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Study of Rolling Resistance and Maneuvering Characteristics of a Prototype Vehicle Under Variations in Negative Camber Angle

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Abstract

In the development of energy-efficient vehicles, two aspects that are often the main concerns are the magnitude of rolling resistance and cornering stability. High rolling resistance can hinder the efficiency of vehicle speed. While the appropriate turning radius setting can maintain vehicle control when maneuvering. This study aims to determine how the tire camber angle can affect both aspects in prototype category vehicles for energy-efficient vehicle competitions. The test was conducted using the Rolling Resistance Test Rig and field testing by varying the negative camber angle by -1°, -2°, and -3°. The test results show that a camber angle of -1° produces an average rolling resistance value of 2.61 N and a tendency to oversteering maneuvers. At a camber angle of -2°, the rolling resistance increases to 2.78 N and the vehicle still shows symptoms of oversteering. While at a camber angle of -3°, the highest rolling resistance is 3.15 N with more balanced and neutral steering. This shows that, the more negative the camber angle can increase rolling resistance, but results in better maneuvering stability, although in this study it was limited to a maximum camber angle of -3°.

1. Introduction

Energy- efficient vehicles are the result of the integration of various interrelated technical aspects, including aerodynamic efficiency, precise mechanical control, transmission system optimization, and the selection and design of the right tires [1]-[4]. In the context of prototype vehicles designed specifically for energy efficiency competitions, energy efficiency is the primary focus in every aspect of their design. Two parameters that are particularly important and contribute significantly to this efficiency are rolling resistance and maneuvering stability, especially when the vehicle is turning at low to moderate speeds.

Rolling resistance plays a significant role in the total energy consumption of wheeled vehicles, prompting manufacturers to prioritize its reduction for environmental reasons [5] The impact of rolling resistance can be very significant, with estimates showing that rolling resistance can account for up to 30% of friction in certain traffic conditions, meaning that a 50% reduction could result in energy savings of 15% [6]. This reduction directly correlates with a decrease in fuel consumption and CO_2 emissions in conventional vehicles, while in battery-powered electric vehicles, it extends driving range, which is a crucial market differentiator [7], [8]. Proper characterization and mitigation of rolling resistance are essential for optimizing vehicle efficiency and enhancing its competitive advantage in the evolving automotive market [9]. In addition, vehicle maneuverability is also a fundamental aspect in the design and performance evaluation of mobility, as it determines the vehicle's ability to adapt to dynamic environments, maintain stability in extreme conditions, and optimize energy efficiency and operational safety [10]-[12]. These two factors are interrelated and directly influence the vehicle's performance in optimizing energy usage.

Furthermore, rolling resistance affects the amount of energy required to keep the vehicle moving straight on the road surface, while maneuvering stability relates to the vehicle's ability to maintain control and balance during direction changes without compromising efficiency or endangering the driver. At low speeds, where aerodynamic drag is not dominant, rolling resistance and maneuverability stability become the primary determinants in achieving maximum range per unit of energy used [4], [13]. Rolling resistance is the force that resists the forward motion of the wheels due to elastic deformation of the tires and road surface [14]. Although rolling resistance is relatively small compared to aerodynamic forces and inertial forces in conventional high-speed vehicles, rolling resistance is one of the dominant factors in energy consumption in low-speed prototype vehicles such as energy-efficient vehicles [15], [16].

Subsequently, at low speeds, the influence of aerodynamic forces decreases significantly, so rolling resistance contributes more significantly to the total resistance to motion. Therefore, optimizing the parameters that affect rolling resistance is crucial in efforts to improve vehicle energy efficiency [17], [18]. Even a small increase in rolling force can lead to a significant decrease in mileage efficiency per unit energy [19]. One of the wheel geometry parameters that affect rolling resistance and vehicle dynamics during cornering is the camber angle [20]. The camber angle is the slope of the wheel with respect to the vertical line when viewed from the front of the vehicle. Positive camber means the top of the wheel is outward, while negative camber means the top of the wheel is inward [21].

