MULTIDISCIPLINARY SCIENCE JOURNAL

RESEARCH ARTICLE
Published Online: October 17, 2024
https://doi.org/10.31893/multiscience.2025178

Experimental study of traction and drawbar pull of track-type lugged wheel in a soil bin

Muhammad Taufiq[ab] | Tineke Mandang[c] | Wawan Hermawan[c] | Desrial[c]

[a]Study Program of Agricultural Engineering Science, IPB University, Dramaga, Bogor, 16680, West Java, Indonesia.
[b]Department of Agrotechnology, University of Pembangunan Panca Budi, Medan, 20122, North Sumatera, Indonesia.
[c]Department of Mechanical and Biosystem Engineering, IPB University, Dramaga, Bogor, 16002, West Java, Indonesia.

Abstract Paddy fields with saturated and deep mud soil conditions can cause conventional traction devices like cage wheels on walking tractors to perform suboptimally. Therefore, a new traction device design, specifically a track-type wheel with additional lugs, is needed to replace the cage wheel on walking tractors. This study aims to analyze the traction performance and drawbar pull of the track-type lugged wheel experimentally in a soil bin. The tested prototype track-type lugged wheel has dimensions of 60 cm between axles, 20 cm in width, 8.5 cm in height, and a circumference of 152.4 cm. The experiment was conducted by applying horizontal pulling loads varying from 1 to 4 kg at a speed of 0.064 $m.s^{-1}$ and an angular speed of 3.14 $rad.s^{-1}$. The observed traction performance parameters included drawbar pull, sinkage, slip, and tractive efficiency. The results indicate that increasing horizontal load significantly increases drawbar pull. This increase in drawbar pull significantly affects sinkage and slip, causing them to rise, but it substantially decreases tractive efficiency, based on single-factor ANOVA with a P value < 0.05. The drawbar pull value that still results in optimal traction performance for sinkage (< 8.5 cm) is 32.72 N, while the value for maintaining normal slip limits (< 20%) and optimal tractive efficiency (> 65%) is 24.91 N. The modified lug design acts like a paddle, improving the traction efficiency of the wheel. Adjustments to the spacing and height of the lugs are required to maximize the traction performance of the track-type lugged wheel at increased drawbar pull levels. Therefore, the prototype track-type lugged wheel is most effective in paddy fields with saturated and muddy soil conditions.

Keywords: drawbar pull, lugged track wheel, sinkage, slip, tractive efficiency

1. Introduction

The development of traction devices for agricultural machinery has been an intensive research topic for the past few decades and remains a relevant focus today (Abbasi et al., 2022; Bacco et al., 2019; Cesco et al., 2023; Jerhamre et al., 2022; Knierim et al., 2019). Success in rice cultivation can be achieved if the development of traction devices for agricultural machinery is adapted to paddy field conditions (Fu et al., 2022; Paman et al., 2018; Sagwal et al., 2022; Takeshima & Mano, 2023). These conditions refer to saturated and deep, muddy paddy fields (Ding et al., 2021; Li et al., 2022). Using agricultural machinery with low traction performance is not just a challenge but also a significant obstacle in rice paddy farming activities in rice-producing Asian countries (Jiang et al., 2021; Jin et al., 2014; Paman et al., 2018; Sharma, 2021). Water-saturated and deeply muddy paddy fields pose formidable challenges to the effectiveness and efficiency of agricultural machinery operations (Fu et al., 2022; Mitchell et al., 2013; Wang et al., 2022; Zhang et al., 2022). In Indonesia, where the average size of paddy field plots is generally narrow and small, farmers are forced to use two-wheeled tractors (walking tractors) to till their fields instead of four-wheeled tractors, further exacerbating the traction issue (Choir et al., 2018; Hidayat et al., 2020; Partasasmita et al., 2019).

Walking tractors operated by farmers in Indonesia usually still use conventional wheels such as cage wheels as traction devices (Fuglie, 2010; Khaehanchanpong, 2018; Pitoyo et al., 2017). The traction performance of cage wheels for walking tractors is relatively low (Pradhan et al., 2018; Raheman & Snigdharani, 2020). Saturated and deeply muddy paddy fields cause excessive sinkage of cage wheels, delaying rice farming due to more complex and time-consuming soil tillage (Abubakar et al., 2009; Piyush & Ajay, 2017). Highly saturated paddy fields also sometimes weaken the pull of walking tractors (Keen et al., 2013; Mkomwa et al., 2015). The low pulling force of walking tractors is caused by high slip levels on the traction device (Kebede & Getnet, 2016; Md-Tahir et al., 2019). High slip conditions undoubtedly reduce the traction performance of walking tractors. High slip affects the tractor's speed, causing it to perform suboptimally even at full throttle. This high slip condition results in traction wheels spinning in place without significant movement (S.-l. Zhang et al., 2023; Zirek & Onat, 2020; Zirek et al., 2018).

Previous research has shown that the use of track-type wheels provides superior traction performance under poor soil conditions (Ju et al., 2020; Osinenko & Streif, 2017). Compared with conventional wheels, track-type wheels can generate greater pulling forces (Rasool & Raheman, 2016, 2018). The high pulling force produced by track-type wheels is due to the

 Received: May 29, 2024 | Accepted: September 17, 2024

larger ground contact area, leading to a more significant push against the soil than that of wheels (Dobretsov et al., 2018; Maclaurin, 2018; Ozawa et al., 2020). However, the application of track-type wheels in saturated and deep muddy paddy fields requires further research. When this track-type wheel is used as a traction device for walking tractors, it can be modified with additional lug (grouser) designs to enhance its pushing capability (Taufiq et al., 2022). Before applying track-type lugged wheels in actual paddy field conditions, experimental research in a laboratory setting is necessary. Therefore, this study aims to analyze the experimental traction performance and drawbar pull of track-type lugged wheels in a soil bin.

2. Materials and Methods.

2.1. Track-type lugged wheel design and testing device apparatus

The design of a track-type lugged wheel involved developing and testing the traction performance of a prototype in a soil bin (Figure 1). The prototype included gears/sprockets, a chain with 96 links, shafts, idler wheels, and supporting frames. Track shoes (grousers) and lugs were created via a 3D printer with polylactic acid (PLA) plastic material (Figure 2). The dimensions of the prototype were 60 cm in length, 20 cm in width, and 8.5 cm in front axle height, with a track circumference of 152.4 cm. These measurements were based on the proportional dimensions needed for application on a walking tractor.

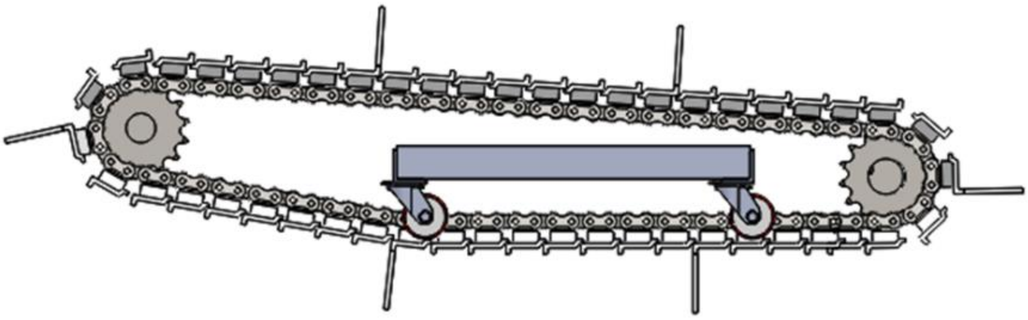

Figure 1 Design of a track-type lugged wheel.

