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# Optimizing Bonding Parameters for Glued Laminated Timber from Fast-Growing Laran Species Using Polyurethane Adhesive

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**Abstract**

This study investigates the optimization of bonding parameters for glued laminated timber (glulam) made from fast-growing Laran species using Polyurethane (PUR) adhesive, focusing on the adhesive spread rate and press pressure. The research aims to determine the shear strength, delamination properties, and wood failure percentage of Laran glulam, contributing to the sustainable use of fast-growing timber species in engineered wood products. The results showed a complex relationship between adhesive spread, press pressure, delamination, shear strength, and wood failure percentage. Higher press pressures generally reduced delamination but also decreased shear strength and increased wood failure. The optimal bonding parameters, determined through response surface methodology (RSM), were a adhesive spread of 400 g/m2 and a press pressure of 0.74 MPa, yielding a predicted shear strength of 7.68 N/mm2 and a wood failure percentage of 83.74%, although the predicted total delamination slightly exceeded the acceptable limit. The study successfully identified the optimal bonding parameters for Laran glulam using PUR adhesive, highlighting the trade-offs between delamination resistance and shear strength and underscoring the potential of Laran in glulam production.

## 1. Introduction

The construction industry has increasingly turned to fast-growing timber species as sustainable and cost-effective alternatives to traditional hardwoods. One such species is Laran, a fast-growing wood from Malaysia and Indonesia, which has shown great promise for use in adhesive laminated timber (glulam). Glulam is a popular engineered wood product that combines the strength and durability of wood with the design flexibility of engineered materials. Recent research [1]–[5] has focused on Laran's potential in engineered wood products. A critical factor in the performance of adhesived products is the integrity of the wood-adhesive bond, which heavily depends on the wood species used [6], [7]. Ensuring the structural integrity and performance of glulam is essential for its application in various construction scenarios.

The type of adhesive used significantly affects these properties. This is an important technical achievement in producing engineered timber products (ETP) [8]–[11]. In a previous study, the investigation on the shear strength of glulam bonded with phenol-resorcinol-formaldehyde (PRF) adhesive was conducted [12]. The study revealed that PRF adhesive provided excellent bonding strength and durability under various environmental conditions, with a shear strength of 8.68 MPa at 400 g/m$^2$ adhesive spread and 1.0 MPa press pressure, demonstrating its suitability for structural applications. Despite PRF adhesive's proven performance, there is growing interest in exploring alternative adhesives that may offer additional benefits. One such adhesive is Polyurethane (PUR), known for its flexibility, resistance to moisture, and ease of application and more environment friendly adhesive. However, despite its increasing use in the industry, the performance of PUR-adhesive glulam has not been extensively studied specifically in fast-growing tropical plantation species.

To optimise the bonding parameters for adhesive laminated timber made from fast-growing Laran species using PUR adhesive, it is essential to consider the key factors influencing bond strength and durability [13], [14]. One critical factor is the adhesive spread rate, which refers to the amount of adhesive applied to the wood surface. An appropriate adhesive spread rate ensures sufficient coverage and promotes strong adhesion between the wood surfaces. Additionally, the press pressure applied to the laminations and the duration of this pressure are crucial in the bonding process [15], [16]. It is also important to consider the specific characteristics of the Laran species itself. The surface properties of the wood, particularly its density and moisture content, play a significant role in the effectiveness of the bonding process.

This research aims to fill a knowledge gap by examining the shear strength of glulam beams bonded with PUR adhesive and comparing it to the performance of PRF adhesive. The focus on PUR adhesive is particularly unique, as its use in glulam has not been extensively studied. PUR adhesive offers potential benefits like improved environmental resistance and greater bonding flexibility. Through a comprehensive shear test, this study will provide new insights into the performance of glulam bonded with PUR. By evaluating the shear strength and overall performance of PUR-adhesive glulam, this research seeks to expand the material options for glulam construction while ensuring its structural integrity. The research continues the objective of the previous study: finding strong adhesives for glulam. However, it diverges by exploring PUR, a different adhesive material, to assess its suitability and potential advantages compared to the established PRF.