In the world of racing and automotive engineering, negative camber is widely used to increase the lateral force of the tire during a turn, as it maximizes the contact area of the outer side of the tire with the road surface [22]. However, increasing the negative camber angle is also known to cause tire load distribution imbalance, increased rubber deformation, and ultimately increased rolling resistance. In the context of prototype vehicles designed solely for efficiency, choosing the right camber angle is important to maintain a balance between energy efficiency and vehicle control during turns [23]. However, most previous studies have focused on passenger vehicles, racing vehicles, or commercial vehicles, which have very different dimensions, weights, and load distributions compared to lightweight prototype vehicles used in competitions such as the Shell Eco-Marathon or the Kontes Mobil Hemat Energi (KMHE). Empirical data on the effects of camber angle variations on rolling resistance and maneuvering characteristics of prototype lightweight vehicles are limited.

2. Material and Method

2.1 Vehicle Configuration

The object of this research is a bodyless energy-efficient prototype vehicle designed to take part in a fuel-efficient vehicle competition. This vehicle uses a three-wheel configuration, with two front wheels as the steering system and one rear wheel as the main drive wheel, and is designed for one passenger. The vehicle frame is made of mild steel tubular pipes to maintain structural strength at the lowest possible weight. The drive system relies on a 200 cc diesel engine with a maximum power of 6 PK. The vehicle is not equipped with a conventional suspension system, as the main focus is on weight efficiency and structural stability. The front wheel uses a 20-inch diameter Schwalbe Kojak brand slick-type bicycle tire, mounted on a spoke rim. To reduce mechanical friction at the wheel hub, NTN (Japan) type 6003-wheel bearings were used. The braking system consists of hydraulic disc brakes on the front wheels and V-brakes on the rear wheels. The complete specifications of the vehicle are shown in Table 1.

The camber angle of the front wheels is adjustable through a mechanical camber bolt system. This setup allows precise negative camber adjustments to −1°, −2°, and −3°, without modifying the chassis geometry or introducing active suspension elements. Camber values are set and verified using a camber gauge to ensure measurement consistency.

Table 1 *Vehicle specifications*

Parameter	Value
Vehicle type	3-wheel prototype (no body)
Vehicle weight (without body)	62 kg
Vehicle height	609 mm
Vehicle length	2599 mm
Vehicle width	805 mm
Wheelbase	1355 mm
Front track width	734 mm
Engine	200 cc diesel, 6 hp
Front brakes	Hydraulic disc
Rear brake	V-brake
Tire type	20” slick (Schwalbe Kojak)
Rim type	Spoked, 20”
Tire pressure	5.5 bar
Wheel bearings	6003 NTN (Japan)

2.2 Experimental Setup

This research consists of two main types of tests, namely rolling resistance testing in the laboratory and maneuverability testing in the field. Both aims to evaluate the impact of negative camber angle variation on the vehicle's motion efficiency and stability. Meanwhile, the maneuverability test was conducted on a flat asphalt track with a constant turning radius of 9 meters. The aim was to observe the vehicle's motion direction characteristics (understeer, oversteer, or neutral) when turning with different camber angles. During the test, several parameters were controlled so that the results could be compared objectively, as shown in Table 2.

Table 2 *Controlled variables*

Variable	Value/description
Wheel diameter	20 inches
Tire type	Slick (no tread pattern)
Tire pressure	5.5 bar
Maneuvering track radius	9 meters
Driver weight	≥ 50 kg (in accordance with competition rules)
Vehicle weight	62 kg (without body)
Vehicle test speed	25 km/h

2.3 Testing Procedure

2.3.1 Rolling Resistance Test

Rolling resistance tests were conducted for each camber angle variation (-1°, -2°, and -3°). The vehicle was placed on a test rig with a moving belt, and run until it reached a steady speed of 25 km/h. The rolling resistance force (horizontal force required to maintain motion) was measured using a load cell sensor. Measurements were taken three times for each camber angle configuration, and then the average rolling resistance value was calculated.