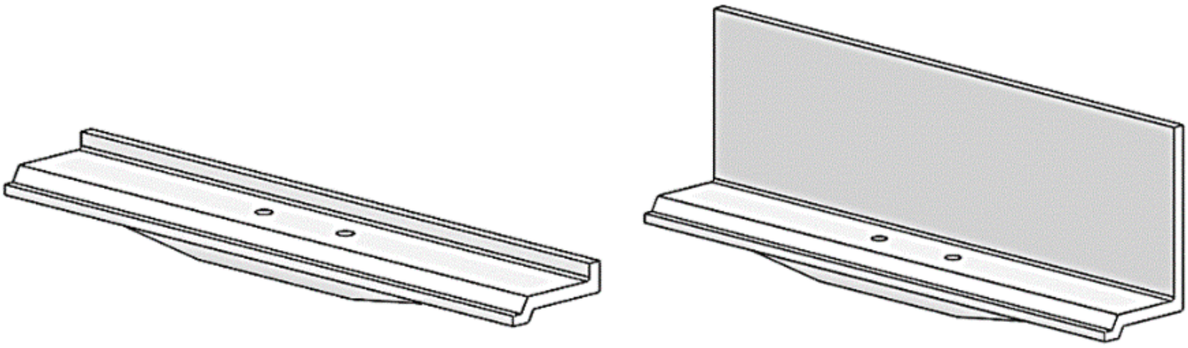

Figure 2 Tracking a shoe (grouser) and lug.

The dimensions of the track-type lugged wheel prototype used in the soil bin were scaled at a 1:2 ratio compared with the full-sized version intended for use with walking tractors in saturated and deep muddy rice fields. The lugs on the track-type lugged wheel were designed to mimic the paddler, helping the wheel move through soil with high plasticity index characteristics, reaching the liquid limit.

The prototype of the track-type lugged wheel used in soil bin testing is supported by two frames (Figure 3). The first is a forward-backward (fixed) frame, and the second is an updown frame. The forward-backward frame is the outermost frame surrounding the lugged wheel prototype. It has a supporting wheel (bearing) to control horizontal movement, allowing the wheel to move forward and backward along the soil bin track. The updown frame, which is directly connected to the track-type lugged wheel prototype, includes shafts that serve as the rear axle/drive shaft and the front axle. This frame also features a supporting wheel (bearing) that interacts with the forward-backward frame, enabling it to move downward under a vertical load and upward due to the forces generated by the lug motion.

The supporting frame for the track-type lugged wheel prototype can be mounted on the soil bin test apparatus in the laboratory, as shown in Figure 4. The soil bin is a rectangular box with soil dimensions of 185 cm in length, 50 cm in width, and 40 cm in height. It can move forward and backward owing to four supporting wheels connected to the track that forms the soil bin's supporting frame. The components making up the soil bin's supporting frame include 500 cm long rails (tracks) for the soil bin, rails (tracks) for the forward-backward supporting frame of the track-type lugged wheel prototype, and horizontal pull load supporting poles for loading on the forward-backward supporting frame, which are 180 cm in height.

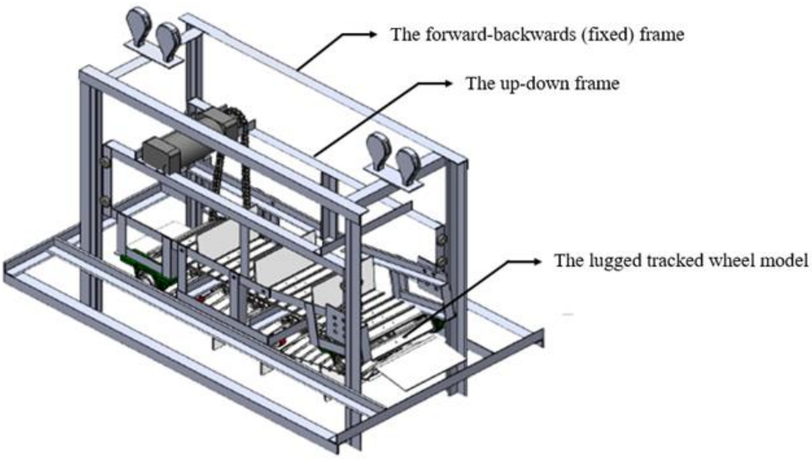

Figure 3 Support frame for the prototype of the track-type lugged wheel.

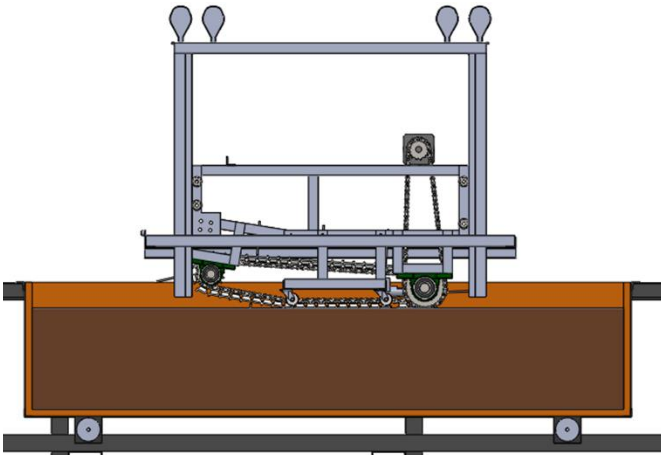

Figure 4 Prototype of the track-type lugged wheel mounted on a soil bin.

2.2. Sensor and data recording devices

Figure 5 shows the components of the instrumentation system and the sensor-measuring devices used in this study. The instrumentation tools include strain gauges, multiturn potentiometers, ultrasonic sensors, and load cells. Data were collected by connecting an Arduino Uno microcontroller to a computer. Figure 6 illustrates the configuration of the data acquisition system, which integrates multiple sensors within the soil bin test apparatus.

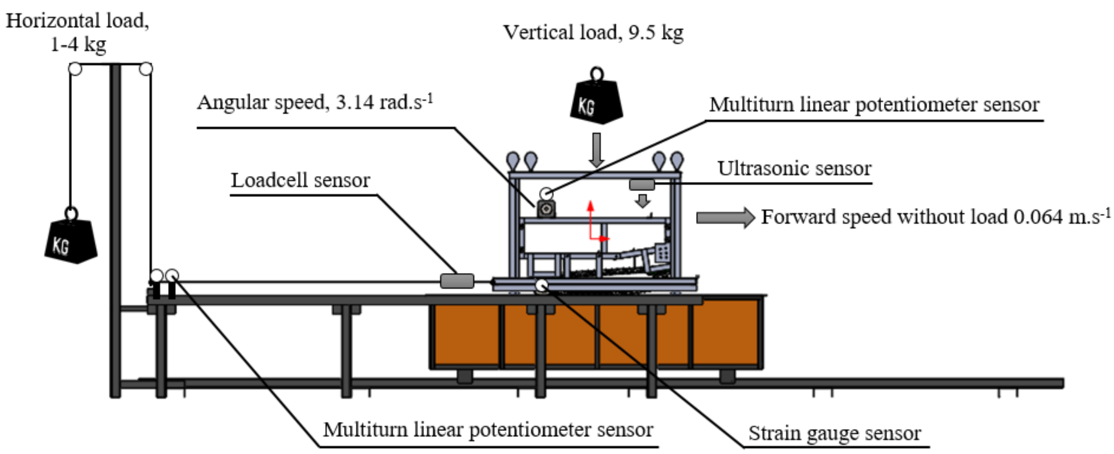

Figure 5 The instrumentation system mounted on the soil bin.

The instrumentation for testing the lugged track wheel prototype includes a load cell sensor connected to an HX711 module, which measures the pull force and provides drawbar pull data. An ultrasonic sensor measures distance to obtain sinkage data. Multiturn linear potentiometer sensors measure actual and theoretical travel distances, supplying data on forward speed, slip, and the RPM. Strain gauge sensors connected to slip rings, bridge boxes, and strain amplifiers measure the torque on the wheel axle. An Arduino Uno microcontroller is used to manage the recorded sensors. It transmits the test data to a laptop during traction performance testing of the lugged track wheel prototype in a soil bin.

