

Mechanical and morphological assessment of kenaf fibers-reinforced nylon for FDM 3D printing of dental prosthesis

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Abstract. Fused Deposition Modeling (FDM) is one of the popular technologies for 3D printing. One significant limitation associated with this technology is the poor mechanical strength of the printed material. In this study, natural fibers (kenaf) were used for nylon filament reinforcement, and were evaluated through mechanical and morphological analysis. Kenaf fibers were submitted to water retting and bleached with 6% sodium hypochlorite solution. Then, the fibers were silanized by 3-aminopropyl triethoxysilane solution before being incorporated with nylon beads using thermal extruder machine. The study groups consisted of control and 0.1%, 0.3%, 0.5%, and 1% kenaf fibers reinforced nylon groups. For morphological analysis, fibers distribution in the filament was assessed through digital microscopic images and FeSEM cross-sectional images. Filament diameter was evaluated using digital caliper. For mechanical analysis, compression and flexural strength tests were conducted on the study samples. Both microscopic and FeSEM analysis revealed fibers distribution parallel to filament extrusion direction except for the 1% kenaf fibers reinforced group that showed some irregular fibers distribution. Filament diameter was not significantly different among the study groups. Mechanical analysis showed that 0.5% kenaf fibers reinforced group was not significantly different from the control group while the rest of the experimental groups were lower than the control group in terms of both compressive and flexural strength. Although kenaf fibers reinforcement with nylon filament showed regular morphological outcome at concentrations of 0.5% and lower, only 0.5% concentration appeared to have no significant effect on the mechanical strength of the FDM printed material, while the other studied concentration showed decreased mechanical strength.

Keywords: 3D printing; FDM; Kenaf fibers

1. Introduction

Recently, additive manufacturing technology have become popular for dental prosthesis construction. Several types of 3D printing technologies are utilized in this field due to several

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mechanical and processing advantages (Shahrubudin *et al.* 2019, Al-Kaabi 2025). Fused Deposition Modeling (FDM) is a 3D printing technology that relies on polymeric filament as feed stock. Its mode of action depends on thermally liquefying polymeric filament and build a physical structure layer by layer according to predesigned CAD file (Deng *et al.* 2018, Guo *et al.* 2022, Rezaie *et al.* 2023). One of the most popular polymers used for FDM filament production is nylon (polyamide) since this polymer is known for its adequate strength and fracture resistance (Zeidan *et al.* 2023). According to the literature, some researcher reported mechanical and physical limitations associated with FDM 3D printed models such as lower flexural strength and dimensional instability mostly attributed to FDM buildup technique (Park *et al.* 2021, Freitas *et al.* 2023).

Synthetic fibers such as carbon fibers, glass fibers, aramid fibers, and basalt fibers, are human made type of organic and inorganic fibers that can be used for a variety of industrial applications (Ahmad *et al.* 2021). Natural fibers such as jute, hemp, kenaf, and flax, are plant-based cellulosic fibers that have gained a significant popularity for engineering industry due to their low cost, environmental friendliness, availability, and lower density besides their suitable mechanical properties (Gallo *et al.* 2013). Synthetic and natural fibers as well as Nano fillers have been utilized for polymer reinforcement to enhance certain mechanical and physical properties (Garigipati and Malkapuram 2020, Muhsin *et al.* 2022, Kati 2022). When it comes to environmental and economic considerations, natural fibers have taken the precedence over synthetic fibers for polymers reinforcement (Silva *et al.* 2021, Sakhare and Borkar 2022, Sayeed *et al.* 2023, Maziero *et al.* 2023).

One of the main sources for natural fibers is from kenaf plant (*hibiscus cannabinus*). It is a tropical plant that can grow up to 5 meters, and it is mostly inhibited in China, India, as well as some parts of south east Asia (Giwa Ibrahim *et al.* 2019, Sim and Nyam 2021). The stem of the plant is rich in cellulosic fibers than can be utilized in several industrial purposes. Two types of fibers are extracted from the plant stem which are the inner core and outer bast fibers. The core represents 60-75% of the total fiber content, while the bast constitutes only 25-40% of the total fiber content (Abdul Khalil *et al.* 2010, Arsad *et al.* 2013, Abbas *et al.* 2022). Kenaf fibers have been used for polymers reinforcement to produce composites with optimized mechanical and tribological properties (Rozyanty Rahman 2019) (Silva *et al.* 2021, Sayeed *et al.* 2023). Raw kenaf fibers require alkaline treatments for removing lignin, pectin, and hemicellulose, leaving only pure cellulose for polymer reinforcement. The fibers act as a shock absorber in the polymer matrix that increases the composite resistance to fracture (Lee *et al.* 2021).

