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Traction Performance Analysis of Three Models of Traction Device for Muddy Soil

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ABSTRACT

Muddy paddy fields cause the traction performance of conventional traction devices to be suboptimal. Research on the analysis of traction performance on various traction devices is needed. The objective of this research is to design, analyze traction performance, and determine the best design from three models of traction devices, i.e. 1) track type, 2) pedal type, and 3) screw type on deep muddy soil. The research method used in this study is experimental, testing the traction performance of the three models at soil bin in muddy soil conditions at 25 cm deep. The parameters measured during the traction performance test are slip, sinkage, and traction efficiency. The treatment used in this study is a vertical load ranging from 93.2 N to 222.7 N. The best traction device design was chosen using the Analytical Hierarchy Process method. The results show that the traction performance achieved the highest score in determining the best traction device design, with a score of 0.78 (track) for the minimum load, 0.83 (track) for the medium load, and 0.87 (track) for the maximum load. Therefore, the track design was ideal, scoring the highest across all parameters.

1. INTRODUCTION

Agricultural mechanization is one approach to increasing productivity and work efficiency in farming (Karimah *et al*., 2020). The success of agricultural operations, especially those involving soil cultivation, heavily depends on the type of equipment and machinery used, such as tractors. According to Suyuti (2015), the two-wheel tractor is commonly used to pull soil cultivation devices like ploughs, allowing for more uniform and faster soil processing than conventional devices like hoes (Azzuhra *et al*., 2019). As technology advances rapidly, all human activities can be done more easily and quickly. Technological progress in agriculture is crucial in increasing production yields (Kamal *et al*., 2021).

The two-wheel tractor is used for transportation and wetland cultivation, such as in rice fields. The practical and efficient use of two-wheel tractors has become a favorite among Indonesian farmers, especially in the Java region, where most farmers have relatively small size of land (Handayani, 2017). Rice field soils in Indonesia typically have very high water content and deep mud layers (Taufiq *et al*., 2017). Rice fields in Indonesia even have a depth of more than 20 cm. Using a two-wheel tractor for cultivating muddy paddy fields with a depth of more than 20 cm still results in high slippage, thus requiring traction devices capable of addressing this issue. Because the performance of agricultural mechanization devices and the resulting cultivation depends heavily on the soil's soil mechanical properties (Tagar *et al*., 2015), several types of traction devices, such as pedal-driven tractors, hydro tillers, track-type tractors, and screw-type vehicles, can be operated in these conditions.

Research on track-type traction devices by Tamam (2021) and Iswandana (2022) has demonstrated favorable performance in deep muddy soil. Tests on track-type traction devices have shown traction efficiencies of 68.46% when pulling loads of 9.5 kg (Taufiq *et al*., 2022). According to Jiang *et al*. (2021), boat-type tractors designed explicitly for deep, muddy rice fields have been used since the 1970s. These floating tractors are effective in rice fields, causing minimal soil disruption and less damage to the complex soil layers, and offer higher soil processing efficiency.

Screw type traction device can also be operated in muddy soil due to their high maneuverability in soft terrain, such as snow, mud, and swamps. These vehicles can easily overcome difficult conditions without getting stuck (Koshurina *et al*., 2016). Some screw type traction device with amphibious designs can even operate on water, with helix-shaped propellers functioning similarly to boat propellers when submerged (He & Long, 2018). However, boat-type and screw-type traction device performance should be evaluated under rice field mud conditions. Therefore, this study aims to design pedal-type and screw-type traction devices in a model prototype and evaluate their traction performance. The performance of the pedal and screw traction devices will be compared to that of the track-type device, which has been previously studied, to determine which device has the best traction performance. The best designs have low slip values, low sinkage, and high traction efficiency. This traction device can be used as a tractor wheel which is able to overcome high slip and sinking conditions for operation in deep mud fields. The traction device with the best performance will be recommended for future use in soil cultivation, plant maintenance, and rice or other crop harvesting machinery, especially in deep, muddy soil conditions.

2. MATERIALS AND METHODS

2.1. Design and Construction of Traction Device Models

The traction device models were designed for performance testing and comparison as it was tested in a soil bin. The pedal and screw traction devices were designed based on previous research but scaled down to 1:4 to fit the soil bin dimensions. The pedal-type traction device was based on the dimensions of the Agropro brand boat tractor, and the screw-type traction design is referenced to the research by Bouchard *et al.* (2016) and Strizhak *et al.* (2019). Three types of traction devices were constructed: track-type, pedal-type, and screw-type. These devices were mounted on a frame that allowed vertical and horizontal movement and installed on the soil bin. The designs of the three traction devices are shown in Figure 1.