## 2. Testing Materials

### 2.1 Lamination

This study utilises Laran (*Neolamarckia cadamba*) for the glulam beam laminations. Laran wood is a light hardwood known for its softness and lightweight properties. When air-dried, its density falls within a range of 290 to 465 kilograms per cubic meter. It is a versatile wood, well-suited for both pulp production and small construction projects. Notably, Laran exhibits good workability. It can be easily re-sawn and crosscut for shaping and planning the wood results in a smooth surface finish. The thickness of the lamination used was 35 mm and the moisture content was adjusted between 12% and 19%.

### 2.2 Adhesive

Polyurethane (PUR) adhesive, a popular room-temperature setting adhesive in construction, is used in the manufacture of glued laminated timber (glulam). Its versatility and strong adhesion properties make it ideal for bonding individual laminates together. This makes it ideal for various applications, from structural projects like gluing beams and laminates to adhering countertops and installing flooring. The adhesive used in this study complies with the requirements for Type I adhesives as outlined in MS 758:2020 [17]. Type I adhesives are suitable for use at any temperature and are designed for service classes 2 and 3, making them ideal for more demanding conditions. In contrast, Type II adhesives are restricted to temperatures below 50°C and are only suitable for service classes 1 and 2.

### 2.3 Manufacture of Block Shear and Delamination Specimen Based on the Various Condition

Twelve glulam test specimens, each consisting of three layers measuring 135 mm width, 105 mm thickness, and 1500 mm length, were manufactured at a glulam factory in Konsortium PEKA, Karak, Pahang. The manufacturing process adhered to the standards set forth in MS 758:2020 [17]. Polyurethane (PUR) adhesive was applied to these specimens during manufacturing, with variations in application volume and press pressure as detailed in Table 1. The selection of press pressure and adhesive spread in this study was guided by the specifications provided by AkzoNobel, the adhesive manufacturer, which recommend adhesive spreads of 240–350 g/m$^2$ for hardwoods and 350–420 g/m$^2$ for softwoods. To broaden the scope of the evaluation, adhesive spreads of 200, 250, 350, and 400 g/m$^2$ were included in the experiments. This range was also informed by values reported in several studies on glulam manufacturing, ensuring that the selected parameters could provide a comprehensive assessment of the adhesive's performance across varied conditions.

**Table 1** *Description of beam test specimens for bonding study*

| Specimens | Adhesive type | Adhesive spread (g/m$^2$) | Press pressure (MPa) |
|---|---|---|---|
| LRN/PUR/200/0.7 | PUR | 200 | 0.7 |
| LRN/PUR/200/1.0 | PUR | 200 | 1.0 |
| LRN/PUR/200/1.4 | PUR | 200 | 1.4 |
| LRN/PUR/250/0.7 | PUR | 250 | 0.7 |
| LRN/PUR/250/1.0 | PUR | 250 | 1.0 |
| LRN/PUR/250/1.4 | PUR | 250 | 1.4 |
| LRN/PUR/350/0.7 | PUR | 350 | 0.7 |
| LRN/PUR/350/1.0 | PUR | 350 | 1.0 |
| LRN/PUR/350/1.4 | PUR | 350 | 1.4 |
| LRN/PUR/400/0.7 | PUR | 400 | 0.7 |
| LRN/PUR/400/1.0 | PUR | 400 | 1.0 |
| LRN/PUR/400/1.4 | PUR | 400 | 1.4 |

The adhesive spread was controlled using a roller to apply the adhesive, which was pre-weighed according to the specifications provided in Table 1. Rather than directly controlling the thickness of the adhesive layer, the focus was on ensuring a consistent adhesive weight per unit area. This method accounts for the varying absorbency limits of different wood species, as each species can absorb adhesive to different extents. If the adhesive application is too low, certain areas of the wood may remain uncovered, leading to voids or weak bonding zones [6]. On the other hand, if the adhesive spread is excessive, it can result in waste, with surplus adhesive potentially being squeezed out during pressing. The press pressure is also a critical factor, as it helps to evenly distribute the adhesive across the wood surface and ensures a consistent bond.

Then, the manufactured glulam beams were fully utilised to create test specimens for block shear strength and delamination testing. Table 2 details the cutting dimensions used, ensuring no wasted material from the beams except for 300 mm discarded from each end. This process results in a total of 96 test pieces for the delamination test and 72 test pieces for the block shear test.