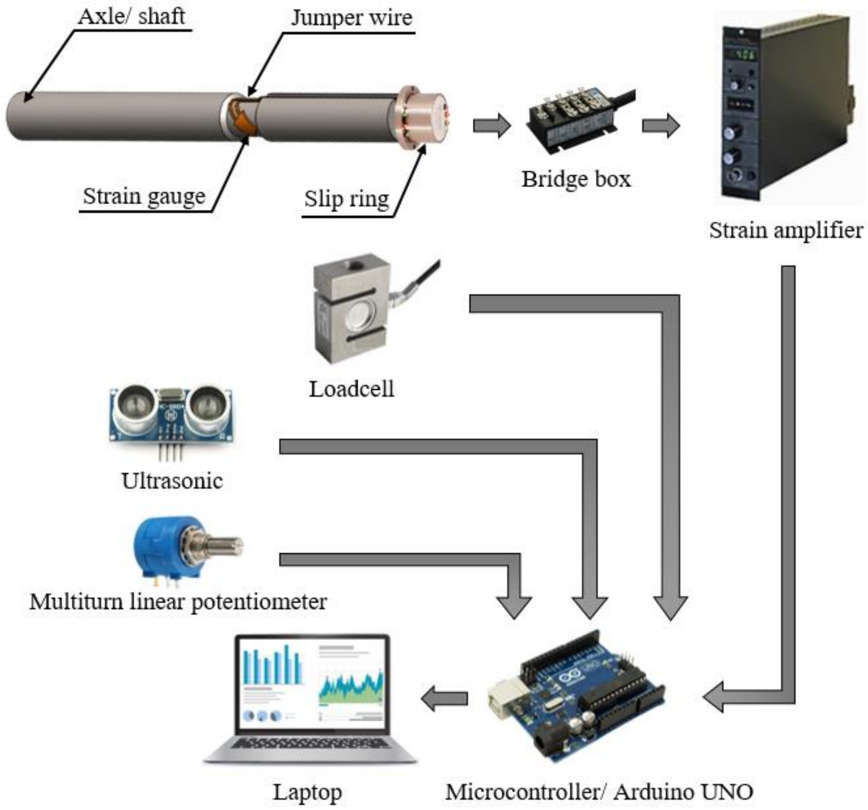

Figure 6 Setup of the data acquisition system with multiple sensors.

2.3. Experimental design

The research used silty clay soil, focusing on characteristics at the liquid limit, which has a higher moisture content than the plastic limit. The soil moisture content was measured via the oven method, and the liquid limit was determined via the Casagrande method. This testing aimed to establish suitable soil conditions for the soil bin. The liquid limit test results were essential for determining the correct soil and water composition to ensure that the soil bin conditions matched the research requirements. Using soil at the liquid limit was crucial for addressing the poor traction performance of walking tractors with cage wheels in flooded paddy fields and deep mud, aligning with the study's focus.

The dimensions of the track-type lugged wheel prototype are detailed in Table 1. The lug spacing on this prototype was adjusted to 25.40 cm. On the basis of the number of chain links in the lug attachment system, the number of lugs of this 25.40 cm lug spacing is six. Moreover, the lug height on this prototype was adjusted to 5 cm. Figure 7 illustrates the lug spacing and height design for the track-type lugged wheel prototype.

Table 1 Prototype of the track-type lugged wheel dimensions.

Dimensions of the track	Value
Track lenght (cm)	60
Track width (cm)	20
Front axle height (cm)	8.5
Circumference (cm)	152.4
Lug height (cm)	5
Lug spacing (cm)	25.40

The experiment started after the soil was prepared in a designated soil bin, ensuring that the soil moisture content reached the liquid limit (75% db). The soil was homogenized for consistency across all layers. The parameters observed and recorded during each test included torque, drawbar pull, actual speed, theoretical speed, and sinkage. The different horizontal loads applied throughout the tests were 1 kg, 2 kg, 3 kg and 4 kg. The velocity of the track-type lugged wheel prototype was maintained at 0.064 m.s-1, and the angular speed was set at 3.14 rad.s-1. Each test configuration was replicated three times for robustness and reliability. The detailed specifications of the experimental setup are provided in Table 2.

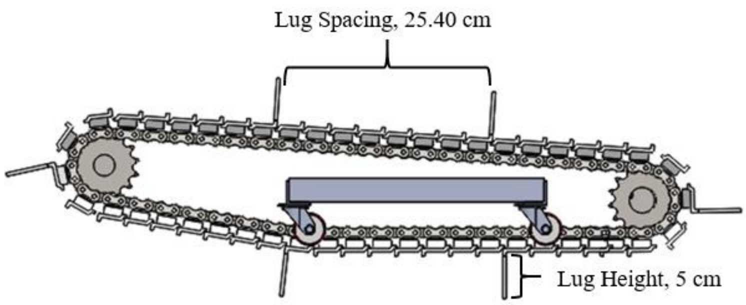

Figure 7 Lug spacing and height design of the track-type lugged wheel prototype.

Table 2 Experimental design.

Treatment variables	Value
Horizontal loads (kg)	1 – 4
Vertical load (kg)	9.5
Soil water content (% db)	75
Velocity ($m.s^{-1}$)	0.064
Angular speed ($rad.s^{-1}$)	3.14

2.4. Traction performance parameters

The traction performance evaluation of the track-type lugged wheel prototype focused on three critical parameters: slip, sinkage, and tractive efficiency (TE). The slip was calculated by comparing the actual speed with the theoretical speed. Sinkage was measured via an ultrasonic sensor. Drawbar pull measurements from a load cell sensor and actual speed were used to calculate the output power. The velocity was determined by comparing the measured distance with the travel time. The input power was calculated by multiplying the torque measurements from a strain gauge sensor with the wheel's angular velocity. Tractive efficiency was then determined by comparing the output and input powers. The following are several equations used to calculate the traction performance parameters of a track-type lugged wheel prototype.

$$V=\frac{S}{t} \tag{1}$$

$$\text{Slip} = \left(1-\frac{AS}{TS}\right)\cdot 100\% \tag{2}$$

$$\text{Db Pull} = m \cdot a \tag{3}$$

$$\text{Output Power} = \text{Db Pull} \cdot V \tag{4}$$

$$\text{Input Power} = T \cdot \omega \tag{5}$$

$$TE = \frac{\text{Output power}}{\text{Input power}} \cdot 100\% \tag{6}$$

where V refers to velocity, S refers to actual distance, t refers to travel time, AS refers to actual speed, TS refers to theoretical speed, Db Pull refers to drawbar pull, which also means net traction, m refers to mass or load, a refers to acceleration due to gravity, V refers to velocity of a traction device, T refers to torque, ω refers to angular velocity of the driving axle of a traction device, and TE is tractive efficiency. The definitions of these terms follow the ASAE Standard: ASAE S296.4 (Liljedahl et al., 1989).

3. Results and Discussion

3.1. Drawbar pull

The traction performance experiment conducted by a track-type lugged wheel in a soil bin includes observations of drawbar pull, sinkage, slip, and tractive efficiency parameters. The drawbar pull observation was carried out using a load cell sensor. The data recorded by the load cell sensor during three repetitions for each horizontal load treatment can be processed into drawbar pull values via the equation shown in Equation 3. Four levels of average drawbar pull values were obtained on the basis of the various horizontal loads applied in this traction performance experiment, as presented in Figure 8. The average values for each level of horizontal load applied are 24.91 N (1 kg), 32.72 N (2 kg), 41.83 N (3 kg), and 61.44 N (4 kg). The drawbar pull results for the track-type lugged wheel yielded a coefficient of determination (R^2) of 0.9475. This result indicates that the relationship between the applied horizontal load and the drawbar pull is directly proportional. The more significant the increase in horizontal load is, the higher the drawbar pull value. The analysis based on a single-factor ANOVA test, as shown in Table 3, indicates that the increase in horizontal load has a significantly different effect on the drawbar pull, as evidenced by a P value of 0.000 (P value < 0.05).

Table 3 Results of single-factor ANOVA of drawbar pull with various horizontal load increments.

Source of variation	SS	df	MS	F	P value	F crit
Between groups	139255.85	3.00	46418.62	5732.46	0.000*	2.62
Within groups	5814.01	718.00	8.10			
Total	145069.86	721.00				

* A P value smaller than the 5% significance level (P value < 0.05) indicates that drawbar pull significantly differs with different increments of horizontal load.