Regarding FDM 3D printing, the buildup technique might result in poor mechanical connection between the deposited layers which eventually reduces the printed object resistance to fracture (Wickramasinghe *et al.* 2020). To overcome this issue, synthetic fibers have been applied for FDM filament reinforcement (Liu *et al.* 2023). However, there is limited information in the literature that point out the applicability of natural fibers reinforcement for FDM 3D printing filament. Therefore, this study focused on evaluating the impact of kenaf fibers reinforcement on nylon filament morphological and mechanical properties in terms of compressive and flexural strength.

2. Methods

2.1 Materials

Torewell™, China FDM filament was used for control specimens printing. Nylon polyamide pellets (QIPLAS, China) was used for the production of fibers reinforced filament that were used

for experimental specimens printing. Grade A kenaf fibers (SKM2-Bio Grade A) from the National Kenaf and Tobacco Board, Kota Bharu, Kelantan, Malaysia, were used in this study for nylon reinforcement. Sodium hypochlorite (FAS, Iraq) was used for fibers bleaching and processing. 3-aminopropyltriethoxysilane (APTES) from Bide Pharmatech Ltd., China, was used as a conditioner for the fibers to enhance their bonding with nylon polymer during filament production.

2.2 Kenaf fibers treatment

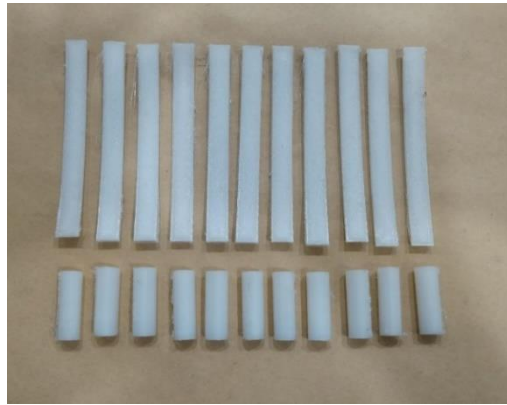
Firstly, kenaf fibers were submitted to water retting for 24 hours to eliminate dust and contaminants. Then the fibers were washed out and dried at room temperature for 48 hours. The next step was the bleaching process. The fibers were submerged in 6% sodium hypochlorite solution for 24 hours to remove the unwanted plant components such as lignin, pectin, and hemicellulose. This will result in relatively pure cellulosic kenaf fibers. The fibers were then washed thoroughly with deionized water and dried in an oven at 40°C for 24 hours. The final step was conditioning the fibers with APTES. The fibers were added to 1:3 ratio solution of ethanol and water containing 0.2% of APTES. The fibers and the solution were stirred for 24 hours then washed with deionized water and acetone respectively. After that, the fibers were dried in the oven at 40°C for 24 hours.

2.3 Filament production and specimens printing

Kenaf fibers were ground and sieved using mesh size 40 (400µm). The fibers were added to nylon pellet at weight ratios based on the predetermined study groups which were (0.1%, 0.3%, 0.5%, and 1% of kenaf fibers concentrations). The mix was processed and extruded thermally at 250°C using thermal extruding machine. The study specimens were printed by Creality Ender 3 Neo FDM 3D printer, China, using the extruded filaments for the experimental groups, and the as-received nylon filament for printing the control group. The specimens were designed by Design Spark Mechanical 6.0.3 software. Rectangular shape with dimensions of 100mm length, 10mm width, and 2mm thickness, was designed for the flexural strength test following ASTM D790 while the dimensions were adapted within a permissible range. A cylinder shape with dimensions of 30mm height and 10mm in diameter was designed for the compressive strength test following the general procedure of ASTM D695. The height-to-diameter ratio (3:1) was selected based on material stiffness and testing constraints, and no buckling was observed during testing. The Standard Tessellation Language (STL) file was sliced by Prusa Slicer 2.6.1 software before being transferred to the printer. The printing specifications are illustrated in Table 1. The total sample size was determined by G*power software (version 3.1.9.4). A power analysis for One Way ANOVA test indicated that the minimum sample size to yield a statistical power of at least 0.8 with an alpha of 0.05 and a medium effect size ($d=0.5$) is 55. Fig. 1 shows the study groups.

