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DESIGN AND PERFORMANCE OF HOLD-ON TYPE SORGHUM THRESHER FOR HIGH MOISTURE CONTENT

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Sorghum is a plant with broad adaptability, is resistant to drought, and is very suitable in marginal areas. Sorghum plants contain 7% to 17% seed composition and 83% to 93% leaf stems. At harvest, the moisture content of seeds is 20% to 30%, and the stem is around 76% to 88%. Several stages are carried out after the sorghum harvesting process, and one of them is threshing the sorghum seeds. The threshing of sorghum seeds requires a hold-on threshing machine so seeds can be threshed immediately after harvest, and the stems from sorghum plants can be chopped directly for cattle feed. This study aims to design and test the performance of a hold-on type sorghum threshing machine that can be used to thresh sorghum seeds immediately after harvesting at a grain moisture content of around 20% to 30%. The methods used include problem considerations, the preparation of structural designs, functional designs, manufacturing drawing designs, and manufacturing functional and performance testing. The results of testing the performance of the threshing machine revealed that the working capacity of the machine was affected by rod clamp rotation, the threshing cylinder, and the moisture content of sorghum seeds. The cleanliness level of sorghum seeds is above 90%, while the level of seed damage ranges from 0% to 1%.

Keywords: engineering properties; sorghum plant; sorghum threshing; technical performance

Sorghum is a multipurpose plant which is currently widely used, starting from its grains for food (Meena et al., 2022), pressed sorghum juice for energy in the form of bioethanol (Wirawan et al., 2024) and residual biomass used for animal feed (Beretta et al., 2021), and other valuable products such as bio pellets (Wiloso et al., 2020). Sorghum grain could be processed into many food types such as bakery products, extruded products, beverages, and porridge (Rashwan et al., 2021).

Using sorghum as a material for the food and bio diversification industry requires accurate, systematic postharvest handling that is easy to understand and implement in the field. The postharvest technology applied starts from harvesting, drying, threshing, re-drying, and storage (Boxall et al., 2004). Threshing activity is one of the stages in the postharvest handling of sorghum (Byansi, 2021; Nurhasanah et al., 2023). The threshing of sorghum in Indonesia is generally carried out after harvesting by cutting the panicles at the sorghum planting age around 105 to 110 DAP (days after planting). Sorghum panicles are dried in the sun for about 3 to 4 days until the moisture content is around 13% to 14%, and then threshing is carried out (Gu et al., 2019; Lubadde et al., 2019). If threshing is done correctly, good-quality seeds will be obtained. Besides that, threshing can affect the yield at the next processing stage (Prasad et al., 2008). The sorghum thresher that has been widely sold in the market is generally a sorghum threshing machine with a throw-in system, namely the process of finishing sorghum panicles through the hopper at the top of the threshing cylinder and a seed moisture content of 13% to 14%. The country of Ethiopia carries out the process of handling postharvest sorghum in conditions of the low water content of around 14% to 16% because, after harvesting, farmers cut the sorghum panicles and dry them in the sun for about 3 to 4 days and then thresh them (Bedada, 2017). This sorghum thresher model is a simple manual throw-in type but has been very helpful for farmers to thresh sorghum. This threshing machine uses a gear design model with rotating energy from human power at a capacity of 3, 5, and 7 kg·min^{-1}. The standard and proven tooth shape is widely used to remove throw-type sorghum in tooth types such as human fingers (Sale et al., 2016). In Indonesia, the finger tooth type is also used for sorghum threshing machines (Suparlan, 2018).

The aim of appropriate postharvest management processes for sorghum plants is to prevent yield loss, both quantitative (abandoned, eaten by birds) and qualitative (postharvest pests and diseases) (Muui et al., 2013). Postharvest handling is one of the critical links that must receive attention in sorghum farming, such as harvesting, drying, threshing, milling, and storage. The punctuality of planting and harvesting, harvesting methods, and postharvest handling largely determines the quality and quantity of sorghum yields. The habit of drying sorghum seeds by leaving the plants in the field will increase the risk of yield loss due to bird attacks. Therefore, harvesting should be directly followed by threshing at a seed moisture content of above 20% to reduce yield loss.

