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# Sustainable Warm Mix Asphalt: Incorporating Waste Motor Engine Oil for Enhanced Performance

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## Abstract

The production of Hot Mix Asphalt (HMA) requires high energy input and releases substantial amounts of greenhouse gases and other hazardous emissions, contributing significantly to air pollution. Warm Mix Asphalt (WMA) offers a more sustainable alternative, as it requires lower mixing and production temperatures, thereby reducing both energy consumption and emissions. This study investigates the potential of waste motor engine oil (WMEO) as a asphalt modifier in WMA. WMEO was incorporated at varying dosages of 0%, 3%, 4%, and 5% by weight of asphalt. The modified binders and mixtures were evaluated through penetration, softening point, stability, flow, and stiffness tests. The highest stability is at 7000 N (3%), indicating a substantial improvement in load-bearing capacity and structural integrity of the modified asphalt, which reflects the effectiveness of WMEO in enhancing both mechanical strength and overall mixture performance. These findings suggest that WMEO can serve as an effective modifier for WMA, contributing to improved performance and sustainability in asphalt pavement applications.

**Keywords:** Waste Motor Engine Oil, Warm Mix Asphalt, Sustainable Asphalt, Stability

## Introduction

Conventional hot-mix asphalt (HMA) production is energy-intensive and emission-heavy, largely because most plant energy is consumed in heating mineral aggregates to high temperatures [1]. Recent assessments report that aggregate heating can account for ~97% of total plant energy use, underscoring the decarbonization potential of lower-temperature technologies [2]. Warm-mix asphalt (WMA) reduces mixing and compaction temperatures by roughly 20–40 °C, which in turn lowers fuel consumption and plant-stack emissions while improving working conditions and enabling longer haul distances [3]. Controlled studies and systematic reviews confirm temperature drops on the order of ~25–26 °C for typical binders and additives, with associated energy and emissions savings relative to HMA [4,5]. At the production scale, monitoring of plants that switch from hot to warm mixes shows tangible reductions in energy demand and environmental burdens, aligning WMA with industry carbon-footprint guidance for efficiency-first mitigation [6,7].

In parallel with temperature reduction, circular-economy strategies are advancing the use of recycled constituents and waste-derived modifiers to enhance performance and sustainability [8]. Among these, waste motor/engine oil (WEO/WMEO) has emerged as a promising rejuvenator or viscosity-reducing modifier because its light fractions can diffuse into oxidized binders and restore lost maltenes [9]. Recent reviews and mechanistic studies indicate that WEO can effectively soften and rejuvenate aged asphalt, with dosage-dependent benefits and trade-offs that must be balanced against rutting and cracking resistance [10]. Molecular-scale simulations corroborate the diffusion-driven rejuvenation mechanism [3], [11,12]. When combined with WMA, waste-oil-based modifiers can further facilitate low-temperature mixing while maintaining or improving mechanical response [13] field and lab programs increasingly explore these synergies, including high-RAP (Reclaimed Asphalt Pavement) WMA produced with chemical/bio-based aids [14].

Environmental stewardship remains essential when valorizing waste oils. Contemporary assessments highlight potential leaching concerns from asphalt materials depending on source oil quality and treatment, motivating careful selection, pre-treatment, and risk assessment protocols alongside performance testing [15].

Building on this context, the present work evaluates WMEO as a bitumen modifier for WMA. WMEO is incorporated at 0%, 3%, 4%, and 5% by binder mass, and performance is assessed via penetration, softening point, Marshall stability and flow, and stiffness metrics to quantify the balance between workability and mechanical resistance at reduced production temperatures [16].

This study investigates the potential of WMEO as a asphalt modifier in WMA. While numerous additives have been studied for improving WMA, the application of WMEO as a modifier is still relatively underexplored. In particular, further investigation is needed to clarify its influence on binder properties and mixture performance, presenting an opportunity to advance both performance and sustainability in asphalt pavements. To address this gap, WMEO was incorporated at varying dosages of 0%, 3%, 4%, and 5% by weight of bitumen, and the modified binders and mixtures were evaluated through penetration, softening point, stability, flow, and stiffness tests.

## Materials and Methods

Figure 1 presents the flowchart of this study, where WMA was prepared by incorporating WMEO at dosages of 0%, 3%, 4%, and 5% by weight of the original asphalt.

