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Optimization of Mechanical Properties of Reinforced Plastic Composites

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Abstract

This study investigated the optimization of mechanical properties of banana fibre-reinforced plastic composites for use in ceiling boards, with a focus on environmental protection by avoiding use of wood. Using Minitab software to perform ANOVA and Taguchi analysis were applied to evaluate the effects of binder type (epoxy resin and polyester resin), Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC) and fibre content on properties such as Young's modulus, Universal Tensile Strength/Universal Compression Strength (UTS/UCS), elongation, and yield strength. Results showed that polyester resin had better results than epoxy resin, with the optimal composition identified as 28% binder, 15% PET, 15% PVC and 40% fibre. The study successfully established optimal mix ratios and further research on a wider range of binders is recommended.

Keywords: Optimisation, Mechanical properties, Taguchi analysis, Sustainability and banana fibres.

1 | Introduction

The problem of environmental degradation and the depletion of non-renewable resources has intensified the need for sustainable and eco-friendly materials. Conventional composite materials, typically reinforced with synthetic fibers like glass or carbon, offer excellent mechanical properties but are non-biodegradable, and costly. This has led to an increasing interest in natural fibre-reinforced composites, which provide a more sustainable alternative. Among natural fibers, banana fibers stand out for their abundance, biodegradability, low cost, and excellent mechanical properties. However, their potential as reinforcements in plastic composites remains underexplored and underutilized.

This study investigates the influence of four factors; binder type (epoxy resin and polyester resin), Polyvinyl Chloride (PVC), Polyethylene Terephthalate (PET), and fibre reinforcement on the mechanical properties [1]; yield strength (MPa), Universal Tensile Strength Universal Compression Strength (UTS/UCS) (MPa), young's

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modulus (GPa) and elongation (mm) for composite materials. Through systematic analysis of interaction effects and main effects, this work aims to identify optimal material combinations for enhanced composite performance. In order to achieve that, Taguchi was employed to generate a Design of Experiments (DOE) as shown in table 1 to show the interactions of various factors. A study by [2], [3] used the same software and produced incredible outcomes.

The project focus on optimizing these parameters to improve mechanical strength, durability, and environmental performance. The findings contributes to the advancement of innovative and sustainable composite materials, providing a pathway for eco-friendly alternatives to conventional composites in industrial applications [4], [5]. For instance, ceiling boards are majorly made of wood products which are posing danger to the environment by cutting down trees to produce. Plastic composites will provide an alternative to wood ceiling boards and hence reduce deforestation.

2|Methods

A statistical DOE approach was employed to optimize composite performance as shown in *Table 1*. The independent variables included; fibre content, binder type, PVC proportion and PET proportion while the dependent variables were; tensile strength, flexural strength and compressive strength for mechanical properties while interfacial bonding and porosity and void content for microstructural properties [6].

Table 1. Experimental matrix.

Binder	PVC	PET	Fibre	Tensile Strength	Flexural Strength	Compression Strength	Elongation
1	1	1	1				
1	1	2	2				
1	1	3	3				
1	2	1	1				
1	2	2	2				
1	2	3	3				
1	3	1	2				
1	3	2	3				
1	3	3	1				
2	1	1	3				
2	1	2	1				
2	1	3	2				
2	2	1	2				
2	2	2	3				
2	2	3	1				
2	3	1	3				
2	3	2	1				
2	3	3	2				

ANOVA was used to determine the significance of each factor and between their means, while Signal to Noise (SN) ratios identified the optimal mix ratios by employing larger is better or smaller is better criteria [7]. A clear discussion of the results was done. A conclusion was then drawn from the the analysis of the results from set of samples produced.

3|Results and Discussion

Through systematic analysis of interaction effects and main effects, this work aims to identify optimal material combinations for enhanced composite performance. In order to achieve that, Taguchi was employed to generate a DOE as shown in *Table 2* to show the interactions of various factors. The factors effects on mechanical properties where then analyzed using Taguchi and Anova and the results discussed in the following subsections.

Table 2. Taguchi DOE.

