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DESIGN AND PERFORMANCE EVALUATION OF TRANSPORTER WITH SCISSOR LIFT MECHANISM FOR OIL PALM FRESH FRUIT BUNCH

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Available oil palm fresh fruit bunch transporters, such as wheelbarrows, tracked machines, and tractors with trailers, present notable limitations in terms of load capacity, accessibility, and causing soil compaction. Additionally, most existing machines lack the capability for direct unloading into collection bins. This research aimed to design and develop a wheeled oil palm fresh fruit bunch transporter equipped with a scissor lift mechanism to facilitate direct unloading, thereby addressing the limitations. Based on the design analysis, the transporter could operate effectively on steep mineral terrains and low ground pressure peat soils, with a load capacity of up to 750 kg. Design evaluations confirmed that the scissor lift mechanism could raise maximum loads and unload them directly into collection truck bins. The average field working capacity of the transporter was found to be 15 $t \cdot day^{-1}$. The development of this transporter represents a significant contribution in medium-sized fresh fruit bunch evacuation systems, combining operational efficiency with minimal soil compaction.

Keywords: agriculture transporter; oil palm fresh fruit bunch evacuation; scissor lift mechanism

Oil palm, the world's most productive oil crop (Goh et al., 2017), grows in diverse conditions, including mineral and peat soils across flat to steep terrains. Although slopes under 13.5° are recommended for mineral soils (Firmansyah, 2014), plantations are commonly found on undulating land with gradients of 10–20° (Rhebergen et al., 2016). Approximately 1.7 million hectares of Indonesia's plantations are located on peat soils, which are noted for low bearing capacity, shear strength, and high compressibility (Islam and Hashim, 2009; Hua et al., 2016; Dewi et al., 2020).

Harvesting and transport are key operations in plantation management, accounting for a significant share of labour costs (Shuib et al., 2020) which are around 15% of fresh fruit bunch (FFB) production expenses (Henson, 2012). A critical task in FFB transport involves collecting and evacuating the bunches from the field to collection or container bins, which are subsequently hauled to the mill by truck.

Various equipment types have been introduced for this activity, including manual wheelbarrows, wheeled and tracked transporters, and tractors with trailers. Machine selection typically depends on plantation topography and cost considerations, with smallholders favouring compact tools and larger estates opting for high-capacity machinery.

Awaludin et al. (2015) highlighted that wheelbarrow-based FFB evacuation is labour-intensive and low in capacity, increasing the risk of musculoskeletal disorders (Nawik et al., 2015). Although tracked machines perform well in wet conditions, they are relatively slow (Shuib and Hitam, 2003). Tractors with trailers, while offering higher capacity, have been associated with soil compaction, which negatively affects palm root development (Shuib et al., 2020). Their operation is also typically restricted to firm, flat, or gently undulating terrain (Shuib and Hitam, 2003).

Tracked machines are commonly employed for harvesting and transporting oil palm on steep mineral terrains (Matthies et al., 2003). Meanwhile, wheeled transporters designed with low ground pressure have been introduced to enable operation on both mineral and peat soils. This feature is crucial for peatland applications due to its inherently low bearing capacity (Agus and Subiksa, 2008; Aljawadi et al., 2021). Consequently, specialised agricultural machinery must be engineered to maintain ground pressure below the allowable threshold of 100 kPa to operate effectively on peat or similarly soft soils (Omar and Jaafar, 2000; Shenbagavalli et al., 2017).

To address this need, Shuib and Hitam (2003) developed a six-wheel-drive transporter powered by a 23 HP water-cooled diesel engine. Subsequently, Shuib et al. (2020) enhanced the design by incorporating a larger 45.3 HP engine and a four-wheel steering system. The respective weights without loads of these machines were 1500 kg and 2750 kg, and both achieved productivity levels ranging from 20 to 28 $t.day^{-1}$. These transporters were capable of direct loading into container bins using grabber attachments. However, their comparatively high price makes them less affordable for small-scale farmers. Additionally, Mojžiš et al. (2024) reported that heavy machinery should not enter the soil as it will cause excessive compaction at increased soil moisture content.

In response to cost and design concerns, researchers have proposed lighter transport designs suitable for general goods transport. Hitam and Deraman (2001) introduced a powered wheelbarrow driven by a 4 HP petrol engine, with a carrying capacity of 300 kg and daily productivity of 4–5 tonnes. Similarly, Deraman et al. (2006) developed a compact transporter featuring a single chassis and a double sprocket chain transmission system, offering a comparable payload of 300 kg and a productivity rate of 5–7 t·day^{-1}. Nevertheless, these machines lack the capability for direct unloading into container bins.

Based on these considerations, a wheeled transporter with higher carrying capacity and able to perform direct unloading into a container bin needed to be designed. For this purpose, a six-wheel drive transporter with a carrying capacity of 750 kg and employed scissor lift mechanism was developed.