2.3.2 Maneuverability Tests

Maneuvering tests were conducted on a circular track with a fixed radius of 9 meters. The vehicle was driven by the same driver in all test sessions to minimize subjective variables. The speed was kept constant at about 25 km/h during corner traversal and the steering angle was kept at 12°. Vehicle response is observed directly on a marked and measured track. Then, it is drawn to determine the vehicle's turning trajectory. The observation focuses on the vehicle's behavior tendencies when turning, whether it exhibits oversteer (excessive rear-end widening), understeer (difficulty turning the front end), or neutral (stable and proportional control). Fig. 1 shows the measurement scheme in vehicle maneuverability testing, which aims to identify directional stability characteristics, namely understeer, neutral steer, or oversteer. The test is conducted using a predefined measurement scale, enabling monitoring of the vehicle's position on the track during maneuvers. Based on this data, the actual scale values can be analyzed to determine the vehicle's tendency to respond to changes in direction during turns. The test track is 11 meters wide, with the diameter of the turning circle measured from the center of the circle to the center of the track being 25 meters. The distance between measurement scales is set at 1.57 meters. This method provides a quantitative approach to analyzing vehicle maneuverability characteristics, particularly in observing the effect of camber angle on directional stability when the vehicle is turning.

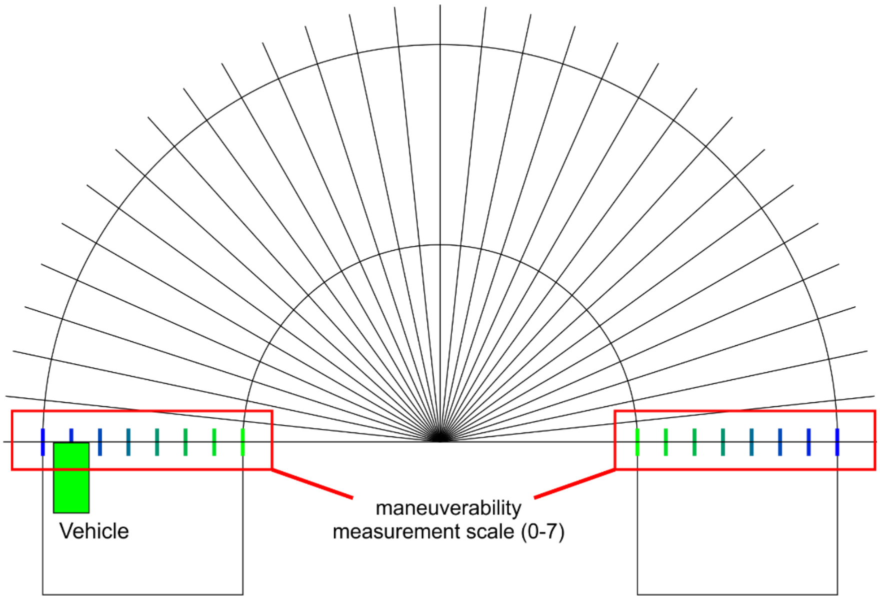

Fig. 1 *Maneuverability measurement scheme*

3. Results and Discussion

3.1 Rolling Resistance Test Results

Rolling resistance testing was conducted for three different negative camber angles (−1°, −2°, and −3°), with five repetitions performed for each configuration. The data collected were averaged to obtain representative values for each camber setting. The summary of average rolling resistance results is presented in Table 3. The data showed an increasing trend in rolling resistance as the negative camber angle increased. At −1°, the lowest rolling resistance was measured at 2.61 N, while at −3°, the highest value reached 3.15 N. Changes of 6.5% from −1° to −2°, and 13.3% from −2° to −3°, resulted in a total increase of about 20.6% between the smallest and largest angles. This increase occurred because the more negative the camber angle became, the more uneven the distribution of tire-to-surface contact pressure was. This triggered greater elastic deformation in the load-bearing part of the tire, resulting in a higher rolling resistance force.

Table 3 *Average rolling resistance at different camber angles*

Negative chamber angle	Rolling resistance (N)
−1°	2.61
−2°	2.78
−3°	3.15

3.2 Maneuverability Test Results

Maneuvering tests were conducted to evaluate the effect of negative camber angle on directional stability and vehicle steering response. The tests were conducted on a track with a fixed turning radius of 9 meters and a speed of 25 km/h. Variations in vehicle behavior were observed directly and through visual documentation for each camber angle. At a camber angle of -1°, the vehicle showed noticeable symptoms of oversteer (see Fig. 2). The tire treads of the vehicle were seen to exit the track with a large turning angle, indicating high steering response but low directional stability. This condition occurs because the tire contact area on the inside of the corner becomes smaller, causing reduced traction on the rear wheels.