Binder	PVC	PET	Fibre	Yield (Mpa)	Uts/Ucs (Mpa)	E (Gpa)	Elongation
1	1	1	1	2.02	21.43	0.1496	0.1513
1	1	2	2	5.82	23.81	0.3237	0.1558
1	1	3	3	9.94	26.45	0.8463	0.1617
1	2	1	1	29.00	29.63	1.6370	0.0011
1	2	2	2	28.73	31.42	1.8003	0.0017
1	2	3	3	29.19	29.15	1.6728	0.0020
1	3	1	2	31.40	30.38	2.4688	0.1639
1	3	2	3	30.46	31.70	2.5451	0.1627
1	3	3	1	29.55	33.07	2.6256	0.1610
2	1	1	3	4.34	26.05	0.3552	0.1641
2	1	2	1	8.14	28.43	0.1182	0.1686
2	1	3	2	12.25	31.07	0.6408	0.1745
2	2	1	2	31.32	34.25	1.4315	0.0117
2	2	2	3	31.05	36.04	1.5947	0.0110
2	2	3	1	31.51	33.77	1.4672	0.0108
2	3	1	3	33.72	35.00	2.2633	0.1767
2	3	2	1	32.78	36.32	2.3396	0.1755
2	3	3	2	31.87	37.69	2.4200	0.1738

4 | Taguchi Analysis

4.1 | Effects of Parameters on Yield Stress

The study of parameters illustrated on *Fig. 1* shows that pvc content greatly affect yield stress, increase in PVC concentration result in increase in yield stress. This preicts that PVC is the major contributor to the load-bearing capacity of the composite matrix, since it has good molecular packing and increased matrix density. Another factor (binder) shows a significant effect on yield stregth. Binder level 2 (polyester resin) consistently outperform yield values compared to binder level 1 (epoxy resin) across various material combinations. This improvement is likely to be caused by enhanced load transfer mechanisms and superior matrix cohesion achieved by the polyeter resin, which facilitates more effective stress distribution in the composite structure.

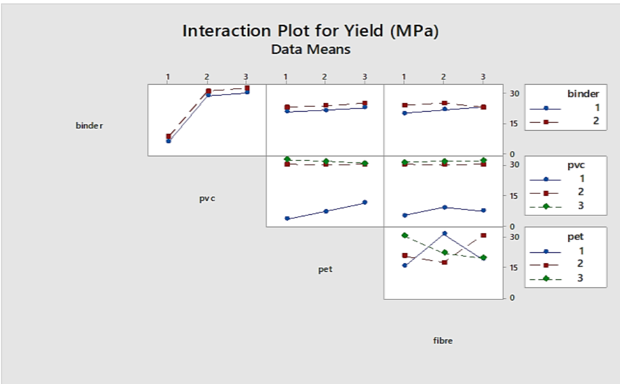


Fig. 1. Interaction plot for yield stress showing the combined effects of binder, PVC, PET, and fibre.

PET shows influence that is not more significant on yield stress. Its effect is largely dependent on mixture with other factors, particularly fibre content. This interaction, behavior indicates that PET does not independently contribute to yield improvements but it influence composite response when combined with specific levels of other factors. Fibre, have low independent effect on yield stress. Variations in fibre content from level 1 (20%) to level 3 (40%) produce only small changes in yield values. Nevertheless, the interaction between fibre and PET suggests that fibre plays an important role in modifying the overall composite response rather than directly increasing yield capacity. This finding implies that fibres may influence other mechanical properties more upon optimal matrix composition.

The analysis shows that PVC is the most influential fator followed bybinder type, fibre, and lastly PET, which serve as the principal determinants of matrix strength and cohesion and agrees with the results of [8]. While

PET and fibre play secondary roles through their interaction effects makes them important in the composite, emphasizing the need to consider combined factor behavior in material optimization.

4.2 | Effects of Parameters on Ultimate Tensile Strength and Ultimate Compression Strength

The *Fig. 2* shows relationships of UTS/UCS with the process factors. Binder type and PVC are the most influential factors both individually and through their interactions with other factors. Increasing PVC levels leads to consistent higher UTS/UCS for both binder types; however, binder level 2 (polyeater resin) achieves shows higher strength values across all PVC leves. This relationship indicates that the effectiveness of PVC in enhancing strength is amplified when combined with the polyester resin, which has proven to be more superior due to improved interfacial bonding and more efficient stress transfer within the composite matrix.

