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Comparing Conventional and Modified Cage Wheel Performance in Lowland Conditions

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In agricultural production, significant cost consumption from tillage due to high energy input and low work performance may be reduced by improving the design of hand tractor components, specifically tractive devices. This study aimed to compare the field performance of conventional and modified cage wheels for hand tractors in terms of field efficiency (FE), wheel slip, and fuel consumption (FC). Using the Philippine standard methods of testing for walking-type tractors and a two-tailed *t*-test to analyze the data, results showed that the modified cage wheel had an FE of 90.09%, wheel slip of 7.78%, FC of 0.22 L/h, and FC per area of 0.71 L/ha while the conventional cage wheel had an FE of 86.90%, wheel slip of 13.37%, FC of 0.40 L/h, and FC per area of 1.11 L/ha. The reduced wheel slip and FC values prove that utilization of the modified cage wheel in wetland conditions is more suitable in improving field performance than the conventional cage wheel.

Keywords: tillage operation, hand tractor, cage wheel, wheel slip

INTRODUCTION

Walking-type agricultural tractors (WTAT), also known as hand tractors or power tillers (UN ESCAP-CSAM 2017), are described in PNS/BAFS 345:2022 as “self-propelled machines having a single axle designed primarily to pull and propel trailed, semi-mounted, and/or mounted agricultural implements and machinery that are properly matched and with the operator walking behind” (BAFS-DA 2022a, p. 3). These tractors are a well-accepted power source for lowland cultivation of paddy in the Philippines. The most commonly used WTAT has an engine size rating of 7.40–11.80 kW and weight of about 220 – 480 kg with two drive wheels (Sahay et al. 2009). Various brands include Kubota, Briggs and Stratton, and Yanmar (Mitarai et al. 2008). WTATs are usually equipped with two types of tractive devices for locomotion—cage wheels and pneumatic rubber wheels. Cage wheels support the machine by distributing the weight of the machine (lower soil pressure) which reduces soil compaction and prevents field bog down. Pradhan and Verma (2017) observed that cage wheels exert three times more pull than pneumatic rubber wheels in flooded soil conditions. Rubber-tired wheels (usually pneumatic) have poor performance in paddy lowland conditions and are instead recommended for transportation.

The yield of drawbar performance measures the effectiveness of tractors (Russini et al. 2018). Pull and travel speed determine drawbar work. At the tractor drawbar, the tractor transforms all of the energy from the fuel inputs into productive work. In addition to losses from the engine through the drivetrain and the tractive device (wheels), the majority of potential energy is lost during the conversion of chemical energy (fuel) to mechanical energy (output shaft) (Zoz and Grisso 2003). Studies found that around 20% – 55% of the tractor energy available is eventually lost when the tractive device is in contact with the soil interface (Zoz and Grisso 2003; Simikić et al. 2014). The performance of the WTAT is greatly influenced by both the traction device design and the performance of its transmission system. Tractive efficiency is defined as the efficiency of a traction device, while power delivery efficiency is defined as the efficiency of an entire WTAT (Zoz et al. 2002).

In a study that analyzed the performance of cage wheels for small WTATs in agricultural soil, Triratanasirichai et al. (1990) observed that the tractive efficiency of a WTAT is the most important traction index of a tractive device. Zoz et al. (2002) also investigated the traction performance of wheeled and rubber belt tractors and discovered that the best parameter for estimating and comparing traction performance was power delivery efficiency, which is the ratio of drawbar power to engine power. It is, therefore, appropriate for comparing different tractor types with varying traction systems.

Hendriadi and Salokhe (2002) conducted a study on the traction performance of a cage wheel in swampy peat soils in Indonesia and reported that the traction performance significantly improved due to an increase in the lug angle (from 15° to 35°) and the lug length; however, the effect of the increased number of lugs (from 14 to 18) was insignificant. They also concluded that the cage wheel with a lug size of 325 x 80 mm^2, a lug angle of 35°, and 14 lugs with 26° spacing outperformed lug angles of 15°, 25°, and 45°, and lug lengths 275 x 80, 375 x 80, and 275 x 95 mm^2 in swampy peat soils. Pradhan et al. (2018) also analyzed the traction performance of different sizes of cage wheels for WTATs and found that the selection of cage wheels for tillage operation is important in optimizing tractive performance. Proper cage wheels limit slip and fuel consumption, thereby minimizing losses and time required for tillage operation.