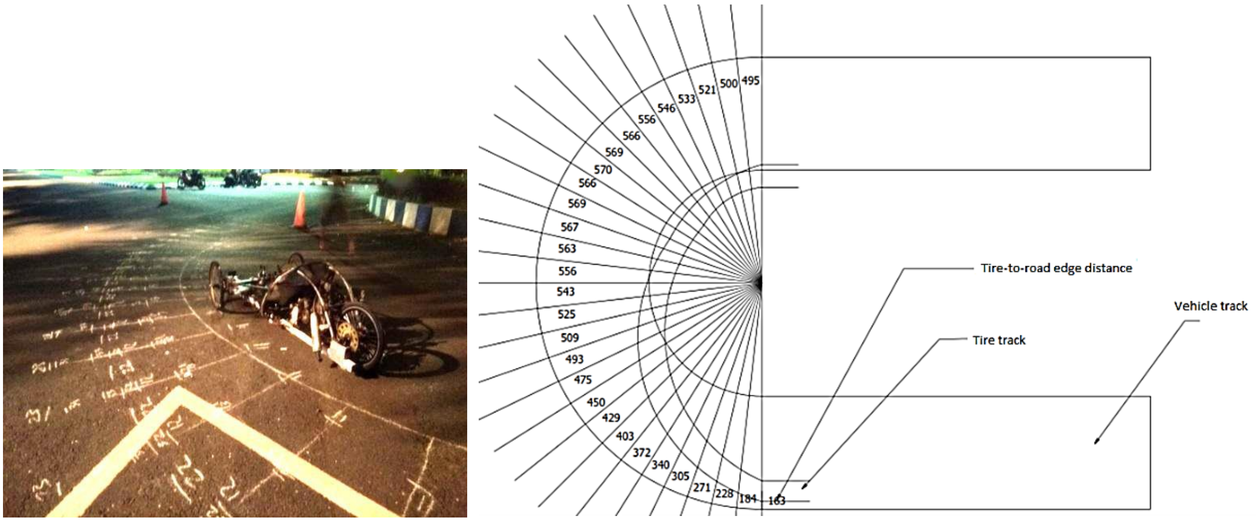

Fig. 2 *Vehicle maneuver at a camber angle of −1°*

When the camber angle is increased to -2°, as shown in Fig. 3, the vehicle characteristics improve. Although oversteer symptoms still appear, the turning behavior becomes more controllable. The tire tread is not too far out of the turning path compared to the -1° camber angle. This is due to the improved lateral load distribution on the wheels during cornering, which results in increased lateral traction on the outer wheel. This improves the stability of the vehicle motion during the turning phase.