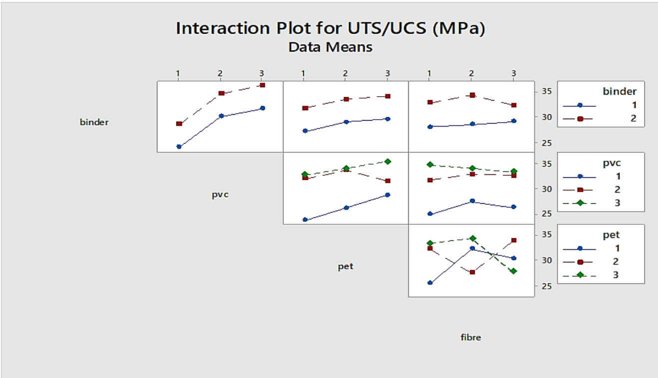


Fig. 2. Interaction plot for UTS/UCS showing the combined influence of binder, PVC, PET, and fibre.

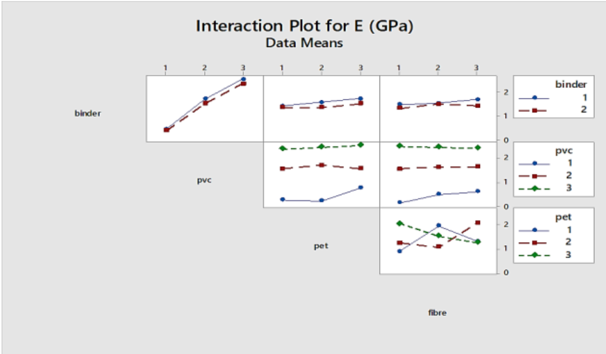
The interaction between PVC and PET shows that the PET has enhancing strength at level 3. At lower PET content the strength improves, suggesting that PET and PVC affect the composite when both are present at low concentrations. The interaction effect is observed between PET and fibre content is more evident. The interaction plot displays clear non-parallel and crossing trends, demonstrating that the influence of fibre reinforcement on UTS/UCS is dependent on PET levels. PET at level 3 and fibre at level 3 combines to produce optimal strength through maximum load transfer and reinforcement efficiency, while other combinations result in reduced performance. This might be caused by poor fibre-matrix adhesion or inadequate PET content to facilitate effective stress transfer to the fibres.

The results demonstrate that, binder and PVC provide contributions to composite strength, the performance is determined by the optimization of material combinations, particularly the PET-fibre ratio together with appropriate PVC levels. This multi-factor dependency highlights the necessity of employing design of experiments methodologies and interaction analysis in composite material optimization.

4.3 | Effect of Parameters on Young's Modulus

The *Fig. 3* shows interactions plot for young's modulus with composite factors. A decrease in PVC content is directly propotional with increased young's modulus across both binder (epoxy resin and polyester resin), though the magnitude of improvement differs between binders. Binder l (epoxy resin) yields higher stiffness values than binder level 2 (polyester resin). This suggests that binder level 1 facilitates more effective load transfer or provides superior matrix cohesion, resulting in a stiffer composite structure. The differential response between binders indicates that matrix chemistry plays a crucial role in determining stiffness characteristics which agree with results of [9], [10].In contrast to the binder effect, PET content produces relatively similar trends across both binder levels, indicating that PET's contribution to stiffness is largely additive and independent of binder type. This suggests that PET affect stiffness in mechanical properties of composite.

Fig. 3. Interaction plot for elastic modulus showing the combined influence of binder, PVC, PET, and fibre on composite stiffness.



Fibre content is a major factor influencing young's modulus, with clear improvements in stiffness accompanying increased fibre levels. However, the magnitude of these improvements varies significantly with binder and PET concentrations, as evidenced by non-parallel and intersecting lines in the interaction plot this was also seen in the study by [11]. This behavior indicates that fibre reinforcement efficiency is dependent on matrix composition. The variable effectiveness of fibre reinforcement is attributed to differences in fibre-matrix interfacial bonding and fibre dispersion quality. When the matrix composition is optimal, stress transfer from the matrix to the fibres is efficient, and the full reinforcing potential of the fibres is realized. At different PET levels, the stiffness increases when fibre concentraions are reduced, suggesting saturation effects due to reduced stress transfer efficiency due to suboptimal matrix-fibre compatibility.