Despite the importance of postharvest handling in sorghum farming, there remains a notable research gap in the development of sorghum threshing machines suitable for high-moisture sorghum (20–30%). Existing literature primarily focuses on threshing machines designed for sorghum with lower moisture content (around 13–14%), where usually the feeding type was used in the throw-in mechanism (only panicle). The clamping system for direct harvest of high-moisture sorghum has received limited attention in previous studies, and there is a need for innovative solutions to address this gap in the postharvest handling process.

The primary purpose of this study is to design and evaluate the performance of a hold-on type sorghum thresher specifically designed for high-moisture sorghum with moisture content ranging from 20% to 30%, which is usually cut along with stems. To address the primary purposes, some key points are introduced, such as the use of clamping system for direct harvest and the possibility to be applied into an integrated sorghum processing plant with continuous system. Understanding its adaptability to various scales of sorghum production and processing will be a crucial aspect of the research.

Material and methods

Design of hold-on type threshing machine for high moisture sorghum (20–30%)

The method used in this study was the general design approach, which is based on the functional and structural design approaches. The hold-on type sorghum threshing machine was designed for threshing sorghum seeds with the sorghum panicle stalk system being held or clamped because the sorghum panicles that are threshed are brought directly after harvesting the lower stems without experiencing the previous process of cutting and drying the panicles (moisture content 20–30%). Some design criteria for the machine are:

1. the threshing machine has a minimum capacity of 650 kg·h^{-1} with a maximum power of 5.6 kW;
2. the threshing machine is used for direct harvesting of sorghum with a seed moisture content of around 20–30%;
3. total losses from threshing are less than 3%;
4. it must be equipped with a clamping system to hold the sorghum stems during threshing;
5. the threshing machine can also be combined with a sorghum stalk chopping machine.

The design of the threshing machine and the description of its components is shown in Fig. 1. The function is to release the seeds from panicles through the feeder by clamping the entire sorghum panicle into the clamping chain, and then seeds are threshed in the threshing chamber (hold-on). The components of this threshing machine consist of:

a) a channel or clamping chain as a feeder, it serves as a clamping place for sorghum panicles;
b) a threshing tube is a place to thresh the seeds from the sorghum panicle;
c) a frame holder serves as a seat and the establishment of the machine;
d) a threshing cylinder serves as a place for threshing fingers;
e) a pulley and v-belt transmit power from one shaft to another;
f) an engine as a source of power to rotate the threshing cylinder;
g) a shaft serves to continue the power together with rotation;
h) a blower separates intact seeds from dirt, litter, panicle stalks, and other;
i) an electric motor to rotate the hold-on/clamping chain system;
j) an outer channel as a channel for seeds outlet;
k) an outer channel for removing dirt and litter.

Analysis design

Several parameters were calculated to consider that the thresher design meets the design criteria. The analysis of the parameters includes the theoretical capacity of sorghum, cylinder rotation, cylinder torque, required conveyor power, and required motor power.

For the analysis of machine capacity, the motor selection was made based on the target capacity of sorghum being processed. In this case, the target is to process 1 ha of sorghum per day. Based on information, the average sorghum biomass is 50 t·h^{-1} (Slameto, 2022), and the yield of sorghum seeds was 13%. Therefore, theoretical target capacity can be calculated using Eq. 1.

$$Q_t = 0.13\ Q_s \tag{1}$$

where: Q_s – the capacity of sorghum plant (t·h^{-1}); Q_t – the theoretical capacity of sorghum seed in the threshing machine (t·h^{-1})

The analysis of the required conveyor power was done using Eq. 2, threshing cylinder rotation using Eq. 3, threshing cylinder torque using Eq. 4, and motor power using Eq. 5.

