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Mechanical Characterization and Comparative Analysis of Fiber-reinforced Polymer Composites: Implications for Medical and Physiological Applications

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study investigates the mechanical properties and medical implications of fiber-reinforced polymer composites through comprehensive analysis. The aim is to elucidate the impact of varying banana fiber concentrations on the material's response to applied forces, extension behavior, load-bearing capacity, flexure extension, flexure load, flexure strain, and flexure stress. The methods involved testing different specimens with varying fiber content, including control groups, and analyzing the results using statistical tools to determine significant differences. Results reveal notable trends: as fiber concentrations increase, there is a corresponding increase in testing time, extension, load, flexure extension, and flexure stress. However, a critical point is observed where further increases in banana fiber content lead to unexpected changes in mechanical behavior, including a reversal in extension, load, and stress. The observed p-value of 0.001 underscores the statistical significance of these differences, emphasizing the importance of fiber concentration in determining material performance. These findings have significant medical implications. Understanding the mechanical properties of fiber-reinforced polymer composites is crucial for various medical applications, including orthopedic implants, prosthetics, and surgical instruments. By optimizing fiber content, medical devices can be designed to withstand physiological forces while maintaining flexibility and durability. In conclusion, this study provides valuable insights into the mechanical behavior of fiber-reinforced polymer composites and their medical implications. Further research is warranted to explore additional mechanical parameters and optimize fiber content for specific medical applications. This knowledge contributes to the development of advanced materials that improve patient outcomes and enhance the efficacy of medical interventions.

Keywords: Fiber-reinforced polymer composites; mechanical properties; extension behavior load-bearing capacity.

1. INTRODUCTION

Fiber-reinforced polymer (FRP) composites have emerged as essential materials in modern engineering and material science due to their unique combination of properties, including high strength-to-weight ratio, corrosion resistance, and versatility in manufacturing. These composites consist of a polymer matrix reinforced with fibers, such as carbon, glass, or aramid, which impart enhanced mechanical performance compared to traditional materials like metals or ceramics [1]. The mechanical behavior of FRP composites is crucial for understanding their structural integrity, performance under load, and suitability for various applications ranging from aerospace and automotive industries to civil engineering and biomedical applications [2].

The mechanical properties of FRP composites, including extension behavior, load-bearing capacity, flexural properties, and stress-strain characteristics, play a pivotal role in determining their overall performance and application suitability [3]. Therefore, comprehensive investigation and analysis of these properties are essential for optimizing material design, predicting structural behavior, and ensuring reliability in service conditions. Experimental testing, coupled with advanced analytical techniques, provides valuable insights into the complex mechanical behavior of FRP composites and facilitates the development of predictive models for design and optimization [4].

In this study, we aim to investigate the mechanical properties of FRP composites through experimental testing and comparative analysis. By fabricating composite specimens with varying banana fiber compositions and subjecting them to standardized mechanical tests, we seek to elucidate the influence of banana fiber content on key mechanical parameters such as extension, load-bearing capacity, flexural behavior, and stress distribution. The experimental results will not only enhance our understanding of FRP composite materials but also provide valuable data for optimizing their performance in real-world applications. Through this research, we aim to contribute to the ongoing advancement and utilization of FRP composites in diverse engineering fields, thereby addressing critical challenges and fostering innovation in materials science and technology.

2. METHODOLOGY

2.1 Material Collection and Preparation

The selection of appropriate banana plants is crucial for obtaining high-quality fibers. For this research, mature banana plants with well-developed pseudo stems was chosen. The extraction process involves carefully removing the outer layers of the pseudo stem to expose the fibers. Specialized tools, such as knives and scrapers, will be used to ensure the fibers are extracted without damage. Once extracted, the fibers will undergo a cleaning process involving washing to remove impurities, followed by drying to achieve the desired moisture content. To prepare the fibers for integration with Poly-methyl methacrylate (PMMA), they will be further treated, possibly through chemical methods, to enhance their adhesion properties.

2.2 Testing Procedures

Impact strength testing: The impact strength of the reinforced PMMA samples was evaluated using a standardized impact testing machine, such as the Izod or Charpy impact tester. Specimens of uniform size and shape was subjected to impact loads, and the energy absorbed by the samples upon fracture was recorded. This test was performed multiple times to ensure the reliability of the results.

