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Effect of palm fiber volume fraction for enhancing the physical and mechanical properties of epoxy composites

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Abstract

Reinforcing materials such as fiber; are most widely used to give new properties to composites. This study investigates the effect of palm fiber (Arenga pinnata) volume fraction on the physical and mechanical properties of epoxy-based composites. Composite specimens with 0% and 2.5% fiber volume fractions were fabricated, maintaining a uniform thickness of 2 mm. The fabrication process involved fiber extraction, mixing with epoxy resin, and controlled curing. The physical properties assessed included density, porosity, and water absorption, while mechanical testing involved tensile and bending tests. The results demonstrated that the 2.5% fiber-reinforced composite exhibited improved properties compared to the 0% fiber composite. The density increased from 5.85 g/cm³ to 13.43 g/cm³, while porosity and water absorption rose slightly to 0.40% and 0.03%, respectively. In mechanical testing, the tensile strength increased from 2.64 MPa to 6.29 MPa, while strain improved from 1.06% to 4.59%. Young's modulus, however, decreased from 2.49 MPa to 1.37 MPa, indicating enhanced flexibility. The bending stress increased from 6.35 MPa to 10.85 MPa, and deflection improved from 1.45 mm to 7.35 mm. These findings indicate that incorporating 2.5% palm fiber provides an optimal balance between strength and flexibility, making it a promising reinforcement for lightweight composite applications.

Keywords:
Composites, natural fibers, mechanical properties, physical properties.

1 Introduction

A composite is a combination of two or more materials that still have their constituent properties [1][2]. Composite formation elements consist of reinforcement and matrix; both parts have their characteristics. A combination of both materials is expected to complete each constituent material property so it produces an improved material. The benefits of composite are its lightweight, rigidity, and high durability. The use of fiber as reinforcement can make a composite that has maximum strength and rigidity. The matrix functions as a fiber barrier so the fibers are united, distribute the weight, and are a wrapper [3].

Fiber functions as a power buffer in the composite structure; the initial weight that goes through a matrix passes the fiber, so the fiber must have a higher tensile strength and elasticity than the matrix [4]. The fiber used as a composite reinforcement material is expanding, especially those that are being developed are natural fibers. The development of natural fiber-reinforced composites (NFRC) can reduce energy consumption and environmental impact. The benefits of natural fibers are that they are cheap, lightweight, have good thermal properties, have high toughness, are not irritating, have relatively high specific mechanical properties, and are biodegradable. Based on their advantages, natural fibers are an alternative reinforcement material for composites [5].

The basic properties that you should know of the composite are physical properties. These properties can affect other properties that are in composites, such as mechanical properties. The addition of fiber to reinforced composites can make composites have good properties [6]. Usually, fibers that are added to composites are synthetic. These fibers are limited, and the processing of fiber can add more cost to manufacture, so the development of alternative fibers becomes important. The alternative to replace synthetic fibers is natural fibers, such as palm fibers. Natural fiber, such as palm fiber (Arenga pinnata Merr.), is one of the fibers that have the potential to be developed as composite reinforcement [7].

Palm fiber has high mechanical properties and abundant availability, making this fiber potential to develop as a reinforcement composite [8]. Palm fiber production in Indonesia nationally reaches 14,000 tons per month or 165,000 tons per year. Palm fiber has a diameter range starting from 99 µm to 400 µm, often in 250–400 µm. Palm also has an advantage in high durability, slowing down the weathering, resistance to acids and sea salt water, and can prevent termites [9],[10]. High mechanical properties and the advantages of palm fiber make it a potential as a reinforcement composite. The fiber-reinforced composite structure can be divided into continuous fiber composites, woven fiber composites, chopped fiber composites, and hybrid composites. Composite, in general, is used for many needs such as automotive, aviation, marine, and architecture. Composites are also widely used in consumer products such as skis, golf clubs, and tennis rackets [11].