Kumar and Baruah (2013) also reviewed previous studies on tractive performance of cage wheels on wetlands, which involved performance analysis of cage wheels operated under lowland conditions, the behavior of soil under the action of traction devices, new designs of lowland traction devices, traction dynamics, and optimization of design parameters of traction devices. Different cage wheels were designed particularly for diverse field conditions which were of different lug configurations, wheel dimensions, wheel materials, and coatings, among others. One of these cage wheels is designed and manufactured by D.B. Varona Metal Craft Industries. Hence, this study aimed to compare the field performance of conventional and modified cage wheels manufactured by D.B. Varona to determine which type can achieve increased field efficiency and reduced wheel slip and fuel consumption.

MATERIALS AND METHODS

Description of Cage Wheels

Fig. 1 shows the cage wheels used during the field test, and their specifications are presented in Table 1 and Fig. 2. The conventional cage wheel has a higher number of lugs (10) and a lug angle of 45°, while the modified cage wheel's lug is oriented with a circumferential angle of 14° (Fig. 3)—a common design and configuration of most available cage

Fig. 1. Conventional (left) and modified (right) cage wheels.

Table 1. Specifications of the conventional and modified cage wheels.

Specifications	Conventional	Modified
Rim diameter, mm	420	390
Rim width, mm	500	515
Lugs made from mild steel flat plate size	60	50
No. of lugs	12	10
Lug angle, °	45	30
Circumferential lug angle, °	0	14
Weight of cage wheel, kg	22	15

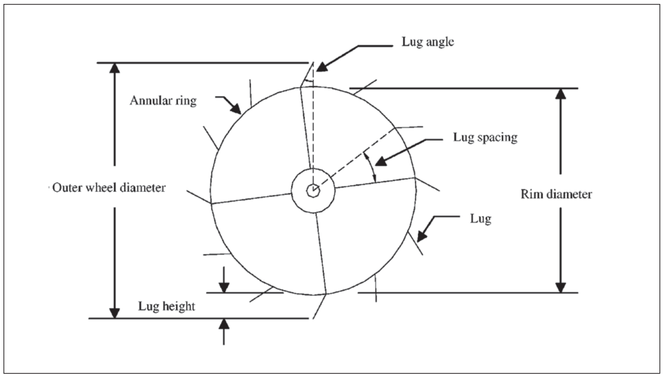

Fig. 2. Specification determination of the cage wheel (adopted from Watyotha and Salokhe [2001b]).

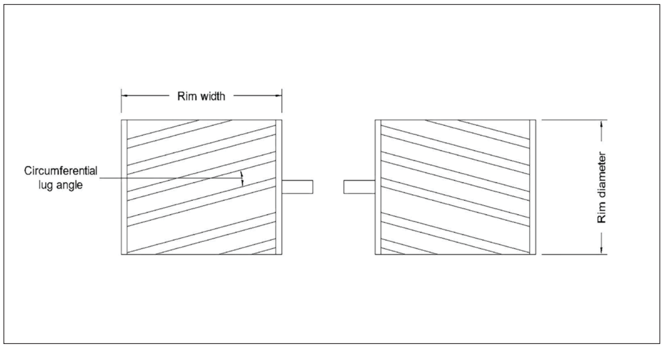

Fig. 3. Modified cage wheel parameters.

wheels in the Philippine market, while the modified cage wheel's lug is oriented with a circumferential angle of 14°(Fig. 3.). D.B. Varona Metal Craft Industries (located at 90 Katipunan St., Brgy. Poblacion, Lucban, Quezon, Philippines) has been manufacturing modified cage wheels since 2005. Compared to the conventional cage wheel's hexagonal shafting, round shafting is used for the modified cage wheel's axle. The idea for this design was to modify existing hand tractors to become lightweight, operator-friendly, and have a shortened machine length for ease of turning even on highlands with high headlands (personal communication with D.B. Varona; unreferenced).

Description of the Walking-type Agricultural Tractor (WTAT)

The WTAT is a single-axle, pull-type tractor and is also manufactured by D.B. Varona Metal Craft Industries (Fig. 4). Engine power is transmitted to the shaft through a single-groove pulley and V-belts. The engine mounted is a four-stroke, single-cylinder, inclined, air-cooled diesel engine with a rated power of 2.30 kW. Engine power is then transmitted from the drive shaft to the axle through a chain-and-sprocket transmission system. The main assembly of the WTAT consists of an engine mounting frame bolted to the transmission assembly and the handlebar. The WTAT has a clutch lever on the right handlebar. During operation, an axle made of a 32 mm solid round shaft is fitted with a spike-tooth harrow with eight spikes, a 965 mm operating width, and 16 mm bars. A single-hole hitch point assembly is provided for attachments such as plows and harrows.