2.4 Characterization and testing

The reinforced filament was observed for kenaf fibers distribution using Field-emission Scanning Electron Microscopy (INSPECT 50, FEI, USA) for cross-sectional observation, and digital microscopy for fibers orientation analysis. The filament diameter was analyzed using a digital caliper by taking a measurement every 10mm for a total of 30 readings per group. The specimens were submitted to compressive strength and flexural strength tests using a universal testing machine (Tinius Olsen, Model H50KT, UK). The test speed was 1mm / min, and the load cell type was 50KN.



Control



0.1% Kenaf-reinforced nylon specimens



0.3% Kenaf-reinforced nylon specimens



0.5% Kenaf-reinforced nylon specimens



1% Kenaf-reinforced nylon specimens

Fig. 1 Study groups' specimens

Table 1 specimens printing specifications

Printing specification	Printing speed	Infill percentage	Nozzle diameter	Nozzle temperature	Bed temperature	Layer thickness
Value	50 mm/s	100%	0.4 mm	250 °C	90 °C	0.2 mm

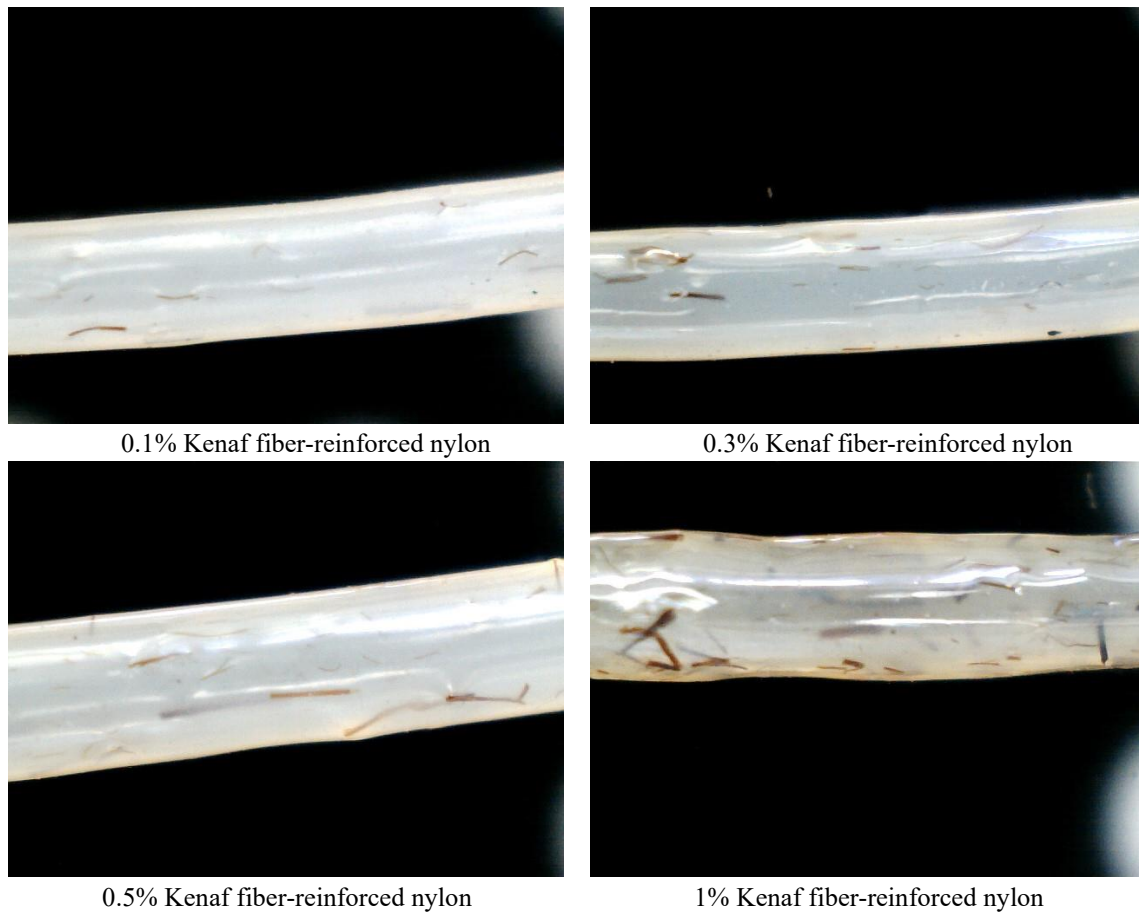


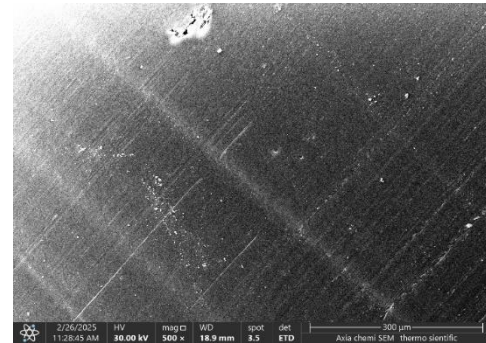
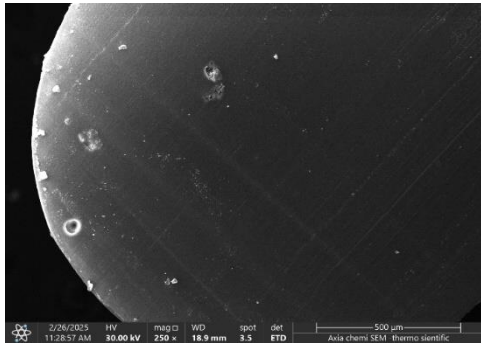
Fig. 2 digital microscopic images for fiber-reinforced filament

All the study data was analyzed by The Statistical Package for The Social Sciences IBM SPSS (version 20) for significant difference.

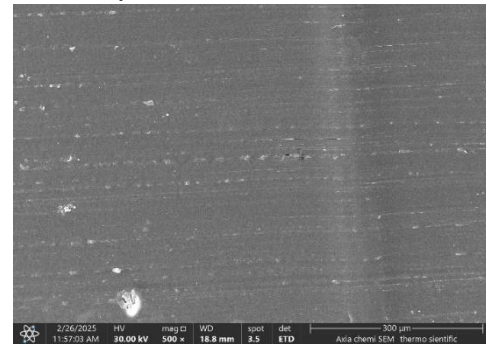
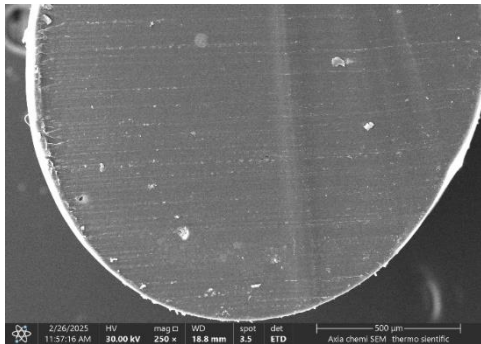
3. Results and discussion

