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Development of Directly Recycled AA6061 Aluminium Composite Reinforced with Graphite Using Casting (Foundry) Method

Hamzah Luqman Rosdi[1], Mohamed Nasrul Mohamed Hatta[1*]

[1] *Faculty of Mechanical and Manufacturing Engineering*
Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Johor, MALAYSIA

*Corresponding Author: mnasrul@uthm.edu.my
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Abstract

Aluminum alloy AA6061 is widely used in engineering applications due to its favorable strength-to-weight ratio, corrosion resistance, and good machinability. With an increasing emphasis on sustainability and energy efficiency, secondary aluminum recycling has become a crucial alternative to primary production, which is highly energy intensive. This study investigates the development of directly recycled AA6061 aluminum composites reinforced with graphite using a casting (foundry) method. Recycled AA6061 chips were reinforced with different graphite volume fractions (5%, 10%, and 12.5%) and fabricated through controlled casting conditions. The mechanical and physical properties of the composites were evaluated through tensile testing, Vickers microhardness measurements, and density analysis. Microstructural characteristics were examined using optical microscopy, scanning electron microscopy (SEM), and energy-dispersive spectroscopy (EDS). The results indicate that incorporating graphite improves microhardness and reduces density, thereby enhancing the material's lightweight characteristics. An optimum graphite content was observed to enhance tensile strength, whereas excessive graphite addition led to particle agglomeration, increased porosity, and weakened interfacial bonding. Microstructural analysis confirmed grain refinement and successful incorporation of graphite within the aluminum matrix. Overall, the findings demonstrate that graphite-reinforced recycled AA6061 composites produced by casting offer a promising, sustainable approach for lightweight engineering applications, provided that the reinforcement content and processing parameters are carefully optimized.

1. Introduction

Aluminum alloys, notably AA6061, are widely used in various technical applications due to their desirable properties, including lightweight design, a high strength-to-weight ratio, and excellent corrosion resistance. These features make them ideal for industries that require strength and durability, such as aerospace, automotive, and construction [1]. With the increasing global demand for aluminium products, there is a growing interest in aluminium manufacturing through secondary recycling. Traditional primary production from bauxite ore is energy-intensive, consuming approximately 113 GJ per ton, whereas recycling aluminium waste decreases energy use to just 13.6 GJ per ton, saving nearly 88% [2]. In addition to lowering energy consumption, recycling aluminium reduces environmental pollution and manufacturing costs, making it a more sustainable option than primary manufacture. Among various recycling methods, casting (foundry) techniques such as sand casting, die casting, and investment casting provide an efficient approach to recycling aluminium while reducing energy consumption and material waste. To improve the sustainability of aluminium recycling, solid-state recycling methods have been developed, which entail directly turning aluminium chips into useful material without remelting [3]. This method saves up to 95% of the original material while minimizing metal loss during processing [4]. Graphite has been investigated as a reinforcing material to improve the mechanical properties of recycled aluminium alloys [5]. Graphite's low density, thermal stability, and self-lubricating properties make it an ideal additive to enhance the hardness, wear resistance, and overall performance of recycled aluminium composites [6]. The purpose of this study is to investigate the effect of graphite reinforcement on the mechanical and physical properties of AA6061 when it is recycled through casting processes. Specifically, the study examines how casting procedures such as sand casting, die casting, and investment casting affect the performance of graphite-reinforced AA6061 composites. Furthermore, this study aims to investigate how varying amounts of graphite reinforcement (5%, 10%, and 12.5%) affect material properties, including tensile strength, microhardness, and microstructure. This study utilizes casting processes to develop a sustainable recycling technology that enhances the mechanical properties of recycled aluminium while minimizing industrial waste and reducing energy consumption.

2. Methodology

2.1 Material Selection and Preparation

The AA6061 aluminum alloy was selected as the matrix material for this study due to its high strength, corrosion resistance, and excellent machinability. These properties make it one of the most used materials in engineering applications, particularly in the automotive and aerospace industries. The alloy is well-suited for casting and composite formation, providing a durable base material for reinforcing with graphite.

Graphite powder was chosen as the reinforcement material due to its low density, high thermal stability, and self-lubricating properties. These attributes enhance the hardness and wear resistance of the aluminum matrix, making it suitable for applications that require high strength and thermal performance. Graphite's ability to reduce friction and improve wear resistance enhances the composite's overall performance. Table 1 shows the composition of graphite that added into the A6061 aluminium composite.