**Table 2** *Description of testing for manufacturing study*

| Item | Test | Width (mm) | Depth (mm) | Length (mm) | Number of specimens per beam |
|---|---|---|---|---|---|
| A | Delamination test | 135 | 105 | 75 | 8 |
| B | Block shear test | 50 | 105 | 50 | 6 |
| C | Moisture content and density test | 135 | 105 | 25 | 3 |

## 3. Test Method

### 3.1 Delamination Properties of Laran Glulam

The bonding quality of all glulam samples was evaluated in this study using block shear and delamination tests. These tests adhered to the procedures outlined in MS 758:2020 [17]. Based on observations, the Laran glulam was classified as Service Class 3. For the delamination test, Method A from ISO 12580:2007 [18] was employed. This test assessed both the total delamination ($Delam_{tot}$) and the maximum delamination ($Delam_{max}$) for each glulam sample. Equation (1) provides the calculation for $Delam_{tot}$, expressed as a percentage. Equation (2) calculates $Delam_{max}$ for a single adhesive line within the test piece. It is important to note that for all delamination methods, the maximum delamination percentage of any individual adhesive line must not exceed 20%.

$$Delam_{tot} = 100 \frac{\ell_{tot.delam}}{\ell_{tot.glueline}} (\ in\ \%\ ) \tag{1}$$

$$Delam_{max} = 100 \frac{\ell_{max.delam}}{2\ell_{glueline}} (\ in\ \%\ ) \tag{2}$$

The total delamination length ($\ell_{tot.delam}$) encompassed all separations within adhesive bonds in the specimen, while the total adhesive line length ($\ell_{tot.adhesive\ line}$) referred to the combined length of all adhesive lines on both end-grain faces. The maximum delamination length ($\ell_{max.delam}$) represented the largest single separation within a adhesive line, and the individual adhesive line length ($\ell_{adhesive\ line}$) typically corresponded to its width.

## 3.2 Block Shear Strength of Laran Glulam

The block shear test will then be conducted to determine the shear strength properties. A constant load will be applied using the Universal Testing Machine (UTM) and shearing tool (Fig. 1), and the load readings will be continuously recorded until failure occurs or the ultimate load is reached, after a minimum of 20 seconds.

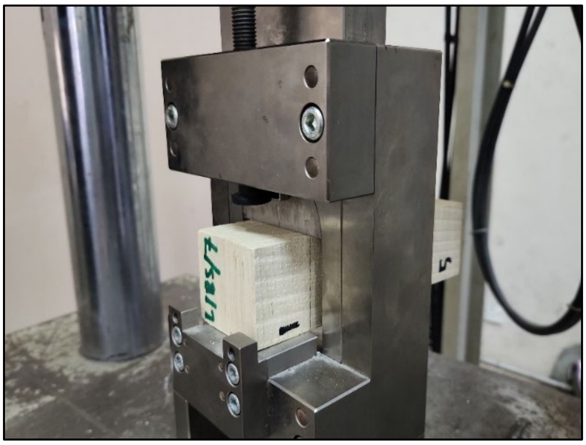

**Fig. 1** *Shearing tool with test bar*

The average wood failure percentage across all adhesive lines within a cross-section, as well as any individual value, must surpass the minimum wood failure percentages specified in Table 2 of MS 758:2020 [17]. Following that, the shear strength ($f_v$) should be calculated using Equation (3) and reported to two significant digits.

$$f_v = k_v \frac{F_u}{A} \tag{3}$$

The modification factor, k, given by (k = 0.78 + 0.0044t), where t is the thickness in millimeters, adjusts the shear strength of test specimens when the thickness of the sheared area, measured in the grain direction, is less than 50 mm. The sheared area (A) is calculated as A = bt for a test bar and A = lt for a drill core, with b representing width and l representing length. According to the standard, the average shear strength across all adhesive lines within a cross-section must be at least 6.0 N/mm$^2$. However, a shear strength of 4.0 N/mm$^2$ is acceptable if the wood failure percentage reaches 100%.