Previous research conducted about pressure and impact tests for palm fiber-reinforced polymer composites soaked in NaOH 5% resulted in bending strength with polyester resin 25.17 MPa and epoxy resin 16.43 MPa. The strain values obtained were 55.8 percent and 34.0 percent for polyester resin and epoxy resin [12]. The tensile strength test of hybrid composite material palm fiber reinforced with random fiber orientation. The test result obtained from the tensile strength test of the hybrid composite with fiber fraction volume (30% palm fiber: 0% coconut fiber) is 21.06 MPa, fraction volume (20% palm fiber: 10% coconut fiber) is 18.10 MPa, fraction volume (20% palm fiber: 10% coconut fiber) is 21.64 MPa and the fraction volume (0% palm fiber: 30% coconut fiber) is 17.19 MPa. The maximum value is owned by a composite with a fiber volume fraction of 15%: 15% with a value of 23.48 MPa [13].

This study aims to determine the maximum value of the physical and mechanical properties of the composite with 0% and 2.5% fiber volume fractions with a thickness of 2 mm. The 0 and 2.5% fiber volume fraction a relatively low, amounts which help in assessing the initial impact of fiber reinforcement without overwhelming the matrix material. This low percentage can provide insights into the minimum effective amount of fiber needed to enhance properties. A thickness of 2 mm is a practical choice for testing, as it is thick enough to ensure structural integrity during mechanical testing while still being manageable for fabrication and analysis. This thickness can also be relevant for various applications where such dimensions are common. The selected fiber volume fractions and thickness are strategic choices aimed at providing meaningful data on the effectiveness of palm fiber reinforcement in epoxy composites. Physical properties are density, porosity, and water absorption. Mechanical tests carried out are tensile tests and bending tests. The effect of the palm fibers-reinforced composite can be environment-friendly, easy to obtain, and low in cost.

2 Research Methodology

2.1 Materials

The materials used in this research were palm fibers, paper waste, and epoxy resin. The palm fibers utilized for the development of the reinforced composites are derived from Arenga pinnata, commonly known as the sugar palm or rumba palm. This species is chosen due to its abundant availability and favorable mechanical properties, making it a suitable candidate for composite reinforcement. The fabrication of composite was constructed in the Materials and Nucleonics Laboratory, Jenderal Soedirman University, Nucleonics Laboratory, and Material Technique Laboratory, Gadjah Mada University.

2.2 Characterizations

The palm fibers are sourced from the species Arenga pinnata or other suitable palm varieties. The palm fibers are cleaned and processed to remove any impurities or non-fibrous materials. This may involve cutting the fibers to a uniform length, typically in the range of a few centimeters, to ensure consistent distribution within the composite. The epoxy resin is mixed with a hardener or catalyst according to the manufacturer's instructions. The mixing ratio is crucial for achieving the desired curing properties and mechanical performance of the composite. A mold is prepared to shape the composite. The mold is typically made of a non-stick material to facilitate easy removal of the cured composite. The dimensions of the mold are designed to produce samples with a thickness of 2 mm.

The mechanical characteristics of the composites that have been made and then tested, in the tests carried out are tensile, bending, and physical tests. The tensile tests were used with standard ASTM D 638-02 and ASTM D 790-02 for bending tests [14]. The physical test used ASTM C20-93 for water absorption and ASTM C134-95 for density. The tensile and bending tests were carried out at the Technical Materials Laboratory of the Vocational School of Gadjah Mada University using a TN20MD type UTM tester with a tensile test standard of ASTM D 638-01 and a bending test standard of ASTM D 790-07 (ASTM, 2002a; ASTM, 2002b) [15]. The physical test was tested at the Core Physic and Advanced Materials of Jenderal Soedirman University.

2.3 Research design

The composite to be made is a type of continuous fiber composite with a long and straight fiber arrangement. The process of making composites begins with the selection and cutting of fibers, epoxy resin, and a catalyst as the constituent materials of the matrix, mixed and stirred until homogeneous. Then the matrix is poured into the mold until half the volume is filled and the fibers are arranged on top of the matrix; the remaining matrix is poured to cover the entire fiber [16]. The variation of fiber volume fraction used is 0% and 2.5% with a thickness of 2 mm. The research design used in Fig. 1.

