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Effect of Fishbone Ash on the Physical and Mechanical Properties of Artificial Teeth

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ABSTRACT

The increasing demand for cost-effective and environmentally sustainable materials in dental restorations has prompted the exploration of biowaste-derived materials. This research investigates the application of fishbone ash (FBA), a byproduct of the fish processing sector, as an additive in the production of artificial teeth. FBA was included into a kaolin, quartz matrix with polyvinyl alcohol (PVA) as a binder to evaluate its effects on the physical and mechanical qualities of dental composites. This research highlights the potential of fishbone ash as a sustainable resource in the creation of new dental materials, facilitating the progress of environmentally friendly and high-performance dental applications. Various concentrations of FBA (0-25 wt%) were assessed in parameters such as firing shrinkage, bulk density, porosity, water absorption, hardness, compressive strength, and diametral tensile strength. Chemical stability assessments were conducted in alkaline (25% NaOH), acidic (25% HCl), and neutral (distilled water) conditions to simulate oral environments. The results indicate that an increase in the quantity of FBA within the material enhances its performance. The tensile strength increased from 19.5 MPa at 0% to 29 MPa with 25% FBA. At 25% FBA, the compressive strength, hardness, and density measured 338.3 MPa, 574 HV, and 2.65 g/cm³, respectively. The porosity and water absorption were reduced to 0.05%. The results indicate that increasing the amount of FBA enhances the mechanical and physical properties of the material. This research highlights the potential of fishbone ash as a sustainable resource in the creation of new dental materials, facilitating the progress of environmentally friendly and high-performance dental applications.

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Keywords: Fishbone Ash (FBA), Dental Composites, Artificial Teeth, Mechanical Properties, Sustainable Dental Ceramics

1. Introduction

The development of biocompatible and cost-effective materials for dental restorations has been a prolonged obstacle in the field of dental materials science. Artificial teeth, which are typically made of porcelain, composite resins, or polymer-ceramic hybrids, must have exceptional mechanical strength, chemical stability, wear resistance, and dimensional stability in order to withstand the hostile oral environment. Nonetheless, the expensive cost of raw materials and energy-intensive production methods of traditional dental ceramics have led scientists to investigate sustainable, alternative materials that improve performance while lowering production costs [1][2][3]. A common biowaste from the fish processing industry, fishbone is mostly composed of collagen [4] and hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$]. A calcium-phosphate rich ash with a Ca/P ratio similar to stoichiometric hydroxyapatite is produced when fishbone is calcined, making it a viable bio-ceramic precursor for use in dental and biomedical applications [5]. When added to ceramic matrices, hydroxyapatite produced from fishbones has been shown in earlier research to improve mechanical, bioactive and densification [6][7][8]. Fish-derived materials, known for their abundance, biocompatibility, and adaptability in biomedical applications, have recently garnered attention as sustainable biomaterials [9].

For instance, hydroxyapatite made from fish scales has demonstrated promise as a polymer filler, enhancing the mechanical characteristics of PMMA resin [10][11]. Materials derived from fish have also shown promise in regenerative medicine and bone tissue engineering, with applications ranging from collagen membranes for directed tissue regeneration to bone graft alternatives. Additionally, it has been shown that calcium phosphate obtained from fishbones improves the remineralization of dental enamel, indicating its potential for use in dental restoration applications [1][12]. The current research explores fishbone ash's (FBA) potential as a sustainable addition in the manufacturing of prosthetic teeth in accordance with these findings. FBA was calcined at 1000 degrees Celsius and then mixed with polyvinyl alcohol (PVA) as a binder to create a kaolin-quartz matrix. The study methodically investigates how different FBA contents (0–25 wt%) affect the mechanical and physical characteristics of artificial tooth materials, such as bulk density, porosity, water absorption, hardness, compressive strength, diametral tensile strength, firing shrinkage and chemical stability. The objective is to determine whether FBA can improve the performance of artificial teeth, offering a cost-effective and eco-friendly alternative to traditional dental ceramics [13]. In order to replace costly, energy-intensive traditional ceramics, it is imperative that sustainable, biocompatible, and affordable materials be developed for dental restorations.