Material and methods

Material

The materials for developing the prototype of the transporter, such as construction steel, wheels, scissor lift mechanism, hydraulic systems, engine and transmission components, were selected based on the strength of the materials, mechanical properties, machinability, availability, and economic considerations (Fadeyibi and Ajao, 2020).

Design criteria

The design criteria for the wheeled transporter are as follows:

1. capable of operating on peat soil with a maximum ground pressure of 100 kPa;
2. stable on uneven terrain, with suitable centre of gravity and tipping angle;
3. able to carry 750 kg of FFB;
4. equipped with a hydraulic scissor lift for direct unloading into a collection bin.

Design analysis

Ability to operate on peat soil

The transporter was designed to operate on peat soil, which requires low ground pressure (GP); therefore, the theoretical GP must remain below 100 kPa (Omar and Jaafar, 2000; Shenbagavalli et al., 2017). GP was determined as the ratio of the vehicle's total loaded weight (1997.6 kg) to its contact surface area (Poršinsky et al., 2012). Calculations were performed under full load for both four-wheel and six-wheel drive configurations, assuming a wheel sinkage of 30 mm. The tire inflation pressure used in the assumption was 230 kPa. Under this condition, contact dimensions were estimated as $a = 216$ mm and $b = 276$ mm, as shown in Fig. 1.

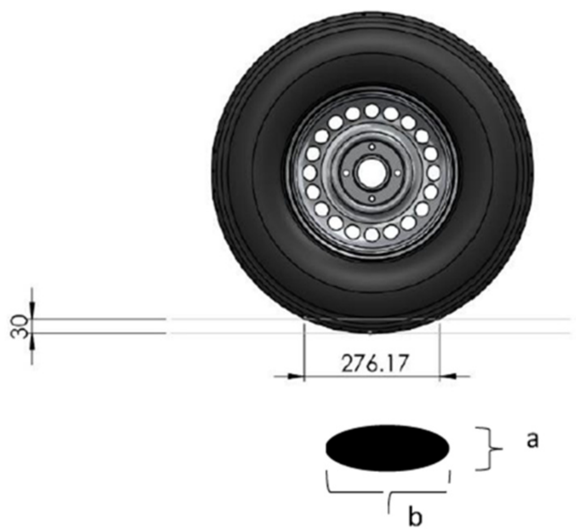

Fig. 1 Contact surface area of the wheel

GP was calculated using Eq. (1):

$$GP = \frac{G}{0.78 \times a \times b \times n} \tag{1}$$

where: *GP* – ground pressure (kPa); *G* – vehicle weight at full load (kN); *a* – width of the contact area (mm); *b* – length of the contact area (mm); *n* – number of wheels

Ability to operate on undulating terrain

The transporter was required to operate on undulating terrain typical of plantation environments, with capability on slopes up to 20°. To assess its stability, the centre of gravity (CoG) position and maximum tipping angle were calculated. The CoG position of the transporter was determined by dividing the total moments acting on each transporter's component with the total weight of the transporter (Eqs (2) and (3)) (Meriam and Kraige, 2002). The CoG was expressed in an (x, y) coordinate system, indicating longitudinal and lateral distances relative to the centre of the rear wheel as the reference point. The CoG was calculated for both raised and normal bucket positions under no-load and full-load conditions.

$$x = \frac{\sum_{i=1}^{n} M_n \times X_n}{\sum_{i=1}^{n} M_n} \tag{2}$$

$$y = \frac{\sum_{i=1}^{n} M_n \times Y_n}{\sum_{i=1}^{n} M_n} \tag{3}$$

where: M_n – mass of each component (kg); x_n – longitudinal distance from the centre of each component to the centre of the rear wheel (mm); y_n – lateral distance from the centre of each component to the centre of the rear wheel (mm); x – CoG of the transporter at x-axis (mm); y – CoG of the transporter at y-axis (mm)

Afterwards, the maximum tipping angle was calculated using a trigonometric approach based on the CoG at full load (Fig. 2; Eqs (4) and (5)) (Royal Academy of Engineering, 2023) as well as considering the friction force of the different types of roads (Fig. 3; Eq. (6)).