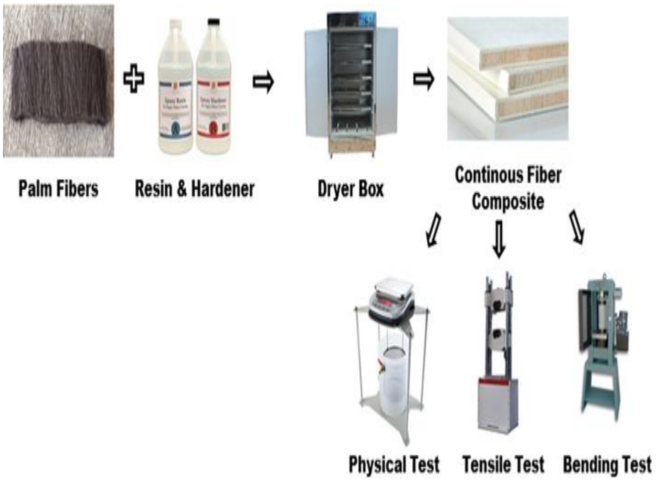

Fig. 1. The research design

Based on the results of testing the physical and mechanical properties of the composites. At this stage, each data point is compared from each variation of the fibers fraction, and the relation of physical and mechanical properties of the composite is seen; also, it can be seen that the variation of the fibers volume fraction produces the most optimum physical and mechanical properties

3 Results and discussion

3.1 Physical properties analysis

Density, resin percentage, fiber percentage, percentage of porosity or void content, and water absorption are significant fundamental material physical qualities of composites that must be defined by constituent content testing before the raw material moves on to the next stage of manufacture. Physical tests of the composite were carried out on its density, porosity, and water absorption. The physical properties were carried out to obtain the relation with mechanical properties because these properties can affect mechanical properties. Composites with optimum physical properties are expected to have great mechanical properties. Eqs (1-3) are used to calculate the physical test of the composite [17].

$$\rho = \frac{m_o}{m_w - (m_{tot} - m_s)} \times \rho_w \tag{1}$$

$$P = \frac{m_w - m_o}{m_w - (m_{tot} - m_s)} \times 100\% \tag{2}$$

$$WA = \frac{m_w - m_0}{m_0} \times 100\% \tag{3}$$

Where ρ is the density of composites (gram/cm^3), P is porosity (%), WA is water absorption (%), m_0 is the dry mass of composite (gram), m_w is wet mass after composites are soaked in water (gram), m_s is mass of string in the water (gram), and m_{tot} is mass of composites and string in water (gram).

The density of materials describes a dense structure**,** the higher of density, the denser of materials [18]. The composites have a high density**,** indicating the palm fibers have filled the space in the matrix. In Fig. 2, the addition of palm fibers can double the density of composites because of the moisture content of this fiber.

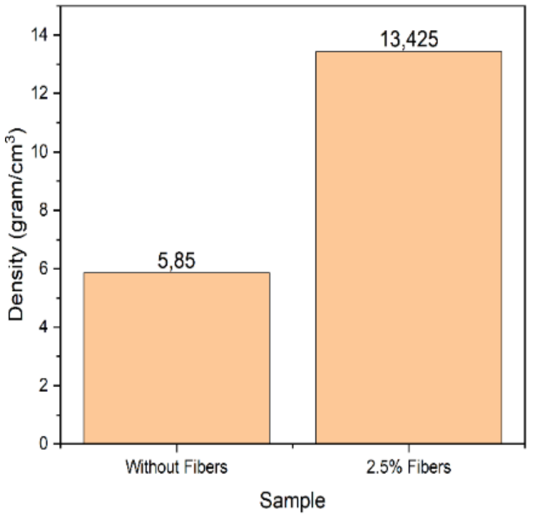

Fig. 2. The density of composites

The addition of palm fibers makes more cavities between matrices get smaller**;** this can affect a higher density of composites. The space between the composite bonds causes voids, which increase porosity; porosity is a measure of the material's space [19]. The results of the porosity test in Fig. 3**;** the addition of fiber fibers to the porosity value of the composite without fiber indicates the presence of space between the matrix and fiber bonds in the composite.