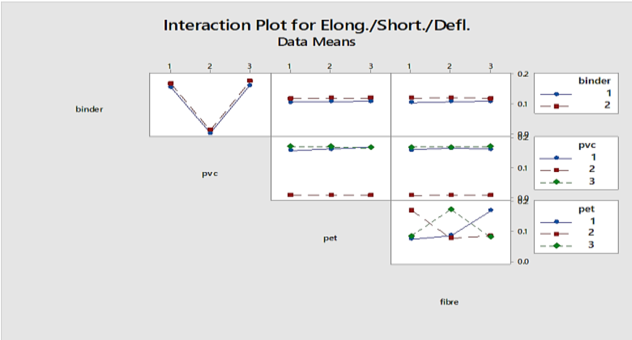
Interactions between PVC and PET are also observed to have moderate effect on composite, where higher PET and PVC levels appear to enhance the stiffness of the composite. This effect result from improved molecular packing between these polymer constituents within the matrix, leading to a denser, more cohesive structure. Contralluy interactions between PVC and fibre are relatively weak, indicating that fibre reinforcement contributes to stiffness in a fairly consistent manner regardless of PVC concentration. The elastic modulus is affected by all factor. Fibre content effects the composite most while binder have least effect, however, its effectiveness is affected by binder PVC and PET levels.

4.4 | Effects of Parameters on Elongation

The interaction plot *Fig. 4* shows the effects of different factors on the elongation. The graph shows that binder exhibits a V-shaped response pattern, indicating a great effect on elongation. The mean response is lowest at binder level 2 and increases sharply at both levels 1 and 3. This V-shaped behavior suggests that the binder level affects elongation and deflection. This can be caused by enhanced matrix rigidity or cross-linking, while both lower and higher binder levels permit greater deformation, either through increased matrix flexibility or reduced cohesion. PVC demonstrates nearly parallel lines across all levels in the interaction plots, indicating minimal interaction with other factors. This suggests that PVC's effect on elongation and deflection remains fairly constant and predictable regardless of changes in other parameters. Such behavior makes PVC a stable factor in controlling deformation characteristics.

PET displays moderate interaction effects, with some crossing lines observed particularly in combination with fibre content. This indicates that PET's influence on deformation is partly dependent on fibre level, suggesting that the PET-fibre interface plays a role in determining how the composite responds to loading. Fibre content shows mixed interaction effects across different factor combinations. When combined with PET, the interaction plot reveals intersecting lines, indicating a strong interaction where the effect of fibre on deformation is affected by PET content. However, when combined with binder and PVC, the lines remain nearly parallel, suggesting weak or negligible interactions. This selective interaction pattern indicates that fibre's role in controlling deformation is primarily controlled through its relationship with PET rather than with binder or PVC.

Fig. 4. Interaction plot for elongation, shortening, and deflection showing the combined effects of binder, PVC, PET, and fibre.



The most significant interactions affecting elongation, occur between binder, PET and fibre content. Optimizing the deformation response requires study of binder and PET levels in relation to fibre composition since, PVC remains largely stable and independent in its effect, providing a predictable contribution to deformation characteristics that is minimally influenced by other factors.

5 | Anova Analysis

5.1 | Effects of Parameters on SN Ratios: Larger is Better Responses

The main effects plot for *Fig. 5* shows mean response of yield strength, USC/UTS and young's modulus with larger values more desirable, varies across different levels of the four factors. The dashed horizontal line represents the overall mean, serving as a reference for evaluating factor influence.

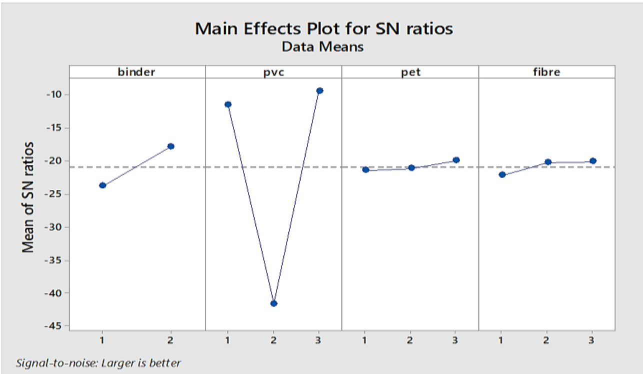


Fig. 5. Main effects plot for S/N ratios using the larger-is-better criterion.