Field Testing

Test Site Conditions. Part of the PhilRice rice farm at Agripark, College of Agriculture and Food Science (CAFS), University of the Philippines Los Baños (UPLB) was selected as the test site, with conditions shown in Table 2. The soil texture was classified as "Maahas clay" containing 19.33% sand, 28.67% silt, and 52.00% clay with a particle density of 2.30 g/cm^3, plastic limit of 42%, liquid limit of 71%, and plasticity index of 29% (Fajardo et al. 2014). The test site was unplowed soil soaked for 24 h with a water level of 7.9 cm for the lowland field. The test plots were rectangular with a length and width of 32 x 17 m (2:1 ratio) equivalent to 544 m^2. These conditions are compliant with the Philippine National Standards/Bureau of Agricultural and Fisheries Standards (PNS/BAFS) 348:2022 (BAFS-DA 2022b).

Actual Field Test. The spike-tooth harrow's depth of cut was 100 mm for harrowing with an operating width of 965 mm. The specifications of the spike-tooth harrow are compliant with the Philippine National Standards/Philippine Agricultural Engineering Standards (PNS/PAES) 169:2015 (DTI-BPS 2015). Before the test, the WTAT underwent a running-in period for various adjustments as no tunings were allowed during the testing operation. During the test, a handheld GPSMAP @ 64s, 2.6 in sunlight-readable color screen, 160 x 240 pixels display resolution, and 4 GB memory was used to gather the forward speed (Fig. 5). Forward speed was gathered at without load and with load (harrowing operation) conditions per test plot. Each plot had an area of 544 m². A handheld contact/non-contact digital tachometer with an accuracy of ± 0.5% was used to measure the output shaft speed of the engine during harrowing.


Fig. 4. WTAT used in the field test developed by D. B. Varona Metal Craft Industries.

Table 2. Test site conditions.

Site Parameters	Value
Soil type*	clay
Soil texture, %*	
Sand, %	19.33
Silt, %	28.67
Clay, %	52
Particle density, g/cm^3*	2.30
Plastic limit, %*	42
Liquid limit, %*	71
Plasticity index, %*	29
Water level, cm	7.90
Plot dimension (L x W), m	32 x 17

*from Fajardo et al. (2014)

Research Design

This study utilized a two-tailed *t*-test as an experimental design to compare the means of field efficiency, wheel slip, and fuel consumption of conventional vs. modified cage wheels. The field performance test (based on PNS/BAFS 348:2022 [BAFS-DA 2022b]) per cage wheel underwent two trials with 544 m² per trial, amounting to a total of 1088 m². The data was analyzed using IBM SPSS Statistics V26.

Fig. 5. Actual field test of the conventional (left) and modified (right) cage wheels.

Evaluation Performance Parameters

Field efficiency (FE) is the ratio of effective field capacity (EFC) to theoretical field capacity (TFC), expressed in percent. It includes time loss (turning, adjustments, etc.) in the field and failure to utilize the full width of the machine (overlap and underlap). Equations 1 to 8 which were adopted from the PNS/BAFS 348:2022 (BAFS-DA 2022b) were used to calculate FE. The calculation commences with determining the average swath of width of cut, total distance traveled, effective area accomplished, effective field capacity, and theoretical field capacity.

$$S = \frac{W}{2n} \tag{1}$$

$$D = \frac{A}{S} = 2\,nl \tag{2}$$

$$A_e = 2\,nlw \tag{3}$$

$$A_o = A_e - A \tag{4}$$

$$A_u = A - A_e \tag{5}$$

$$C_E = \frac{60\,A_e}{t} \tag{6}$$

$$C_T = w_e - v \tag{7}$$

$$F_{eff} = \frac{C_E}{C_T} x\,10 \tag{8}$$

where: S – average swath, m; W – width of plot, m; n – number of trips per round; D – total distance traveled, m; A – area of the plot, m²; L – length of the plot, m; A_e – effective area accomplished, m²; w – operating width of implement, m; A_o – is the overlap, m²; A_u- untilled area, m²; C_e – effective field capacity, m²/h; t – time per trial, h; C_t – theoretical field capacity, m²/h; v – operating speed, m/h; F_{eff} – field efficiency, %.