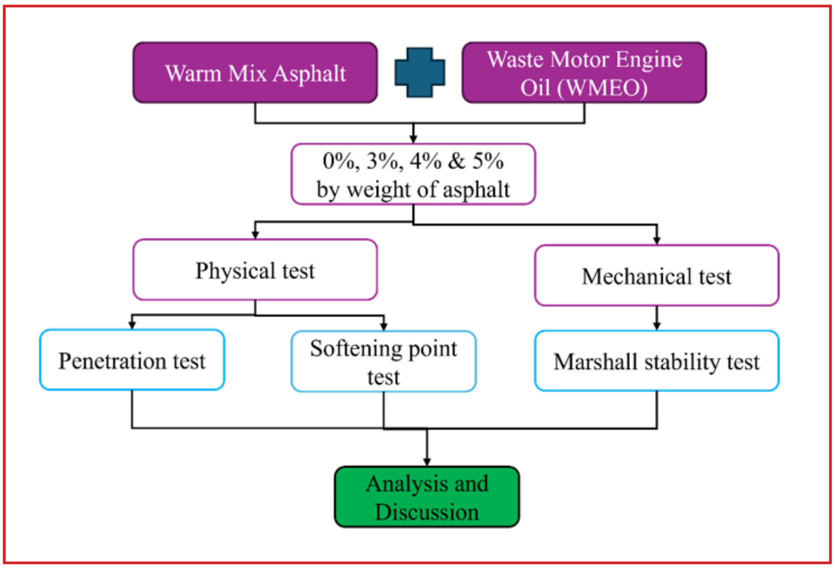


**Figure 1.** Flowchart of this study

### Asphalt Binder

Asphalt binder that was used in this study was penetration 60-70.

### Aggregate

Crushed granite aggregates were used to prepare the warm mix asphalt mixture where the asphaltic concrete grade 14 was chosen for the mixture design based on the Jabatan Kerja Raya (JKR) specification (JKR/SPJ/2008-S4) [17]. The mix design incorporated a range of aggregate particle sizes, with each aggregate particle size in a given Figure 2.

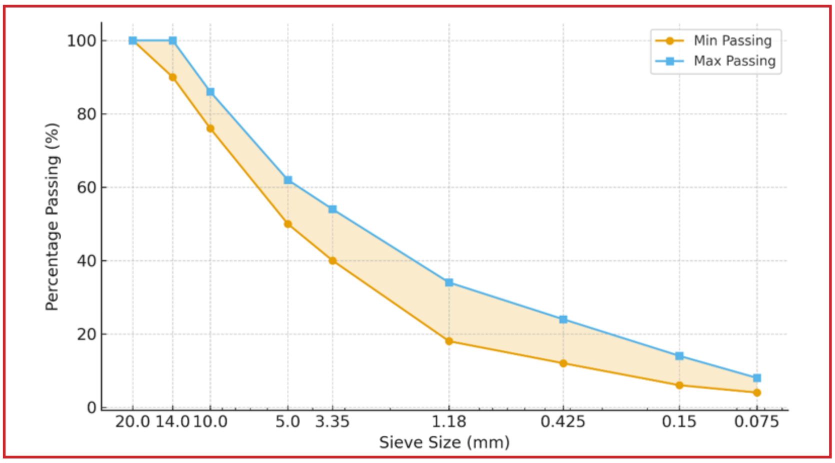


**Figure 2.** Gradation used in this study

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### Waste Motor Engine Oil (WMEO)

The waste motor engine oil (WMEO) used in this study was sourced from a local motor workshop. Prior to utilization, the raw WMEO was filtered through laboratory-grade filter paper to eliminate dirt and impurities, with the contaminants retained on the paper and the purified oil collected for further use. Modified asphalt binders were then prepared by incorporating WMEO at dosages of 0%, 3%, 4%, and 5% by weight of asphalt into the control binder. The mixtures were homogenized using a high-shear mixer operating at a constant speed of 1000 rpm. The resulting binders were subsequently employed in the evaluation of warm mix asphalt performance.