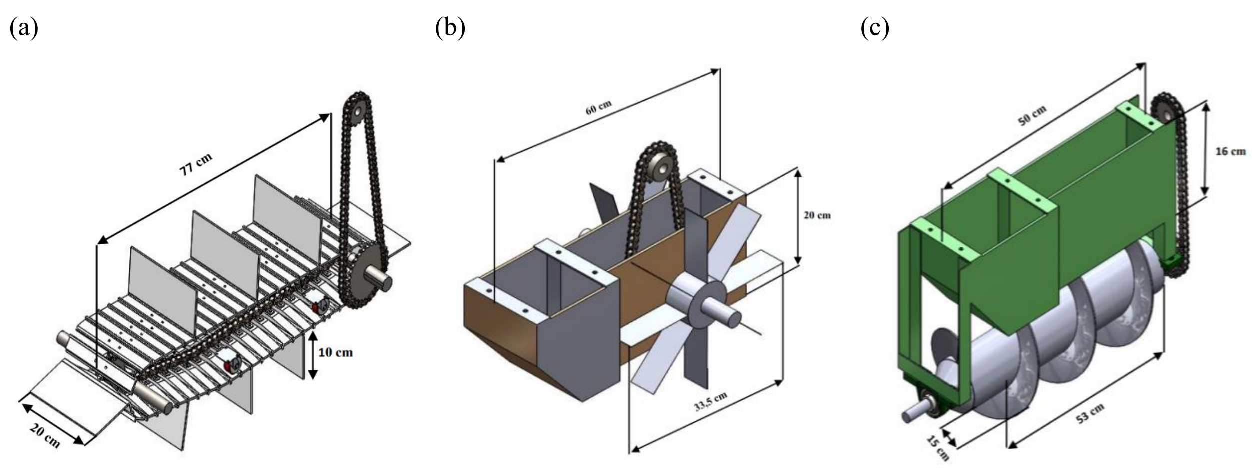
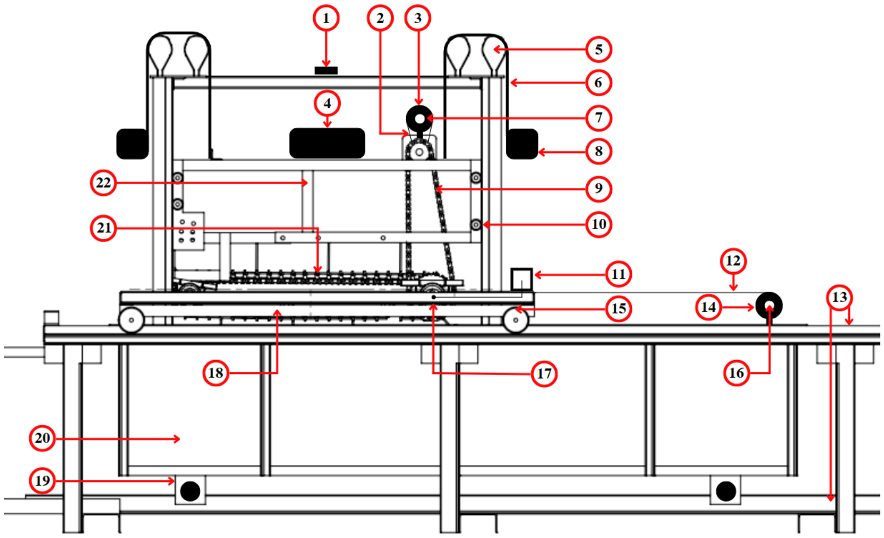


Figure 1. Three traction device designs (a) track-type; (b) pedal-type; and (c) screw-type.

The pedal and screw traction devices were tested using the same testing equipment used for the track-type traction device, including the soil bin frame, forward and backward frame, up and down frame, and sensors. The only difference was the placement of the motor for each traction device due to the different positions of the driving wheels, as seen in Figure 1. The testing setup is illustrated in Figure 2.



Description:
(1) ultrasonic; (2) thread; (3) roll; (4) vertical load; (5) pulley; (6) wire; (7) Potensiometer (theoretical range); (8) Balancing load; (9) Chain; (10) Roller; (11) Bridge box; (12) Thread; (13) Rail/track; (14) Roll; (15) Roller; (16) Potensiometer (actual range); (17) Strain gauge (torque); (18) Forward & backward frame; (19) Roller; (20) Soil bin; (21) Traction device; and (22) Up and down frame.

Figure 2. Testing apparatus for track-type traction device (Taufiq *et al.*, 2022).