2. Methodology

Bone waste from fish markets was cleaned with distilled water to get rid of pollutants, muscle, and fat. It was then sanitized with ethanol wipes and rinsed with sterile water. 13.5 grams of dried fish bones were produced after the bones were sun-dried and baked at 100°C. Fish bones were burned in a muffle furnace at 1000°C for an hour, increasing in temperature by 5°C every minute, to create fish bone ash (FBA). The chilled sample was ball-milled with zirconia balls in ethanol for 18 to 24 hours at 600 rpm. The fish bone powder was combined with feldspar, FBA, quartz, and kaolin, and then ball-milled after being dried for 24 hours at 120°C. After 30 to 40 minutes of stirring in a mortar, a PVA binder solution—which was created by heating PVA in water at 120°C until it became viscous—was added. After combining the powder and binder, it was uniaxially compressed for three minutes at 300–400 MPa. Pellets were washed with ethanol after compression and then thinly coated for sintering. Using $MoSi_2$ heating elements in an air environment, sintering was carried out in a high-temperature furnace (Base Unit Nabertherm GMBH UK). The heating stages were conducted at a rate of 3°C/min augmenting the temperature to 500°C with a one hour hold to remove the binder, followed by heating at 5 °C/min to 1050 °C with a two hour hold for densification. The samples were then cooled at 5 °C/min to a temperature of room temperature. Compositions of the sample were followed according to Table-1.

Table 1: Batch Composition of the samples

Batch	Feldspar (%)	Fishbone (%)	Quartz (%)	Kaolin (%)
1	75	0	20	5
2	70	5	20	5
3	65	10	20	5
4	60	15	20	5
5	50	25	20	5

3. Results and Discussion

3.1 Structural Analysis

X-ray diffraction was used to analyze the phase composition of the fish bone ash (FBA). The X-ray diffraction patterns of the calcined fish bone (Figure.1) showed several peaks which confirms that the sample is crystalline in nature. Prior to calcination, fish bone contains calcium carbonate ($CaCO_3$) in the crystalline form of calcite as the dominant phase. When fish calcined above 800 °C a thermal decomposition reaction occurs as follows.

$$CaCO_3\ (s) \longrightarrow CaO\ (s) + CO_2\ (g)$$

The XRD pattern of the ash of calcinated fish bones showed characteristic diffraction peaks at 2θ = 27.76°, 33.50°, 40.25°, and 52.57°. These peaks correlate to the diffraction data of CaO with the JCPDS card no. 37-1497. The lack of strong peaks of calcite suggests that $CaCO_3$ was fully transformed into CaO during the calcination process. These results are in accordance with those in the literature. Many researchers have noted comparable phase changes of fish bone and other biogenic apatite materials during thermal exposure. For instance, in 2013, biogenic $CaCO_3$ was converted to CaO at a temperature exceeding 800 °C [14], and the major diffraction peaks were in the 2θ range of 27°-52°. These findings are similar to those in the present work, demonstrated by S. Sobczak-Kupiec and co-workers. Research on fish bone derived hydroxyapatite shows that at higher (>900 °C) calcination temperatures, hydroxyapatite tends to partially decompose, forming β-tricalcium phosphate and CaO. These findings are consistent with the XRD patterns we generated. The XRD data confirms that calcite was converted into calcium oxide through thermal decomposition, meaning that the calcination temperature of 1000 °C and the duration of the process were adequate to complete transformation.