The binder shows a moderate increase in mean response from level 1 to level 2, with the mean rising from approximately 17.3 to 19.6. This upward trend indicates that binder level 2 (polyester resin) has improved output than level 1 (epoxy resin), suggesting that polyester resin provides enhanced material properties. PVC exhibits the steepest slope among all factors, with the mean response rising from approximately 11.2 at level 1 to 22.7 at level 3. This substantial increase demonstrates that PVC has the most significant influence on the response variable. The linear upward trend across all three levels indicates that PVC content is directly related with improved performance. PVC at level 3 has most desired output than level 1 and 2 although it has most significant influence on the composite.

PET displays a slight upward trend across its three levels, with the mean response increasing from about 17.6 at level 1 to 19.2 at level 3. The gradual increase indicates that PET provides effects that do not change much the performance. However, level 3 of PET shows much more desired output performances than levels 1 and 2. Fibre content exhibits the flattest trend among all factors, with mean response values ranging only from 18.0 to 18.8 across the three levels [3]. This nearly horizontal line indicates that variations in fibre content have minimal influence on the mean response. But fibre at level 3 has larger signal hence having more desired outputs.

5.2 | Effects of Parameters on SN Ratios: Smaller is Better Responses

The effects plot for the S/N ratios using the smaller-is-better criterion. In this case, lower S/N ratio values indicate improved performance and reduced variability of elongation response. The plot *Fig. 6* illustrates how binder, PVC, PET, and fibre levels influence the output of the system relative to the overall mean S/N ratio.

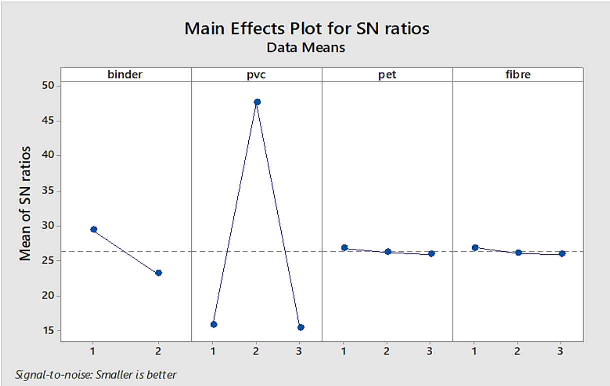


Fig. 6. Main effects plot for S/N ratios using the smaller-is-better criterion.

PVC exhibits main effect, characterized by a sharp peak at level 2 and substantially lower S/N ratios at levels 1 and 3. This non-linear behavior indicates that the response is highly sensitive to PVC content. The binder exhibits an effect, with binder 2 (polyester resin) producing a lower mean S/N ratio than binder 1 (epoxy resin). This indicates that binder 2 (polyester resin) is more effective in minimizing the response.

PET displays a nearly flat trend across its levels, with only a slight decrease in S/N ratio from level 1 to level 3. This minimal slope suggests that PET has small effect on the response under the smaller-is-better criterion. Fibre shows a slight downward trend in S/N ratio with increasing levels which is the same trend observed by [12]. Although the effect is modest, fibre level 3 yields the lowest S/N ratio, indicating a marginal improvement in achieving a smaller and more consistent response. The main effects plot indicates that PVC is the most influential factor under the smaller-is-better objective, followed by binder, while PET and fibre have limited effects.

5.3 | Effects of Parameters on Means

To determine the effect of each parameter on the means a tukey HSD method at a 95% confidence level was used and demonstrated in *Table 3*.

Table 3. Grouping information using the tukey method and 95% confidence.

Factor	N	Mean	Grouping		
UTS/UCS (MPa)	18	30.87	A		
Yield (MPa)	18	22.95		B	
E (GPa)	18	1.483			C
Elongation	18	0.1127			C

Means that do not share a letter are significantly different.