3.1 Morphological analysis

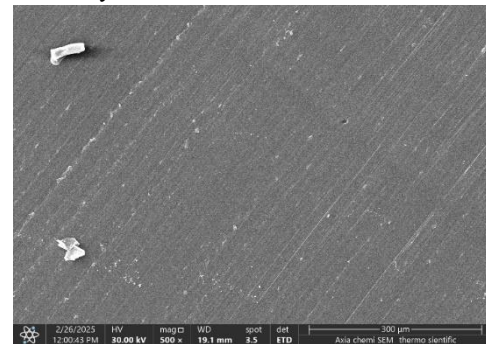
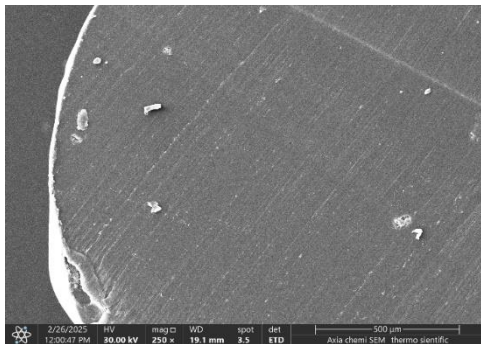
According to the digital images for experimental filament groups, the fibers appeared to show regularly parallel orientation following the extrusion direction for the composite filament. The fibers orientation was slightly disoriented as the concentration increases particularly at 1% fibers-reinforced group which revealed more irregular distribution as shown in Fig. 2. The cross-sectional FeSEM images confirmed the fibers parallel orientation. However, Interfacial bonding between the fibers and the polymer matrix exhibited some defects, particularly in the group with the highest fiber concentration (1%) indicating potential issues such as poor dispersion or fiber agglomeration at elevated loading levels as displayed in Fig. 3. Moreover, darker fibers were observed for the highest



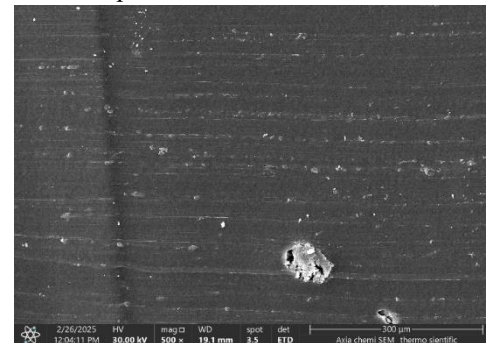
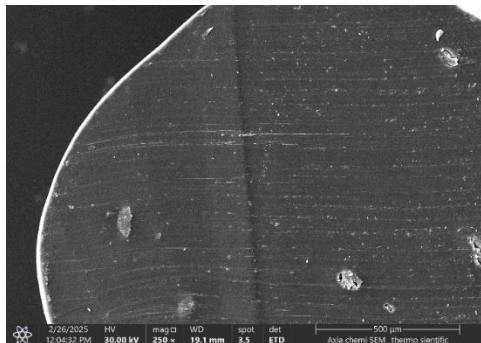
0.1% Kenaf fiber-reinforced nylon



0.3% Kenaf fiber-reinforced nylon



0.5% Kenaf fiber-reinforced samples



1% Kenaf fiber-reinforced samples

Fig. 3 FeSEM cross-sectional images for fiber-reinforced filaments

Table 2 Descriptive statistics for nylon groups filaments diameter (mm)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
control	30	1.7380	0.02140	0.00391	1.7300	1.7460	1.71	1.78
0.1% kenaf-reinforced nylon	30	1.7387	0.03082	0.00563	1.7272	1.7502	1.70	1.79
0.3% kenaf-reinforced nylon	30	1.7373	0.02741	0.00500	1.7271	1.7476	1.70	1.78
0.5% kenaf-reinforced nylon	30	1.7367	0.02746	0.00501	1.7264	1.7469	1.70	1.79
1% kenaf-reinforced nylon	30	1.7427	0.03118	0.00569	1.7310	1.7543	1.70	1.79
Total	150	1.7387	0.02758	0.00225	1.7342	1.7431	1.70	1.79

Table 3 One Way ANOVA test for filament diameter

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.001	4	<0.001	0.214	0.930
Within Groups	0.113	145	.001		
Total	0.113	149			

concentration group which might be resulted from the extrusion processing temperature which was significantly high to be tolerated. This was an unexpected finding since the fibers were conditioned with APTES to provide protection from thermal degradation and facilitate bonding with the polymer during filament processing. These finding agrees with the results reported by Gallo and his associates who found that kenaf fibers has limited temperature resistance compared to synthetic fibers for polymer reinforcement (Gallo *et al.* 2013).

According to Tables 2 and 3, filament diameter results showed no statistically significant difference among the study groups (p -value >0.05) with average filament diameter of 1.78 mm. This indicates that kenaf fibers in its current form did not affect the morphology of the extruded filament material compared with the as-received control filament. This finding ensures the capability to reinforce nylon filament with kenaf fibers at the given concentrations in the study.