Table 1 The C*omposition of Graphite in Composite*

Sample	A	B	C	D
The composition of graphite in composite	0%	5wt%	10wt%	12.5wt%

The chip preparation process involved selecting and conditioning AA6061 aluminum chips for composite formation. The chip was collected from CNC milling using the parameters shown in Table 2. Initially, the chips were thoroughly cleaned to remove surface contaminants, such as oil, dirt, and oxidation, that could affect subsequent steps. This was achieved by washing the chips with a mild solvent and then drying them under controlled conditions. After cleaning, the chips were sieved to ensure a consistent particle size distribution, which is critical for achieving uniformity during casting and ensuring consistent mechanical properties in the final composite.

Table 2: *Machining Parameters using CNC Milling*

Feed Rate (mm/min)	Depth of Cut (mm)	Number of Cycles	Speed (m/min)	Feed	Feed Rate (mm/min)	Depth of Cut (mm)
1100	1.0	11000	345.4	0.1	1100	1.0

2.2 Casting Process

The A6061 aluminium composite was prepared via die casting with using reusable metal molds. Metal mold was chosen for small component and need for more precise dimension [7, 8]. The mixture of aluminium and graphite powder was heated in the furnace at temperature of 750°C until all the aluminium powder is melted. The molten metal then was poured into the metal mold.

The pouring temperature of the molten metal was carefully controlled and maintained between 660°C and 750°C, depending on the specific alloy requirements and the casting method employed. The temperature was critical to maintaining the fluidity of the molten aluminum, allowing it to properly fill the mold and minimizing the formation of defects such as cold shuts or incomplete mold filling. Figure 1 shows the furnace and the mould used during the sample preparation process.

The solidification time was carefully managed to prevent defects such as shrinkage porosity. The time required for the molten aluminum to cool and solidify was controlled based on the thickness of the casting. Thicker sections required longer solidification times. The solidification rate also influenced the grain structure and mechanical properties of the final product, so care was taken to ensure uniform cooling.

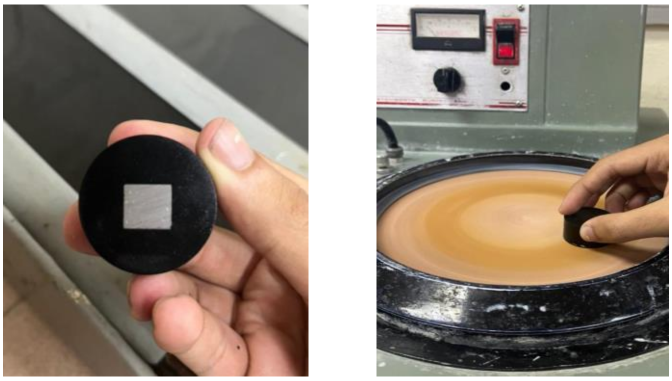
(a) **(b)**

Fig. 1 *Casting Process (a) Furnace; (b) Mould*

2.3 Sample Preparations

After casting, the composite samples were ground to prepare the surfaces for further analysis. This was done using progressively finer grades of silicon carbide abrasive papers: P600, P800, P1000, P2000, and P3000. Each grade of abrasive paper was used to progressively remove material and smooth the surface, eliminating visible scratches from the previous grit. Throughout the grinding process, continuous water cooling was applied to prevent overheating and ensure a smooth finish.

Following grinding, the samples were polished to achieve a mirror-like finish. This was done using an alumina suspension with a particle size of 0.05 microns. Polishing is essential to further refine the surface and prepare it for microscopic examination. The polishing process was carried out using the FORCIPOL 2V Grinder-Polisher, ensuring a high-quality finish and removing any final surface defects. Figure 2 shows the mounted sample (a) and the polishing process.



(a) **(b)**

Fig. 2 *Sample Preparation Process (a) Mounting; (b) Polishing*

2.4 Mechanical and Physical Testing

Tensile testing was conducted to measure the tensile strength of the composite samples. The tests were performed using a universal testing machine, where the samples were subjected to a gradually increasing load until failure [6]. The maximum stress the material could withstand before breaking was recorded. The tensile-strength data were used to evaluate the effectiveness of graphite reinforcement in improving the mechanical properties of recycled AA6061.