2.2. Muddy Soil Condition in the Soil Bin

According to Ani *et al.* (2018), the advantage of using a soil bin is that it allows for the testing of soil tillage traction devices under varying soil conditions, helping to overcome traction device failures during tillage testing. Typically, soil and machine parameters within the soil bin can be controlled during testing in a soil bin. The soil composition used follows Taufiq *et al.* (2022), with a liquid limit value of 69%, an air-dried moisture content of 9.4%, and soil fractions consisting of 8% sand, 42% silt, and 50% clay. The soil has a plastic limit of 38% and a plasticity index of 31%. The soil is classified as silty clay in texture based on the soil fraction and plasticity characteristics. The moisture content in the soil tank was conditioned to 75% (dry basis).

The soil bin conditioning was carried out by lining the soil tank with a tarpaulin to prevent water leakage during the addition of water. Subsequently, water and soil were added periodically, followed by mixing. To facilitate the mixing process, a electric drill equipped with a paint mixer bit was utilized. This approach made the soil mixing process easier and faster. The process of preparing the muddy soil is shown in Figure 3.

Figure 3. Muddy soil preparation in the soil bin

2.3. Instrumentation and Data Acquisition System

The use of sensors in this research was carried out for real-time data measurement in the laboratory. The traction devices were tested using a sensor-equipped test apparatus to capture real-time performance data. The sensors used in this study included an ultrasonic sensor to measure the sinkage of the traction device. Two potentiometers were used for different purposes; potentiometer 1 measured the distance traveled by the moving frame, while potentiometer 2 measured the theoretical distance on the electric motor shaft. The last sensor, strain gauge was used to measure torque.

Sensor was calibrated and acquired data then were converted the analogue signals into desired digital values. Afterward, the sensors were installed on the traction device and the soil bin. The sensors were connected to an Arduino electronic device, and traction performance data were recorded using the data streamer feature in Microsoft Excel, which was integrated with the Arduino application. The sensor system setup used for measurements can be seen in Figure 4.

