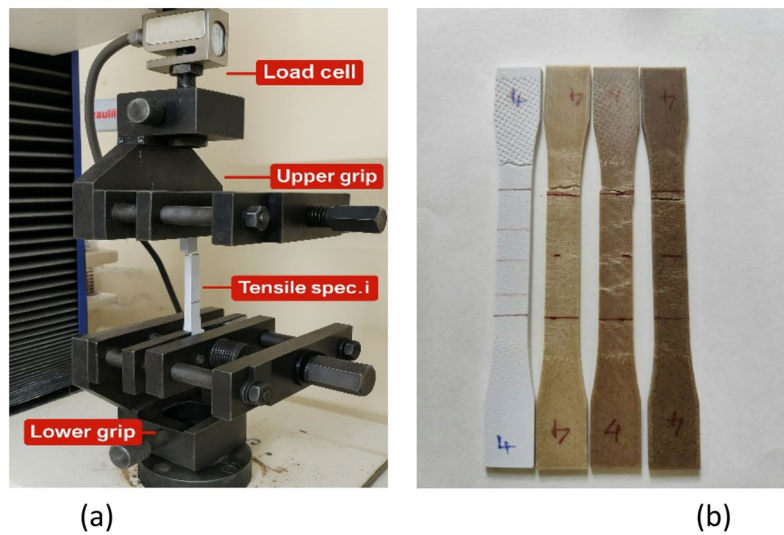


Fig. 4 (a) UTM, (b) Tensile tested specimen

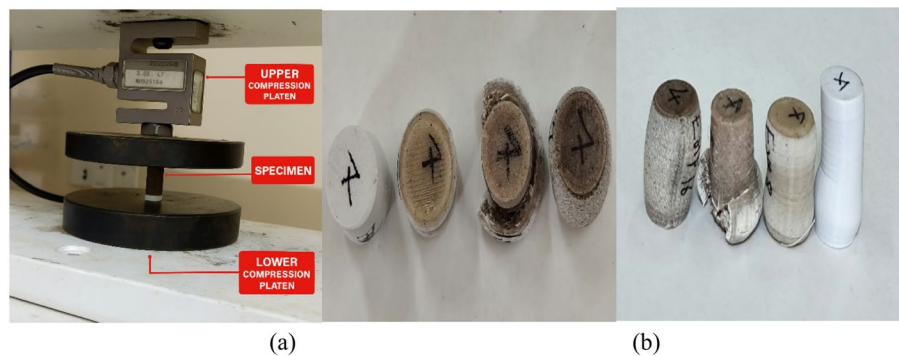


Fig. 5 (a) Compression tester, (b) Compression tested specimen

following ASTM D638 standard to evaluate the tensile strength and tensile modulus of the FDM printed specimen. The experiment was done five times independently to ensure the accuracy and repeatability of the results. Depending on the material form, the specimen's thickness may vary significantly, but it usually measures 3.2 mm. With a radius of 76 mm, the shoulder fillets, which join the narrow section and the wider gripping region, provide a uniform distribution of stress and reduce stress concentrations. 115 mm separates the grips during testing, guaranteeing that the specimen is held securely without slipping or bending on the Universal Testing Machine (UTM) equipped with a 10.16 kN load cell. During the test, the load vs. displacement data was continuously recorded, along the tensile strength and tensile modulus were calculated. Figure 4 (a-b) shows the UTM and the specimens.

Compression test

The compression machine and specimen developed are shown in Fig. 5(a-b), respectively. Tests were conducted following ASTM D695 standard [20]. The cylindrical specimen has a 12.57 mm diameter and with 1 mm gauge length.