The Vickers hardness test was used to measure the composite samples' hardness. This test involves applying a known force to a diamond indenter and measuring the size of the resulting indentation. Vickers' hardness values were recorded for each sample to assess the effect of graphite inclusion on the wear resistance and hardness of the aluminum matrix.

The density of each sample was measured to evaluate the overall material quality and identify any porosity. Porosity is a common defect in cast materials, and the presence of voids can significantly reduce the material's mechanical properties. The samples were weighed, and their volumes were calculated to determine density. Figure 3 shows the equipment used for tensile testing, hardness testing and density measurement.

$$\boldsymbol{Density}, \boldsymbol{\rho} = \frac{\boldsymbol{W_{air}} - \boldsymbol{W_{water}}}{\boldsymbol{W_{water}}} \times \boldsymbol{\rho_{distilled\ water}} \tag{1}$$

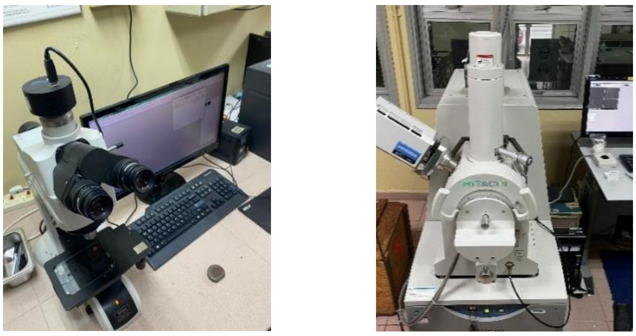
(a) **(b)** **(c)**

Fig. 3 *Sample testing (a) Tensile Strength; (b) Vickers hardness (c) Density*

2.5 Microstructural Analysis

For microstructural analysis, the samples are first prepared by cleaning and drying the aluminum specimens, then mounted on glass slides. The optical microscope (Figure 4a) is then used to examine the samples at magnifications typically ranging from 50x to 100x. This allows for detailed observation of surface features such as particle size, shape, and texture, which are essential for understanding the material's characteristics.

Additionally, Scanning Electron Microscopy (SEM) (Figure 4b) is employed for more advanced analysis. The samples are coated with a thin conductive layer, typically gold, to prevent charging under the electron beam. The specimen is then placed in the SEM chamber, where it is scanned with a high-energy electron beam. This provides high-resolution images of the surface morphology, offering a detailed view of the material's structure and the effects of graphite reinforcement on AA6061 aluminium.



(a) **(b)**

Fig. 4 *Microstructure Analysis (a) Optical Microscope; (b)* Scanning Electron Microscopy *(SEM)*

3. Results and Discussion

3.1 Ultimate Tensile Strength (UTS)

The ultimate tensile strength of the recycled AA6061 composite shows a noticeable variation with increasing graphite content, as illustrated in Fig. 5. The addition of graphite at lower volume fractions contributes to an improvement in tensile strength compared to unreinforced aluminum. This improvement can be attributed to the effective load transfer between the aluminum matrix and the graphite particles, as well as the restriction of dislocation movement within the matrix. Graphite particles act as secondary phases that impede plastic deformation, thereby enhancing the composite's strength.

However, at higher graphite volume fractions, a reduction or plateau in tensile strength may be observed. This behavior is likely due to the agglomeration of graphite particles and weak interfacial bonding between the graphite and aluminum matrix. Excessive graphite content can introduce stress concentration sites and increase the likelihood of microcrack initiation during tensile loading. Additionally, graphite is inherently brittle and does not contribute significantly to load-bearing under tensile stress, which can negatively affect the overall tensile performance when present in excessive amounts. Therefore, an optimal graphite content exists at which tensile strength is maximized.