## 3.3 Moisture Content and Density of Laran

The moisture content of each specimen was evaluated by splitting it into three mid-span sections at the conclusion of the test. The timber moisture content, calculated as a percentage of oven-dry weight, was determined using the widely recognized oven-drying method (MS 837:2006 [19]). Following sample cutting, each test piece was weighed and placed in an oven maintained at a constant temperature of 103±2℃. The samples were removed after 24 hours, weighed, and returned to the oven in 2-hour intervals until weight loss stopped. The final weight was recorded, and moisture content was calculated using Equation (4). Prior to moisture content testing, the weight and volume of each specimen were measured, facilitating the determination of specimen density using Equation (5).

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$$Moisture\ content = \frac{Weight\ at\ test\ -\ Oven\ dry\ test}{Oven\ dry\ test} x100\ (\ \%\ ) \tag{4}$$

$$Density,\ \rho = \frac{Mass}{Volume} \left( {kg}/{m^3} \right) \tag{5}$$

## 4. Results and Discussion

Table 3 presents the average delamination, shear strength, wood failure percentage, moisture content, and density of Laran glulam using Polyurethane (PUR) adhesive. The glulam was produced with varying adhesive spread rates (200 g/m$^2$, 250 g/m$^2$, 350 g/m$^2$, and 400 g/m$^2$) and different press pressures (0.7 MPa, 1.0 MPa, and 1.4 MPa).

**Table 3** *Delamination, shear strength, wood failure percentage, moisture content and density*

| Adhesive spread (g/m²) | Press pressure (Mpa) | Moisture content (%) | Density (kg/m³) | Total delamination (%) | Maximum delamination (%) | Shear strength (N/mm²) | Wood failure percentage (%) |
|---|---|---|---|---|---|---|---|
| 200 | 0.7 | 11.3 | 411.5 | 6.2 | 8.8 | 7.09 | 85.42 |
| 200 | 1.0 | 10.9 | 443.9 | **45.1** | **33.6** | 6.06 | 79.45 |
| 200 | 1.4 | 11.5 | 433.5 | 4.1 | 4.6 | 4.26 | 93.33 |
| 250 | 0.7 | 11.4 | 389.8 | **50.1** | **45.4** | 8.63 | 79.17 |
| 250 | 1.0 | 11.1 | 449.7 | **27.3** | **29.2** | 6.54 | 82.08 |
| 250 | 1.4 | 11.3 | 449.3 | 2.7 | 3.4 | 6.01 | 92.08 |
| 350 | 0.7 | 11.4 | 395.7 | 8.7 | 10.5 | 7.24 | 90.17 |
| 350 | 1.0 | 11.3 | 432.5 | **18.4** | **22.1** | 5.76 | 86.67 |
| 350 | 1.4 | 11.2 | 456.7 | **13.5** | 19.7 | 5.72 | 94.58 |
| 400 | 0.7 | 11.2 | 466.7 | **10.6** | 12.5 | 7.64 | 77.25 |
| 400 | 1.0 | 11.2 | 464.3 | **31.4** | **24.8** | 7.07 | 93.83 |
| 400 | 1.4 | 11.2 | 437.8 | **32.7** | **35.8** | 6.02 | 82.92 |

Note: Bold values means that the specimen had delamination higher than the respective limit.

The experimental results presented in Table 3 reveal a complex relationship between adhesive spread, press pressure, and the resulting delamination, shear strength, and wood failure percentage in laminated wood specimens. For a adhesive spread of 200 g/m$^2$, increasing press pressure from 0.7 MPa to 1.0 MPa led to a substantial increase in total delamination (from 6.2% to 45.1%) exceeding the acceptable limit of 20%, likely due to excessive adhesive displacement and void formation. The resulting total delamination exceeded the acceptable limit of 20% for several specimens, particularly those with a adhesive spread of 200 g/m$^2$ and 250 g/m$^2$ at 1.0 MPa press pressure. However, increasing the press pressure to 1.4 MPa consistently reduced delamination to acceptable levels for all adhesive spreads, indicating that higher pressure can enhance adhesive penetration and bonding [20]. The shear strength of the specimens generally decreased with increasing press pressure, suggesting a trade-off between delamination resistance and shear strength. The highest shear strength values were observed at 0.7 MPa press pressure for all adhesive spreads, but these specimens also exhibited higher delamination.