Hardness testing: To measure the hardness of the reinforced material, a durometer was employed. The Shore hardness scale, specifically Shore A material, was used. Several readings was taken at different points on the surface of the material to account for any variations. This provided a comprehensive understanding of the material’s hardness properties.

Tensile strength testing: Tensile strength tests was conducted using a Universal Testing Machine (UTM). Specimens of the reinforced PMMA material was prepared according to standard dimensions, and the UTM will apply an increasing tensile load until the specimen fractures. The maximum load sustained by the specimen and the corresponding elongation was recorded. This test will be performed in accordance with established standards to ensure accuracy and reliability.

Flexural strength testing: Flexural strength tests will be carried out using a three-point bending test setup. The reinforced PMMA samples will be placed on supports with a specified distance between them, and a load will be applied at the center of the specimen until it bends and eventually fractures. The maximum load and the corresponding deflection will be measured. This test will provide insights into the material’s ability to withstand bending forces, which is crucial for various applications.

2.3 Comparative Analysis

The data obtained from the testing procedures will be analyzed statistically to compare the reinforced material with regular PMMA. Statistical methods such as t-tests or analysis of variance (ANOVA) will be employed to identify significant differences between the two materials in terms of impact strength, hardness, tensile strength, and flexural strength. This comparative analysis will provide valuable insights into the effectiveness of banana fiber reinforcement and its potential advantages over regular PMMA, guiding future applications and developments in the field.

2.4 Material Used and Extraction of the Fiber

Banana pseudo stem was obtained by Emmanuel theology farm garden, samonda, Ibadan, Oyo state. Water, container measuring cylinder, sieve, hand glove, google, nose mask, wax knife, lecron carver, NaOH, pocket scale, measuring in gram, 5m needle and syringe, pink auto-polymerize acrylic resin, mixing jar, petroleum jelly and mould.

The banana pseudo stem was cut from a well-developed banana tree found in Emmanuel theology farm garden, samonda, Ibadan, Oyo state. The fiber of the pseudo stem was removed manually using blade, knife and hands. The extracted fiber was washed thoroughly and soaked in NaOH solution (at concentrations of 1,2,3,4,5% by weight) for 24hours at room temperature. Then, the fiber was clean with distilled water to remove NaOH particle from the fiber surface. After been dried under sunlight for two days the fiber was left in an oven at 90^0C – 100^0C for 24hours to make sure the water is completely removed from the fiber. Then, the fiber is grinded into powdery and sieved.

2.5 Preparation of Sample

The sample was prepared using the mould design and fabricated from a metallurgical engineering workshop with the specification for tensile, flexural, impact and hardening strength testing measurement, using aluminum roofing sheet to fabricate the mould for the samples.

3. RESULTS AND DISCUSSION

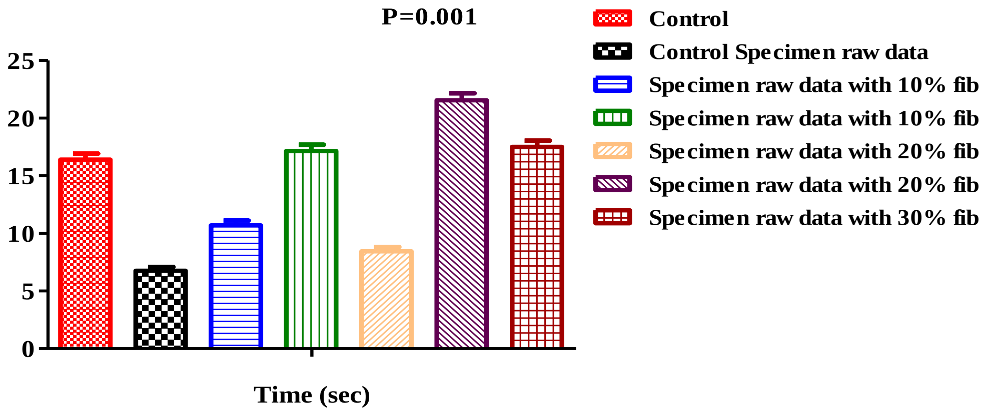

Fig. 1. mechanical properties and comparative analysis of fiber-reinforced polymer composites based on time