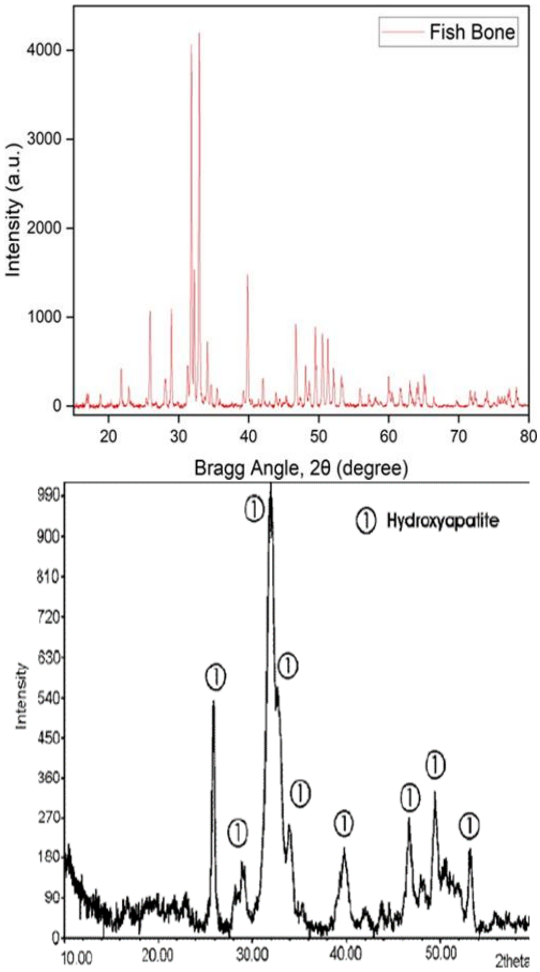

Figure 1: XRD analysis of fishbone powder

3.2 Mechanical analysis

3.2.1 Firing shrinkage

Shrinkage is a critical property as it affects the final dimensions and tolerances of dental ceramic products. The linear firing shrinkage (LFS) is determined according to ASTM C326-03 following equation

$$LFS\% = \frac{Ld - Lf}{Ld} X\ 100 \quad (1)$$

Where L_d and L_f are dried and fired specimens, respectively. According to Figure 2(i), firing shrinkage rises as FBA content does, from 5.2% for the control (0% FBA) to 6.3% at 25% FBA. This implies that FBA increases linear shrinkage and sintering densification because fluxing agents like calcium oxide and other reactive phases lower the sintering temperature. More shrinking is also achieved by the removal of pores and the reorganization of particles caused by the small particles in FBA and the liquid phases that develop after fire. The moderate 1.1% increase in shrinkage has little effect on dimensional control. FBA is appropriate for dental applications where accuracy and strength are crucial, as these results are consistent with research demonstrating that controlled shrinkage enhances densification and mechanical strength.

3.2.2 Diametral tensile strength

Figure 2(ii) shows the diametral tensile strength (DTS) readings for the samples reinforced with fish bone ash (FBA). Samples containing 5%, 10%, 15%, and 25% FBA (S1–S4) demonstrated progressive increases to 22, 24, 26, and 29 MPa, respectively, while the control specimen (S0) showed a DTS of 19.5 MPa. The increased tensile strength is ascribed to better particle packing, increased densification, and the development of a more robust matrix–filler bond as a result of the presence of CaO and phosphate-rich phases from FBA. Higher DTS is especially preferred for dental applications because it increases the prosthetics', crowns', and artificial teeth's resistance to crack propagation under masticatory forces. The steady rise in strength suggests that the addition of FBA improves the material's resistance to functional stresses in the oral cavity without failing too soon. The best results were obtained at 25% FBA, which improved the strength of the dental composites by almost 50% when compared to the control. This suggests that FBA has potential as a reinforcing agent, the findings align with the literature.

3.2.3 Hardness

Vickers hardness tests which are illustrated in Figure 2(iii) revealed that when the amount of fish bone ash (FBA) in the samples grew, so did their hardness. The hardness of the 25% FBA sample (S4) increased from 460 HV for the control sample (S0) to 574 HV. Increased densification, pore filling, and the development of hard calcium phosphate phases during sintering are responsible for this improvement. FBA-reinforced samples are appropriate for dental applications because of their greater hardness values, which imply improved surface durability and wear resistance. The 25% FBA sample satisfies the hardness requirements for artificial teeth.