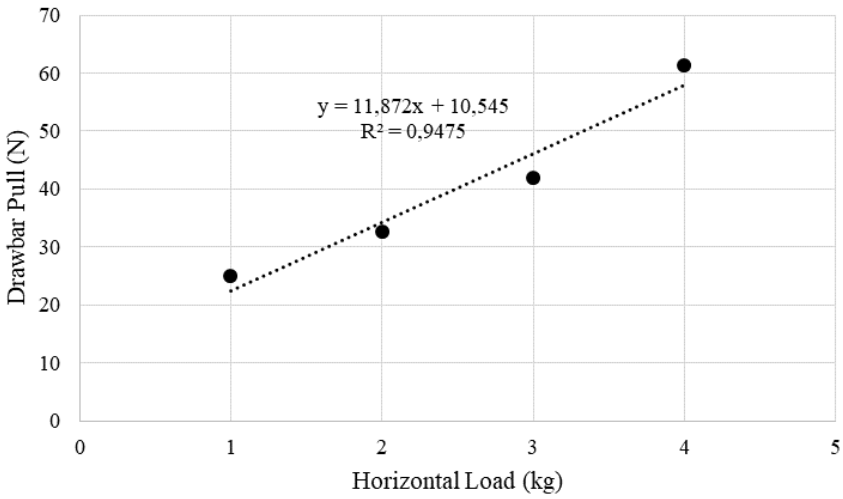

Figure 8 Effect of horizontal load on drawbar pull.

Research has shown that the relationship between increased horizontal load and drawbar pull is directly proportional (Nassiraei & Skonieczny, 2020; Park et al., 2008; Ten Damme et al., 2021). Adding more horizontal loads to tasks using track-type wheels impacts the increase in traction required by the machine (Bruzzone et al., 2022; Gelin & Björheden, 2020; Maclaurin, 2018). Several studies have also indicated that there is an optimal limit to the pulling load that allows a machine to operate optimally. Previous research has shown that an increase in drawbar pull can result in optimal traction performance if the torque, which contributes to the output power of the traction device, can effectively overcome rolling resistance (Battiato & Diserens, 2013; Dizqah et al., 2020; Preda, 2022). However, if the torque generated by the wheel is low, it can reduce the wheel's output power, leading to decreased traction efficiency (Ani et al., 2013). Several studies have also shown that increased drawbar pull significantly affects traction performance parameters such as sinkage, slip, and tractive efficiency (Du et al., 2017; Park et al., 2008; Wang et al., 2023). This study confirms the findings of previous studies, where the increase in drawbar pull also resulted in significantly different outcomes for other traction performance parameters, such as sinkage, slip, and traction efficiency.

3.2. Relationship between drawbar pull and sinkage

The sinkage parameter in the traction performance of a track-type lugged wheel was measured via an ultrasonic sensor. Experimental data on sinkage in the soil bin show that sinkage increases with increasing drawbar pull, as illustrated in Figure 9. The coefficient of determination (R^2) for the rate of sinkage increase is 0.8601, indicating that the increase in sinkage is linearly correlated with the increase in drawbar pull. According to the linear trendline equation, sinkage continues to rise as the drawbar pull increases. On the basis of the axle height of the track-type lugged wheel, which is 8.5 cm, the allowable horizontal load is less than 2 kg or the drawbar pull is less than 32.72 N. If the horizontal load exceeds 2 kg or the drawbar pull exceeds 32.72 N, the track-type lugged wheel may not operate optimally. This suboptimal performance is due to excessive sinkage, which occurs when the track-type lugged wheel's sinkage exceeds the designed ground clearance. Figure 9 also shows that the sinkage at a drawbar pull of 32.72 N (2 kg) is 8.56 cm. Furthermore, the analysis results based on a single-factor ANOVA test, as shown in Table 4, indicate that the increase in drawbar pull has a significantly different effect on the sinkage parameter, as evidenced by a P value of 3.56 × 10-72 (P value < 0.05).

Table 4 Results of single-factor ANOVA of sinkage with various drawbar pull increments.

Source of variation	SS	df	MS	F	P value	F crit
Between groups	1388.50	3.00	462.83	141.85.46	3.56E-72*	2.62
Within groups	2342.69	718.00	3.26			
Total	3731.19	721.00				

*A P value smaller than the 5% significance level (P value < 0.05) indicates that sinkage significantly affects difers with different increases in drawbar pull.

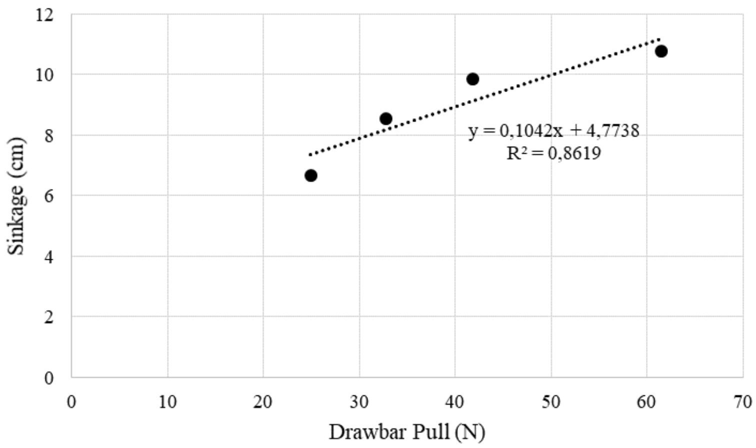

Figure 9 Effect of drawbar pull on sinkage.

Previous research has shown that high sinkage is a significant issue, causing more of the wheel surface to sink into the soil (Di Maria et al., 2021; Sandu et al., 2010). This issue, in turn, increases rolling resistance and reduces traction efficiency, forcing the engine to work harder to move forward (Hall & Moreland, 2001). The consequences are severely increased rolling resistance, which requires more power from the engine, leading to higher fuel consumption (Barrand & Bokar, 2008). Moreover, increased rolling resistance can reduce the machine's operating speed, which decreases productivity, as more time is needed to complete tasks (Bawden et al., 2014; Gonzalez-de-Soto et al., 2015; Wang et al., 2012). The negative impact of sinkage on machines and vehicles is also substantial. High sinkage places greater stress on wheels and other machine components, leading to faster wear and higher maintenance and repair costs (Gao et al., 2022; La Monaca et al., 2021). Excessive sinkage can also make the vehicle less stable, increasing the risk of tipping over or having difficulty maneuvering in challenging terrain (Comin et al., 2017; Rodríguez-Martínez et al., 2019).

3.1 Relationship between drawbar pull and slip

The influence of the slip parameter on the traction performance of a track-type lugged wheel was measured via a multiturn linear potentiometer sensor. The slip experiments conducted with the track-type lugged wheel in a soil bin revealed that slip increased with increasing drawbar pull, as illustrated in Figure 10. The obtained coefficient of determination (R^2) of 0.8311 indicates that the rate of slip increase with drawbar pull is linear, indicating that the increase in slip is directly proportional to the increase in drawbar pull. Slip continues to rise, similar to the increase in the sinkage parameter, as the drawbar pull increases. If the drawbar pull increases, the linear trendline equation indicates that the slip will also consistently increase. Under the same speed conditions, the ideal slip condition is 20%, meaning that the wheel rotation is 0.8 times greater than the rotation without braking, maximizing the adhesion between the tire and the road and minimizing the stopping distance with existing friction (Storckenfeldt & Ganatra, 2021). Therefore, the optimal pulling load to apply is less than 1 kg or a drawbar pulling below 24.91 N. If the pulling load exceeds 1 kg or the drawbar pulling exceeds 24.91 N, the track-type lugged wheel may not operate optimally. Excessive slip in the designed track-type lugged wheel can occur because the soil conditions are at the liquid limit. The soil in the slip experiment has physical properties resembling those of a fluid, resulting in very low friction between the track-type lugged wheel and the soil. Therefore, the function of the lugs as paddles is crucial for the track-type lugged wheel to operate optimally. Figure 10 also shows that the slip at a drawbar pull of 24.91 N (1 kg) is 17.75%, which is still within the ideal slip condition because it is less than 20%. Additionally, the analysis based on a single-factor ANOVA test, as shown in Table 5, indicates that the increase in drawbar pull has a significantly different effect on the slip parameter, as evidenced by a P value of 0.000 (P value < 0.05).