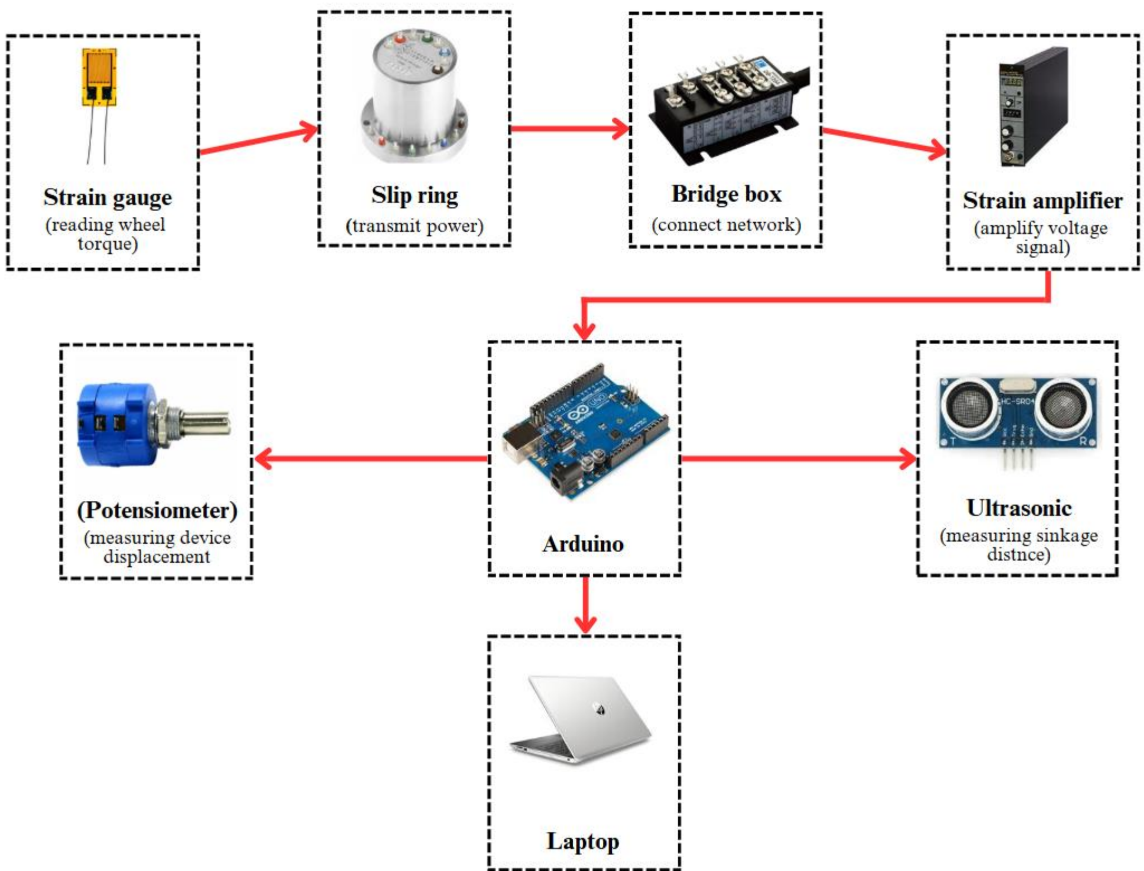


Figure 4. Sensor and data acquisition system

2.4. Traction Test Condition and Method

Performance testing of the traction device models was conducted in the soil bin and horizontal loading was done to optimize the traction performance test results. Vertical load treatments of 93.2 N, 122.6 N, 152.1 N, 181.5 N, and 222.7 N were applied to measure the three traction devices' slip, sinkage, pressure, and traction efficiency. The traction device testing was conducted in a soil bin measuring 30x40x180 cm, filled with soil to a depth of 25 cm. The tests were repeated three times. Between each test, the soil was stirred to maintain homogeneity. The loading conditions followed those used in previous track-type traction device tests. The three model traction device tested are shown in Figure 5.