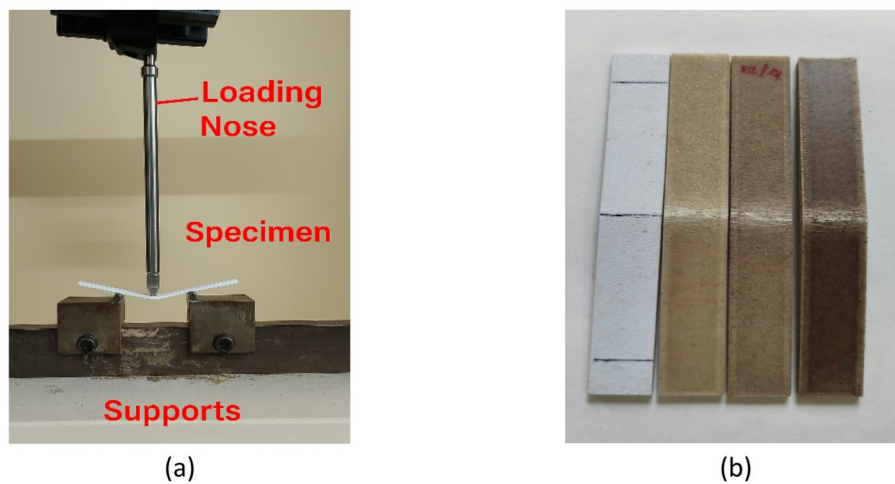


Fig. 6 (a) Three-point flexural tester, (b) Flexural tested specimen



Fig. 7 (a) Impact tester, (b) Impact tested specimen

Flexural test

Figure 6 (a-b) shows that a three-point flexural test is conducted following ASTM D790 standard for developed specimens [21]. $127 \times 12.7 \times 3.2$ mm standard rectangular specimens were used. The cross head is adjusted for a 1.5 mm/min speed with a 10 kN load capacity.

Impact test

The Izod impact tester machine (Fig. 7 (a-b)) was utilized to carry out tests following the ASTM D256 standard. For impact testing, specimens in the form of strips with measurements of $64 \times 13 \times 3.2$ mm in length, width, and thickness were employed.

Results and discussion

Analysis of variance (ANOVA)

ANOVA is a statistical method that is used to analyse the significance of process parameters. It makes it easier to see how the response variable is impacted by the tensile

Table 5 ANOVA contribution table

Source	Ultimate Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Impact strength (KJ/m ²)	Compressive Strength (MPa)
Composition	64	54	15	7	70	2
Extruder Temperature	3	5	39	35	10	5
Layer Thickness	14	24	36	14	11	3
Infill Density	17	16	5	21	5	85
Infill pattern	2	2	5	23	4	5

Table 6 Mechanical properties

Run	Ultimate Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Impact strength (KJ/m ²)	Compressive Strength (MPa)
1	24±0.37	369±39	34±5.05	877±9	16±0.99	35±0.25
2	23±0.46	367±19	38±3.08	819±66	17±0.72	42±2.92
3	28±0.75	300±0	45±2.74	1150±50	21±1.25	61±2.28
4	30±0.64	360±55	48±1.82	932±13	25±1.15	71±4.96
5	27±0.26	355±62	43±1.11	974±14	17±0.53	61±10.16
6	27±0.71	407±30	36±5.13	940±70	16±0.84	60±8.22
7	30±0.67	170±27	49±1.97	1059±141	19±0.77	43±1.44
8	25±0.50	150±0	48±1.22	1005±5	19±2.08	48±1.69
9	30±0.51	453±52	48±2.42	1050±68	16±1.13	70±3.87
10	33±0.96	429±44	45±2.27	947±44	15±1.60	64±0.83
11	27±0.28	429±0	45±5.25	889±97	16±0.34	59±5.41
12	23±0.37	457±39	44±2.05	1093±104	14±1.05	34±1.80
13	19±0.53	200±12	41±1.33	940±37	12±3.43	52±2.42
14	18±0.42	222±36	40±1.95	881±35	11±0.10	42±1.38
15	21±0.69	300±15	46±1.23	1002±51	12±0.39	71±1.50
16	20±0.45	354±21	42±1.42	1017±32	12±1.78	55±2.73