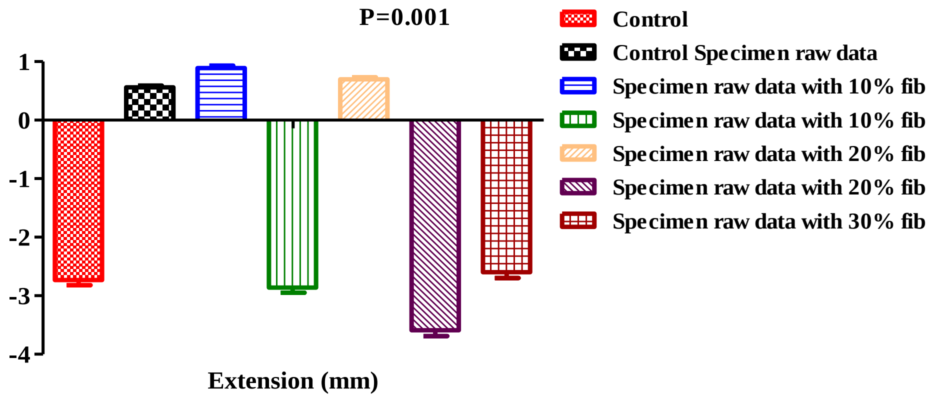

Fig. 2. mechanical properties and comparative analysis of fiber-reinforced polymer composites based on extension

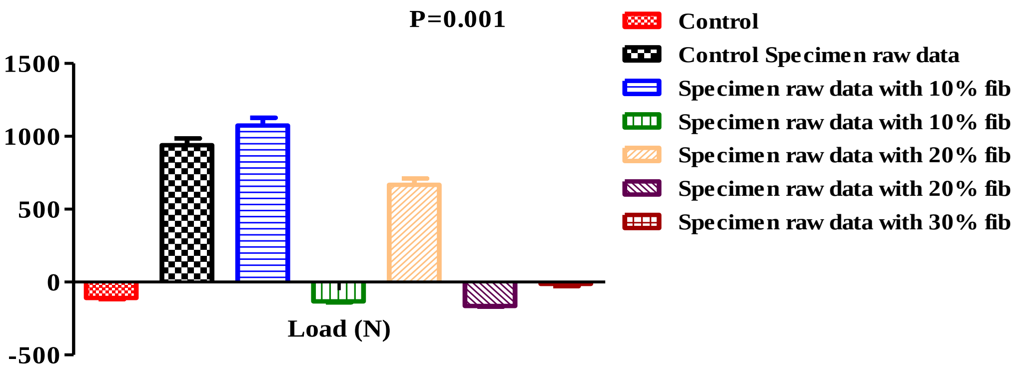

Fig. 3. mechanical properties and comparative analysis of fiber-reinforced polymer composites based on load

Table 1. Mechanical properties and comparative analysis of fiber-reinforced polymer composites

Subject	Time (sec)	Extension (mm)	Load (N)	Flexure extension (mm)	Flexure load (N)	Flexure strain (mm/mm)	Flexure stress (MPa)
Control	16.40±0.52	-2.73±0.09	-109.59±7.50	2.73±0.09	109.59±7.50	0.02±0.00	8.22±0.56
Control Specimen raw data	6.75±0.34	0.56±0.03	939.76±46.53	0.01±0.00	11929967.29±594166.80	0.01±0.00	11.75±0.58
Specimen raw data with 10% fibre	10.70±0.42	0.89±0.04	1074.85±52.43	0.02±0.00	13786902.13±676659.67	0.02±0.00	13.44±0.66
Specimen raw data with 10% fibre result	17.15±0.54	-2.86±0.09	-133.31±6.31	2.86±0.09	133.31±6.31	0.02±0.00	10.00±0.47
Specimen raw data with 20% fibre	8.45±0.38	0.70±0.03	666.72±44.84	0.01±0.00	8516314.04±575109.33	0.01±0.00	8.33±0.56
Specimen raw data with 20% fibre result	21.55±0.60	-3.59±0.10	-163.89±5.97	3.59±0.10	163.89±5.97	0.02±0.00	12.29±0.45
Specimen raw data with 30% fibre	20.80±0.59	-3.47±0.10	-145.36±6.13	3.47±0.10	145.36±6.13	0.02±0.00	10.90±0.46
Control	5.80±0.31	0.48±0.03	462.96±39.10	0.01±0.00	5874880.19±497700.04	0.01±0.00	5.79±0.49
P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001