$$\theta_1 = 90° - \tan^{-1}\left(\frac{y}{x_1}\right) \tag{4}$$

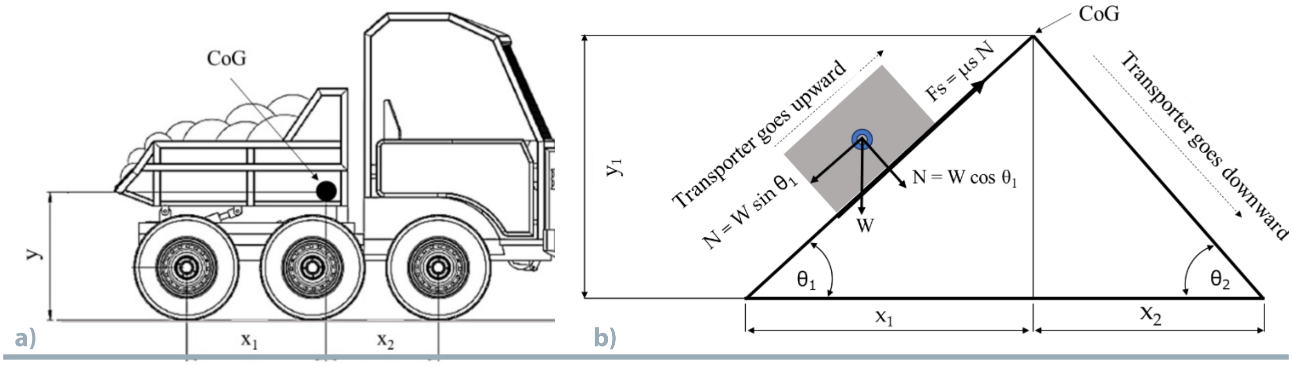

Fig. 2 Schematic diagram to calculate tipping angles: a) Diagram of the transporter; b) Trigonometric illustration

$$\theta_2 = 90° - \tan^{-1}\left(\frac{y}{x_2}\right) \qquad (5)$$

where: θ_1 – tipping angle at upward position (°); x_1 – horizontal distance between the rear axle and CoG (mm); y – vertical distance between the bottom edge of rear wheel and CoG (mm); θ_2 – tipping angle at downward position (°); x_2 – horizontal distance between the front axle and CoG (mm)

$$\theta_f = \tan^{-1} \mu_s \qquad (6)$$

where: θ_f – tipping angle based on the type of roads (°); μ_s – friction coefficient of the road

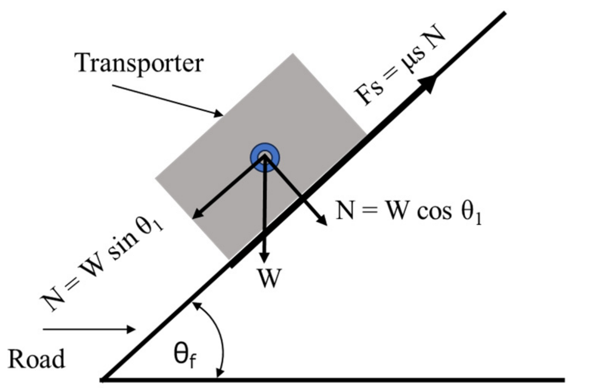

Fig. 3 Schematic diagram to calculate tipping angles based on different types of roads

Ability for direct unloading with hydraulic scissor lift

The hydraulic scissor lift was designed to raise and tip a bucket carrying 750 kg of FFB, exceeding the container bin height (>1400 mm) and ensuring a tipping angle greater than the FFB's angle of repose (>20°). The bucket was set to tip at 25.1°, based on a measured FFB angle of repose of 20°, aligning with values reported by Owolarafe et al. (2007) and Morakinyo and Bamgboye (2015), who found dynamic angles ranging from 18.59° to 26.29° on mild steel.

Bucket movement was powered by a hydraulic scissor lift actuator with a 90 mm bore diameter, 45 mm rod diameter, 600 mm initial length, and 300 mm stroke. For unloading, a hydraulic dumper actuator 60 mm bore diameter, 35 mm rod diameter, 460 mm initial length, and 200 mm stroke was used. Both actuators were operated via two control valve handles located in the cabin. A 55 lpm Honor gear pump with an operating pressure of 120 bar was used to operate the system.

Construction detailed drawing and general description

The transporter was built with total length, width, and height 3035 mm, 1693 mm, and 2038 mm, respectively. Figure 4 presents the detailed parts of the transporter, while Fig. 5 illustrates the parts of the scissor lift.

Power was supplied by an 11.5 HP water-cooled diesel engine. A gear-chain gearbox with a maximum transmission