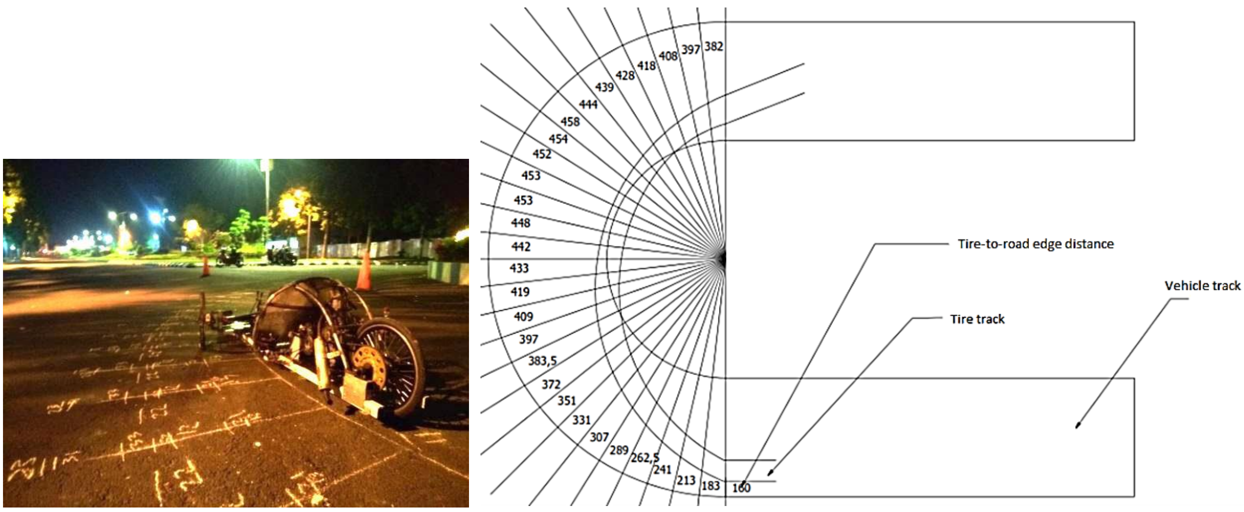

Fig. 3 *Vehicle maneuver at a camber angle of −2°*

At a camber angle of -3°, the vehicle exhibits neutral turning characteristics, as shown in Fig. 4. There is no significant shift between the direction of the front wheels and the overall direction of motion of the vehicle. This indicates that the pressure distribution between the outer and inner sides of the tire becomes more balanced during cornering, resulting in optimal traction conditions. A moderate amount of negative camber can improve the cornering ability of the vehicle by expanding the contact surface of the outer tire against the road when the vehicle is inclined. Directional stability is significantly improved, and drivers report a safer and more comfortable driving experience during cornering.

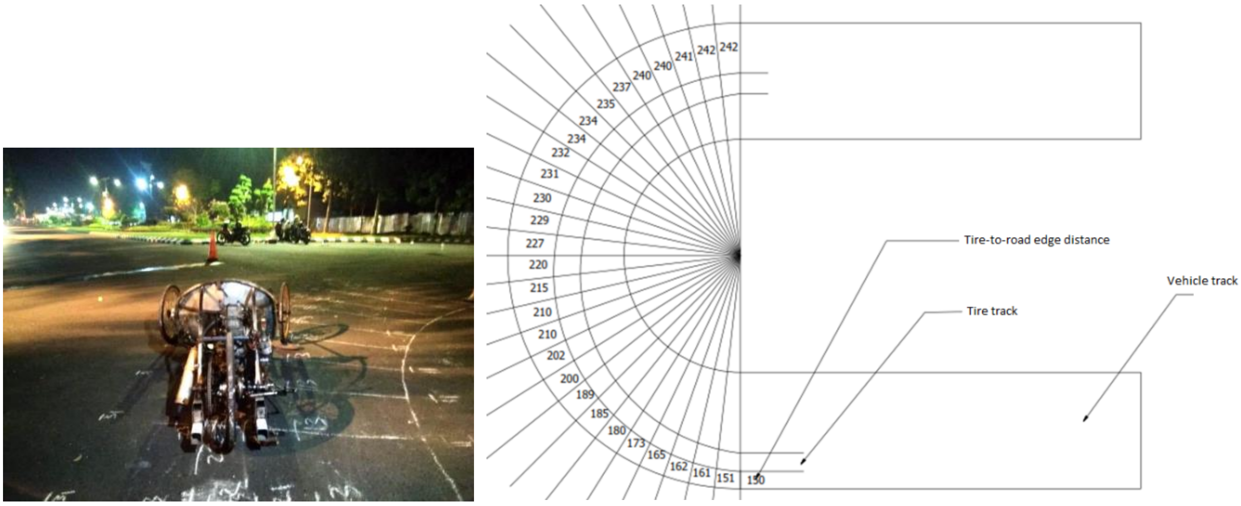

Fig. 4 *Vehicle maneuver at a camber angle of −3°*

From the three configurations, it can be concluded that increasing the negative camber angle has a positive influence on maneuvering stability, especially in reducing the oversteer effect. Negative camber improves the lateral traction performance of the outer tires when cornering. However, increasing the camber angle also has the consequence of increasing the rolling resistance due to uneven lateral loading, so a compromise between energy efficiency and maneuvering performance is needed in the design of energy-efficient vehicles [24]. The rolling resistance and maneuverability test results show a significant trade-off between motion efficiency and control stability. A small camber angle (-1°) provides the best efficiency in terms of rolling resistance, but sacrifices steering stability due to excess steering response leading to oversteer. Conversely, a larger camber angle (-3°) results in better stability, but the rolling resistance increases significantly. For racing conditions or tracks with many corners, a -3° camber angle could be the optimal choice as it prioritizes directional control. On the other hand, for straight tracks or maximum mileage requirements, a -1° angle is more efficient in terms of energy consumption. The -2° camber angle is the middle option-presenting a balance between efficiency and control.