### Penetration Test

According to ASTM D5 [18], the penetration test is widely used due to its simplicity and ease of execution; however, it does not determine a fundamental rheological parameter and is limited to a single test temperature of 25 °C. In this study, the test was employed to evaluate the consistency of bitumen before and after thermal conditioning.

### Softening Point Test

As specified in ASTM D36 [19], the softening point test determines the temperature at which asphalt binder reaches a defined degree of softness under standardized conditions. With increasing temperature, asphalt cement transitions from a solid to a more fluid state, resulting in a progressive reduction in stiffness. In this study, the softening point was determined using the ring-and-ball method to characterize the thermal susceptibility of the asphalt binder.

### Stability Test

The Marshall method was employed to evaluate the volumetric and mechanical properties of the asphalt mixtures, including stability, flow, and stiffness. For this test, three compacted specimens were prepared and positioned laterally under the loading head. A compressive load was applied until specimen failure, after which the stability and flow values were recorded. The procedure was conducted in accordance with ASTM D5581 [20]. Figure 3 illustrates the specimens compacted using the Marshall compactor.

## Results and Discussions

### Penetration

Based on Figure 4, The penetration test results reveal a distinct influence of Waste Motor Engine Oil (WMEO) on the consistency of the asphalt binder. For the control sample without WMEO, the penetration value was approximately 67 mm, which reflects the typical hardness of a 60/70 penetration-grade binder and serves as the reference point for comparison. When 3% WMEO was incorporated, the penetration increased slightly to about 71 mm, indicating a softening effect on the binder. This behavior can be attributed to the presence of light oil fractions in WMEO, which are capable of diffusing into the bitumen

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**Figure 3.** Compacted samples

matrix and restoring maltene components, thereby enhancing binder flexibility and workability. However, when the WMEO content was increased to 4%, the penetration value decreased significantly to around 55 mm. This reversal suggests that excessive addition of WMEO disrupts the balance between asphaltenes and maltenes, leading to binder stiffening rather than further softening. The effect became more pronounced at 5% WMEO, where penetration dropped further to approximately 48 mm. Such stiffening at higher dosages may result from chemical interactions, potential volatilization of light fractions, or residue accumulation within the binder, ultimately reducing ductility and increasing susceptibility to cracking under low-temperature conditions. Overall, the results highlight that low WMEO content enhances binder softness and workability, while higher contents cause undesirable stiffening. Thus, the optimum dosage appears to be around 3% WMEO, which provides the most favorable balance between softening and mechanical performance.

### *Softening Point*

From Figure 5, The softening point test results illustrate the influence of Waste Motor Engine Oil (WMEO) on the thermal behavior of the asphalt binder. At 0% WMEO, the softening point reached the highest value of approximately 49 °C, indicating greater resistance to temperature-induced softening. However, at 3% WMEO, the softening point decreased sharply to 41.5 °C, suggesting that excessive oil at this dosage weakened the binder structure and reduced its thermal stability. Beyond 4%, a gradual increase in softening point was observed, with values of 44 °C and 45.5 °C at 5% WMEO. This recovery trend implies that moderate WMEO content can enhance binder performance by balancing softening and rejuvenation effects, potentially due to improved molecular interactions between the oil fractions and asphalt components. These findings highlight the dual role