Table 5 Results of single-factor ANOVA of slip with various drawbar pull increments.

Source of variation	SS	df	MS	F	P value	F crit
Between groups	257087.30	3.00	85695.76	1764.60	0.000*	2.62
Within groups	34868.84	718.00	48.56			
Total	291956.10	721.00				

*A P value smaller than the 5% significance level (P value < 0.05) indicates that slip significantly differs with different increments in drawbar pull.

Previous research has shown that high slip can cause the wheels to spin more than the distance traveled by the vehicle, meaning that much energy is wasted and not used to move the vehicle forward; this phenomenon decreases the overall traction efficiency (Grunditz, 2016; Yong et al., 2012). High slip conditions also require the engine to work harder to achieve the desired movement, leading to higher fuel consumption; this issue can be a significant problem, especially for heavy vehicles or machinery that require optimal fuel efficiency (Joshi, 2019; Mersky & Samaras, 2016). Several previous studies have highlighted the negative impact of slips on machines and vehicles. High slip causes excessive friction between the tyres and the ground surface, accelerating wear on the tyres and other mechanical components; this phenomenon can result in increased maintenance and replacement costs (Genovese et al., 2020; Zhang et al., 2023). High slip can also make vehicles less stable and more difficult to control, especially on challenging or slippery terrain, increasing the risk of accidents and skidding (Ahangarnejad et al., 2021; Gao & Abeysekera, 2004). The adverse effects of high slip also extend to soil conditions, causing surface damage, particularly in the field. High slip can lead to soil degradation and damage the work environment (Cambi et al., 2015; Hamza & Anderson, 2005). High slip can also cause the terrain to become very uneven. Naturally, the greater the degree of slip on the vehicle's wheels is, the greater the degree of sinkage. As a result, tools and machinery need help to operate in such terrain (Ding et al., 2010; Reina et al., 2006).

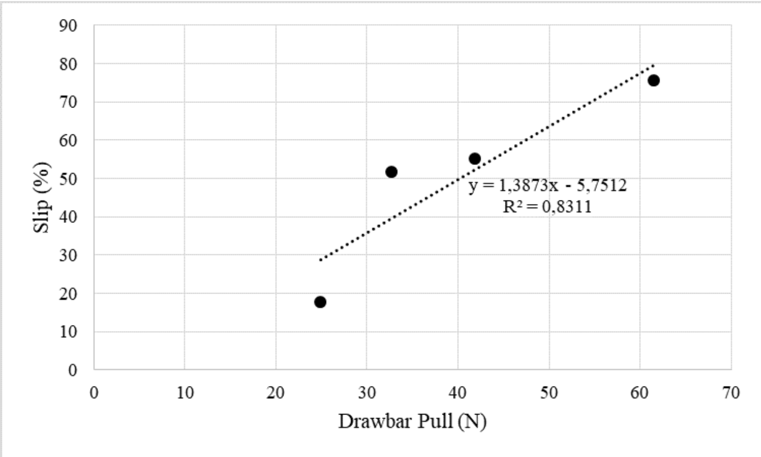

Figure 10 Effect of drawbar pull on slip.

3.3. Relationship between drawbar pull and tractive efficiency

The tractive efficiency parameter in the traction performance of a track-type lugged wheel is calculated via Equation (6). The output power is obtained by multiplying the drawbar pull (net traction) by the velocity. In contrast, the input power is obtained by multiplying the torque on the wheel axle by the wheel's angular velocity (Jenane & Bashford, 2000; Zoz et al., 2002). On the basis of the calculations of tractive efficiency for the track-type lugged wheel in a soil bin, an increase in drawbar pull evidently leads to a decrease in tractive efficiency, as shown in Figure 11. The coefficient of determination (R^2) obtained for the tractive efficiency parameter concerning drawbar pull is 0.8304, indicating that the decrease in tractive efficiency with increasing drawbar pull is inversely proportional. As explained by the parameters of sinkage and slip, which continue to rise with increasing drawbar pull, the tractive efficiency parameter conversely decreases. The reason for the decreasing tractive efficiency is the high levels of sinkage and slip (Baek et al., 2020; Xu et al., 2022). As the track-type lugged wheel sinks deeper, the wheels struggle with mobility, leading to increased slip (Shi et al., 2023). This increased slip occurs because the load the track-type lugged wheel pulls is greater than the traction generated by the wheels to move forward (Wulfsohn et al., 2009).

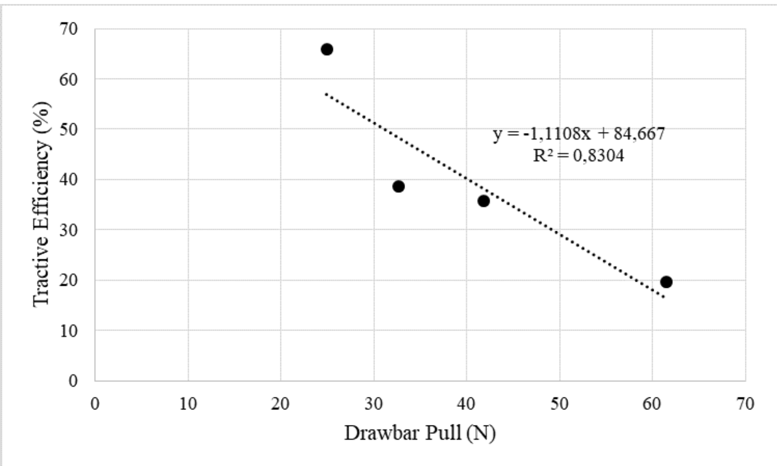

Figure 11 Effect of drawbar pull on tractive efficiency.

The lug penetration required to paddle the wheels optimally does not yet improve tractive efficiency. The tractive efficiency achieved at a slip condition of 17.75% and a drawbar pull of 24.91 N is 65.87%; the slip condition within its threshold results in relatively high tractive efficiency. However, the tractive efficiency successively decreases to 38.68% and 19.59% at slip conditions above 50% to 75% or at drawbar pulls of 30 N to 60 N. Therefore, to achieve optimal tractive efficiency, the drawbar pull applied to the track-type lugged wheel should be below 30 N or when the slip is below 17.75%. The results indicate that the current design of track-type lugged wheels needs modification, particularly with respect to the lugs. The lugs, which function as paddles on the track-type lugged wheel, should positively influence the traction performance. Modifications can be made by altering the lug spacing and lug height (Wong & Huang, 2006). Different lug spacings and heights can impact the traction performance of track-type lugged wheels (Yang et al., 2014). Varying the lug spacing affects the number of active lugs, which is crucial for traction performance during soil penetration. Similarly, a greater lug height increases the contact surface area between the lug and the soil, increasing the penetration force and traction performance (Liu et al., 2024). The analysis based on a single-factor ANOVA test, shown in Table 6, indicates that the increase in drawbar pull has a significantly different effect on the tractive efficiency parameter, as evidenced by a P value of 0.000 (P value < 0.05).

Table 6 Results of single-factor ANOVA of tractive efficiency with various drawbar pull increments.

Source of variation	SS	df	MS	F	P value	F crit
Between groups	257087.30	3.00	85695.76	1764.60	0.000*	2.62
Within groups	34868.84	718.00	48.56			
Total	291956.10	721.00				

*A P value smaller than the 5% significance level (P value < 0.05) indicates that tractive efficiency significantly differs with different increments in drawbar pull.