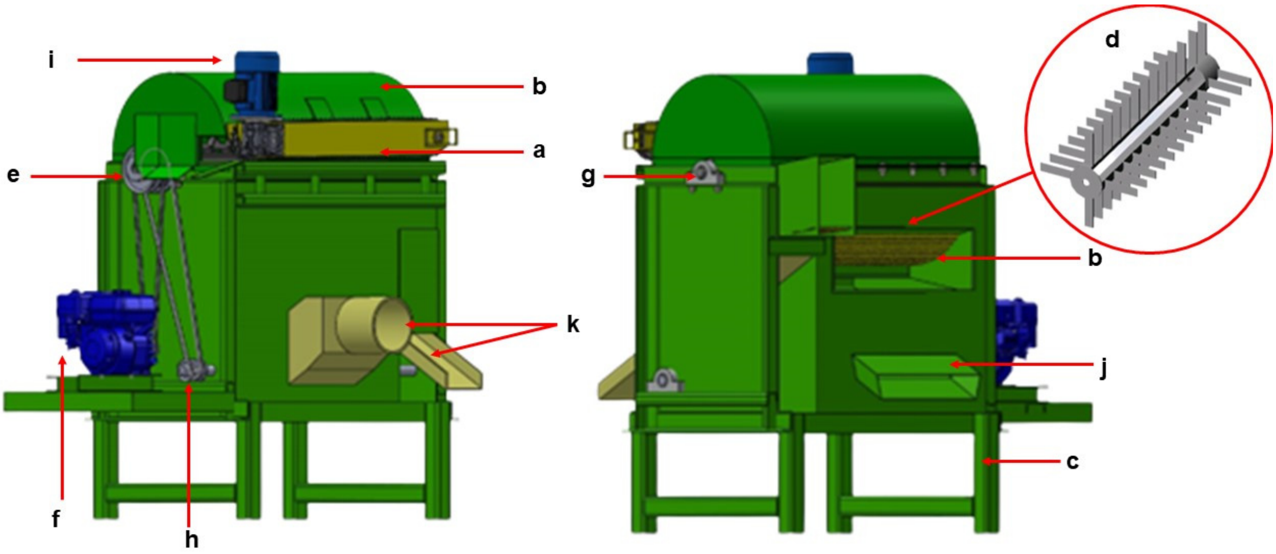

Fig. 1 Design of the hold-on type sorghum threshing machine
a – camping chain, b – threshing tube, c – frame holder, d – thresher cylinder, e – pulley and v-belt, f – engine, g – shaft of threshing cylinder, h – blower shaft, i – electric motor, j – seeds outlet, k – outer channel for removing dirt and litter

$$P_c = \frac{\pi \cdot D \cdot n \cdot g\left(\left(f_d(d_s+s_s)\left(\left(\frac{m_s \cdot H}{d_s+s_s}\right)+\left(0.04\left(\frac{m_b(d_s+s_s)+m_s \cdot L}{(d_s+s_s)}\right)\right)\right)\right)+\left(m_s \cdot L+m_b(d_s+s_s)\right)\right)}{60 \cdot \eta_m(d_s+s_s)} \quad (2)$$

$$n_d = \frac{z_m}{z_p} \cdot n_m \quad (3)$$

$$T_d = W_d \cdot R_d \quad (4)$$

$$P_m = \frac{2 \cdot \pi \cdot n_d \cdot T_d}{60{,}000} \quad (5)$$

where: P_c – required clamping system power (W); g – Earth's gravitational acceleration (m·s^{-2}); f_d – drive factor (1.4); H – conveyor height difference (m); m_b – the total mass of belt (kg); η_m – motor efficiency (0.85); n_d – threshing cylinder rotation (min^{-1}), z_m – the number of sprocket teeth on the motor; z_p – the number of sprocket teeth on the threshing cylinder; n_m – output motor rotation (min^{-1}); T_d – the threshing cylinder torque (Nm); W_d – the total mass of the threshing cylinder (N); R_d – the radius of the threshing cylinder (m); P_m – motor power required for the threshing cylinder (W)

Based on calculation, the required power for the threshing cylinder (P_m) was 5.6 kW, and the motor power for the panicle clamp system (P_c) was 0.73 kW.

Performance test

During the threshing process, the measured and observed test parameters included: motor rotation without and with load, threshing cylinder rotation without and with load, threshing capacity, the proportion of damaged sorghum kernels, the proportion of scattered sorghum kernels, the proportion of sorghum kernels not threshed, the proportion of shrinkage yield, threshing efficiency, the level of cleanliness, and electricity consumption. The method of measuring each test parameter is carried out by referring to SNI 7428:2008.