3.2.4 Density

The bulk density of the kaolin–quartz–PVA composite augmented with increased fish bone ash (FBA) content, escalating from 2.45 $g\cdot cm^{-3}$ for the control to 2.65 $g\cdot cm^{-3}$ at 25% FBA depicted in Figure 2(iv). This augmentation results from the fluxing influence of calcium phosphate phases in FBA, which improves particle reorganization and densification during sintering. The increase in density corresponds with prior research indicating that calcium phosphate enhances densification by facilitating grain boundary diffusion. The highest density at 25% FBA signifies near-complete densification, corroborated by little water absorption and porosity.

3.2.5 Compressive strength

The change in compressive strength as a function of fish bone ash (FBA) content is depicted in Figure 2(v). Fish bone ash (FBA) enhanced the samples' compressive strength, which for 5%, 10%, 15%, and 25% FBA was 220 MPa, 260 MPa, 300 MPa, and 338.3 MPa, respectively. The increased density, decreased porosity, and improved grain rearrangement and neck growth are all ascribed to the calcium phosphate phases in FBA, which facilitate liquid-phase formation during sintering. The 25% FBA sample's compressive strength of 338.3 MPa was higher than that of conventional feldspathic porcelain and on par with leucite-reinforced glass ceramics used in dental crowns. FBA is a sustainable and efficient additive for enhancing the mechanical qualities of dental materials, according to these findings.

3.2.6 Water absorption

The water absorption (%) fluctuation of prosthetic tooth specimens made with varying amounts of fish bone ash (FBA) is depicted in Figure 2(vi). Water absorption (WA%) has been calculated according to ASTM C373.

$$WA\% = \frac{Mw - Mf}{Mf} X\ 100 \qquad (3)$$

where Mf and Mw are the mass of the specimen after water absorption and dry mass of specimen after firing. The control sample (0% FBA) exhibited a water absorption of 0.30%, which fell to 0.27% and 0.20% with the addition of 5% and 10% FBA, respectively, suggesting that moderate FBA incorporation enhances density and diminishes porosity. This decrease in water absorption improves dental prosthesis by increasing durability, dimensional stability, and minimizing discoloration. Water absorption rose to 0.35% at 15% FBA, indicating that an excessive amount of filler may lead to bonding complications and heightened porosity. In comparison to conventional fillers, FBA's reduced water absorption (0.20–0.35%) demonstrates that 10% FBA enhances hydrophobicity. Although adequate filler loading enhances characteristics, excessive filler may result in agglomeration and diminished performance.

3.2.7 Porosity

Figure 3 demonstrates the impact of fish bone ash (FBA) on the porosity of prosthetic dental specimens. The control sample (0% FBA) exhibited the greatest porosity at 1.2%, signifying a less dense microstructure. Porosity markedly diminished with the incorporation of FBA, attaining a minimum of 0.15% at 10% FBA and 0.30% at 5% FBA, indicating that moderate FBA concentrations enhance packing and densification. Nonetheless, porosity rose to 0.70% at 15% FBA, presumably attributable to inadequate filler-matrix adhesion or agglomeration. Reduced porosity is advantageous for dental applications, improving polish ability, strength, and minimizing water absorption and microbial colonization. The ideal FBA content for enhanced performance is approximately 10%, aligning with results from other bio-filler reinforced composites.