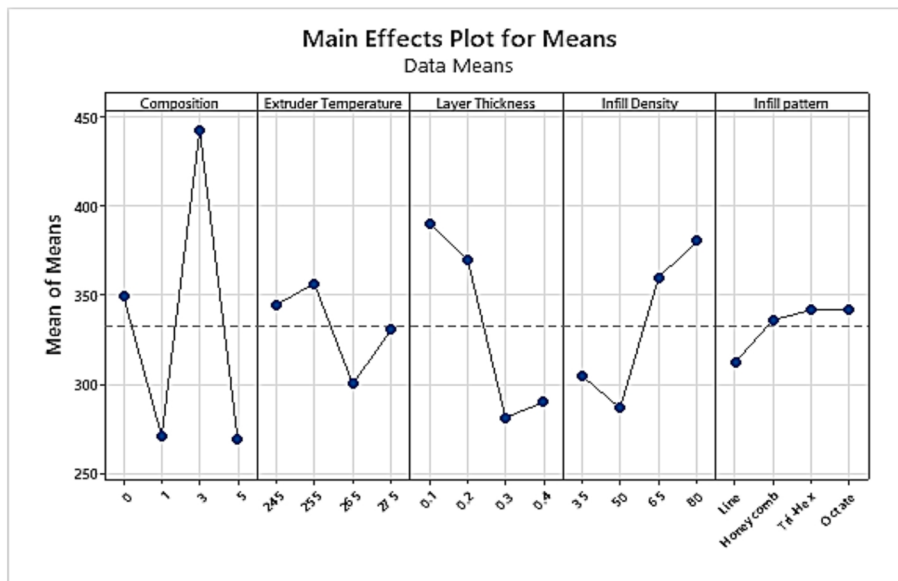
strength of 3D printed components [22–24]. The ANOVA contribution (Table 5) illustrates the most significant printing parameter on each mechanical property. UTS, TM, and IS are the most affected by composition, i.e. the PSP-ABS mix is the primary determinant in tensile and impact behaviour. Flexural properties (FS and FM) are dominated by extruder temperature and layer thickness. The key factor of compression strength (CS) is infill density, which has an 85% contribution, i.e., it is the compressive performance that primarily relies on the solidity of the print. Infill pattern does not have a significant influence with the exception of FM. In general, each property is governed by different parameters, and their role in each mechanical response is the most significant.

The mechanical properties obtained through various tests have been reported in Table 6. In order to minimise error, five specimens were tested and the mean of their results has been estimated. Five specimens were 3D printed using an FDM printer and tested for every experiment run. Shows the mean of each specimen as a representative result for ultimate tensile strength (UTS), tensile modulus (TM), flexural strength (FS), flexural modulus (FM), impact strength (IS) and compressive strength (CS).

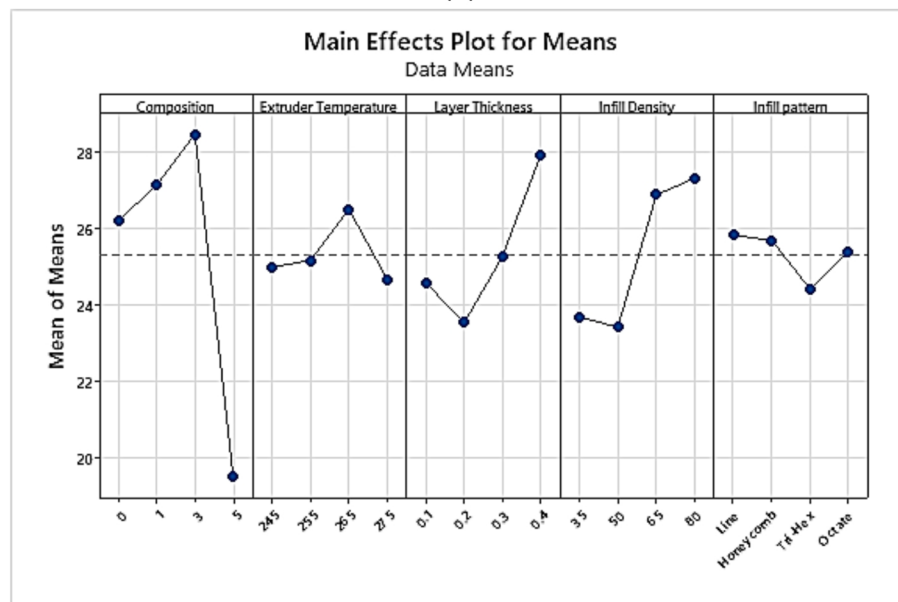
Effect of process parameter on tensile strength

The main effect plots for tensile strength and modulus are shown in Fig. 8 (a, b). For ABS reinforced 3% PSP composites, the highest tensile strength (33 MPa) was observed at 65% infill density, 255 °C, 0.4 mm LT, and line pattern. The maximum tensile modulus (457 MPa) was determined at 275 °C, 0.2 mm LT, 35% IL, and line pattern.