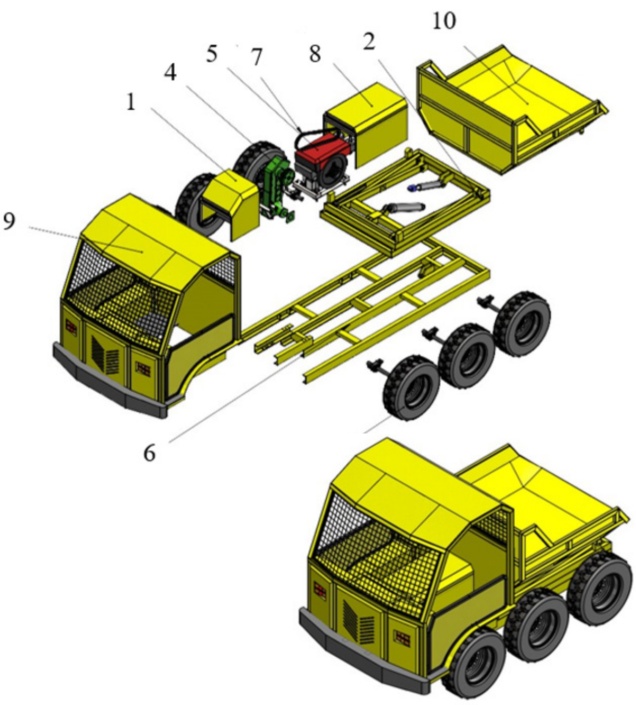

Fig. 4 General description of the transporter
(1) gearbox cover; (2) scissor lift mechanism for unloading the load; (3) six wheel-drive of tires; (4) gearbox and mounting; (5) engine and mounting; (6) chassis as the main structure forms the basis for the rest all components of the transporter; (7) belt connecting engine pulley to gearbox pulley; (8) engine cover; (9) cabin as space for operator and co-operator to control the operation of the transporter; (10) bucket to carry FFB

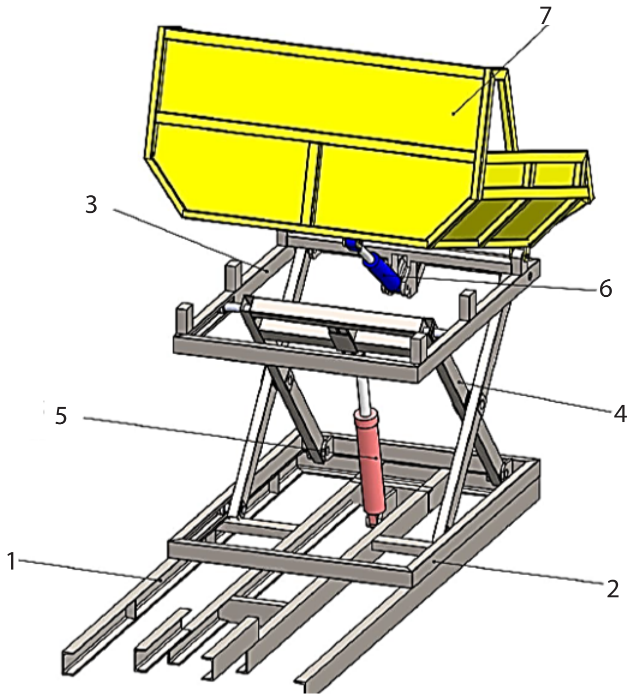

Fig. 5 General description of the scissor lift and dumping mechanism
(1) chassis as the base of the (2) bottom frame of scissor lift; (3) upper frame of scissor lift; (4) scissor lift arm; (5) hydraulic cylinder for scissor lift mechanism to lift and down the bucket (hydraulic scissor lift); (6) hydraulic cylinder for dumping or unloading FFB in the bucket (hydraulic dumper); (7) bucket

ratio of 24 : 1 was used, with power transmitted from the engine to the gearbox via belt and pulley, and from the gearbox to the wheel shaft via chains and sprockets. Hydraulic cylinder movement was manually controlled by the operator using a control valve located in the cabin.

Performance evaluation

Instrument test and performance analysis

Instruments used in this research were stopwatch, distance meter, sling, load cell and handy strain meter, tachometer, and laptop. Each performance test parameter of the transporter was conducted in three replications. The results from these repetitions were then averaged to obtain representative values for analysis and comparison. Graphical analysis was utilised to visually compare and interpret the performance results.

Drawbar performance

The drawbar performance test was conducted with three different vehicle conditions:

- Six-wheels drive (6 × 6 WD): The vehicle was equipped with six wheels – two on the front axle, two on the middle axle, and two on the rear axle – all of which were driven wheels.
- Four-wheels drive (4 × 4 WD): The vehicle was equipped with four wheels by removing two wheels on the middle axle, and all four wheels were driven wheels.
- Two-wheels drive (4 × 2 WD): The vehicle was equipped with four wheels by removing two wheels on the middle axle, and only two front wheels were driven wheels (Fig. 6).

This setup can be done by changing the arrangement of transmission chain to the wheel axles. The drawbar performance was tested under three conditions of driven wheels: six-wheels drive (6 × 6 WD), four-wheels drive (4 × 4WD), and two-wheels drive (4 × 2 WD).

The tests were conducted low transmission F2 with an engine speed of 2200 rpm. A 30 HP four-wheel tractor applied five levels of drawbar load, with drawbar pull measured using a Kyowa LTR-S-50KNSA1 load cell and recorded in a handy strain meter of Kyowa UCAM-1A. The test was carried out on a grassy surface, and the setup is shown in Fig. 7.