Additionally, the data indicates that wood failure percentage generally increased with higher press pressures across all adhesive spreads, reaching its peak at 1.4 MPa. This implies that excessive pressure, while reducing delamination, can compromise the wood's integrity, potentially leading to cell wall collapse and reduced load-bearing capacity [21]. Moreover, the moisture content and density of the wood specimens remained relatively consistent across the varying parameters, suggesting that their influence on delamination and shear strength was minimal in this study. The consistent moisture content might indicate that the adhesive used was not sensitive to minor variations in wood moisture [22]. Future research could explore the effect of different wood density and moisture levels, as well as adhesive types, on these properties to further optimize the lamination process. Understanding the interaction between wood properties, adhesive characteristics, and process parameters is crucial for producing high-quality laminated wood products.

To determine the optimal combination of adhesive spread and press pressure that maximized bonding quality while adhering to MS 758:2020 [17] standards, a response surface methodology (RSM) analysis was conducted. This analysis utilized the experimental data presented in Table 3, which included the total delamination, shear strength, and wood failure percentage for various combinations of adhesive spread and press pressure. By fitting a mathematical model to this data, the RSM analysis generated response surfaces that illustrated the relationship between the input variables (adhesive spread and press pressure) and the output variables (bonding quality metrics) [23]. The resulting response surfaces enabled the identification of the optimal adhesive spread and press pressure that simultaneously minimized delamination, maximized shear strength, and ensured adequate wood failure percentage, considering the acceptable limits and requirements specified in MS 758:2020 [17]. The Design Expert Software Version 11 was employed to facilitate the RSM analysis and generate the response surfaces, providing a visual representation of the optimal bonding parameters for Laran glulam using PUR adhesive.

In details, the optimization process using Response Surface Methodology (RSM) involves several key stages. First, the problem and objectives are defined, such as identifying the ideal press pressure or adhesive rate to enhance glulam performance. Relevant factors (e.g., adhesive spread, press pressure) and responses (e.g., bonding quality metrics) are selected, and an experimental design like Central Composite or Box-Behnken is created to systematically study these variables. Experiments are conducted, and data are used to build and validate a predictive model, typically a second-order polynomial [24]–[26]. Optimization is performed to find the best combination of factors using tools like desirability functions, and results are verified experimentally. Sensitivity analysis ensures the robustness of the optimized conditions, which are then implemented and documented for consistent production. This approach not only identifies optimal parameters but also provides valuable insights into factor interactions and system behaviour.

Finally, bonding quality data were analyzed and assessed in accordance with MS 758:2020 [17] using Response Surface Methodology (RSM). Fig. 2 presents the optimal outcome selected from twelve potential results generated by the software. This selection was based on the desirability function, a statistical tool in RSM that combines multiple responses into a single value, indicating the overall desirability of a particular set of input parameters [27]. In this context, desirability refers to the degree to which a specific combination of adhesive spread, and press pressure satisfies the desired criteria for bonding quality, such as minimizing delamination and maximizing shear strength. The chosen result represents the combination of adhesive spread and press pressure that yields the highest overall desirability, indicating the optimal balance between these parameters for achieving the best possible bonding quality in Laran glulam.