The threshing capacity of the hold-on type sorghum threshing machine is the net weight of sorghum seeds (whole and broken) coming out of the central dispensing hole per unit of time. Threshing capacity (K_{po}) is calculated using Eq. 6 as follows:

$$K_{po} = \frac{(W_{po} \cdot 60)}{t} \quad (6)$$

where: K_{po} – the output capacity of sorghum seeds (kg·h^{-1}); W_{po} – the total weight of sorghum seeds stored in the main discharge hole for t minutes (kg); t – predetermined threshing time (min)

The percentage of damaged sorghum seeds is the ratio of the weight of damaged sorghum seeds caused by the threshing process from the central dispensing hole to the total weight of the threshing products from the same discharging hole expressed in per cent. The percentage of damaged sorghum seeds is calculated using Eq. 7 as follows:

$$W_r = \frac{W_{r1} - W_{r2}}{W_s - W_k} \cdot 100\% \quad (7)$$

where: W_r – the percentage of damaged sorghum seeds (%); W_{r1} – sorghum grain weight damaged due to removal from the sorghum threshing machine (g); W_{r2} – the weight of damaged sorghum seeds before threshing (g); W_s – the weight of the sample of sorghum (g); W_k – manure weight (g)

Yield loss percentage is the total ratio of the unthreshed sorghum grain weight and the damaged/scattered sorghum grain to the total weight of sorghum grain that should be threshed. Yield loss percentage is calculated using Eq. 8.

$$W_l = \frac{W_d + W_{tt}}{W_s - W_k} \cdot 100\% \qquad (8)$$

where: W_l – yield loss percentage (%); W_d – the weight of damaged/scattered sorghum seeds (g); W_{tt} – the weight of sorghum seeds that are not threshed (g)

The level of cleanliness is the ratio between the weight of sorghum seeds (whole and broken) coming out of the primary outlet to the total weight of threshing products coming out of the same outlet expressed in percent (Ali et al., 2022). The cleanliness level of threshed sorghum seeds is calculated using Eq. 9 as follows:

$$C_l = \frac{W_{p1}}{W_p} \cdot 100\% \qquad (9)$$

where: C_l – the cleanliness level of sorghum seeds (%); W_{p1} – the weight of sorghum seeds (whole and broken) coming out of the main outlet (g); W_p – the total weight of sorghum seeds and manure coming out of the main outlet (g)

Data analysis

Data analysis was carried out using the analysis of variance (ANOVA) consisting of two factors, namely thresher rotation (min^{-1}) and the moisture content of sorghum seeds. The post hoc test was performed by using the *T*-test at a significance level of 0.05.

Results and discussion

Hold-on type sorghum threshing machine prototype

The previous threshing machine prototype was developed using the throw-in type sorghum threshing machine for dry sorghum seeds (13% to 14%), which had been developed by Suparlan (2018). In this research, a new prototype was developed by modifying several components to meet the design criteria for high-moisture sorghum. The modified main parts include a threshing cylinder and concave, panicle rod-clamping system, and cleaning system. The differences between the throw-in thresher developed by Suparlan (2018) and the hold-on type thresher are shown in Table 1. The threshing unit is the most critical component of the sorghum threshing machine, which is composed of several components and materials having the function of each component, such as the rotor, screw, square iron on the back of the rotor, and other (Cahyadi et al., 2021).

This threshing machine was designed according to the need to thresh various varieties of sorghum seeds directly from the field after the harvesting process, cutting down the segment about 10 cm from the ground. The sorghum threshing machine is driven by an electric motor with a power of 5.6 kW. The driving motor is a power source to rotate the thresher unit (Cahyadi et al., 2021). The threshing machine being developed is a threshing machine with a spike tooth type threshing cylinder. The material is fed using the hold-on method (the material to be threshed is put through the feeder table with a panicle rod clamp and then enters the threshing cylinder). Cleaning the threshed seeds is done using a suction system blower.

Table 1 The differences between the throw-in thresher developed by Suparlan (2018) and the hold-on type thresher

Parameter	Prototype of throw-in type threshing machine (Suparlan, 2018)	Prototype of hold-on type threshing machine
Harvesting method	for panicle only with moisture lower than 14%	for both low moisture and direct harvest of high-moisture sorghum (20–30%) with stems
Feeding mechanism	manual feed with operator's assistance	can be combined with conveyor system for continuous feeding
Efficiency	moderate	potentially higher due to direct threshing after harvest
Moisture content handling	suitable for low moisture content	suitable for high moisture content
Grain loss	moderate	low
Maintenance requirements	moderate	moderate
Threshing requirement	required drying prior to threshing	no drying requirement
Cost	generally lower	higher at initial investment due to clamping system
Environmental impact	potential grain loss and waste due to throwing action	reduced grain loss, less waste
Application	for individual farmer	for both individual and integrated sorghum processing plant

Performance test results of hold-on type sorghum threshing machine

Testing the performance of the sorghum threshing machine was carried out using the test material in the form of Bioguma sorghum varieties harvested with a seed moisture content of 30.26% and 15.33% on a wet basis. The initial conditions of the sorghum test material used in the threshing machine are shown in Table 2.