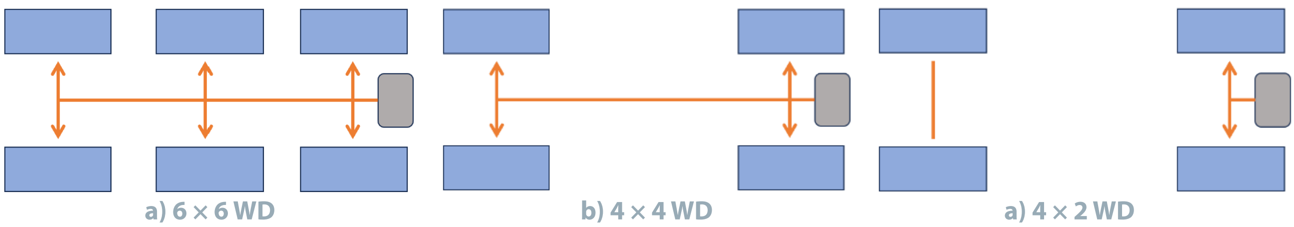

Fig. 6 Vehicle set up for drawbar performance test

Fig. 7 Drawbar test setup

During the experiment, the moisture content of the grassy surface was identified. Based on the gravimetric moisture content test, the moisture content of the grassy surface ranged from 17.9% to 28.1%.

Steering performance

Steering performance was assessed by measuring drive axle torque and turning radius. Torque tests were conducted for both 6 × 6 WD and 4 × 4 WD configurations on asphalt, concrete, and soil surfaces. A strain gauge mounted on the gearbox drive axle captured axle torque data, which was amplified using a Minebea DAS-406B strain amplifier and Kyowa DB-120A bridge box. The output from the strain amplifier was connected to a Minilab 1008 USB data acquisition (DAQ) and recorded by PC. The instrumentation setup is shown in Fig. 8.

The turning radius was determined as the radius of the outer wheel tread during a 180° U-turn, measured with a tape measure (Fig. 9). The U-turn was executed by driving one side of the wheel while fully braking the other.

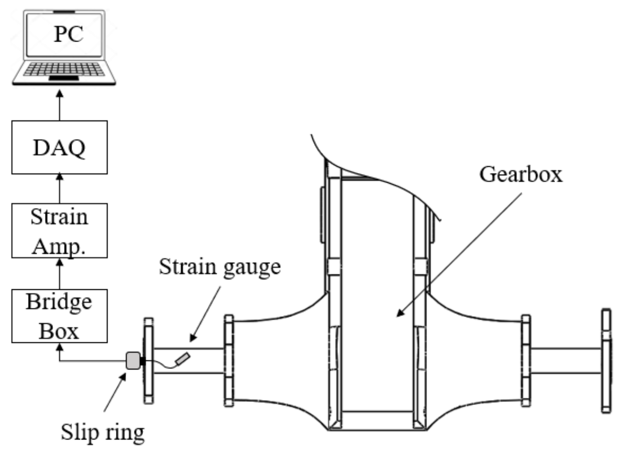

Fig. 8 Axle torque setup for steering performance test

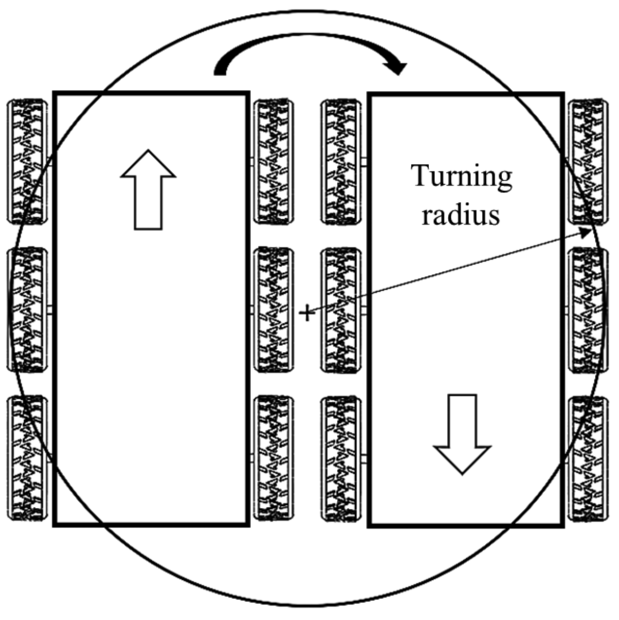

Fig. 9 Measurement of turning radius

Results and discussion

Design result

Ability to operate on peat soil

A key design consideration was ensuring the transporter could operate on peat soil, which requires low ground pressure, and on mineral soil with undulating and steep terrain. Thus, a specially designed wheeled transporter was developed. The maximum bearing capacity on soft peat soil is 100 kPa (The Engineering Toolbox, 2014).

The transporter used commercially available off-road mud tires (27/8.5 R13). Based on Eq. (1), the calculated maximum ground pressure was 104.13 kPa for the 4 × 4 WD and 69.42 kPa for the 6 × 6 WD. Since the allowable bearing capacity on peat soil is 100 kPa, only the 6 × 6 WD met the requirement, with a GP of 69.42 kPa. Its lower ground pressure resulted from even load distribution across six wheels. Furthermore, the six-wheel drive system reduced slippage, which is common on peat and wet mineral soils.