3.3. Chemical analysis

For Chemical analysis five samples were exposed to 25% NaOH, 25% HCl, and distilled water in order to examine the effects of various chemical solutions on fishbone ash shown in Table 2, which is utilized for artificial teeth. In line with earlier research demonstrating that sodium hydroxide dissolves organic compounds like collagen and the mineral content in bone-like materials, the samples treated to NaOH showed the most notable degradation, losing 2.5–3% of their weight [15]. In line with studies showing that acid exposure causes mineral deterioration in bone-derived materials, the HCl solution caused a weight loss of 1.4–1.7%, mostly as a result of calcium phosphate dissolving. According to tests that found distilled water had little effect on the structural integrity of bone ash or comparable materials, distilled water, on the other hand, showed no discernible change and lost zero weight, indicating no contact with the material [15].These findings support previous research showing that bone-like materials deteriorate in acidic and alkaline conditions, although distilled water typically has little to no effect on them.

3.4. Whiteness

Figure 4 display samples illustrating the final output with varying percentages of increased whiteness after the addition of fishbone ash. It seems that demonstrating the progressive enhancement of whiteness as the concentration of fishbone ash is increased.

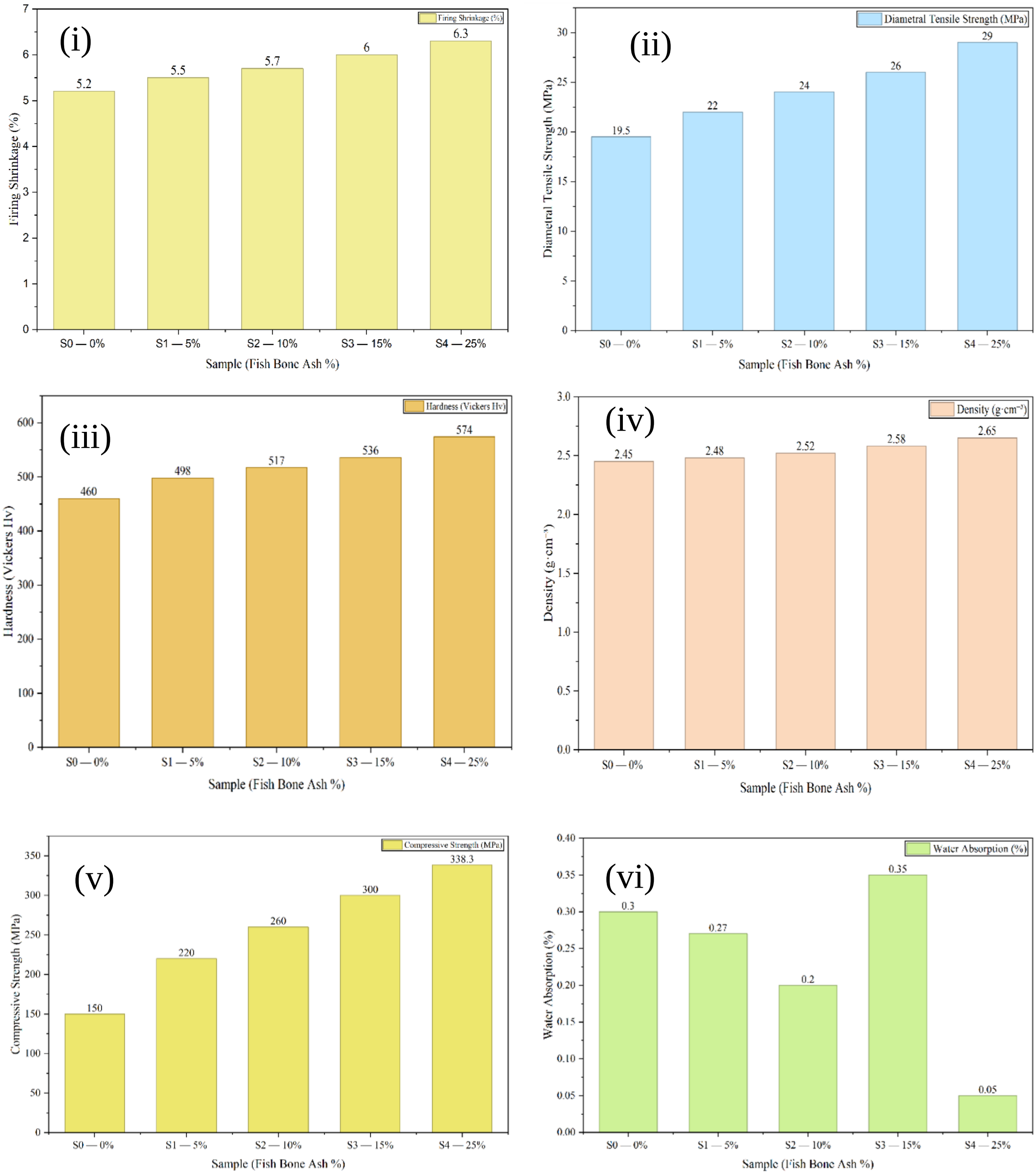

Figure 2: i) Firing Shrinkage of Fishbone Containing sample ii) Diametral Tensile Strength of fishbone containing samples iii) Hardness of Fishbone Containing sample iv) Density of Fishbone Containing sample v) Compressive Strength of Fishbone Containing sample vi) Water Absorption of Fishbone Containing sample

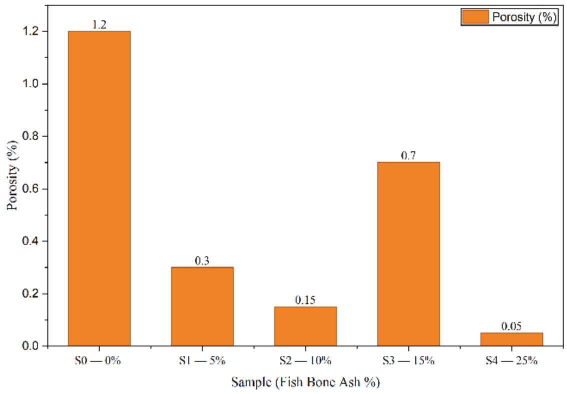

Figure 3: Porosity of Fishbone Containing sample.

Table 2: Weight Change after PH Cycling

Sample	Solution Type	Pre-Exposure Weight (g)	Post-Exposure Weight (g)	Weight Change (%)
Sample 1	25% NaOH Solution	0.309	0.301	2.5%