The field performance test results of the sorghum threshing machine is presented in Table 3. These results represent the average value of five threshing repetitions. The results showed that the average input work capacity of the developed sorghum threshing machine was 950.4 kg·h^{-1} of sorghum plants, while the output work capacity (sorghum seeds) was 200.4 kg·h^{-1}. The cleanliness level of the resulting seeds reached about 90.6%. The percentage of seeds not threshed reached around 0.84%, while the rate of seeds covered in dirt reached approximately 0.56%. Thus, sorghum grain yield losses were 1.40%. This result aligns with the sorghum threshing machine made by the local workshop, where the total yield losses reached more than 3.0% (seeds were not threshed, and seeds were covered in dirt) (Suparlan, 2018). Based on the value of the percentage of seeds that were not threshed, it can be seen that threshing efficiency was 90.16%. The noise level generated by the threshing machine during the test was 79 dB during the no-load test and 81.9 dB during the test with load.

The performance test results of the sorghum threshing machine at two levels of panicle sorghum moisture content and different threshing cylinder rotations are presented in Table 4. The results indicate that threshing clamp rotational speed and sorghum seed moisture content had a significant effect (P >0.05) on sorghum threshing work capacity.

In the threshing of sorghum with the same initial moisture content, the higher the rotation of the threshing clamp, the greater the threshing capacity. At high threshing clamp rotation and high moisture content, threshing capacity was higher, and the lower the clamp rotation, the lower the capacity of sorghum processed. For low moisture content, high threshing clamp rotation could handle up to 1000 kg·h^{-1} of sorghum plants (input capacity), while at a low clamp rotation, the input capacity decreased.

Regarding the seed output capacity (K_{po}), a contradictive result was found between high and low moisture content. In high moisture content, K_{po} increased with the increase in clamp rotation, but in low moisture content, K_{po} decreased. This happens because at low water content, seeds were more easily released from the panicle. When clamp rotation is low, the threshing cylinder has a longer opportunity to thresh so that more seeds are threshed. Contrary to this, at high water content, the slower the clamp rotation, the smaller the seed capacity. This may occur due to the difficulty of seeds to escape from the panicle. Therefore, reducing the clamp speed does not really increase the seed

Table 2 Initial characteristics of sorghum sample (Bioguma variety)

No	Parameters	Values
1	sorghum panicle length	22.0 cm
2	sorghum stem length	250.54 cm
3	moisture content of sorghum seeds during threshing	30.26%
4	moisture content of sorghum stems during threshing	83.42%
5	diameter of sorghum seeds	4.5 mm
6	diameter of sorghum stem	17.7 mm
7	ratio of sorghum seed to panicle	87.0%
8	ratio of sorghum seeds to plants	12.0%

Table 3 Performance test results of the hold-on type sorghum threshing machine

No	Parameters	Value	No	Parameters	Value
1	no-load engine speed	1492 min^{-1}	11	seed cleanliness level	90.6%
2	engine speed with load	1477 min^{-1}	12	non-thrown seeds	0.84%
3	no-load threshing cylinder rotation	740 min^{-1}	13	seeds knocked out and covered with dirt	0.56%
4	threshing cylinder rotation with load	668 min^{-1}	14	threshing efficiency	90.16%
5	no-load rod clamp rotation	25.4 min^{-1}	15	electricity consumption	1.38 kWh
6	rod clamp rotation with load	16.5 min^{-1}	16	no-load noise level	79.0 dB
7	moisture content of sorghum seeds	29.7%	17	noise level with load	81.9 dB
8	sorghum grain ratio	84.0%	18	no-load blower wind speed	9.81 m·s^{-1}
9	input capacity	950.4 kg·h^{-1}	19	blower wind speed with load	9.25 m·s^{-1}
10	output capacity	200.4 kg·h^{-1}			

Note: the value shown is the average result of five threshing repetitions

Table 4 Effect of threshing clamp rotation and sorghum moisture content on machine performance