These optimal parameters for ABS composite with 3% pistachio shell powder include 80% infill density, 0.4 mm layer thickness, 265 °C extruder temperature, and line infill pattern. Increased material contributes to more load transmission during the tensile test because thicker layers have greater interlayer adhesion and increased infill density creates a dense internal structure, which enhances the strength and integrity of the 3D



(a)



(b)

Fig. 8 Main effect plots for tensile (a) strength, (b) modulus

printed part. ANOVA revealed that all parameters have an effect on tensile modulus; however, the composition of the PSP was found to be dominant, with 54% contribution. This leads to improved load-bearing capacity and stress distribution efficiency [25].

Effect of process parameters on compressive properties

Maximum compression strength (71 MPa) was obtained at 5% PSP composition. The best process parameters to be selected based on the mean effective plot as 3% PSP composition, 265 extruder temperature, 0.4 mm layer thickness, 80% infill density and octet pattern. These parameters will give increased compressive strength. The ANOVA showed that impact strength was not significantly impacted by LT, composition, extruder temperature, IP; nevertheless, the ID was the most important process parameter, accounting for 85% of the observed variances. Figure 9 shows the main effect plots for compressive strength.

Effect of process parameters on flexural properties

The findings of the experiment (Table 5) revealed that the greatest flexural strength and modulus, 1% PSP composition, were 49 MPa and 1150 MPa. The mean effect for flexural properties are shown in Fig. 10 (a-b). It was found that optimum parameters for flexural strength were 3% PSP composition, 265 extruder temperature, 0.4 mm layer thickness, 80% of infill density and honey comb pattern is suitable as per the mean effective plot, similarly for flexural modulus 1 to 3% composition, 0.3 mm LT, 65% infill density and tri-hexa is selected for better results.

The ANOVA results indicated that the flexural strength and flexural modulus were not considerably affected by the infill pattern and infill density for strength and composition for modulus, which had a negligible effect. Mostly, the extruder temperature around 39 and 35% is mostly had an effect on flexural strength and modulus. Specimens printed with 25% and 50% infill density result in the lowest flexural properties.