The measured mechanical properties are classified into distinct statistical groups based on their mean values. UTS/UCS (30.87 MPa) forms Group A, indicating it is significantly different to all other measured responses. Yield strength 22.95 MPa falls into Group B and is significantly different from both UTS/UCS and the properties in Group C. The modulus of elasticity, E 1.483 GPa, and elongation/shortening/deflection 0.1127 are both assigned to Group C, showing that their mean values are not significantly different from each other but are significantly different to those of UTS/UCS and yield strength. The results demonstrate a clear statistical separation between strength-related properties UTS/UCS and yield and deformation-related properties E and elongation, confirming that these factors exhibit significantly different mechanical responses at the 95% confidence level.

The main effects plot for means illustrated on *Fig. 7* show how the mean response varies across different levels of the four factors. The dashed horizontal line represents the overall mean, serving as a reference point for comparison.

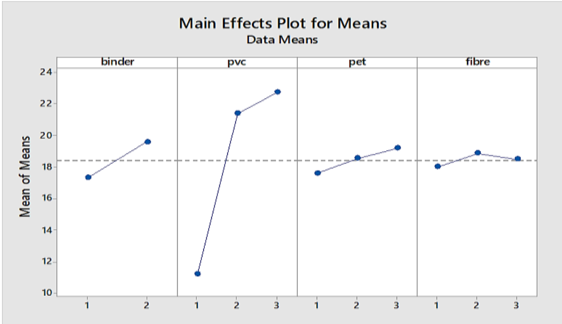


Fig. 7. Effect plot for means showing how each factor influences the average response.

From the graph, it is evident that the binder shows slow increase in the mean response from binder 1(epoxy resin) to binder 2 (polyester resin), therefore using the binder 2(polyester resin) improves the overall the mechanical properties. PVC, on the other hand, shows the steepest slope, with the mean rising sharply from around 11 at level 1 to about 23 at level 3. This suggests that PVC has the most significant influence on the response variable, suggesting that changes in PVC levels have a substantial effect on the system's overall behavior. [13] investigated PET effects and noted an upward trend across its levels meaning its effect on the response was small. The fibre factor exhibits a nearly flat line across its levels, indicating that its variation has minimal or negligible influence on the response. Overall, the plot demonstrates that PVC is the most influential factor, followed by binder and PET, while fibre has the least effect [14]. This implies that optimizing PVC levels is crucial in improving the overall performance although, binder, PET and fibre changes have slight impact on the results.

6 | Conclusion

For optimal strength and stiffness, the recommended configuration is PVC at 15%, binder (polyester resin) at 28%, PET at 15%, and banana fibre at 40%. At optimal level the yield strength was 31.81 MPa for tensile, 12.25 MPa for compression and 31.51 MPa for flexural, young's modulus was 2.42 GPa for tensile, 0.6408 GPa for compression and 1.4672 GPa for flexural, ultimate tensile strength was 37.69 MPa for tensile and 33.77 MPa for flexural, ultimate compression strength was 31.07 MPa and elongation was 0.1738 mm for tensile, 0.1745 mm for compression and 0.0108 mm for flexural. The study by [15] shows that at optimal yield strength have 40% fibre which is almost the same with my findings.

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Author Contributaion

W. K. conceived and designed the study, developed the methodology, conducted the experiments, performed data analysis, curated the data, prepared visualizations, and wrote the original manuscript draft. S. R. contributed to the study conceptualization, methodology development, supervision, project administration, and critical review and editing of the manuscript. E. O. contributed to the study design, validation of results, provision of resources, supervision, and review and editing of the manuscript. All authors participated in the interpretation of the results, reviewed the manuscript, and approved the final published version.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. The datasets generated and analyzed during the current study are not publicly available due to their use in ongoing research but are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest. The research was conducted independently, and no financial or personal relationships exist that could have inappropriately influenced the reported findings. No external funding was received for this study.

Statements Declaration

The authors declare that this manuscript is original and has not been published previously, nor is it under consideration for publication elsewhere. All authors have read and approved the final version of the manuscript and agree to its submission to the journal. The work presented in this manuscript was conducted ethically and responsibly and all sources of information have been appropriately acknowledged and cited.

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