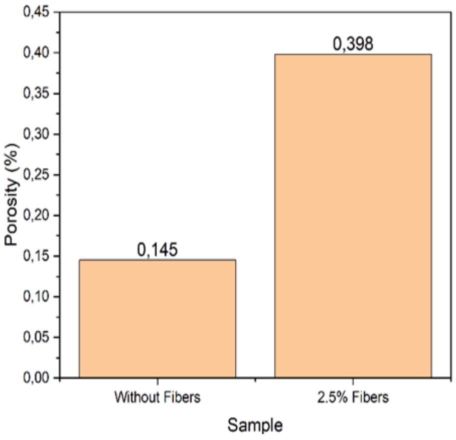

Fig. 3. The porosity of composites

Porosity and density are linearly related to the mechanical properties of the composite. This is due to the bond between the fibers and the matrix in the composite structure; the higher the density value, the smaller the space in the composite structure; however, the orientation of the fibers that fill the composite matrix also influences this. Although fiber orientation can affect the bond and space formed in a composite structure, linear fiber orientation has the advantage of distributing mechanical loads evenly, resulting in higher mechanical properties [20].

Water absorption is the last test to determine the composite's physical properties. Density and porosity describe the amount of density and space possessed by the material, respectively. Water absorption refers to the ability to hold and flow through water particles in a composite structure [21]. The ability of a material to absorb water is strongly influenced by its structure; water particles can pass through the space created by the matrix and fiber bonds. Fig. 4, the water absorption of the composite with fiber fibers is only slightly higher than that of the composite without fiber. The water absorption properties are influenced by the density and porosity of the composite [22].

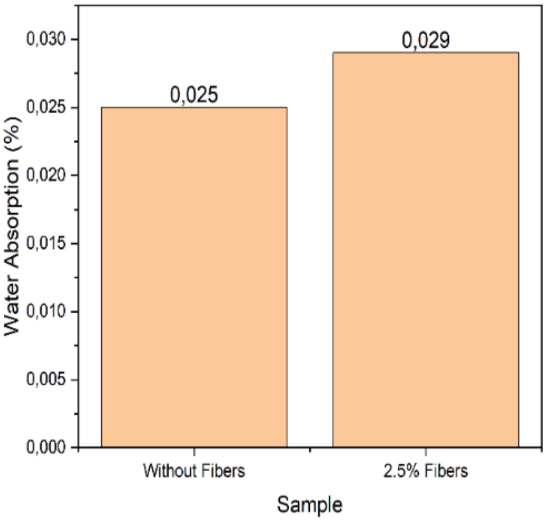

Fig. 4. The water absorption of composites

3.2 Mechanical Properties Analysis

a) Tensile Strength Analysis

The results of the tensile test obtained maximum force (P) and elongation (ΔL), then processed to obtain composite stress and strain values, as well as Young's modulus with the Eqs (3-5) [23].

Stress
$$\sigma = \frac{P}{A} \tag{3}$$

Strain
$$\varepsilon = \frac{\Delta L}{L_0} \tag{4}$$

Young's modulus
$$E = \frac{\sigma}{\varepsilon} \tag{5}$$

Where P is the maximum force (KN), A is the composite area (mm^2), and L is the increase in length (mm). The comparison of fiber volume fraction and tensile stress in Fig. 5.

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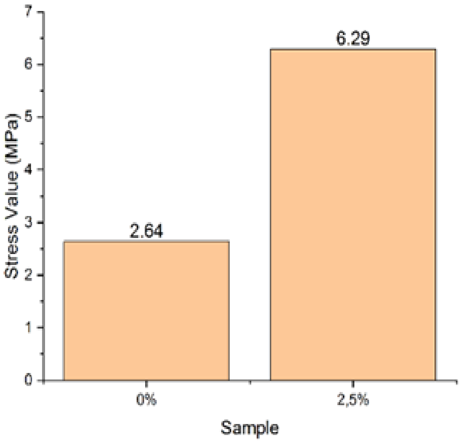

Fig. 5. Stress Values of Tensile Test Composite Palm Fibers

The highest tensile strength value is 6.29 MPa**,** owned by the composite with a 2.5% fiber volume fraction**,** and the lowest value is 2.64 MPa of the composite with a 0% volume fraction. A comparison of strain and stress values in Fig. 6. The value of the strain that is owned by the composite is linear with the stress value. The highest strain is owned by the composite with a fiber volume fraction of 2.5% at 4.59%**,** and the lowest value is owned by a composite with a fiber volume fraction of 0% at 1.06%.