Wheel slip is the percentage difference between drive wheel speed and ground speed—when tractive devices such as cage wheels lose traction during tillage operation and rotate at a speed different from the desired or intended rate. Wheel slip was computed as travel reduction ratio (TRR) (Eq. 9) and was also computed using Eq.10 adopted from Zoz et al. (2002) and Hendriadi and Salokhe (2002).

$$TRR = 1 - \frac{V_a}{V_t} \tag{9}$$

$$Vt = \omega \;\; x\,rr\,x\,\frac{2\pi}{60} \tag{10}$$

where: TRR – travel reduction ratio; Va – actual velocity, m/s; Vt – theoretical velocity, m/s; w – angular speed, m/s; rr – rolling radius of wheel.

Fuel consumption (FC) refers to the amount of fuel consumed by the engine during operation. It serves as a key metric for evaluating the efficiency and cost-effectiveness of the equipment, reflecting how efficiently the engine converts fuel into mechanical work for tasks like plowing or cultivating. Monitoring and optimizing fuel consumption are essential for agricultural practices to minimize operating costs and environmental impact. This is determined using Eq.11. The tank is filled before and after each trial (PNS/BAFS 348:2022 [BAFS-DA 2022b]).

$$FC = \frac{V}{t} \tag{11}$$

where: FC – Fuel Consumption, L/h; V – Volume of fuel consumed, L; t – time per trial, h.

RESULTS AND DISCUSSION

Field Efficiency

With an area of 544 m², the conventional cage wheel had a TFC of 0.42 ha/h with an EFC of 0.36 ha/h while the modified cage wheel had a TFC of 0.34 ha/h and an EFC of 0.31 ha/h (Table 3). Results from the *t*-test analysis show that the FE comparison of means is significant at a 5% significance level (Table 4), proving that the difference of 3.2% in FE is not comparable (Table 3). Although the width of cut was 135 cm for the conventional cage wheel and 128 cm for the modified cage wheel, the 7 cm difference did not affect the FE. The 3.2% FE difference is merely attributed to the design of the cage wheel, number of lugs, and circumferential angles. Watyotha and Salokhe (2001a; 2001b) reported that increasing the circumferential angle and decreasing the lug spacing would result in better balancing of side forces. The cage wheels with opposing circumferential lugs at a 15° circumferential angle and 24° and 30° lug spacings showed superior performances in comparison with normal cage wheel configurations. The presence of circumferential angles in the modified cage wheel improves field efficiency by enhancing the tractor's ability to maintain consistent traction and minimize slippage.

Results from local studies on hand tractors agree with the obtained FE values in this study. Amongo et al. (2020) developed an e-tractor tested in wetland operations with a plowing FE of 92.29% and a TFC of 0.11 ha/h. Bautista and Bato (2008) also evaluated ride-on-type hand tractors for plowing, harrowing, and leveling. Results from this study show that field capacity during side plowing, plowing, harrowing, and leveling were: 0.71 at 2.4; 0.2 at 3.6; 0.41 at 3.7; and 0.41 ha/h at a traveling speed of 3.2 km/h. The FE values obtained were 96.5%, 84.8%, 84.9%, and 84.1%, respectively. The FE values during side plowing were lower because it was difficult to align the cage wheel at the edge of the dike as the operator was riding during the operation. The range of the obtained FE values (84.1%–96.5%) is acceptable; however, since the FE of the modified cage wheel is higher, it could also be recommended for use in wetland conditions.

Table 3. Performance of the conventional and modified cage wheels.

	Conventional	Modified
Theoretical field capacity, ha/h	0.42	0.34
Effective field capacity, ha/h	0.36	0.31
Field efficiency, %	86.90	90.09
Wheel slip, %	12.37	7.78
Fuel consumption, L/h	0.40	0.22
Fuel consumption per area, L/ha	1.11	0.71

Table 4. Field efficiency (%) *t*-test of two samples assuming equal variances.

	Conventional	Modified
Mean	86.900	90.090
Variance	0.231	0.024
Observations	2	2
Pooled variance	0.128	
Hypothesized mean difference	0	
df	2	
t stat	-8.927	
P(T<=*t*) two-tail	0.012	

Wheel Slip

According to Raheman and Jha (2007) and Ekinci and Çarman (2017), the ideal range of wheel slip (TRR) for power tillers is between 8% and 15%; below this range, traction efficiency begins to decrease. This study found that wheel slip values were 12.37 % and 7.78% for conventional and modified cage wheels, respectively (Table 3). The *t*-test also revealed a significant difference at a 5% significance level between cage wheels (Table 5). This implies that using a modified cage wheel which has a lower wheel slip would lead to higher FE, lower FC, and higher tractive efficiency. Moreover, it could be observed that the circumferential lug angle configuration provided continuous contact with the soil surface. This setup may have reduced the wheel slip of the modified cage wheels.