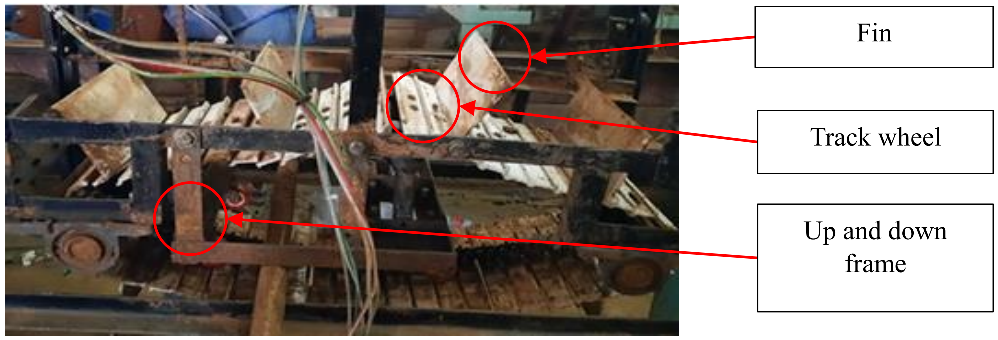


Figure 5 (a). Fabrication results of the track-type traction device

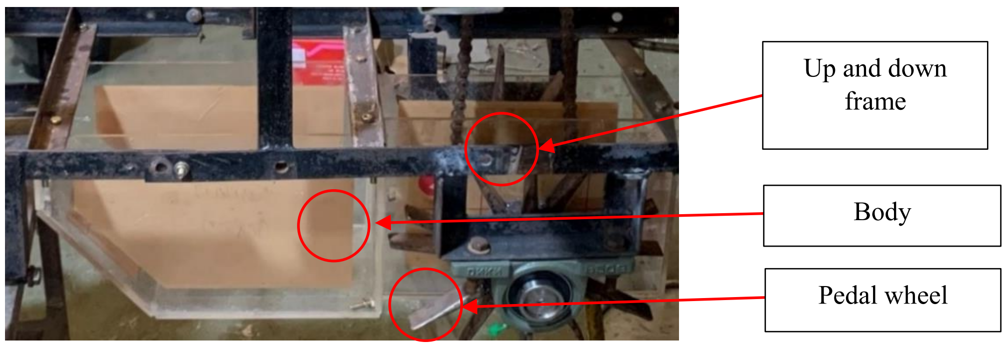


Figure 5 (b). Fabrication results of the pedal-type traction device

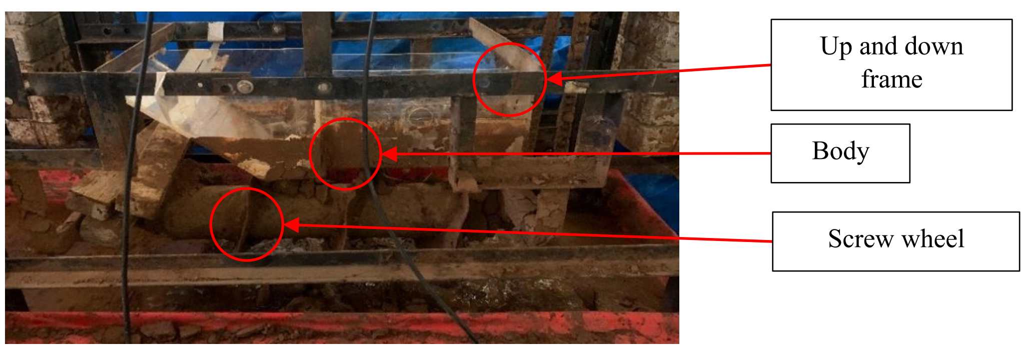


Figure 5 (c). Fabrication results of the screw-type traction device

To calculate traction efficiency, forward velocity and angular velocity were measured using Equations (1) and (2). Slip on the wheel can be calculated using the equation (3), and the pulling force was calculated using Equation (4). According to Polcar *et al.* (2017), pulling power was calculated using Equation (5), which multiplies pulling force by forward velocity. Torque was measured using the strain gauge sensor, and the voltage output was substituted into the calibration equation y = (9.2965 x volt) – 0.0586. According to Ubaidillah *et al.* (2017), power input and traction efficiency were calculated using Equations (6) and (7). After testing, the actual performance data were obtained, and the performance of the three traction devices was compared. The pressure value is obtained based on Equation (8).

$$v_t = \frac{j_a}{t} \tag{1}$$

$$\omega = \frac{2\pi \times rpm}{60} \tag{2}$$

$$S = 100 \times \left(\frac{l_t - l_a}{l_t}\right) \tag{3}$$

$$f_t = w \times g \tag{4}$$

$$p_t = f_t \times v_t \tag{5}$$

$$p_i = T \times \omega \tag{6}$$

$$\eta = \frac{p_t \times v}{p_i \times T} \tag{7}$$

$$p = \frac{F_b}{A} \tag{8}$$

where:
v_t : Forward velocity (m/s)
j_a : Actual distance (cm)
t : Time (s)
ω : Angular velocity (rad/s)
S : Slip (%)
jt : Theoritical distance (cm)
f_t : Pulling force (N)
w : Weight (kg)
g : Gravitational force (m/s^2)
p_t : Output power (W)
p_i : Input power (W)
T : Torque (nm)
η : Traction efficiency (%)
p : Pressure (N/m^2)
F_b : Vertical load (N)
A : Contact area (m^2)

2.5. Data Analysis Method

After the testing, data on slip, sinkage, and traction efficiency for the three traction devices were obtained. The results from these three data sets were analyzed to determine which design had the best traction performance. The best design is determined using the Analytical Hierarchy Process (AHP) method. Following this, the traction device with the highest total score for each load treatment was identified.

The determination of the best design is carried out using the Analytical Hierarchy Process (AHP) method. The analysis steps include defining the goal, determining the criteria, constructing, and filling out the pairwise comparison matrix. Weighting values are assigned to each criterion based on Table 1, followed by normalization calculations on the weighted criteria matrix. Next, the calculation of λ max is performed, derived from the highest eigenvalue ratio. The consistency index (CI) is calculated using Equation (9), and the consistency ratio (CR) is calculated using Equation (10) based on the random index (RI) values (Table 2) to check for a valid consistency ratio (CR < 0.1). The final criteria score (FCS) is computed using Equation (11) (Rivantoro & Arief, 2015) by multiplying the normalized criteria weight (NCW) with the normalized criteria value (NCV).

$$CI = \frac{\lambda\text{max} - N}{N-1} \tag{9}$$

$$CR = \frac{CI}{RI} \tag{10}$$

$$FCS = \sum(NCV\ x\ NCW) \tag{11}$$

where *CI* is consistency index, λmax is maximum eigenvalue, *N* is number of elements in the matrix, *CR* is consistency ratio, and *RI* is random index.

Table 1. Comparison rating scale (Rivantoro & Arief, 2015)

Intensity of Importance	Description
1	Both elements are equally important
3	One element is slightly more important than the other
5	One element is more important than the other
7	One element is clearly and powerfully more critical than the other
9	One element is more important than the other
2, 4, 6, 8	Intermediate values between adjacent importance ratings
Reciprocal	If activity *i* is assigned a specific value when compared to activity *j*, then *j* has the reciprocal value when compared to *i*

Table 2. Random index values based on each matrix order (Putra & Epriyanto, 2017)

Matrix Order	1	2	3	4	5	6	7	8	9	10
(RI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3. RESULTS AND DISCUSSION

3.1. Slip

Based on the test results, an initial vertical load of 93.2 N applied to the track, pedal, and screw-type traction devices resulted in slip values of 8.57%, 28.74%, and 49.86%, respectively, with speeds of 0.076 m/s, 0.068 m/s, and 0.05 m/s (Table 3). Increasing the load to 152.1 N for the three traction devices resulted in slip values of 24.33%, 46.52%, and 66.65%, respectively, with speeds of 0.074 m/s, 0.047 m/s, and 0.031 m/s. The pedal and screw-type traction devices already exhibited high slip levels exceeding 45% at this load. Further increasing the load to 222.7 N resulted in slip values of 39.53%, 62.45%, and 80.80%, respectively, with speeds of 0.056 m/s, 0.032 m/s, and 0.015 m/s.