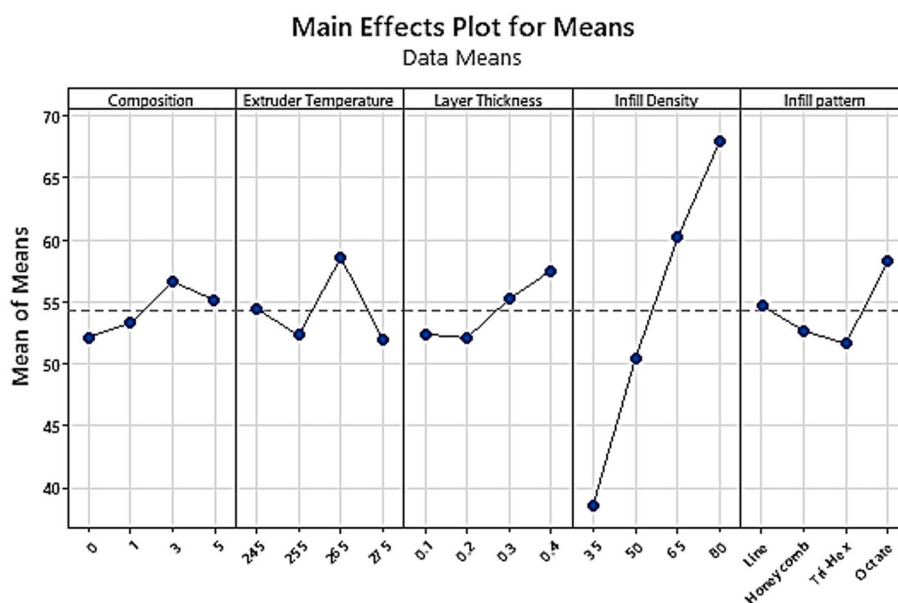
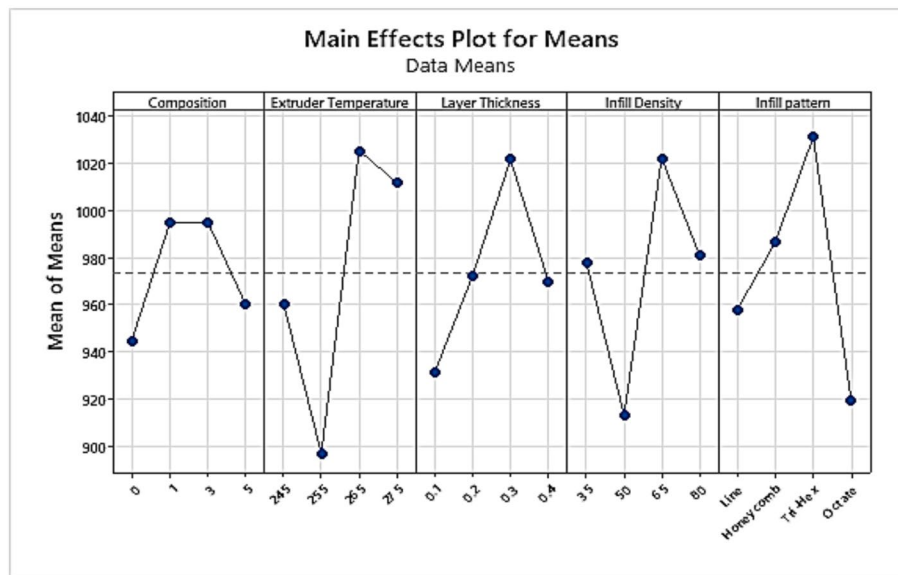
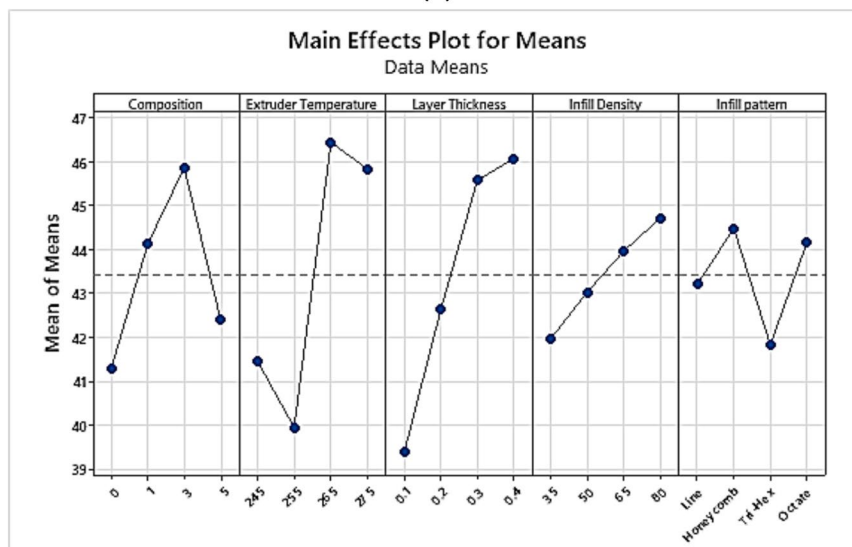


Fig. 9 Main effect plots for compressive strength



(a)



(b)

Fig. 10 Main effect plots for (a) Flexural strength, (b) Flexural modulus

Effect of process parameters on impact properties

Process parameter effects on impact attributes, as shown in Table 5, the 3D printed composite’s impact strength peaked at 25 KJ/m² when using neat ABS with an 80% infill density. Additional information is provided by Signal-to-Noise ratio of impact strength, which is displayed in Fig. 11. The ANOVA results showed that impact strength was not significantly impacted by LT, extruder temperature, ID, or IP; nevertheless, the composition was the most important process parameter, accounting for 70% of the observed variances. It was observed that the increase in PSP content is a decrease in impact strength. This is due to the voids created inside the material will reduce the strength.