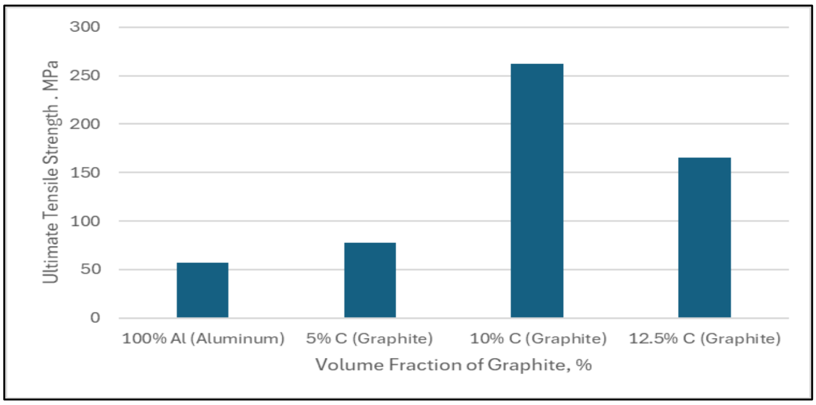


Fig. 5 *UTS Response with respect to different volume fractions of Graphite Composition*

3.2 Microhardness

The microhardness results shown in Fig. 6 indicate an overall increase in hardness with the incorporation of graphite into the AA6061 matrix. The increase in hardness is mainly attributed to dispersion strengthening, in which graphite particles hinder localized plastic deformation and resist indentation [9]. The presence of hard reinforcement phases increases resistance to surface deformation, resulting in higher Vickers hardness values than in unreinforced aluminum.

Therefore, an optimal graphite content exists at which tensile strength is maximized. At higher graphite contents, the hardness may continue to increase or stabilize depending on the uniformity of particle distribution. Well-dispersed graphite particles enhance hardness, whereas particle clustering can lead to localized soft regions. Furthermore, the solidification characteristics of the casting process influence grain refinement, thereby contributing to increased hardness. Fine, uniformly distributed grains enhance indentation resistance, thereby supporting the observed improvement in hardness.

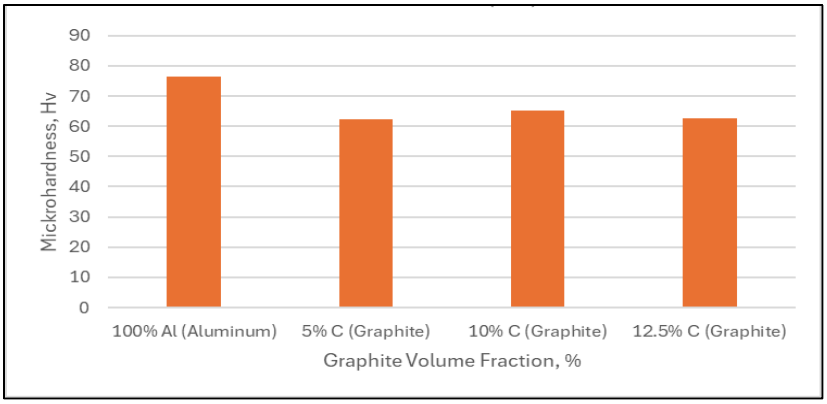


Fig. 6 *Microhardness Response with respect to different volume fractions of Graphite Composition*

3.3 Density

The density results presented in Fig. 7 and Table 3 show variations with different graphite volume fractions. Adding graphite generally reduces density, since graphite is lighter than aluminum. This reduction is particularly beneficial for lightweight applications, such as those in the automotive and aerospace sectors, where weight reduction is crucial [10].

However, the density values also reflect the presence of porosity introduced during the casting process. Inconsistent density trends at certain graphite contents suggest the formation of internal voids and incomplete bonding between aluminum chips and graphite particles. A higher graphite content may increase the risk of gas entrapment and poor wettability, thereby increasing porosity. This porosity negatively affects mechanical properties, particularly tensile strength, and highlights the importance of controlling casting parameters and reinforcement content to achieve optimal composite quality