Seed moisture content (%)	Clamp rotation (min^{-1})	K_{po} ($kg \cdot h^{-1}$)	Input capacity ($kg \cdot h^{-1}$)	W_l (%)	W_r (%)	C_l (%)
30.26	140	80	875D	3A	0A	90A
	93	79	750E	5C	0A	90A
	23	60	665F	8D	0A	90A
15.33	140	90	1000A	3A	0A	95D
	93	112	950B	3A	0A	94C
	23	115	930C	4B	0A	91B

Note: the values followed by the same letter are not significantly different at the α level of 5%. K_{po} – seed output capacity; W_l – the percentage of seed loss; W_r – the percentage of damaged seeds; C_l – the cleanliness level of seed

output, instead it relatively decreases. However, the overall capacity at low moisture content was higher than at high moisture content. This is in line with the results of research conducted by Suparlan (2018), where the threshing capacity of sorghum becomes lower if the water content of sorghum in the panicle stalk is still high. The water content level of panicle sorghum stems is related to the adhesion of seeds to panicle stalks as well as sorghum seed density. The lower the moisture content of sorghum seeds in panicle stalks, the less sticking power and the distance among seeds because the volume of seeds shrinks due to a decrease in water content and the force to release the seeds from panicle stalks is smaller. The lower the moisture content of panicle stalks, the easier the seeds are removed from the panicle.

Results also indicate that sorghum moisture content and rotational speed had a significant effect (P >0.05) on the total threshing losses of sorghum. The threshing of sorghum at a low moisture content of about 15.33% with a threshing cylinder rotational speed of around 700 min^{-1} and a clamping rotational speed of 140 min^{-1} resulted in a total yield loss of 3%. In comparison, a threshing clamp rotational speed of around 23 min^{-1} produced a total yield loss of 4%. The total losses resulting from the threshing of sorghum seeds consist of non-thrown seeds that are included in the panicle stalk and scattered seeds through the manure removal holes.

The quality of the sorghum seeds obtained from the test treatment found that the percentage of broken or damaged seeds due to the threshing process was 0%, the whole grain ranged from 90% to 96%, and the level of cleanliness ranged from 90% to 95%. The statistical analysis results show that the degree of damage to sorghum kernels during the threshing process is not affected by sorghum kernels' initial moisture content and threshing clamps' rotational speed. This happens because sorghum seeds are protected by the litter husk of the panicle stalk, which is quite thick but light to protect it from the impact of thresher teeth. Furthermore, this is in line with the results of research by Suparlan (2018), who reported that threshing sorghum with low seed moisture content did not cause cracked or damaged grains.

The cleanliness level of sorghum seeds produced by the sorghum threshing machine is above 90%. This shows that sorghum seeds planted are clean enough. These results indicate that the cleanliness level of threshed sorghum seeds is significantly affected by the initial moisture content of seeds. This is in line with study conducted by Gawłowski et al. (2020), where the moisture of seeds more influences the process of impact crushing than the change of the rotational speed of the thresher. At a lower moisture content, sorghum seeds tend to produce a higher level of seed cleanliness at high and low threshing clamp rotational speeds. The rotational speed of the threshing clamp has no significant effect on the cleanliness of threshed sorghum seeds. The lower the moisture content of sorghum seeds, the lighter the weight of the dirt in the sorghum so it is easily blown away by the blowing air produced by the cleaning blower. Based on the literature, higher cleanliness level is desirable for product processing because it increases its market value (Muhammad et al., 2021).

Conclusion

In this study, a prototype of a hold-on type sorghum threshing machine has been successfully developed and tested, with a focus on its performance in threshing high-moisture sorghum (20–30%) directly from the field. The key finding included a panicle rod-clamping system to meet the unique requirements of high-moisture sorghum which is commonly cut with its stem. The hold-on type thresher demonstrated the ability to handle high-moisture sorghum with stems, eliminating the need for pre-drying and offering potential improvements in efficiency, grain loss, and environmental impact. It is adaptable for both individual farmers and integrated sorghum processing plants, offering versatility in its application. The performance testing of the hold-on type sorghum thresher using Bioguma sorghum varieties with different moisture contents yielded valuable insights. The machine could be used for both low and high moisture content of sorghum. Higher rotational speeds of the threshing clamp led to increased threshing capacity, while lower initial moisture content resulted in higher threshing work capacity. Additionally, the study highlighted that lower moisture content reduced total yield losses. Regarding seed quality, the machine achieved excellent results, with minimal seed damage and high cleanliness levels (above 90%).

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