Table 3. Slip values based on vertical load levels

Vertical Load (N)	Forward Velocity (m/s)			Slip (%)		
	Track	Pedal	Screw	Track	Pedal	Screw
93.2	0.076	0.068	0.050	8.57	28.74	49.86
122.6	0.082	0.061	0.042	21.13	36.90	55.48
152.1	0.074	0.047	0.031	24.33	46.52	66.65
181.5	0.072	0.044	0.021	29.43	52.88	77.33
222.7	0.056	0.032	0.015	39.53	62.45	80.80

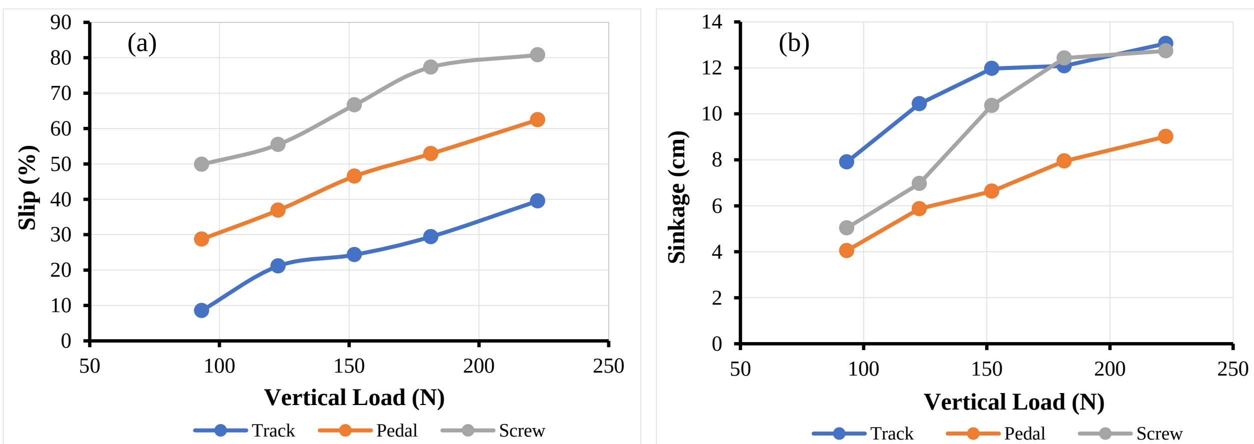


Figure 6. Effect of vertical load on: (a) Slip (%), and (b) Sinkage (cm)

3.2. Sinkage

The measurement of sinkage parameters produced data shown in Table 4. Applying a vertical load of 93.2 N to the traction devices of the track, pedal, and screw types resulted in sinkage values of 7.90 cm, 4.05 cm, and 5.04 cm, respectively. Increasing the load to 222.7 N for the three traction devices resulted in sinkage values of 13.06 cm, 9.01 cm, and 12.74 cm, respectively, at a certain speed. The pedal-type traction device exhibited lower sinkage compared to the track and screw types, as it features a body and wheel alignment parallel to the body of the traction device.

Table 4. The sinkage value is based on the level of vertical loading.

Vertical Load (N)	Sinkage (%)		
	Track	Pedal	Screw
93.2	7.90	4.05	5.07
122.6	10.44	5.87	7.13
152.1	11.97	6.63	10.35
181.5	12.09	7.95	12.43
222.7	13.06	9.01	12.74

The initial sinkage point for the track-type traction device is determined at the lowest position of the grouser, for the pedal-type device at the bottom surface of the body when it touches the ground, and for the screw-type device at the middle part of the screw wheel cylinder when submerged in the soil. Test results show that all three traction device types experience increased sinkage as vertical loading increases, consistent with studies on track-type devices (Taufiq *et al*., 2022), pedal-type devices (Jiang *et al*., 2021), and screw-type devices (Koshurina *et al*., 2016). According to Taufiq *et al*. (2022), an increase in vertical load parameters requires a greater buoyant force to lift and maintain the traction device afloat. A reduction in soil resistance contributes to deeper sinkage. According to Hermawan (2010), slips during land cultivation also determine the extent of wheel sinkage. If the vertical load increases, it will raise the slippage value and cause the wheels to sink deeper.