During the field test, the depth of water was 7.9 cm, which was compliant with the standards. According to Pradhan and Verma (2017), wheel slip improvement is more prominent with the split lug cage wheel design and a compliant depth of water during tillage operation. This study's results are in line with the observation of Pradhan et al. (2018) that the wheel slip is lower at a depth of water of 5–10 cm compared with a depth of water of 0–5 cm. This results in higher tractive efficiency since the cage wheel lug plate cuts the soil. Consequently, soil sticking is reduced or washed by the available water, resulting in less sinkage or wheel slip.

Fuel Consumption

FC is crucial for assessing operational efficiency and cost-effectiveness since it allows farmers and entrepreneurs to make informed decisions on reduced operational expenses from hand tractors. Table 3 shows improved FC using the modified cage wheel, which is significant at a 5% significance

Table 5. Wheel slip (%) *t*-test of two samples assuming equal variances.

	Conventional	Modified
Mean	12.37	7.78
Variance	1.81	0.25
Observations	2	2
Pooled variance	1.03	
Hypothesized mean difference	0	
df	2	
t stat	4.53	
P(T<=*t*) two-tail	0.05	

level (Table 6). The FC reduction of 0.18 L/h may result in reduced operational expenses without sacrificing the quality of work. Moreover, the lower wheel slip (7.78%) of the modified cage wheel is attributed to lower fuel consumption (Table 3). Excessive wheel slip causes poor traction, leading to inefficiencies in power transfer from the engine to the ground. This reduced efficiency necessitates higher energy input to maintain forward motion, resulting in increased fuel consumption (Moitzi et al. 2014; Soylu and Carman 2021). FC may also be affected by the design of the cage wheel. Watyotha and Salokhe (2001a) found that the appropriate lug angle is crucial for optimizing grip and minimizing wheel slip. If lug angles are not aligned properly, excessive wheel slip can occur, leading to decreased efficiency in power transfer and increased fuel consumption. Maintaining an optimal lug angle ensures effective traction, promoting fuel-efficient operation. From their study, it was observed that cage wheels with opposing lugs that had circumferential angles of 15º– 30º had significantly higher power than those that had a circumferential angle of 45º. This confirms that this study's modified cage wheel with a lug angle of 30º is more efficient than the conventional cage wheel with a lug angle of 45º.

Table 6. Fuel consumption (L/h) *t*-test of two samples assuming equal variances.

	Conventional	Modified
Mean	0.4000	0.2200
Variance	0	0.0002
Observations	2	2
Pooled variance	0.0001	
Hypothesized mean difference	0	
df	2	
t stat	18	
P(T<=*t*) two-tail	0.0031	

Paman et al. (2015) conducted a field survey to compare the working performance of three types of power tillers for tillage operations in Kampar Region, Riau Province, Indonesia. They selected 22 rotary tillers, 11 moldboard plows, and 27 hydro tillers. The FC values were 15.88 L/ha for the rotary tillers, 17.75 L/ha for the moldboard plows, and 16.98 L/ha for the hydro tillers. Alizadeh and Allameh (2013) also tested a power tiller with a Kubota GA 70, a 5.2 kW engine for primary tillage, with an FC of 2.05 L/h. Upon conversion from L/h to L/ha, this study's results indicate an FC per area of 1.09 L/ha for conventional cage wheels and 0.83 L/ha for modified cage wheels. The modified cage wheels' value for FC per area, which is notably much lower than the results in the reported references, implies that modified cage wheels are more fuel-efficient than conventional cage wheels.

Moreover, when the modified cage wheel's FC value of 0.22 L/h is divided by its EFC value of 0.31 ha/h, the result is an FC per area value of 0.71 L/ha. On the other hand, the conventional cage wheel, with an FC value of 0.40 L/h, when divided by its EFC value of 0.36 ha/h, yields an FC per area value of 1.11 L/ha (Table 3). These results suggest that the use of a modified cage wheel would result in less volume of fuel consumed per ha of operation.

CONCLUSION

The use of the modified cage wheel with reduced rim diameter, increased rim width, reduced number of lugs, and reduced circumferential lug angle resulted in significant improvements in terms of field efficiency, wheel slip, fuel consumption and fuel consumption per hectare when compared to the conventional cage wheel. These design modifications show the potential of the modified cage wheel in contributing to sustainable machine utilization, reduced fuel consumption, and enhanced overall field performance. Highlighting these practical benefits, this study provides a valuable contribution in recommending the modified cage wheel for adoption.

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