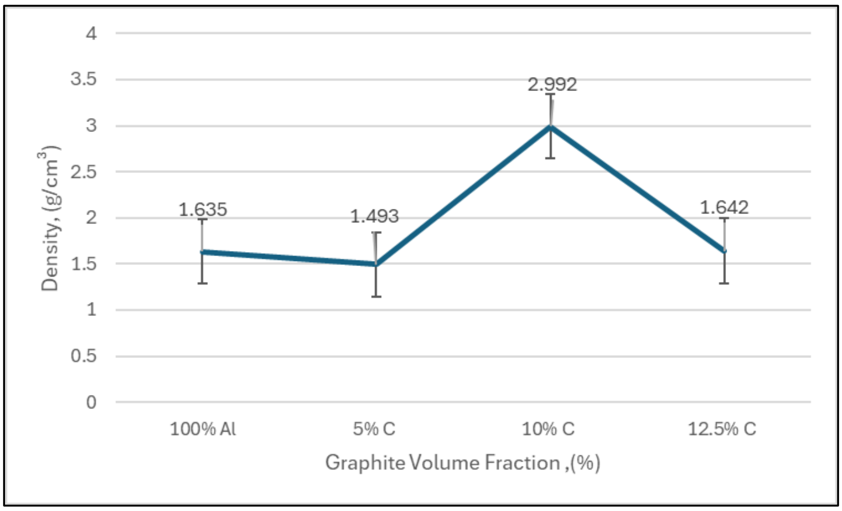


Fig. 7 *Microhardness Response with respect to different volume fractions of Graphite Composition*

Table 3 *Density Data for Each Composition:*

Graphite Volume Fraction (%)	Density (g/cm^3)
100% Al	1.635
5.0% C	1.493
10.0% C	2.992
12.5% C	1.642

3.4 Microstructural and Surface Morphology Analysis

The optical microscopy results shown in Fig. 8 reveal the general grain structure and particle distribution within the composite. The unreinforced AA6061 sample exhibits relatively coarse grains typical of cast aluminum alloys. With the addition of graphite, grain refinement is observed, indicating that graphite particles act as heterogeneous nucleation sites during solidification. Finer grain structures contribute to improved mechanical properties, particularly hardness

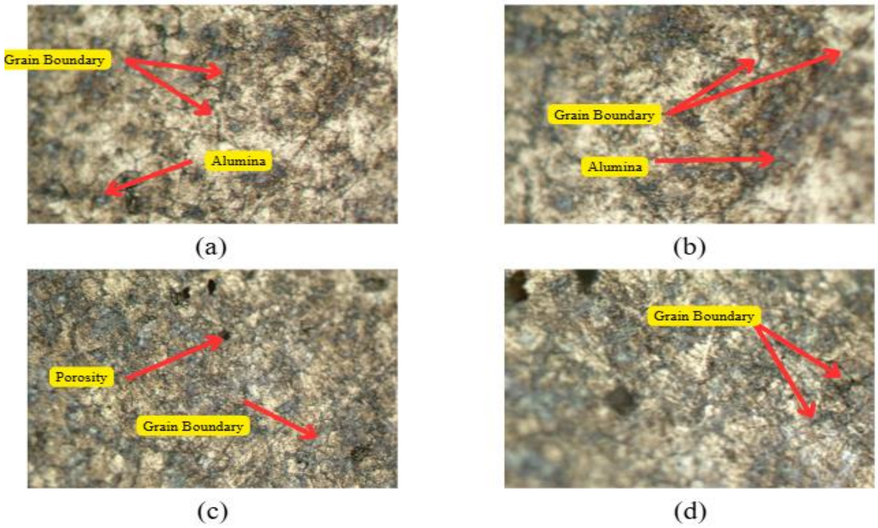


Fig. 8 *Optical Microscope Analysis*

SEM images in Fig. 9 provide a more detailed view of the graphite distribution and interfacial bonding. At lower graphite volume fractions, the particles appear relatively well-dispersed within the aluminum matrix, suggesting effective mixing and bonding during casting. This uniform distribution supports the observed improvements in tensile strength and hardness [11]. In contrast, samples with higher graphite content show signs of particle agglomeration and porosity, which can weaken interfacial bonding and reduce mechanical performance