Fig. 5 shows the effect of the chamber angle on rolling resistance and maneuverability. It is known that as the chamber angle becomes more negative (from −1° to −3°), the rolling resistance value increases from 2.61 N to 3.15 N. This increase indicates that more extreme chamber angles cause uneven distribution of tire contact pressure, thereby increasing the friction force between the tire and the road surface. As a result, the vehicle requires more energy to move, which impacts fuel efficiency. On the other hand, maneuverability decreases significantly from 7 to 3 as the negative chamber angle increases. A −1° angle exhibits oversteer characteristics, meaning the vehicle becomes more responsive when turning. However, at a −3° angle, maneuverability decreases drastically, approaching neutral conditions. This decrease is caused by a reduction in the effective angle of the tires in responding to the direction of movement, making the vehicle less agile and harder to control [25].

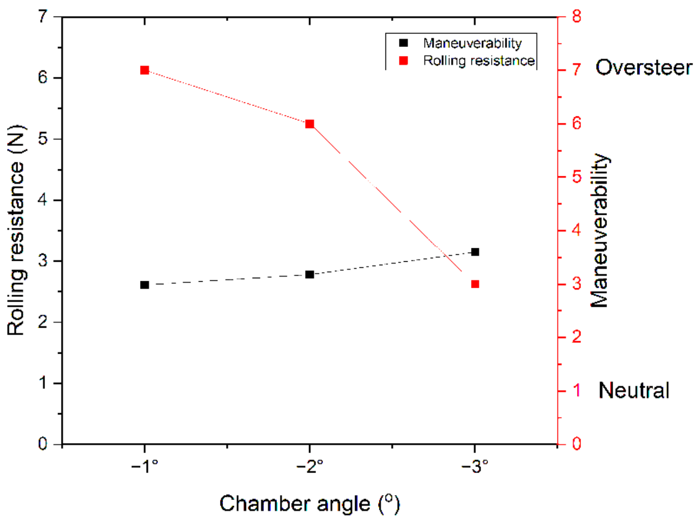

Fig. 5 *Rolling resistance vs maneuverability on chamber angle*

The findings above indicate a trade-off between energy efficiency and vehicle control capabilities. Small chamber angles are more suitable for vehicles that require high agility, such as race cars or urban vehicles [26]. Conversely, large chamber angles can be used in heavy vehicles or those operating on straight terrain, where stability is prioritized over maneuverability [27].

4. Conclusions

This research shows that the variation of negative camber angle has a significant influence on the rolling resistance performance and maneuvering characteristics of the energy-efficient prototype vehicle. The test results show that the larger the negative camber angle applied, the rolling resistance value tends to increase. This is related to the decrease of tire contact area efficiency against the road surface due to the change of lateral load distribution. The -1° camber results in the lowest rolling resistance, but is accompanied by a fairly dominant symptom of oversteer, which can affect the directional stability of the vehicle. In contrast, a -3° camber configuration provides the most stable and neutral maneuvering characteristics. In this condition, the vehicle is able to maintain its direction well during cornering, with no significant oversteer or understeer tendencies. However, this configuration also causes the highest rolling resistance among the three camber angles tested. Thus, the selection of the optimal camber angle must be adjusted to the characteristics of the track and the intended use of the vehicle. For straight tracks and minimal maneuvering, a camber of -1° is recommended. Meanwhile, on technical tracks with many bends, a camber of -3° provides advantages in terms of driving control and safety.

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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****: Rika Dwi Hidayatul Qoryah, Rahmad Fajar Zaini, Haidzar Nurdiansyah;* ***data collection****: Rahmad Fajar Zaini;* ***analysis and interpretation of results****: M. Fahrur Rozy Hentihu, Haidzar Nurdiansyah, Rika Dwi Hidayatul Qoryah, Andi Sanata, Santoso Mulyadi;* ***manuscript preparation****: Haidzar Nurdiansyah, Rika Dwi Hidayatul Qoryah, Rahmad Fajar Zaini. All authors reviewed the results and approved the final version of the manuscript.*

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