Ability to operate in undulating terrain

Following the selection of the 6 × 6 WD configuration, stability was assessed to ensure suitability for steep mineral soil terrain. The transporter was required to safely traverse slopes up to 20° without tipping. To meet this criterion, the tipping angle was evaluated based on the CoG and road conditions. Using Eqs (2) and (3), the CoG was calculated for both normal and unloading positions, as illustrated in Fig. 10. The normal position reflects the transporter carrying a full or empty load, while the unloading position corresponds to tipping the bucket at an angle of 25.1° during unloading the FFB.

The maximum tipping angle refers to the steepest incline the transporter can traverse without tipping. Based on the CoG coordinates (Fig. 10) and Eqs (4) and (5), the maximum tipping angles for upward, downward, and lateral positions are presented in Table 1.

Table 1 presents the maximum slope angles at which the 6 × 6 WD transporter equipped with a hydraulic scissor lift system can operate effectively under both unloaded and fully loaded conditions. These variations highlight the significant influence of payload on the transporter's stability and manoeuvrability, particularly on steep or uneven terrain. To maintain safe and efficient operation, the transporter should not be deployed on slopes that exceed the specified limits corresponding to its load condition.

To ensure the transporter could operate on various road types, especially wet and dry surfaces, the maximum tipping angles on asphalt and soil roads were also calculated, taking frictional forces into account (Table 2). As shown in Tables 1 and 2, all tipping angles exceeded the design criterion of a 20° slope, indicating that the transporter is expected to maintain good stability.

However, the power engine limits the maximum tipping angle at which this transporter can operate. With the available engine power of 11.5 HP (8.76 kW) and for

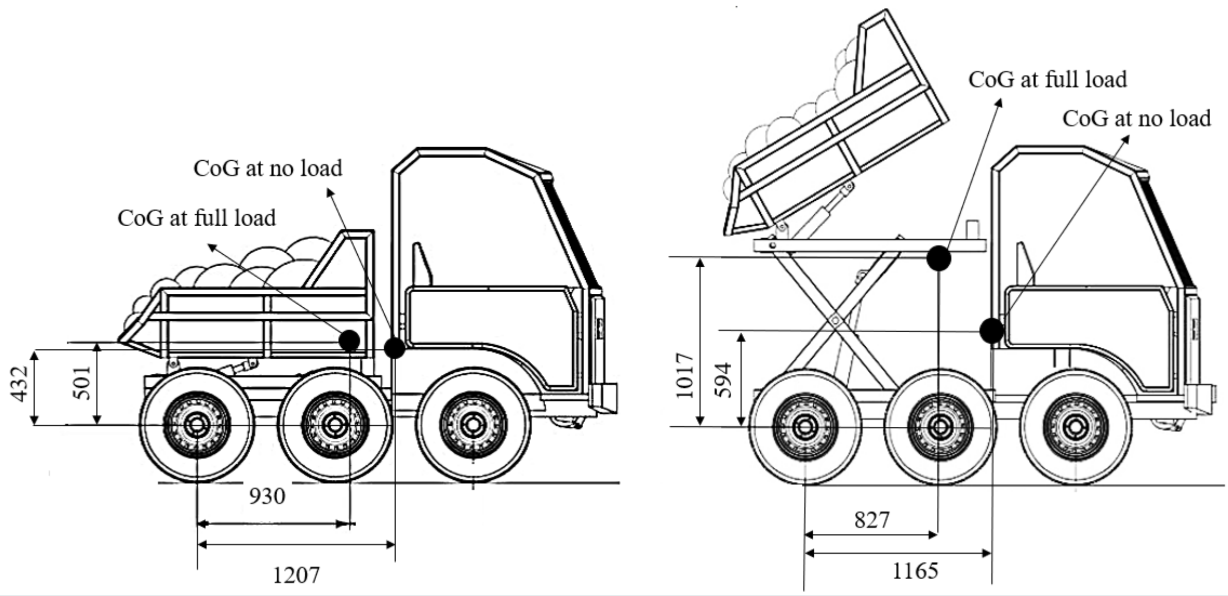

Fig. 10 Location of CoG at normal position (left) and unloading position (right)

slopes greater than 20° under full load conditions, the design analysis indicates that the transporter remains operational on inclines up to 30° by using Gear F1 in the low transmission range. At this setting, the required power is 5.57 kW, which corresponds to approximately 63.6% of the engine's total output. This indicates that the transporter operates within a safe power margin, making it suitable for use on such slopes under the specified conditions.