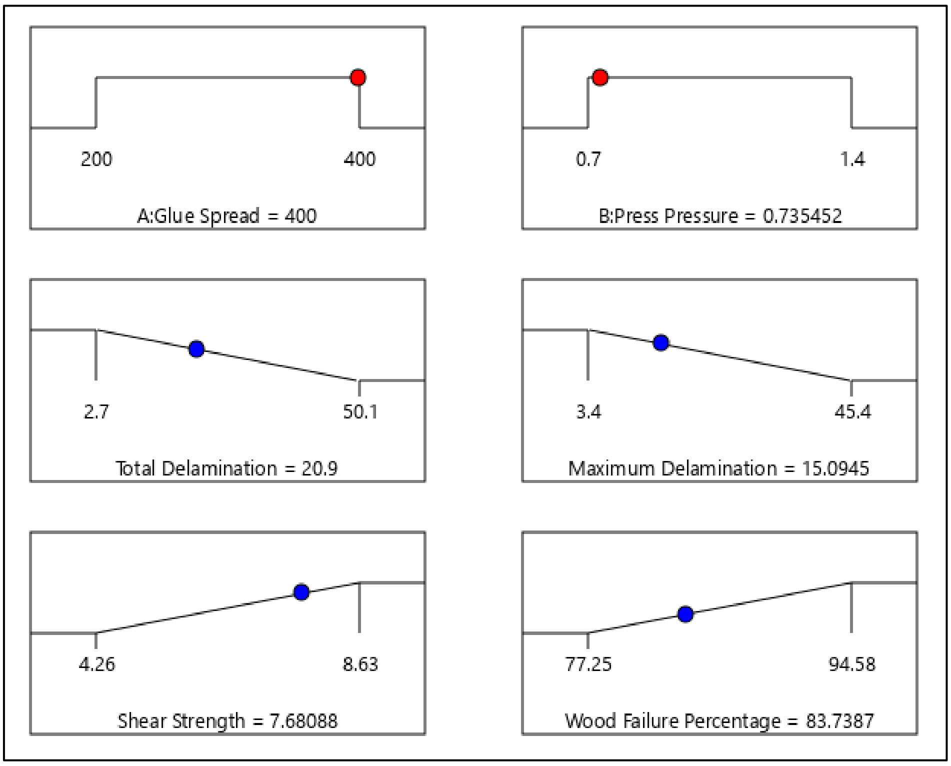


**Fig. 2** *Result from design expert software with RSM analysis*

Based on Fig. 2, the response surface methodology (RSM) analysis identified the optimal adhesive spread and press pressure for Laran glulam beams to be 400 g/m2 and 0.74 MPa, respectively. At these parameters, the predicted shear strength was 7.68 N/mm2 and wood failure percentage was 83.74%. However, the predicted total delamination (20.9%) slightly exceeded the acceptable limit of 10%, as defined in MS 758:2020 [17] but the maximum delamination (15.09%) was within range. While the experimental data in Table 3 did not directly yield this precise combination due to the varied trends observed, the RSM analysis provided a more accurate and refined prediction of the optimal parameters. This highlights the value of RSM in identifying optimal process conditions that may not be readily apparent from raw experimental data alone. Despite the slight deviation in delamination, the RSM-derived parameters offer a promising starting point for further optimization and validation studies to achieve the desired balance between bonding strength and delamination control in Laran glulam production.

## 5. Conclusions

In conclusion, this study investigated the influence of adhesive spread and press pressure on the bonding quality of Laran glulam using Polyurethane (PUR) adhesive. The experimental results revealed a complex relationship between these parameters, with varying effects on delamination, shear strength, and wood failure percentage. While higher press pressures generally reduced delamination, they also led to decreased shear strength and increased wood failure. The optimal bonding parameters, determined through response surface methodology (RSM), were found to be a adhesive spread of 400 g/m2 and a press pressure of 0.74 MPa. Although the predicted total delamination slightly exceeded the acceptable limit, the RSM analysis provided valuable insights into the optimal balance between bonding strength and delamination control. These findings highlight the potential of Laran as a viable material for glulam production and emphasize the importance of optimizing process parameters to achieve desired bonding quality.

The study's findings contribute to the growing body of knowledge on the use of fast-growing timber species like Laran in engineered wood products. The identification of optimal bonding parameters for PUR adhesive not only expands the material options for glulam construction but also promotes sustainable practices by utilizing renewable resources. The application of RSM in this study demonstrates its effectiveness in optimizing complex manufacturing processes, offering a valuable tool for the wood industry to improve efficiency and resource utilization. Further research could explore the effects of different wood species, moisture levels, and adhesive types on the bonding performance of glulam, contributing to the development of sustainable and high-performance engineered wood products. The insights gained from this, and future studies can inform the development of standardized manufacturing processes for Laran glulam, ensuring consistent quality and performance in structural 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 design****: Muhammad Amirul Akmal Rosli, Norshariza Mohamad Bhkari;* ***data collection****: Muhammad Amirul Akmal Rosli, Ameera Amani Amrudin, Norman Wong Shew Yam;* ***analysis and interpretation of results****: Muhammad Amirul Akmal Rosli, Norshariza Mohamad Bhkari, Muhammad Bazli Faliq;* ***draft manuscript preparation****: Muhammad Amirul Akmal Rosli, Norshariza Mohamad Bhkari, Zakiah Ahmad. All authors reviewed the results and approved the final version of the manuscript.*

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