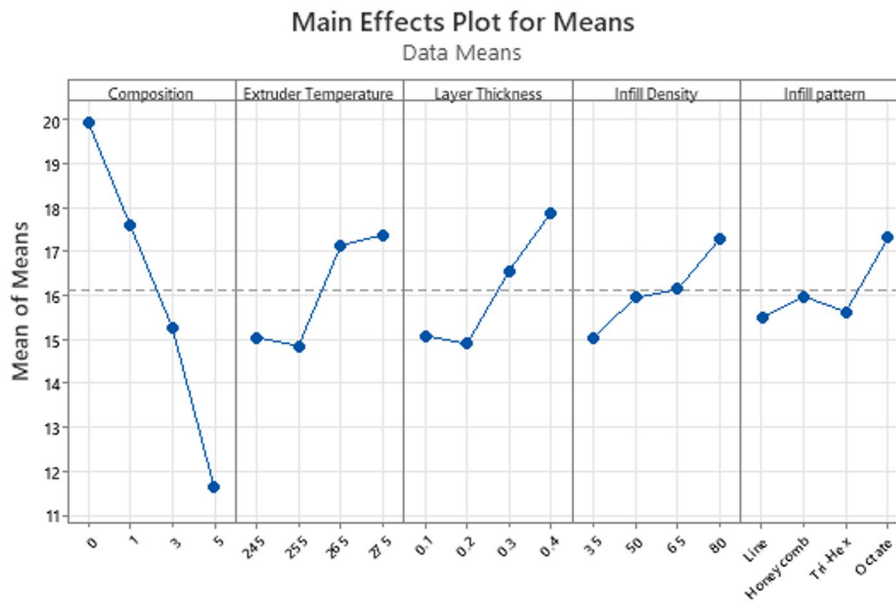


Fig. 11 Main effect plots for impact strength

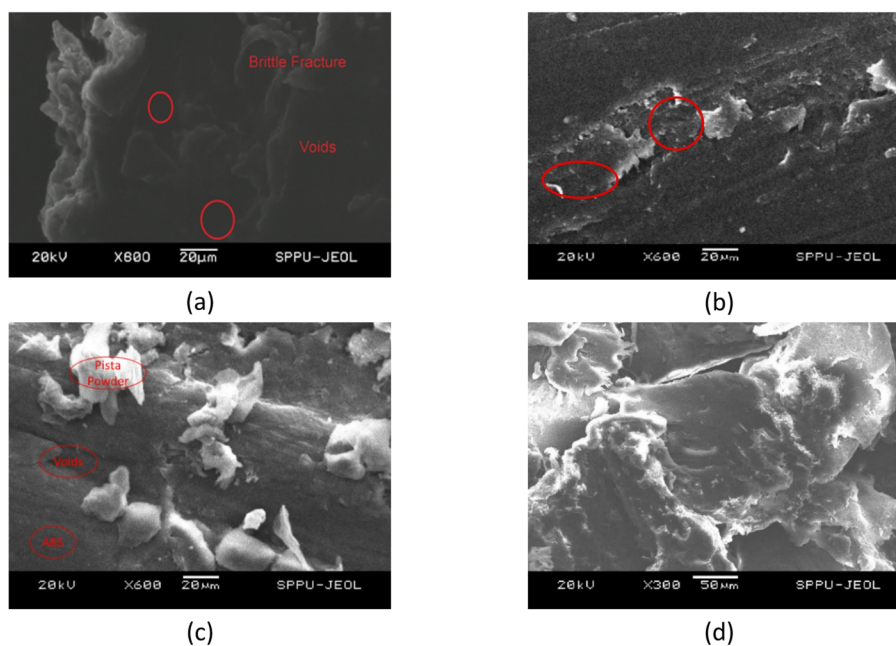


Fig. 12 (a-d): Scanning Electron Microscopy for Microstructural Study

Scanning electron microscopy microstructural study

High-resolution studies of the surface morphology, microstructure, and fiber or filler dispersion of polymer composites are conducted using scanning electron microscopy (Fig. 12). To identify defects like vacancies or cracks, and interfacial bonding can be identified with its assistance. Additionally, SEM sheds light on the distribution and homogeneity of reinforcement, both of which have a direct impact on mechanical and thermal properties. As a result, it is an essential tool for establishing a relationship between microstructural characteristics and polymer composite performance.

According to statistical analysis experiment no 1,7,10 and 15 with neat ABS, along with 1%,3% and 5% fibre reinforcement specimens were selected to study the variation in the microstructure.