Fig. 5, and Fig. 6 can be concluded that the fiber as reinforcement can increase the tensile strength and also the strain strength of the composite. The composite stress value increases when the composite is reinforced with fiber**;** it is seen that the composite that is not fiber-reinforced has the lowest tensile strength value compared to the fiber-reinforced composite [24]. However, the addition of a lot of fiber can affect the bond between the matrix and the fiber or the interface of the composite. Composites with low interfaces will reduce the strength of the composites**;** the stronger the composite interface, the higher the tensile strength value [25].

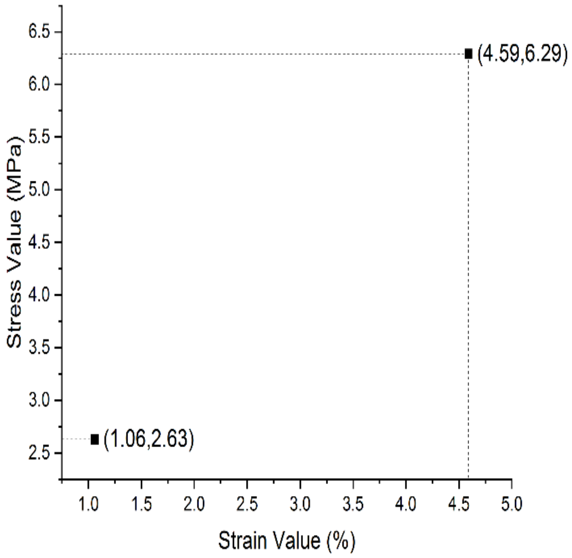

Fig. 6. Stress-Strain Values of Composite Palm Fiber

The value of strain and stress has a linear relationship**;** the higher the stress, the greater the composite strain. Strain is the relative change in the size and shape of a composite. The more distributed the stress on the composite, the greater the strain value [26]. The Young's modulus of the composite in Fig. 7**.** Young's modulus is one of the mechanical parameters that might indicate a material's resistance to occlusal forces. The elastic stiffness of a material is indicated by Young's modulus. Restorative materials with a high Young's modulus are required to tolerate deformation and cuspal fracture, especially when placed in high-stress areas of posterior teeth**,** whereas materials with a low Young's modulus are not required because they deform more under occlusal forces, which may cause catastrophic fracture [2].

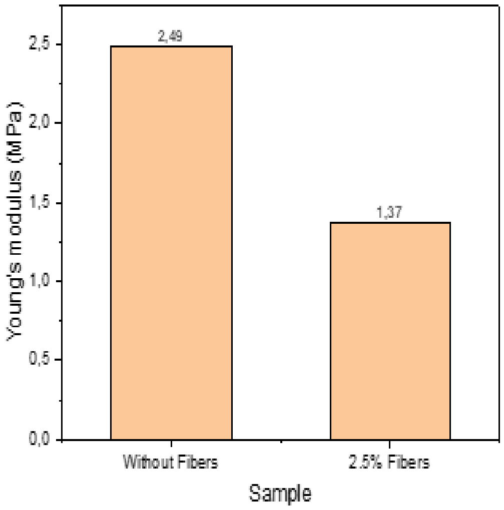

Fig. 7. The Young’s Modulus of palm fibers composite

Fig. 7, the addition of fibers reduces the elasticity of the composite**;** this is due to the type of matrix utilized, which is epoxy resin. Epoxy resin is a type of thermoset resin with limited flexibility. The binding between the fiber-matrix that can distribute the load well determines the strength of the fiber-matrix composite [28].

3.3 Bending strength analysis

The results of the bending test obtained data for the maximum force (P) and deflection and were then processed to obtain the stress value with the equation:

$$\sigma = \frac{3Pl}{2ba^2} \qquad (6)$$

Where P is the maximum force (KN), l is the length of the span (mm), b is the width of the composite (mm), and a is the thickness of the composite (mm).

A comparison of fiber volume fraction with composite bending stress is in Fig. 8.