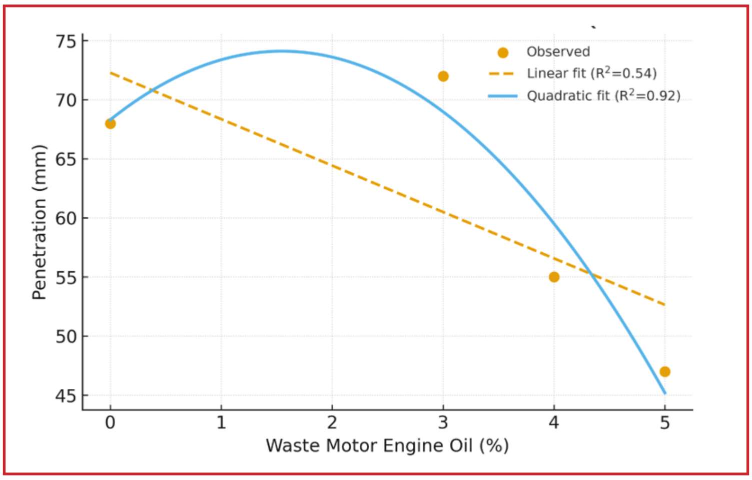


**Figure 4.** Penetration behavior of waste motor engine oil–modified warm mix asphalt

of WMEO as both a rejuvenator (reducing stiffness at certain concentrations) and a stabilizer (improving thermal resistance at optimized levels). The initial decline followed by recovery suggests that there exists an optimum dosage range (3–4%) where WMEO contributes positively to binder softening resistance without compromising performance. Finally, incorporating WMEO provides a pathway for valorizing waste oils while improving binder workability in warm mix asphalt applications. Nevertheless, the variability observed emphasizes the importance of careful dosage optimization to ensure consistent mechanical and thermal performance.

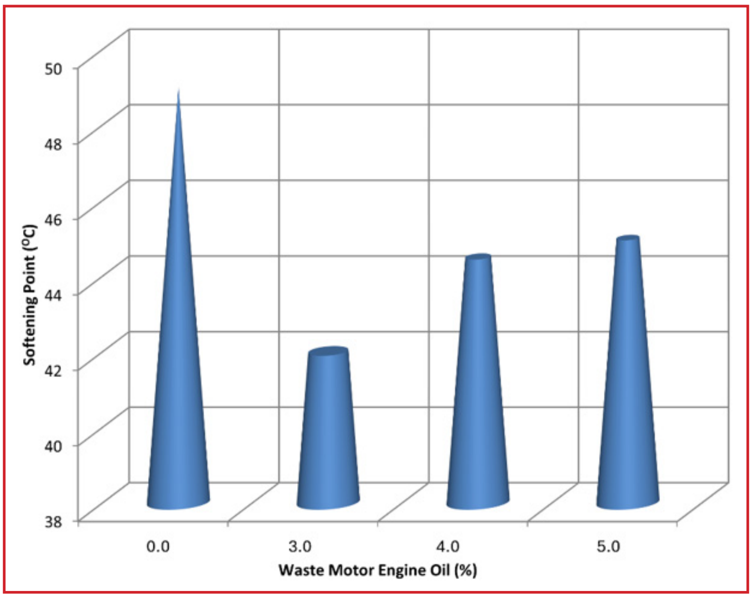


**Figure 5.** Effect of waste motor engine oil on the softening point of warm mix asphalt

### *Stability*

Figure 6 shows the stability of modified samples. The stability values of asphalt mixtures modified with Waste Motor Engine Oil (WMEO) exhibit a non-linear trend. At 0% WMEO, stability was approximately 5700 N, which increased significantly to about 7000 N at 3% WMEO, representing the peak strength.

Beyond this dosage, stability declined to 5700 N at 4% and further to 5600 N at 5%, indicating a reduction in load-bearing capacity.

The regression analysis supports this observation. The linear model shows no meaningful correlation, confirming that stability does not vary in a strictly linear manner with WMEO content. In contrast, the quadratic model with $R^2$ 0.68 better describes the trend, capturing the parabolic behavior with an optimum point near 3% WMEO.

This behavior suggests that at low to moderate dosages, WMEO enhances binder workability and improves adhesion, leading to higher mixture stability. However, at higher dosages (>3%), excess oil likely softens the binder excessively, resulting in diminished cohesion and reduced stability. Overall, the findings indicate that 3% WMEO is the optimum dosage for achieving maximum stability in warm mix asphalt, balancing improved workability with mechanical performance. Excessive WMEO addition could compromise mixture durability, highlighting the importance of dosage optimization in sustainable asphalt design.