3.2 Mechanical analysis

The flexural strength data showed higher mean value for the control group with variable mean values for the fibers-reinforced groups as reported in Table 4. One Way ANOVA tests results showed no statistically significant difference between the control group and 0.5% fibers-reinforced group (p -value >0.05), while there was a significant difference between the control group and the rest of fibers-reinforced groups (p -value <0.05) as reported in Table 5. Similar results were observed with compressive strength data. As shown in Table 6, there was no significant difference between the control group and 0.5% fibers-reinforced group (p -value >0.05). However, there was a significant difference between the control group and other fibers-reinforced group (p -value <0.05). The decreased flexural and compressive strength for the fibers-reinforced group could be attributed to

Table 4 Descriptive statistics for flexural and compressive strength tests (MPa)

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Flexural strength	control	11	20.65	1.20394	0.36300	19.8394	21.4570	18.05	22.12
	0.1%	11	15.25	1.87514	0.56538	13.9903	16.5097	12.50	18.95
	0.3%	11	18.40	1.73498	0.52312	17.2353	19.5665	16.01	20.90
	0.5%	11	19.82	1.99584	0.60177	18.4746	21.1563	16.34	23.00
	1%	11	14.70	1.79454	0.54108	13.4980	15.9092	12.11	17.06
	Total	55	17.76	2.93952	0.39636	16.9690	18.5583	12.11	23.00
Compressive strength	control	11	38.69	1.97893	0.59667	37.3605	40.0195	35.33	41.28
	0.1%	11	34.34	3.12393	0.94190	32.2413	36.4387	29.99	40.58
	0.3%	11	34.72	2.53066	0.76302	33.0190	36.4192	29.86	37.74
	0.5%	11	36.59	2.06893	0.62381	35.1973	37.9772	32.88	40.47
	1%	11	30.99	1.91207	0.57651	29.7091	32.2782	27.39	33.51
	Total	55	35.07	3.44166	0.46407	34.1356	35.9964	27.39	41.28

Table 5 Tukey HSD for multiple comparison for flexural strength test

Groups	N	Subset for alpha = 0.05		
		1	2	3
1%	11	14.7036		
0.1%	11	15.2500		
0.3%	11		18.4009	
0.5%	11		19.8155	19.8155
control	11			20.6482
Sig.		.947	.329	.795

Table 6 Tukey HSD for multiple comparison for compressive strength test

Groups	N	Subset for alpha = 0.05		
		1	2	3
1%	11	30.9936		
0.1%	11		34.3400	
0.3%	11		34.7191	
0.5%	11		36.5873	36.5873
control	11			38.6900
Sig.		1.000	.187	.243

insufficient interfacial fibers adhesion with polymer matrix. Furthermore, fibers inclusion may have introduced internal voids or disrupted filament deposition, increasing porosity and reducing the overall mechanical integrity of the printed parts. These findings contradict what has been reported

in the literature that fiber reinforced polymers and composites are widely known for their high stiffness, damage tolerance, fatigue resistance, as well as the increased interlaminar bonding between the FDM deposited layers (Hofstätter *et al.* 2017).

Filament processing or FDM printing complications such as nozzle clogging or uneven extrusion might have imposed structural weakness or affected printing quality. In contrast to expectations, addition of kenaf fibers at concentrations 0.1%, 0.3%, and 1% reduced the mechanical strength of the printed nylon with the exception of the addition of 0.5% fiber that did not result in a statistically significant improvement or reduction in mechanical strength compared to the control nylon for FDM 3D printing while lower or higher fibers concentrations would lower the printing mechanical quality of nylon.

4. Conclusions

Due to the significant benefits of natural fibers they have been widely introduced as reinforcing agent for polymers and composites. Regarding FDM 3D printing, this study was an attempt to evaluate the application of kenaf fibers as reinforcing factor for nylon filament for the purpose of dental prosthesis construction. The study findings indicated that kenaf fibers can be successfully incorporated with nylon to produce FDM filament. However, the mechanical performance of the resulted composite is still inconclusive. particularly, the addition of 0.5% kenaf fiber content showed no significant effect on the mechanical strength of the printed nylon specimens. Therefore, further observations into other physical properties such as thermal stability, surface morphology, or biodegradability may offer valuable insights and potential avenues for future research.

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