Transporter performance

Soil moisture content is a critical factor that can significantly affect the performance of off-road vehicles such as the 6 × 6 WD transporter. Higher moisture levels generally reduce soil shear strength and increase the risk of slippage and soil deformation under load. The moisture content tends to represent the field conditions in oil palm plantations, particularly in peatland or post-rain scenarios. These conditions are important to consider when evaluating the transporter's capability, as they can influence wheel slip behaviour, ground contact stability, and turning performance. Therefore, the results obtained under these soil conditions provide a realistic representation of the transporter's expected field performance.

Speed

The performance test showed forward speeds of 0.38 $m\cdot s^{-1}$ (Gear F1), 0.75 $m\cdot s^{-1}$ (Gear F2), and 2.58 $m\cdot s^{-1}$ (Gear F3), with a reverse speed of 0.27 $m\cdot s^{-1}$. These speeds fall within the suitable range for in-field machinery operations in oil palm plantations, where terrain conditions are generally poor.

Tractive performance

As mentioned in the methods section, the vehicle was designed with three-wheel axles (front, middle, and rear), where the power transmission can be adjusted for individual wheels by arrangement of transmission chain to each wheel. For evaluating the tractive performance, the vehicle was set up with either six or four wheels by removing the two wheels on the middle axle, and driven wheels were set by arranging combination of the transmission chains to each wheel.

The tractive performance, showing the relationship between drawbar power and drawbar pull at varying wheel slips, is presented in Fig. 11(a) and (b). The results indicate that the 6 × 6 WD transporter achieved superior tractive performance compared to the 4 × 4 WD and 4 × 2 WD

Table 1 Tipping angle based on CoG

Parameter	Upward	Downward	Lateral
No load	57°	31.11°	44.92°
Full load	47.48°	41.33°	42.51°

Table 2 Tipping angle at different types of roads

Parameter	Asphalt (dry)	Asphalt (wet)	Soil (dry)	Soil (wet)
Friction coefficient	0.75	0.60	0.50	0.65
Tipping angle (°)	36.87	30.96	26.56	33.02

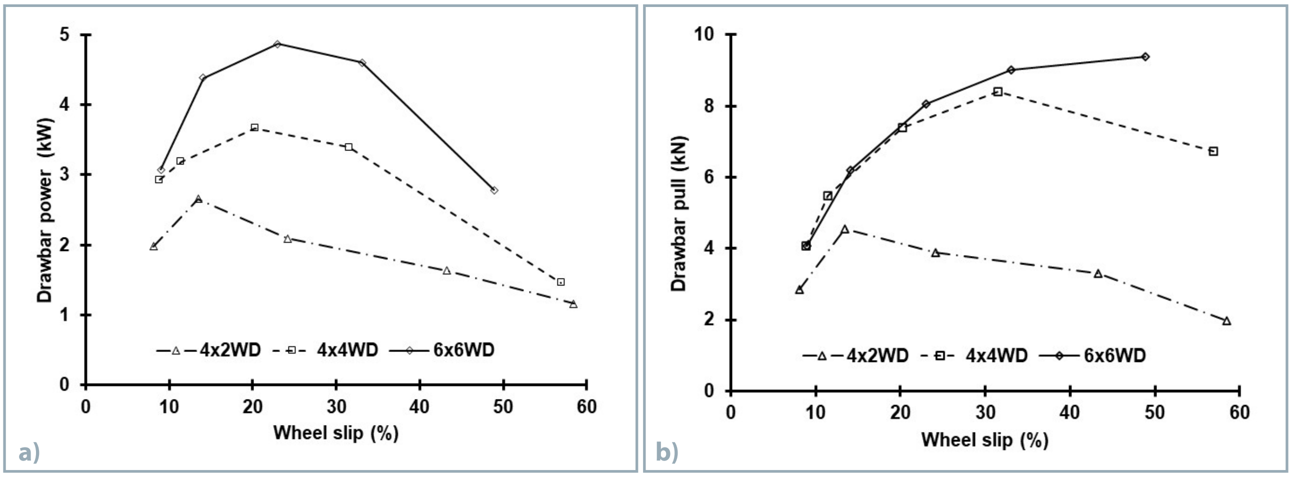

Fig. 11 Tractive performance graphs

configurations. The 6 × 6 WD achieved the highest drawbar pull of 9.41 kN at 48.9% wheel slip and the maximum drawbar power of 4.87 kW at 23.0% slip.

Turning performance

The average turning radius for different wheel configurations is presented in Table 3. The 6 × 6 WD transporter demonstrated the smallest turning radius, attributed to its three driven wheels providing greater tractive force during turning. In contrast, the 4 × 2 WD configuration had the largest turning radius due to limited traction from a single driven wheel, reducing its turning capability.

Table 3 compares the turning torque of 6 × 6 WD and 4 × 4 WD transporters on asphalt and soil surfaces. The results show that the 6 × 6 WD configuration produced significantly higher axle torque than the 4 × 4 WD, supporting its smaller turning radius and enhanced manoeuvrability.