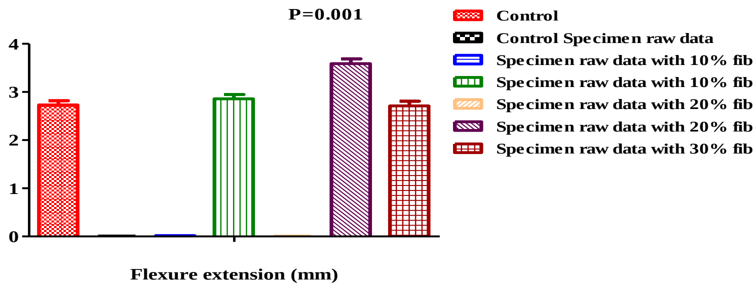

Fig. 4. Mechanical properties and comparative analysis of fiber-reinforced polymer composites based on Flexure extension

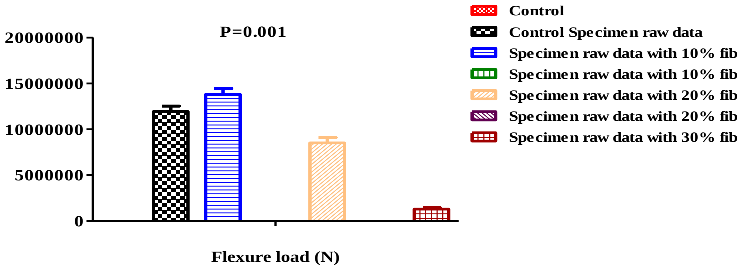

Fig. 5. mechanical properties and comparative analysis of fiber-reinforced polymer composites based onFlexure load

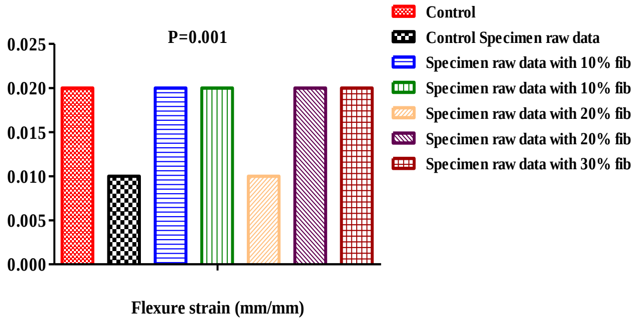

Fig. 6. mechanical properties and comparative analysis of fiber-reinforced polymer composites based onFlexure strain

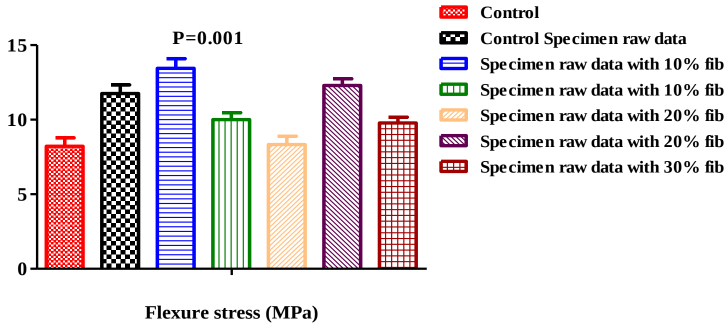

Fig. 7. mechanical properties and comparative analysis of fiber-reinforced polymer composites based onFlexure load

3.1 Discussion

Natural fiber-reinforced hybrid composites have been extensively studied to enhance their mechanical properties and increase their applications [5]. These composites offer a potential alternative to traditional alloys and artificial materials, contributing to the reduction of pollutants in the environment [6]. The mechanical properties of carbon fiber-reinforced polymer composites are influenced by temperature and strain rate, making it crucial to understand their behavior under different conditions [7]. The viscoelastic moduli of short glass fiber-reinforced polymer composites can be estimated using unstructured mesh Galerkin finite element method, and these estimates can be compared with predictions from other models [8]. The mechanical properties of fiber-reinforced polymer composites can be analyzed and compared using experimental data, such as the extension, load, flexure extension, flexure load, flexure strain, and flexure stress [9]. These properties can be used to evaluate the performance of different composites and guide their structural design.