4. Conclusions

Horizontal loading can significantly improve drawbar pull parameters on the basis of single-factor ANOVA, with a P value < 0.05. The increase in drawbar pull significantly affects traction performance, including sinkage, slip, and tractive efficiency, in the prototype track-type lugged wheel tested in a soil bin, according to single-factor ANOVA with a P value < 0.05. Increased drawbar pull leads to increased sinkage and slip but reduces tractive efficiency. The drawbar pull value that maintains normal limits for sinkage (< 8.5 cm) for optimal traction performance is 32.72 N, whereas the value for normal slip limits (< 20%) and optimal tractive efficiency (> 65%) is 24.91 N. The prototype track-type lugged wheel works optimally for paddy fields with saturated and muddy soil conditions. The additional lug design functions as a paddle, enhancing wheel traction performance. Modifications in lug spacing and lug height are necessary to optimize the traction performance of the track-type lugged wheel at higher drawbar pull levels.

Acknowledgment

This research was supported by the Ministry of Education, Culture, Research and Technology of the Republic of Indonesia (Kemdikbudristek RI) for funding doctoral studies and IPB University for serving laboratory facilities.

Ethical considerations

Not applicable.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All the authors have approved the manuscript and agree with the journal's submission process.

Funding

This research is fully supported and funded by the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia (Kemdikbudristek RI).

References

Abbasi, R., Martinez, P., & Ahmad, R. (2022). The digitization of agricultural industry-a systematic literature review on agriculture 4.0. *Smart Agricultural Technology, 2*, 100042. https://doi.org/10.1016/j.atech.2022.100042

Abubakar, M., Ahmad, D., Othman, J., & Suleiman, S. (2009). Present state of research on development of a high clearance vehicle for paddy fields. *Research Journal of Agriculture and Biological Sciences, 5*(4), 489-497.

Ahangarnejad, A. H., Radmehr, A., & Ahmadian, M. (2021). A review of vehicle active safety control methods: From antilock brakes to semiautonomy. *Journal of Vibration and Control, 27*(15-16), 1683-1712. https://doi.org/10.1177/1077546320948656

Ani, O. A., Xu, H., Shen, Y.-p., Liu, S.-g., & Xue, K. (2013). Modeling and multiobjective optimization of traction performance for autonomous wheeled mobile robot in rough terrain. *Journal of Zhejiang University SCIENCE C, 14*(1), 11-29. https://doi.org/10.1631/jzus.C12a0200

Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., & Ruggeri, M. (2019). The digitisation of agriculture: a survey of research activities on smart farming. *Array, 3*, 100009. https://doi.org/10.1016/j.array.2019.100009

Baek, S.-H., Shin, G.-B., Lee, S.-H., Yoo, M., & Chung, C.-K. (2020). Evaluation of the slip sinkage and its effect on the compaction resistance of an off-road tracked vehicle. *Applied Sciences, 10*(9), 3175. https://doi.org/10.3390/app10093175

Barrand, J., & Bokar, J. (2008). Reducing tire rolling resistance to save fuel and lower emissions. *SAE International Journal of Passenger Cars-Mechanical Systems, 1*(2008-01-0154), 9-17. https://doi.org/10.4271/2008-01-0154

Battiato, A., & Diserens, E. (2013). Influence of tyre inflation pressure and wheel load on the traction performance of a 65 kW MFWD tractor on a cohesive soil. *Journal of Agricultural Science, 5*(8), 197. https://doi.org/10.5539/jas.v5n8p197

Bawden, O., Ball, D., Kulk, J., Perez, T., & Russell, R. (2014). A lightweight, modular robotic vehicle for the sustainable intensification of agriculture. *Proceedings of the 16th Australasian Conference on Robotics and Automation 2014*,

Bruzzone, L., Nodehi, S. E., & Fanghella, P. (2022). Tracked locomotion systems for ground mobile robots: A review. *Machines, 10*(8), 648. https://doi.org/10.3390/machines10080648

Cambi, M., Certini, G., Neri, F., & Marchi, E. (2015). The impact of heavy traffic on forest soils: A review. *Forest ecology and management, 338*, 124-138.https://doi.org/10.1016/j.foreco.2014.11.022

Cesco, S., Sambo, P., Borin, M., Basso, B., Orzes, G., & Mazzetto, F. (2023). Smart agriculture and digital twins: Applications and challenges in a vision of sustainability. *European Journal of Agronomy, 146*, 126809. https://doi.org/10.1016/j.eja.2023.126809

Choir, I. R., Iskandar, J., Parikesit, P., Partasasmita, R., Husodo, T., Kusmoro, J., & Megantara, E. N. (2018). The local management and sustainability of swidden farming in the Villages of Bojongsalam and Sukaresmi, Upper Cisokan Watershed, West Java, Indonesia. *Biodiversitas Journal of Biological Diversity, 19*(3), 054-1065. https://doi.org/10.13057/biodiv/d190338

Comin, F. J., Lewinger, W. A., Saaj, C. M., & Matthews, M. C. (2017). Trafficability assessment of deformable terrain through hybrid wheel-leg sinkage detection. *Journal of Field Robotics, 34*(3), 451-476. https://doi.org/10.1002/rob.21645

Di Maria, E., Reina, G., Ishii, K., & Giannoccaro, N. I. (2021). Rolling resistance and sinkage analysis by comparing FEM and experimental data for a grape transporting vehicle. *Journal of Terramechanics, 97*, 59-70. https://doi.org/10.1016/j.jterra.2021.06.004

Ding, J., Li, F., Le, T., Xu, D., Zhu, M., Li, C., Zhu, X., & Guo, W. (2021). Tillage and seeding strategies for wheat optimizing production in harvested rice fields with high soil moisture. *Scientific Reports, 11*(1), 119. https://doi.org/10.1038/s41598-020-80256-7

Ding, L., Gao, H.-b., Deng, Z.-q., & Tao, J.-g. (2010). Wheel slip-sinkage and its prediction model of lunar rover. *Journal of Central South University of Technology, 17*(1), 129-135. https://doi.org/10.1007/s11771-010-0021-7

Dizqah, A., Ballard, B., Blundell, M., Kanarachos, S., & Innocente, M. (2020). A non-convex control allocation strategy as energy-efficient torque distributors for on-road and off-road vehicles. *Control Engineering Practice, 95*, 104256. https://doi.org/10.1016/j.conengprac.2019.104256

Dobretsov, R., Porshnev, G., & Uvakina, D. (2018). Performance improvement of Arctic tracked vehicles. *MATEC Web of Conferences*, https://doi.org/10.1051/matecconf/201824517001

Du, Y., Gao, J., Jiang, L., & Zhang, Y. (2017). Numerical analysis of lug effects on tractive performance of off-road wheel by DEM. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39*, 1977-1987. https://doi.org/10.1007/s40430-016-0633-4

Fu, J., Ji, C., Liu, H., Wang, W., Zhang, G., Gao, Y., Zhou, Y., & Abdeen, M. A. (2022). Research progress and prospect of mechanized harvesting technology in the first season of ratoon rice. *Agriculture, 12*(5), 620. https://doi.org/10.3390/agriculture12050620

Fuglie, K. O. (2010). Sources of growth in Indonesian agriculture. *Journal of Productivity Analysis, 33*, 225-240. https://doi.org/10.1007/s11123-009-0150-x

Gao, C., & Abeysekera, J. (2004). A systems perspective of slip and fall accidents on icy and snowy surfaces. *Ergonomics, 47*(5), 573-598. https://doi.org/10.1080/00140130410081658718

Gao, J.-W., Dai, X., Zhu, S.-P., Zhao, J.-W., Correia, J. A., & Wang, Q. (2022). Failure causes and hardening techniques of railway axles-A review from the perspective of structural integrity. *Engineering Failure Analysis, 141*, 106656. https://doi.org/10.1016/j.engfailanal.2022.106656

Gelin, O., & Björheden, R. (2020). Concept evaluations of three novel forwarders for gentler forest operations. *Journal of Terramechanics, 90*, 49-57. https://doi.org/10.1016/j.jterra.2020.04.002

Genovese, A., D'Angelo, G. A., Sakhnevych, A., & Farroni, F. (2020). Review on friction and wear test rigs: An overview on the state of the art in tyre tread friction evaluation. *Lubricants, 8*(9), 91. https://doi.org/10.3390/lubricants8090091

Gonzalez-de-Soto, M., Emmi, L., Garcia, I., & Gonzalez-de-Santos, P. (2015). Reducing fuel consumption in weed and pest control using robotic tractors. *Computers and Electronics in Agriculture, 114*, 96-113. https://doi.org/10.1016/j.compag.2015.04.003

Grunditz, E. A. (2016). Design and assessment of battery electric vehicle powertrain, with respect to performance, energy consumption and electric motor thermal capability (Doctoral dissertation). Chalmers University Of Technology, Göteborg, Sweden.