Working capacity

The field test of the scissor lift performance is shown in Fig. 12. In this test, the operator pulled the hydraulic scissor lift actuator handle to its maximum position, followed by pushing the hydraulic dumper actuator, allowing the lift to reach its full height and unload the FFB into the container bin. The lifting and dumping processes took 16 and 10 seconds, respectively, totalling 26 seconds.

Fig. 12 Unloading the FFB into collection truck bin by using scissor lift

The field working capacity of the 6 × 6 WD transporter was recorded at 1.6–2.1 t.h^{-1}* depending on the maturity density and weight of the FFB. Compared to secondary data on other FFB transporters, the results indicate that this vehicle can achieve up to 15 times higher productivity than conventional manual wheelbarrows (Table 4).

The 6 × 6 WD transporter effectively addresses the need for a versatile FFB transport solution capable of operating across diverse terrains, including both mineral soils and

Table 3 Turning radius and turning torque performance

Parameter	6 × 6 WD	4 × 4 WD	4 × 2 WD
Average turning radius (m)	4.53	5.59	11.94
Average torque (Nm), on asphalt	1363.9	1079.5	–
Average torque (Nm), on soil	1106.5	1025.3	–

Table 4 Productivity (t·h^{-1}) of FFB transporter and references

6 × 6 WD transporter	Conventional wheelbarrow[1]	Motorised wheelbarrow[1]	Mechanical buffalo[2]	Compact transporter[2]
1.87	0.15	0.56	1.06	0.75

1 – Hitam and Deraman, 2001; 2 – Deraman, et al., 2006; * 8 hours per working day

peatlands, while maintaining high productivity. Its capability for direct unloading into collection bins allows it to compete with grabber-type machines, yet with significantly lower ground pressure. This characteristic reduces the risk of damaging oil palm crops during operation.

In addition to its low ground pressure, the 6 × 6 WD transporter provides good traction and is capable of functioning on steep slopes exceeding 20°. The use of six drive wheels enhances traction and further reduces ground pressure compared to the mechanical buffalo (a three-wheeled transporter), making it particularly suitable for plantation environments with soft or uneven ground conditions. However, the 8.76 kW engine power limits the maximum steep slopes to 30o.

In terms of productivity, the 6 × 6 WD transporter significantly increases both conventional and motorised wheelbarrows, as well as compact transporters. This enhanced performance is largely attributed to its higher payload capacity of 750 kg, compared to 300 kg, respectively, and its ability to directly unloading into collection bins. This design eliminates the need for separate loading and unloading operations, thereby reducing cycle times and increasing overall efficiency.

Since the direct unloading feature not only improves operational efficiency but also contributes to preserving the quality of FFB by minimising delays and handling during the unloading process, a study regarding the quality of FFB should be carried out to justify the advantage of this transporter to FFB quality.

One of the key practical advantages of this transporter is its potential for lower operational costs compared to conventional systems commonly used in Indonesian oil palm plantations, such as manual wheelbarrows. This cost efficiency is achieved through the implementation of mechanisation and a higher carrying capacity, allowing for greater volume of fresh fruit bunches to be transported per trip. As a result, overall work output is increased, reducing the need for repetitive manual labour and improving efficiency in field operations.

In terms of environmental benefits, the transporter is designed to operate on peat and soft soils with minimal ground pressure. Its wide tire profile and even weight distribution help reduce soil compaction – a common issue with heavier or rigid-frame vehicles. Reduced compaction is crucial in oil palm plantations, as excessive soil pressure can damage root systems, inhibit water and nutrient absorption, and ultimately suppress plant growth. By minimising these adverse effects, the transporter supports more sustainable agricultural practices and long-term soil health.

Safety considerations have also been integrated into the machine's design, particularly through ergonomic principles that enhance operator comfort and reduce physical strain. These ergonomic improvements not only increase operator productivity but also help prevent fatigue-related accidents, thus promoting a safer working environment.

For future developments, one potential improvement to the transporter system involves replacing the current chain-sprocket transmission mechanism with a fully hydraulic transmission system. The existing chain-sprocket setup, while relatively simple and cost-effective, poses limitations in terms of torque transmission efficiency, maintenance requirements, and control precision – particularly in demanding field conditions such as peatlands and undulating terrains. Upgrading the transmission to a fully hydraulic system will enhance the performance and control as well as aligns with the trend toward more durable, operator-friendly, and low-maintenance machinery in off-road transport applications.

Conclusion

The objective of this research was achieved through the development of a 6 × 6 WD FFB transporter prototype. Design analysis confirmed that the transporter can operate effectively on both peat and mineral soils, typical of palm oil plantations. A key advantage of the design is its ability to evacuate FFB from the field and directly unload the FFB to the collection truck bin. With a load capacity of up to 750 kg and an average productivity of 15 $t.day^{-1}$, the transporter demonstrated up to a 15-fold increase in working capacity compared to conventional manual wheelbarrows.

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