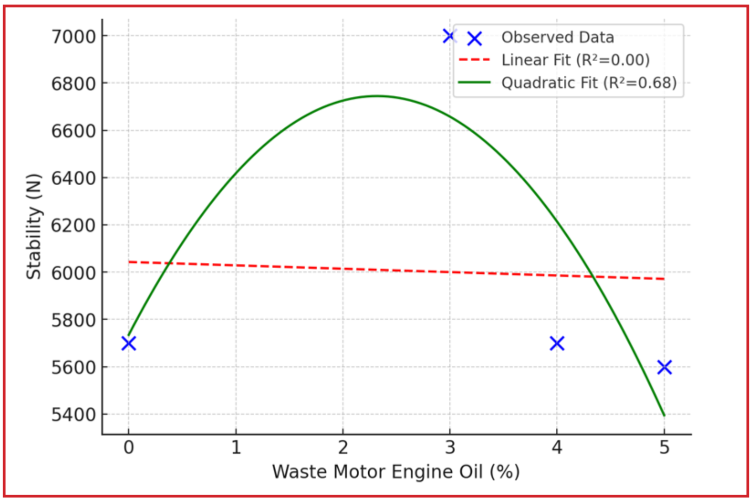


**Figure 6.** Variation in stability of warm mix asphalt with waste motor engine oil content

### *Flow*

Figure 7 shows the effect of WMEO mixture on flow. The flow values of warm mix asphalt (WMA) mixtures modified with Waste Motor Engine Oil (WMEO) reveal a non-linear trend across different dosages. At 0% WMEO, the flow was approximately 3.9 mm, representing the baseline behavior of the control mixture. When 3% WMEO was added, the flow value decreased to around 3.1 mm, suggesting that the binder became stiffer and less deformable due to partial modification effects at this dosage.

Interestingly, at 4% WMEO, the flow reached its maximum value of approximately 4.7 mm, indicating that higher oil content at this level significantly softened the asphalt binder, thereby enhancing mixture flexibility. However, a further increase to 5% WMEO reduced the flow to around 3.3 mm, reflecting a possible imbalance in the binder composition, where excessive oil content may have weakened aggregate interlock and binder cohesion.

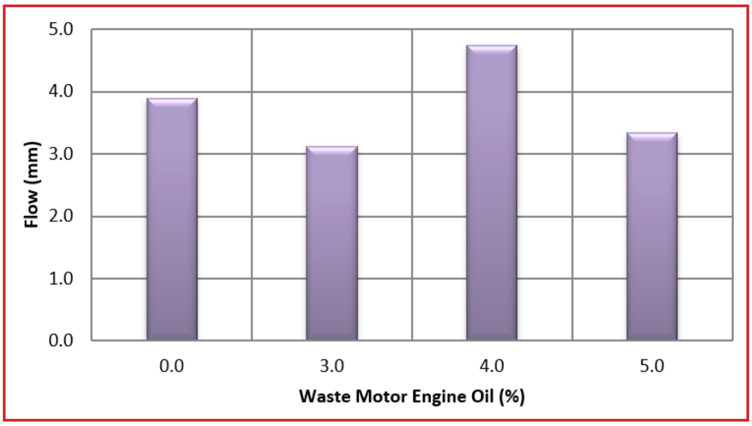


**Figure 7.** Flow behavior of waste motor engine oil–modified warm mix asphalt

These fluctuations highlight the dual role of WMEO in asphalt modification. At low dosages, WMEO may act as a rejuvenator, reducing binder stiffness, whereas at higher concentrations, it can over-soften the binder, leading to instability. The observed optimum around 4% WMEO suggests improved mixture workability and deformability, but caution must be taken as excessive flow can also correlate with a higher risk of permanent deformation (rutting) under traffic loads.

In line with previous studies, the results emphasize that WMEO incorporation requires careful dosage optimization. The balance between adequate flow (to ensure workability and flexibility) and resistance to plastic deformation (to preserve durability) is critical. Overall, the results indicate that 4% WMEO provides the most favorable improvement in flow properties, while both lower and higher contents lead to suboptimal performance.

### *Stiffness*

Figure 8 shows the effect of WMEO on stiffness. Stiffness can be defined as the rigidity of a material or how it resists deformation if load is applied. Stiffness is the stability over flow. The stiffness of the samples is the capability to withstand loads without significant deformation occurred on the samples. High stiffness leads to high strength of the pavement. However, stiffness should not be too high because brittleness will take place thus leads to cracking. From the graph, the stiffness results of WMA containing WMEO exhibit a highly non-linear trend across the tested dosages. The control mixture (0% WMEO) showed a stiffness of approximately 1320 N/mm. With the addition of 3% WMEO, stiffness increased to around 1760 N/mm, indicating that moderate incorporation of WMEO enhanced the load-distribution capacity of the mixture.