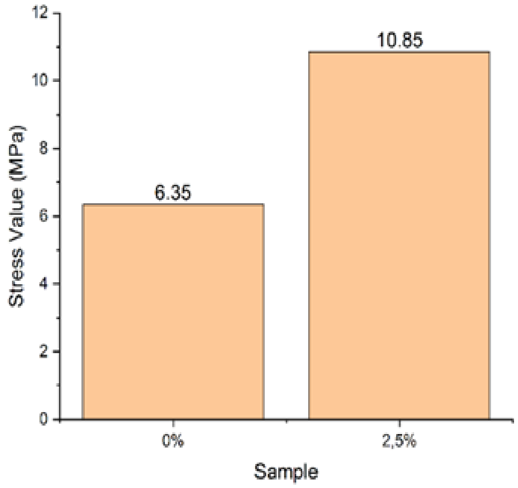

Fig. 8. Stress values of bending test composite palm fiber

The highest tensile strength value is owned by the composite with a fiber volume fraction of 2.5 percent of 10.85 MPa. While the lowest value is owned by the composite with a volume fraction of 0 percent or without fiber of 6.35 MPa. These results are linear with the results in the tensile test**,** where the composite with a volume fraction of 2.5 percent has the highest value. The composite deflection value Fig. 9.

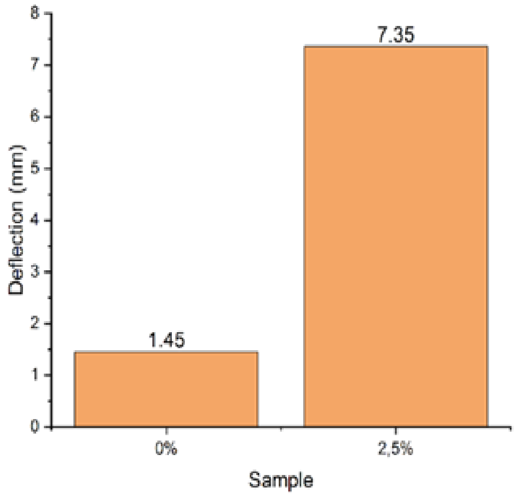

Fig. 9. Deflection of composite palm fiber

The highest deflection value is owned by the composite with a volume fraction of 5 percent of 8.47 mm. While the lowest value is owned by the composite with a volume fraction of 0 percent**,** or without fiber reinforcement, it is 1.45 mm. The results of the bending stress and deflection of the composite in Fig. 7 and Fig. 8 can be concluded that the reinforcement in the composite greatly influences the value of the bending stress and deflection. Fiber can distribute stress before the stress is received by the matrix [29]. Even the distribution of fiber can increase the bending strength of the composite because the stress will be distributed throughout the fiber [30]. In addition, the number of voids or air bubbles in the composite can also reduce the value of the bending strength**;** this is because air voids can cause breaking forces to lead to hollow areas, and the force is not perfectly distributed [31].

Deflection is the bending of a rod caused by the force received by the rod. Deflection is useful for knowing the flexibility of a composite [32]. Linear deflection with the number of fiber volume fractions; the more fibers added to the composite, the greater the deflection. Fiber is useful for spreading the force to minimize the force received by the composite. The results of physical and mechanical properties have a relation that the physical properties of the composite can affect their mechanical properties [33]. The physical properties describe the structure while the mechanic describes responses to the load from the composites. The performance of natural fiber composites is influenced by a synergistic combination of parameters resulting from the characteristics of the reinforcing fiber, the base matrix, and the fiber-matrix interfacial contact (e.g., mechanical interlocking, physical adhesion, chemical bonding) [34].

While the study indicates that the composite with a 2.5% fiber volume fraction shows improved properties compared to the 0% composite, it does not necessarily mean that 2.5% is the optimal amount. Higher fiber volume fractions could potentially yield even better mechanical properties, as fibers generally enhance strength and stiffness up to a certain point before other factors (like fiber-matrix adhesion and void content) may negatively impact performance.

4 Conclusions.

The results indicate that incorporating 2.5% palm fiber significantly enhances the mechanical and physical properties of epoxy composites, providing an optimal balance between strength and flexibility. The increase in tensile and bending strength suggests that palm fiber is a viable reinforcement material for lightweight applications. However, the decrease in Young’s modulus indicates a trade-off between strength and stiffness. To fully optimize composite performance, future research should explore higher fiber volume fractions, alternative fiber treatments, and long-term durability assessments. Additionally, incorporating statistical analyses, such as standard deviation and error margins, will enhance result reliability and identify potential variability in sample properties.

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Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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