Hall, D. E., & Moreland, J. C. (2001). Fundamentals of rolling resistance. *Rubber Chemistry and Technology, 74*(3), 525-539. https://doi.org/10.5254/1.3547650

Hamza, M., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research, 82*(2), 121-145. https://doi.org/10.1016/j.still.2004.08.009

Hidayat, R. A., Partasasmita, R., Iskandar, J., & Gunawan, B. (2020). Changes in paddy field management in sindang hamlet, rancakalong village, sumedang district, West Java, Indonesia. *Biodiversitas Journal of Biological Diversity, 21*(1). https://doi.org/10.13057/biodiv/d210114

Jenane, C., & Bashford, L. (2000). SW-Soil and Water: Tractive Performance of a Mechanical Front-Wheel Assist Tractor as related to Forward Speeds. *Journal of Agricultural Engineering Research, 77*(2), 221-226. https://doi.org/10.1006/jaer.2000.0569

Jerhamre, E., Carlberg, C. J. C., & van Zoest, V. (2022). Exploring the susceptibility of smart farming: Identified opportunities and challenges. *Smart Agricultural Technology, 2*, 100026. https://doi.org/10.1016/j.atech.2021.100026

Jiang, S., Wang, Q., Zhong, G., Tong, Z., Wang, X., & Xu, J. (2021). Brief review of minimum or no-till seeders in china. AgriEngineering, 3(3), 605-621. https://doi.org/10.3390/agriengineering3030039

Jin, H., Zhiqiang, Z., Hongwen, L., & Qingjie, W. (2014). Development of small/medium size no-till and minimum-till seeders in Asia: A review. *International Journal of Agricultural and Biological Engineering, 7*(4), 1-12.

Joshi, A. (2019). Review of vehicle engine efficiency and emissions. *SAE International Journal of Advances and Current Practices in Mobility, 1*(2019-01-0314), 734-761. https://doi.org/10.4271/2019-01-0314

Ju, F., Zhuang, W., Wang, L., & Zhang, Z. (2020). Comparison of four-wheel-drive hybrid powertrain configurations. *Energy, 209*, 118286. https://doi.org/10.1016/j.energy.2020.118286

Kebede, L., & Getnet, B. (2016). Performance of single axle tractors in the semi-arid central part of Ethiopia. *Ethiopian Journal of Agricultural Sciences, 27*(1), 37-53.

Keen, A., Hall, N., Soni, P., Gholkar, M. D., Cooper, S., & Ferdous, J. (2013). A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production. *Journal of Terramechanics, 50*(1), 45-62. https://doi.org/10.1016/j.jterra.2012.08.001

Khaehanchanpong, Y. (2018). Agricultural Mechanization in Thailand: Design and Development of Machinery Implements for Small-Scale Farmers (Doctoral dissertation). University of Tsukuba, Tsukuba, Ibaraki.

Knierim, A., Kernecker, M., Erdle, K., Kraus, T., Borges, F., & Wurbs, A. (2019). Smart farming technology innovations-Insights and reflections from the German Smart-AKIS hub. *NJAS-Wageningen Journal of Life Sciences, 90*, 100314. https://doi.org/10.1016/j.njas.2019.100314

La Monaca, A., Murray, J. W., Liao, Z., Speidel, A., Robles-Linares, J. A., Axinte, D. A., Hardy, M. C., & Clare, A. T. (2021). Surface integrity in metal machining-Part II: Functional performance. *International Journal of Machine Tools and Manufacture, 164*, 103718. https://doi.org/10.1016/j.ijmachtools.2021.103718

Li, C., Tang, Y., McHugh, A. D., Wu, X., Liu, M., Li, M., Xiong, T., Ling, D., Tang, Q., & Liao, M. (2022). Development and performance evaluation of a wet-resistant strip-till seeder for sowing wheat following rice. *Biosystems Engineering, 220*, 146-158. https://doi.org/10.1016/j.biosystemseng.2022.05.019

Liljedahl, J. B., Turnquist, P. K., Smith, D. W., & Hoki, M. (1989). *Tractors and their power units*. Springer. https://doi.org/10.1007/978-1-4684-6632-4

Liu, Y., Xu, Z., & Xia, J. (2024). Understanding front-rear track effect of seabed mining vehicle and traction performance optimization. *Marine Georesources & Geotechnology*, 1-18. https://doi.org/10.1080/1064119X.2024.2333033

Maclaurin, B. (2018). High Speed Off-Road Vehicles: *Suspensions, Tracks, Wheels and Dynamics*. John Wiley & Sons. https://doi.org/10.1002/9781119258827

Md-Tahir, H., Zhang, J., Xia, J., Zhang, C., Zhou, H., & Zhu, Y. (2019). Rigid lugged wheel for conventional agricultural wheeled tractors-optimising traction performance and wheel-soil interaction in field operations. *Biosystems Engineering, 188*, 14-23. https://doi.org/10.1016/j.biosystemseng.2019.10.001

Mersky, A. C., & Samaras, C. (2016). Fuel economy testing of autonomous vehicles. *Transportation Research Part C: Emerging Technologies, 65*, 31-48. https://doi.org/10.1016/j.trc.2016.01.001

Mitchell, J., Cheth, K., Seng, V., Lor, B., Ouk, M., & Fukai, S. (2013). Wet cultivation in lowland rice causing excess water problems for the subsequent non-rice crops in the Mekong region. *Field Crops Research, 152*, 57-64. https://doi.org/10.1016/j.fcr.2012.12.006

Mkomwa, S., Kaumbutho, P., & Makungu, P. (2015). Farm machinery for conservation agriculture. *Conservation Agriculture*, 109-131. https://doi.org/10.1007/978-3-319-11620-4_5

Nassiraei, A. A. F., & Skonieczny, K. (2020). Grousers improve drawbar pull by reducing resistance and generating thrust at the front of a wheel. *Journal of Terramechanics, 91*, 73-84. https://doi.org/10.1016/j.jterra.2020.05.005

Osinenko, P., & Streif, S. (2017). Optimal traction control for heavy-duty vehicles. *Control Engineering Practice, 69*, 99-111. https://doi.org/10.1016/j.conengprac.2017.09.010

Ozawa, Y., Watanabe, M., Tadakuma, K., Takane, E., Marafioti, G., & Tadokoro, S. (2020). Mono-wheeled flexible track capable of climbing high steps and adapting to rough terrains. 2020 *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. https://doi.org/10.1109/SSRR50563.2020.9292576

Paman, U., Bahri, S., Khairizal, K., & Wahyudy, H. A. (2018). Farm machinery development and utilization system policies for small-scale rice farming. *International on Advanced Science Enginering Information Technology, 8*(3). https://doi.org/10.18517/ijaseit.8.3.1758

Park, W., Chang, Y., Lee, S., Hong, J., Park, J., & Lee, K. (2008). Prediction of the tractive performance of a flexible tracked vehicle. *Journal of Terramechanics, 45*(1-2), 13-23. https://doi.org/10.1016/j.jterra.2007.11.002

Partasasmita, R., Iskandar, B. S., Nuraeni, S., & Iskandar, J. (2019). Impact of the green revolution on the gender's role in wet rice farming: A case study in Karangwangi Village, Cianjur District, West Java, Indonesia. *Biodiversitas Journal of Biological Diversity, 20*(1), 23-36. https://doi.org/10.13057/biodiv/d200104

Pitoyo, J., Shoji, K., & Kawamura, T. (2017). Weeding efficacy and power requirement of walking-type power weeder under varying rotor slippage in paddy field. *Journal of the Japanese Society of Agricultural Machinery and Food Engineers, 79*(3), 273-278.