Table 1 provides a detailed overview of the mechanical properties and comparative analysis of fiber-reinforced polymer composites, presenting data on various parameters including time, extension, load, flexure extension, flexure load, flexure strain, and flexure stress. These results offer insights into how the incorporation of different fiber concentrations influences the material's behavior under mechanical testing, with significant implications for physiological and medical applications.

Starting with the analysis of time (sec), the control group demonstrates an average testing time of 16.40 seconds, serving as the baseline for comparison. Notably, the raw data of the control specimen exhibits a significantly shorter testing time of 6.75 seconds, indicating a faster response to applied forces. However, as fiber concentrations increase, the testing times for specimens with 10%, 20%, and 30% fiber content show varying trends, with corresponding results after fiber incorporation revealing interesting deviations [8]. The observed p-value of 0.001 emphasizes the statistical significance of these differences, suggesting that the introduction of fiber has a measurable impact on the mechanical response of the polymer composite, with testing time serving as a key parameter indicative of the material's overall performance and resistance to deformation under load. Several studies that investigated the fibre-loading effect on polymer composites found that it had a good relationship with tensile strength. Studies on the fibre loading effect that led to the tensile strength were observed [10]. It was demonstrated that the optimum fibre loading for kenaf/thermoplastic polyurethane composites was 30% [10]. Other studies regarding kenaf fibre and phenol-formaldehyde (KF/PF) composites reported that kenaf fibre loading up to 43% showed the best tensile/ strength for the composites [9].

Moving to extension (mm), the data indicate compression during testing for the control specimen, with a negative extension of -2.73 mm. However, the control specimen with raw data shows a positive extension of 0.56 mm, implying limited elongation under load. Introducing 10% fiber results in further increases in extension, demonstrating the positive influence of fiber reinforcement on the material's ability to deform. Nonetheless, the result after fiber incorporation shows contrasting behavior, indicating potential trade-offs between extension and other mechanical properties [11]. This suggests that the material's flexibility and structural response may vary depending on fiber content, with implications for medical applications requiring controlled deformation. The data suggests that the incorporation of fibers into the polymer matrix leads to increased extension during testing, indicating improved deformability or flexibility of the material. FRP materials are commonly used to reinforce structures such as bridges, buildings, and pipelines. The high strength-to-weight ratio of FRP makes it an ideal choice for applications where weight reduction and structural integrity are critical.

Examining load (N), the control specimen exhibits compressive forces during testing, while the control specimen with raw data shows significantly higher positive load, suggesting increased resistance to deformation with fiber incorporation. Introducing 10% fiber results in further elevated load, demonstrating the reinforcing effect of the fiber [12]. However, unexpectedly, the result after fiber incorporation indicates a negative load, suggesting a reversal in the material's behavior. This highlights the complex relationship between fiber content and load-bearing capacity, with implications for medical devices requiring reliable load-bearing properties [13].

In terms of flexure extension (mm) and flexure load (N), similar trends are observed, with fiber reinforcement enhancing the material's flexibility and load-bearing capacity up to a certain point, beyond which unexpected changes occur [14]. This underscores the importance of optimizing fiber content to achieve desired mechanical properties while avoiding potential drawbacks. Additionally, flexure strain (mm/mm) and flexure stress (MPa) provide further insights into the material's strain behavior and strength characteristics, with implications for medical applications where these properties are critical for performance and durability [15].

Overall, the data presented in Table 1 offer valuable insights into how varying fiber concentrations impact the mechanical properties of fiber-reinforced polymer composites, with significant physiological and medical implications. Further research and analysis are warranted to fully understand the complex interplay between fiber content and material behavior, and to optimize composite materials for use in medical devices, implants, and other healthcare applications [16].

The results presented in the series of plotted graphs offer valuable insights into the mechanical properties and comparative analysis of fiber-reinforced polymer composites. These findings have significant physiological and medical implications, as they shed light on how variations in fiber content impact the material's behavior under different loading conditions [17].