3.3. The Relationship Between Contact Area, Pressure, and Sinkage

The measurement results for contact area, pressure, and sinkage are presented in Table 5. Applying a vertical load of 93.2 N to the track, pedal, and screw traction devices resulted in pressure values of 7.90 N/m², 7.77 N/m², and 7.90 N/m², respectively, causing sinkage depths of 7.77 cm, 8.47 cm, and 8.32 cm. When a maximum load of 222.7 N was applied to the three traction devices, the pressure values increased to 13.06 N/m², 18.56 N/m², and 13.06 N/m², resulting in sinkage depths of 18.56 cm, 18.77 cm, and 19.88 cm, respectively.

The traction device experiences an increase in pressure as the vertical load increases, consistent with studies on pressure in track-type traction devices (Taufiq *et al*., 2022), pedal-type devices (Jiang *et al*., 2021), and screw-type devices (Koshurina *et al*., 2016). Similarly, sinkage increases with rising pressure, indicating that the traction device penetrates deeper into the soil. Sinkage depends on the type of soil in which the traction device operates; softer and more fluid soils are more prone to sinkage, even with a slight increase in pressure. As explained by Salman *et al*. (2021), vertical loads applied to the soil directly affect pressure.

Table 5. The relationship between contact area, pressure, and sinkage

Vertical Load(N)	Contact Area (m^2)			Pressure (N/m^2)			Sinkage (cm)		
	Track	Pedal	Screw	Track	Pedal	Screw	Track	Pedal	Screw
93.2	7.90	7.90	11.2	7.90	7.77	7.90	7.77	8.47	8.32
122.6	10.44	10.44	11.2	10.44	10.75	10.44	10.75	10.84	10.95
152.1	11.97	11.97	11.2	11.97	13.35	11.97	13.35	13.28	13.58
181.5	12.09	12.09	11.2	12.09	15.12	12.09	15.12	15.54	16.20
222.7	13.06	13.06	11.2	13.06	18.56	13.06	18.56	18.77	19.88

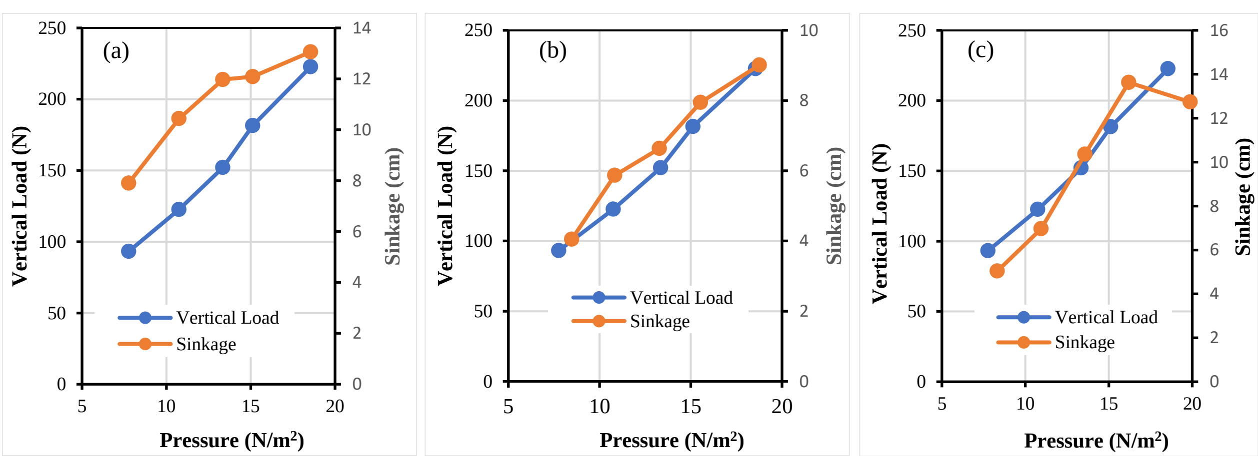


Figure 8. Graph of the relationship between contact area, pressure, and sinkage for the three traction devices (a) track type; (b) pedal type; and (c) screw type.

3.4. Traction Efficiency

The testing of the three traction devices yielded traction efficiency data, as presented in Table 6. Applying an initial vertical load of 93.2 N to the track, pedal, and screw traction devices resulted in traction efficiency values of 73.18%, 60.08%, and 36.65%, respectively. Increasing the load to 277.7 N for the three devices produced efficiency values of 48.38%, 29.23%, and 10.92%, respectively. The track-type traction device demonstrated the best traction efficiency compared to the pedal and screw types.