Piyush, P., & Ajay, V. (2017). Cage wheel for traction improvement in power tiller. *Journal of Plant Development Sciences, 9*(7), 631-636.

Pradhan, P., Verma, A., Guru, P. K., & Pandey, M. K. (2018). Traction performance of different size of cage wheel for power tiller. *ORYZA-An International Journal on Rice, 55*(1), 185-190. https://doi.org/10.5958/2249-5266.2018.00022.X

Preda, I. (2022). Theoretical estimation of the drawbar pull for two-axle automotive vehicles. *IOP Conference Series: Materials Science and Engineering*, https://doi.org/10.1088/1757-899X/1220/1/012013

Raheman, H., & Snigdharani, E. (2020). Development of a variable-diameter cage wheel for walking tractor and its performance evaluation in soil bin (simulating wetland). *Journal of the Institution of Engineers (India): Series A, 101*, 41-48. https://doi.org/10.1007/s40030-019-00413-8

Rasool, S., & Raheman, H. (2016). Suitability of rubber track as traction device for power tillers. *Journal of Terramechanics, 66*, 41-47. https://doi.org/10.1016/j.jterra.2015.08.003

Rasool, S., & Raheman, H. (2018). Improving the tractive performance of walking tractors using rubber tracks. *Biosystems Engineering, 167*, 51-62. https://doi.org/10.1016/j.biosystemseng.2017.12.013

Reina, G., Ojeda, L., Milella, A., & Borenstein, J. (2006). Wheel slippage and sinkage detection for planetary rovers. *IEEE/Asme Transactions on Mechatronics, 11*(2), 185-195. https://doi.org/10.1109/TMECH.2006.871095

Rodríguez-Martínez, D., Van Winnendael, M., & Yoshida, K. (2019). High-speed mobility on planetary surfaces: A technical review. *Journal of Field Robotics, 36*(8), 1436-1455. https://doi.org/10.1002/rob.21912

Sagwal, P., Khandai, S., Bhowmick, M. K., Singh, K., Srivastava, A., Dhillon, B., Rawal, S., Kumar, V., Kumar, A., & Singh, S. (2022). Scale-appropriate mechanization for improving productivity, profitability, and sustainability of rice-based cropping systems in India. In *Innovation in Small-Farm Agriculture* (pp. 195-206). CRC Press. https://doi.org/10.1201/9781003164968-21

Sandu, C., Worley, M. E., & Morgan, J. (2010). Experimental study on the contact patch pressure and sinkage of a lightweight vehicle on sand. *Journal of Terramechanics, 47*(5), 343-359. https://doi.org/10.1016/j.jterra.2010.04.005

Sharma, A. (2021). Conservation agriculture in India: History, progress and way forward. *Indian Journal of Agronomy, 66*(1), 1-18. https://doi.org/10.59797/ija.v66i1.2824

Shi, Y., Liu, J., Huang, D., Xu, M., Zhai, S., Zhang, W., & Jiang, P. (2023). Prediction and Experimental Study of Tire Slip Rate Based on Chassis Sinkage Amount. *Agriculture, 13*(3), 665. https://doi.org/10.3390/agriculture13030665

Storckenfeldt, C., & Ganatra, D. (2021). Vehicle Speed Estimation During Excessive Tyre Slip Conditions *(Mastes thesis). Chalmers University Of Technology, Gothenburg, Sweden.*

Takeshima, H., & Mano, Y. (2023). Intensification of Rice farming: the role of mechanization and irrigation. *Rice Green Revolution in Sub-Saharan Africa*, 143-160. https://doi.org/10.1007/978-981-19-8046-6_7

Taufiq, M., Mandang, T., Hermawan, W., & Desrial. (2022). Traction Performance Analysis of Track Wheels Type on Wet and Deep Muddy of Soil in Soil Bin. *Jurnal Keteknikan Pertanian, 10*(3), 226-239. https://doi.org/10.19028/jtep.010.3.226-239

Ten Damme, L., Schjønning, P., Munkholm, L., Green, O., Nielsen, S., & Lamandé, M. (2021). Traction and repeated wheeling-effects on contact area characteristics and stresses in the upper subsoil. *Soil and Tillage Research, 211*, 105020. https://doi.org/10.1016/j.still.2021.105020

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., & Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production, 33*, 86-96. https://doi.org/10.1016/j.jclepro.2012.05.001

Wang, W.-H., Zou, T.-A., Xu, X.-J., & Xu, H.-J. (2023). Enhancing the tractive performance of unmanned vehicles using an optimised wheel-step driving system. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 237*(5), 958-977. https://doi.org/10.1177/09544070221087002

Wang, Y., Xi, X., Chen, M., Shi, Y., Zhang, Y., Zhang, B., Qu, J., & Zhang, R. (2022). Design of and Experiment on Reciprocating Inter-Row Weeding Machine for Strip-Seeded Rice. *Agriculture, 12*(11), 1956. https://doi.org/10.3390/agriculture12111956

Wong, J. Y., & Huang, W. (2006). "Wheels vs. tracks"-A fundamental evaluation from the traction perspective. *Journal of Terramechanics, 43*(1), 27-42. https://doi.org/10.1016/j.jterra.2004.08.003
Wulfsohn, D., Way, T. R., Upadhyaya, S. K., & Chancellor, W. J. (2009). Traction Mechanics. Part III. Traction Device-Soil Interface Behavior. In *Advances in Soil Dynamics Volume 3* (pp. 85-129). American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/2013.26868
Xu, Z., Liu, Y., Yang, G., Xia, J., Dou, Z., Meng, Q., & Xu, X. (2022). Research on contact model of track-soft sediment and traction performance of four-tracked seabed mining vehicle. *Ocean Engineering, 259*, 111902. https://doi.org/10.1016/j.oceaneng.2022.111902
Yang, Y., Sun, Y., Ma, S., & Yamamoto, R. (2014). Characteristics of normal and tangential forces acting on a single lug during translational motion in sandy soil. *Journal of Terramechanics, 55*, 47-59. https://doi.org/10.1016/j.jterra.2014.05.006
Yong, R. N., Fattah, E. A., & Skiadas, N. (2012). *Vehicle traction mechanics*. Elsevier.
Zhang, M., Yin, H., Tan, J., Wang, X., Yang, Z., Hao, L., Du, T., Niu, Z., & Ge, Y. (2023). A comprehensive review of tyre wear particles: Formation, measurements, properties, and influencing factors. *Atmospheric Environment, 297*, 119597. https://doi.org/10.1016/j.atmosenv.2023.119597
Zhang, S.-l., Wen, C.-k., Ren, W., Luo, Z.-h., Xie, B., Zhu, Z.-x., & Chen, Z.-j. (2023). A joint control method considering travel speed and slip for reducing energy consumption of rear wheel independent drive electric tractor in ploughing. *Energy, 263*, 126008. https://doi.org/10.1016/j.energy.2022.126008
Zhang, Y., Tian, L., Cao, C., Zhu, C., Qin, K., & Ge, J. (2022). Optimization and validation of blade parameters for inter-row weeding wheel in paddy fields. *Frontiers in Plant Science, 13*, 1003471. https://doi.org/10.3389/fpls.2022.1003471
Zirek, A., & Onat, A. (2020). A novel anti-slip control approach for railway vehicles with traction based on adhesion estimation with swarm intelligence. *Railway Engineering Science, 28*(4), 346-364. https://doi.org/10.1007/s40534-020-00223-w
Zirek, A., Voltr, P., Lata, M., & Novák, J. (2018). An adaptive sliding mode control to stabilize wheel slip and improve traction performance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232*(10), 2392-2405. https://doi.org/10.1177/0954409718774139
Zoz, F. M., Turner, R., & Shell, L. (2002). Power delivery efficiency: a valid measure of belt and tire tractor performance. *Transactions of the ASAE, 45*(3), 509. https://doi.org/10.13031/2013.8817