However, at 4% WMEO, stiffness dropped sharply to approximately 1040 N/mm, suggesting that excessive binder softening occurred, leading to reduced structural integrity. Interestingly, at 5% WMEO, stiffness reached its maximum value of about 2560 N/mm, nearly doubling the control mixture, which highlights a strong binder–aggregate interaction at higher oil content.

This fluctuation indicates that WMEO has a dual effect: at low to moderate dosages, it improves binder workability and moderately enhances stiffness, but

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at certain levels (4%), the binder may become over-softened, lowering mixture rigidity. At higher dosages (5%), the oil possibly facilitates stronger binder re-dispersion and improved aggregate adhesion, thereby significantly increasing stiffness.

The findings imply that while WMEO can contribute positively to asphalt stiffness, its effects are highly dosage-dependent, and the relationship is not straightforward. From a performance perspective, higher stiffness values are generally desirable for resisting permanent deformation (rutting), but overly stiff mixtures may be prone to cracking under thermal and fatigue stresses. Therefore, dosage optimization is critical to achieving the right balance between deformation resistance and flexibility in WMA mixtures.

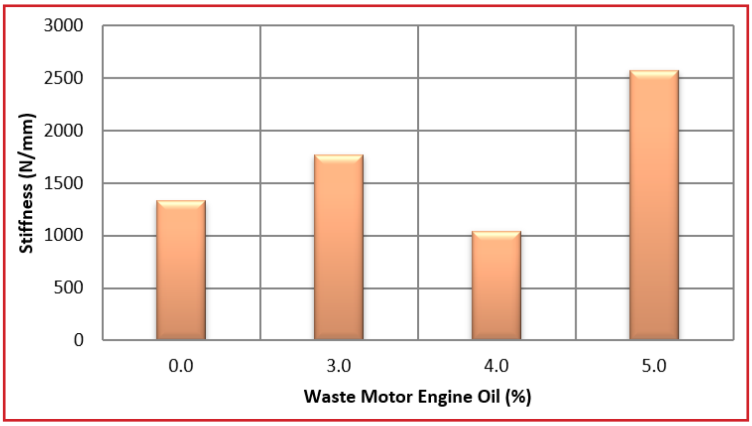


**Figure 8.** Variation in Flow of Warm Mix Asphalt with Waste Motor Engine Oil Content

## Conclusion

This study evaluated the influence of Waste Motor Engine Oil (WMEO) as a modifier in Warm Mix Asphalt (WMA) with the objective of enhancing performance and sustainability through the incorporation of waste-derived materials. WMEO was introduced at varying dosages (0%, 3%, 4%, and 5% by weight of bitumen), and its effects were assessed through penetration, softening point, stability, flow, and stiffness tests. Based on the experimental results, the following conclusions can be drawn:

a. The addition of WMEO exhibited a dosage-dependent effect. At 3% WMEO, the binder showed increased penetration, indicating improved flexibility and workability. However, higher dosages (≥4%) reversed this trend, producing stiffer binders due to imbalances in the asphaltene–maltene system.

b. WMEO significantly influenced binder thermal susceptibility. While the softening point dropped sharply at 3% WMEO, subsequent increases to 4–5% led to partial recovery, suggesting an optimum range where WMEO balances rejuvenation and stability effects.

c. Stability peaked at 3% WMEO, demonstrating enhanced cohesion and load-bearing capacity, but decreased at higher dosages due to excessive softening.

d. The incorporation of WMEO in WMA mixtures highlights its dual role as a rejuvenator and stabilizer. Optimum performance was observed at 3–4% WMEO, providing the best balance between flexibility, stability, and resistance to deformation.

e. The use of WMEO contributes to circular economy practices by valorizing waste oils while reducing the energy demand and emissions associated with HMA production. This positions WMEO-modified WMA as a promising, environmentally responsible alternative for future pavement construction.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contributions

**Dewi Sri Jayanti:** writing-original draft, conceptualization, methodology. **Wan Noor Hin Mior Sani:** investigation, data curation, writing-reviewing and editing. **Zuraini Din:** visualization. **Zaid Hazim Al-Saffar:** validation, resources. **Haryati Yaacob:** validation.

## Data Availability Statement

The data used to support the findings of this study are included within the article.

## Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT to enhance the clarity of the writing. After using the ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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