Sample 2	25% NaOH Solution	0.350	0.340	2.9%
Sample 3	25% NaOH Solution	0.315	0.307	2.5%
Sample 4	25% HCl Solution	0.467	0.460	1.4%
Sample 5	25% HCl Solution	0.480	0.472	1.7%
Sample 6	Distilled Water	0.194	0.194	0%
Sample 7	Distilled Water	0.250	0.250	0%
Sample 8	Distilled Water	0.175	0.175	0%

Figure 4: Visual Whiteness test

4. Conclusion

The research indicates that fishbone ash (FBA) is a viable sustainable substitute for conventional dental ceramics, particularly in artificial tooth materials. Principal findings demonstrate that the incorporation of FBA markedly improves the physical and mechanical attributes of dental composites. The incorporation of FBA enhances densification, mechanical strength, and hardness, while diminishing porosity and water absorption. The enhancements are especially evident as the FBA concentration rises, with peak performance attained at 25% FBA, yielding the greatest values for tensile strength, compressive strength, and hardness. Moreover, FBA exhibits remarkable chemical stability in both acidic and alkaline circumstances, resembling the oral environment, hence guaranteeing the enduring longevity of dental restorations. This stability further reinforces the feasibility of FBA as a biocompatible and economical material for dental applications. The findings highlight that FBA possesses considerable potential to improve the efficacy of dental composites while providing a cost-effective and eco-friendly alternative. Future research should concentrate on enhancing FBA content, augmenting mechanical qualities, and investigating its compatibility with alternative materials. Additionally, extensive clinical trials are required to further confirm its efficacy and reliability in practical settings. This research explores innovative applications of fish waste in sustainable dental materials, enhancing environmental sustainability and the efficacy of dental restorations.

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Conflict of interest: Authors have no conflict of interest.

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