Figure 12 (a) shows that it is of pure ABS SEM image; the rough texture indicates brittle fracture regions along with ductile tearing zones, suggesting mixed failure behaviour. The presence of irregular voids and micro-cracks reflects non-uniform stress distribution during fracture. Figure 12 (b) shows that with 1% pistachio powder indicates that the red-circled bright particles represent embedded pistachio shell powder, which appears brighter due to differences in electron density compared to the ABS matrix and dark colour indicates the regions for voids or micro-cracks formed due to poor interfacial bonding between ABS and the pistachio shell filler. On the other hand, the distribution of pistachio shell powder suggests that the reinforcement has dispersed within the ABS. Figure 12 (c) shows that with 3% of pistachio powder, which indicates good interfacial bonding between ABS and pistachio powder and in the image, there is very little porosity present, which means that increase in mechanical properties and acts as stress concentration points. The broken ABS surface reinforced with 5% pistachio shell powder is seen in the SEM image shown in Fig. 12 (d). An excellent dispersion of filler inside the ABS matrix is indicated by the rough and uneven appearance. Visible pull-outs and micro-voids indicate a somewhat poor interfacial connection between the polymer and filler. The damaged areas demonstrate a heterogeneous failure mechanism, exhibiting both brittle fracture around filler sites and ductile ripping of ABS. This microstructure shows how surface roughness and load transfer efficiency are impacted by a larger filler content.

Conclusion

The current study used FDM-based additive manufacturing to fabricate and characterize ABS composites reinforced with PSP. The impact of PSP content (0%, 1%, 3%, and 5%) and important FDM process variables on the mechanical behaviour of the printed composites was thoroughly investigated in this study. The outcomes demonstrated that, when tuned at the right weight fractions, PSP, a lignocellulosic filler, can significantly improve the performance of ABS composites. In particular, 3% PSP reinforcement demonstrated enhanced modulus values, superior tensile (33 MPa) and flexural (49 MPa) strength, underscoring its function in improving load transfer and stiffness of the polymer matrix. However, the maximum compressive strength (71 MPa) was attained at 5% PSP, suggesting that while larger filler loading improves compressive resistance, it degrades tensile and impact performance because of weak interfacial bonding and more voids. Higher PSP content was found to reduce impact strength, mostly because of filler pull-outs and micro-void development seen in SEM analysis.

PSP composition and infill density are the primary factors affecting tensile and compressive capabilities, according to statistical analysis (ANOVA), with nozzle temperature and layer thickness having a minor but significant impact. Strong microstructural support for the mechanical results was given by SEM micrographs, which showed that while agglomeration and interfacial defects at higher loadings decreased strength, good dispersion and bonding at lower filler loadings improved characteristics. The study concludes that PSP, a by-product of agro-waste, can be used as an economical and environmentally beneficial reinforcement for ABS in 3D printing. A balanced improvement

in tensile, flexural, and compressive properties was shown by the optimized composite (ABS + 3% PSP), highlighting its potential as a sustainable material substitute for light-weight structural applications in consumer goods, functional engineering components, and prototyping.

Future scope of work

Further investigations could involve applying Finite Element Analysis (FEA) based on ANSYS, Abaqus, or COMSOL to numerically study tensile, flexural, and compressive deformations of PSP -ABS composites to validate the experimental data [26–29] and identify the areas of stress concentration and correlate the failure modes observed using SEM images. Also, the thermal simulation of the FDM printing process is suggested to investigate the temperature distribution, interlayer bonding, and development of residual stress, especially taking into account the thermal sensitivity of PSP-filled ABS. Environmental stability studies should be done in the form of long-term studies like moisture absorption, hygrothermal conditioning, and accelerated aging since the natural filler is prone to moisture. In addition, Micro-CT scan could be utilized as a non-destructive technique to analyse internal porosity, interlayer fusion, and filler dispersion and provide more information on the microstructural features that affect the overall mechanical performance.

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Authors' contributions

Praveen Rathod: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing the original draft, Writing-Review & editing, Visualization. Masuk Abdullah: Writing-Review & editing, Formal analysis, Data curation, Project administration, Visualization. Dinesh Washimkar: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing-Review & editing. Nitin Ambhore: Conceptualization, Methodology, Validation, Investigation, Writing-Review & editing, Supervision. Péter Tamás Szemes: Validation, Investigation, Writing-Review & editing, Supervision, Funding acquisition.

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Data availability

Data will be made available on a reasonable request.

Declarations

Competing interests

The authors declare no conflict of interest.

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