Table 6. Traction efficiency values based on vertical load levels

Vertical Load (N)	Traction Efficiency (%)		
	Track	Pedal	Screw
93.2	73.18	60.08	36.65
122.6	63.12	51.82	32.19
152.1	60.52	43.11	22.74
181.5	56.48	37.65	14.21
222.7	48.38	29.23	10.92

The traction devices experienced a decrease in traction efficiency as vertical load increased, consistent with previous studies on track-type traction devices (Taufiq *et al*., 2022), pedal-type devices (Jiang *et al*., 2021), and screw-type devices (Koshurina *et al*., 2016). The high efficiency observed occurs because engine power is effectively utilized, and the fins of the traction devices maintain good contact with the soil, resulting in low slip values. An increase in vertical load also raises the pressing force of the finned track wheels, which aligns with the normal force. This leads to frictional forces opposing the pulling force, hindering the forward motion of the finned track wheels.

The increased pressing force also causes the wheels to spin faster, displacing soil and creating resistance equal to the fin's pressing force. The increase in vertical load also raises the wheels' pulling force and traction requirements (Taufiq *et al*., 2022). According to Osinenko *et al.* (2015), the main factors affecting traction efficiency are wheel pressure, characteristics, vertical load, and slippage. Adjustments to the vertical load and wheel pressure need to be made to balance traction efficiency with traction productivity and slippage.

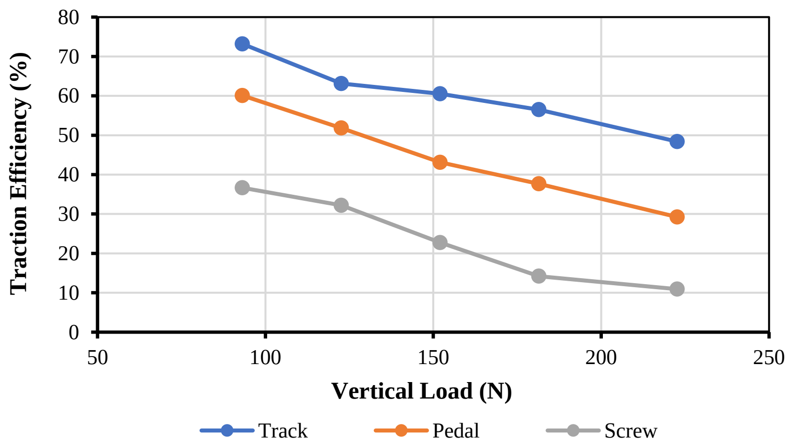


Figure 8. Graph of the relationship between vertical load and traction efficiency

3.5. Analysis Method and Determination of the Best Model Design

The best design was selected using the Analytical Hierarchy Process (AHP) method based on the three traction devices' slip, sinkage, and traction efficiency data. The analysis presents the total score for each loading condition in Table 7. The track-type device achieved the highest scores for determining the best traction device design, with 0.78 for minimum load, 0.83 for medium load, and 0.87 for maximum load. Thus, the track design is the ideal choice as it achieved the highest score across all parameters.

Table 7. Total score values for each loading condition

Type	Total Score		
	Minimum Load (93.2 N)	Medium Load (152.1 N)	Maximum Load (222.7 N)
Track	0.78	0.83	0.87
Pedal	0.77	0.69	0.66
Screw	0.65	0.59	0.51

Based on research that has been carried out, it was evident that the size and design of the fins were critical. Although the pedal and screw traction devices showed lower traction performance, the buoyancy provided by their bodies helped them avoid excessive sinking. However, the fins on these devices needed to be optimized to provide good traction. Future designs should consider adjusting the shape and size of the fins, similar to those of the track-type device, which has a larger surface area in contact with the ground. As explained by Idkham *et al.* (2018), larger fin angles can reduce sinkage. The size of the fin angle also affects the magnitude of the lifting force on the wheel and the pulling force (Cebro *et al.*, 2018).

4. CONCLUSION

The traction performance test for the three types of traction devices, which measured slip, sinkage, and traction efficiency parameters, was carried out on a soil bin in muddy soil at 25 cm deep. Vertical load treatments of 93.2 N, 122.6 N, 152.1 N, 181.5 N, and 222.7 N were applied to measure the three traction devices' slip, sinkage, and traction efficiency. The best traction device design was determined using the Analytical Hierarchy Process (AHP). The highest score in determining the best traction device design for the minimum load was 0.78 for the track-type traction device; for the medium load, it was 0.83 for the track-type traction device; and for the maximum load, it was 0.87 for the track-type traction device. Therefore, the track traction device was the ideal design because it had the highest score across all parameters based on the load treatments applied.

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