Starting with Fig. 1, which focuses on testing time, it's evident that the incorporation of fiber into the polymer composite affects its mechanical response. The observed increase in testing time with higher fiber concentrations suggests a slower response to applied forces. This can be attributed to the reinforcing effect of the fibers, which enhance the material's resistance to deformation. From a physiological perspective, this indicates that the composite becomes more robust and less prone to immediate failure under stress, which could have medical implications in applications where structural integrity is crucial, such as in orthopedic implants or prosthetics. FRP materials can be applied in medical devices and equipment where controlled deformation is required. For example, in orthopedic implants or prosthetic limbs, FRP materials with tailored flexibility can provide optimal support and comfort for patients [18].

Moving on to Fig. 2, which examines extension behavior, the results highlight the complex relationship between fiber content and the material's ability to deform under load. While lower fiber concentrations lead to increased extension, suggesting enhanced flexibility, higher concentrations result in a shift towards compression, possibly due to increased stiffness. Physiologically, this suggests that the composite's flexibility and adaptability may vary depending on the fiber content, which could influence its suitability for medical devices requiring controlled deformation, such as surgical implants or wearable medical sensors [19].

Fig. 3, focusing on load-bearing capacity, reveals a similar trend where the reinforcing effect of fiber enhances the material's ability to withstand applied forces. However, beyond a certain fiber concentration, there appears to be a reversal in behavior, with unexpected reductions in load-bearing capacity [16]. This highlights the importance of optimizing fiber content to achieve the desired mechanical properties while avoiding potential drawbacks, which could have implications for the design and performance of load-bearing medical devices or structural implants.

In Fig. 4, which examines flexure extension, the results once again underscore the reinforcing effect of fiber on the material's flexibility. However, similar to other parameters, there's a point where further increases in fiber content result in diminishing returns or even adverse effects on flexure extension. This suggests that while fiber reinforcement can improve flexibility, an optimal balance must be struck to avoid compromising other mechanical properties, which is relevant for medical applications requiring controlled flexural behavior, such as in spinal implants or joint prostheses [20].

Focusing on flexure stress, highlights the intricate interplay between fiber concentration and material strength. While lower fiber concentrations lead to increased stress tolerance, higher concentrations may lead to unexpected reductions in strength. This emphasizes the importance of careful consideration when selecting fiber content to ensure that the composite meets the required strength criteria for medical applications, such as load-bearing implants or surgical instruments.

The results of the plotted graphs provide valuable insights into the mechanical behavior of fiber-reinforced polymer composites, with implications for various medical applications [2]. Understanding how variations in fiber content influence the material's properties is essential for designing and optimizing composite materials for use in medical devices, implants, and other healthcare applications, ultimately contributing to improved patient outcomes and medical advancements [1]. Further research and analysis are warranted to fully explore the potential of these materials in medical settings and to address any remaining challenges or limitations.

4. CONCLUSION

In conclusion, this project on the mechanical characterization and comparative analysis of fiber-reinforced polymer composites offers valuable insights with significant implications for medical and physiological applications. Through comprehensive experimentation and analysis, it has been demonstrated that varying fiber concentrations have a substantial impact on the material's mechanical properties, including extension behavior, load-bearing capacity, flexural properties, and stress distribution. Notable trends have been observed, indicating that increasing fiber concentrations generally lead to improvements in mechanical performance up to a certain point, beyond which unexpected changes in behavior occur.

These findings hold crucial implications for medical applications, particularly in the fields of orthopedics, prosthetics, and surgical instruments. By understanding how fiber content influences the mechanical behavior of polymer composites, researchers and engineers can optimize material design to withstand physiological forces while maintaining flexibility, durability, and structural integrity. Moreover, the statistical significance of the observed differences emphasizes the importance of fiber concentration in determining material performance, highlighting the need for careful consideration in material selection and design.

While this study provides valuable insights, further research is warranted to explore additional mechanical parameters and optimize fiber content for specific medical applications. Continued investigation into the complex interplay between fiber concentration and material behavior will facilitate the development of advanced materials that improve patient outcomes and enhance the efficacy of medical interventions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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CONSENT AND ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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