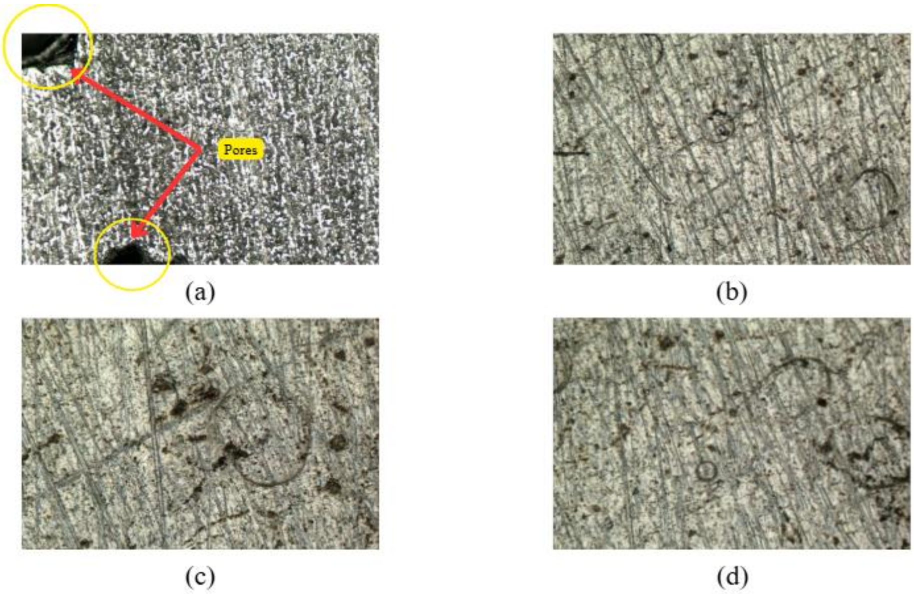


Fig. 9 *SEM image for each sample*

The EDS spectra shown in Fig. 10 confirms the presence of carbon-rich regions corresponding to graphite reinforcement, along with aluminum as the dominant matrix element. The elemental analysis validates the successful incorporation of graphite into the recycled AA6061 composite. However, localized carbon enrichment further supports the observation of graphite clustering at higher volume fractions, which may explain the degradation of tensile properties in those samples.

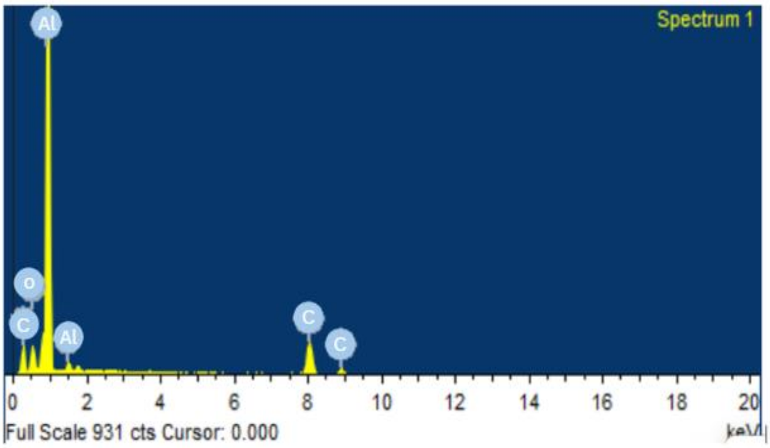


Fig. 10 *EDS spectra for sample 1*

3.5 Discussion

Overall, the results indicate that graphite reinforcement significantly influences the mechanical and physical properties of directly recycled AA6061 aluminum composites. A moderate graphite content enhances the tensile strength and hardness of the composite while reducing its density, making it suitable for lightweight engineering applications. However, excessive graphite addition leads to particle agglomeration, increased porosity, and weakened interfacial bonding, which negatively affect tensile performance. These findings highlight the importance of optimizing graphite volume fraction and casting parameters to achieve a balance between strength, hardness, and material integrity in recycled aluminum composites

4. Conclusions

This study demonstrated the successful fabrication of directly recycled AA6061 aluminum composites reinforced with graphite using a casting (foundry) method and evaluated their mechanical, physical, and microstructural properties. The results indicate that moderate graphite addition improves ultimate tensile strength and microhardness through dispersion strengthening and grain refinement, while reducing density and promoting lightweight characteristics. In contrast, excessive graphite content leads to particle agglomeration, increased porosity, and weakened interfacial bonding, resulting in reduced tensile performance. Microstructural analysis confirmed the effective incorporation of graphite and uniform particle distribution at lower reinforcement levels. Overall, the findings highlight the potential of optimized graphite-reinforced recycled AA6061 composites for sustainable and lightweight engineering applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and experimental design:*** *Hamzah Luqman Bin Rosdi and Mohamed Nasrul Bin Mohamed Hatta;* ***data collection and experimental work****: Hamzah Luqman Bin Rosdi;* ***analysis and interpretation of results****: Hamzah Luqman Bin Rosdi and Mohamed Nasrul Bin Mohamed Hatta;* ***draft manuscript preparation****: Hamzah Luqman Bin Rosdi. All authors reviewed the results and approved the final version of the manuscript.*

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