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Effect of crop maturity condition and operating factors on the threshing performance of wheat thresher

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Abstract

Sustainable agriculture is majorly related to mechanized agriculture systems. The outdated threshing operations lead to a negative impact on wheat threshing performance and contribute to overall post-harvest losses. Mechanized agriculture could produce encouraging results for productivity enhancement including grain damage reduction, better efficiency, and improved threshing technology. The objective of this research study was to assess the effect field operating conditions in the farmers field and maturity characteristics of wheat on threshing performance of locally developed wheat thresher during wheat seasons 2017-18. The wheat thresher produced significantly higher results for wheat (Faisalabad-2008) with the mean threshing efficiency (98.83%) and grain cleaning efficiency (98.93%) at crop moisture (16.6%) and feeding of 52 kg/min. while the least grain breakage percentage (0.75%) was found. The quantity of grain lost in wheat straw was found to be minimum 0.16% at the feeding rate of 47 kg/min and mid harvesting stage (16.6%). The wheat thresher chopped straw size was (2.28 cm) accurate and uniform at moisture content 16.6% (mid harvesting stage) while the straw chopping was non-uniform and irregular at late harvesting stage of wheat crop (1.93cm). The maximum fuel consumption and energy utilized were calculated 6.71 L/h and 76.57 kWh respectively for wheat variety Lasani-2008 (V_3) at feeding rate FR_3, 52 kg/min. The results revealed that the crop moisture content and feeding rate has significant effects on the threshing efficiency, cleaning efficiency and grain damage.

Keywords: Agriculture mechanization, Economic analysis, Operating characteristics, Threshing performance, Wheat thresher.

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Introduction

Wheat is considered the first cereal crop with optimum production (Callaway, 2014; Khan et al., 2016; Anser et al., 2018; Shafqat et al., 2019). The cultivation area for wheat was 8,734 thousand hectares during 2017-18 in Pakistan but the wheat production was 25.492 million tons. Wheat contributes 9.1% in value addition and 1.7% of GDP of Pakistan (Gobbett et al., 2017; Mehmood et al., 2020; Shehzad et al., 2022; Shafqat et al., 2023). The increasing population to 200 million has created a gap between demand and supply of food commodities (Economic Survey of Pakistan, 2018; Shaheen et al., 2023; Shehzad et al., 2023). This can be compensated for with higher crop yields, attractive output prices and supportive government policies towards sustainable agriculture system (Economic Survey of Pakistan, 2018). Wheat production faces various challenges (technology access, capital), that specify the nature of agricultural technologies and their adoptability. Therefore, the farmers have the option to use either traditional or conservation agriculture technologies for wheat threshing. The elevation of conservation agriculture requires identifying the issue of social, financial, agronomic diversity and developing location specific technologies. Agricultural technologies directly impact the dissemination of conservation agriculture-based resources conserving technologies practices (Krishna et al., 2012).

Conservation crop production and mechanized post-production processing of wheat crop play an important role for supplying staple food in sustainable agriculture. The 25 million tons of wheat lost occur at harvesting stage and this loss has been recorded 46% in developing countries (Byerlee & Curtis, 2006). These agricultural practices that can potentially increase crop yield, minimize production cost, and facilitate sustainability of agriculture development may involve minimum grain damage, reduce grin losses, improve grain cleaning, and enhance threshing efficiency, (Krishna et al., 2012). Unlike traditional wheat threshing, the grain damage was reduced four times and the observed threshing efficiency was 99% after this conservation threshing technology. The crop moisture at harvesting stage and rate of feeding wheat into the threshing drum influence threshing performance which results in more losses, thereby reducing wheat yield. Therefore, suitable moisture and feed rate are required for wheat threshing (Byerlee & Curtis, 2006).

Wheat threshing is considered as an important agricultural practice in a sustainable agriculture system. Mechanizing wheat threshing activity to optimize wheat yield and time saving because the losses of mechanical threshing were 2.68% than manual threshing 3.11%. The 2.65% potential production of wheat crop lost during harvesting, threshing, and winnowing operation (Byerlee & Curtis, 2006). The modification and improvement of harvesting and threshing technologies have socio-economic benefits than simple reduction of grain loss, which will result as a natural consequence of development in sustainable agricultural sector in which post harvesting technology plays a critical role (Chaudery, 1979). Agricultural technology connects sustainability with increased crop productivity. To meet the requirement of food grain, sustainable food production is necessary which includes introducing of high yielding varieties coupled with mechanized wheat threshing. Sustainable agriculture system is a fact in developing agriculture to obtain higher yield (Agha et al., 2004).

The grain breakage and grain losses in straw in wheat threshing was significantly associated with threshing method and crop condition (Kumar et al., 2017). There four principles involved in wheat threshing are rubbing of crop material, impact of threshing tool, combining, and grinding of chopped crop material (Kemanian et al., 2007; Yang et al., 2016). The thresher and harvester are the more important agricultural machineries that enhance threshing and harvesting performance respectively (Zami et al., 2015; Wu et al., 2016; Cerquitelli, 2017) but the most important function is threshing (Hanna and Quick, 2013). The wheat threshing performance of thresher like gain damage and gran loss significantly affected by contact method of threshing drum and wheat crop (Spokas et al., 2008; Alizadeh and Bagheri, 2009; Zareiforoush et al., 2010; Khir et al., 2017).

Many researchers have been investigating different types of wheat threshers or threshing components since 1820s (Ndirika, 2005; Li et al., 2012; Gbabo et al., 2013; Yang et al., 2016; Wang et al., 2016) but the peak level of threshing method and machinery are not available due to the gain damage and grain loss factors. Grain loss is the key parameter for performance evaluation of grain thresher (Nawrocka et al., 2012; Abdi and Jalali, 2013; Markowski et al., 2013; Karlen et al., 2014). The grain losses were found nature, cutting & rolling, pick-up and threshing & separating (Pishgar-Komleh et al., 2013). Natural loss resulted from climatic conditions i.e., wind and rain (Audilakshmi et al., 2007) while the rest were associated with threshing method. The only mechanical loss may reduce to optimize grain threshing. Similarly grain damage affects market value and storage (Harrison, 1992; Baryeh, 2003; Khazaei et al., 2008; Lashgari et al., 2008; Mirzazadeh et al., 2012; Behnke and Brune, 2014). The contact between crop grain and threshing surface result gain damage due to high relative speed (Kalkan et al., 2011; Agelet et al., 2012; Shahbazi, 2012; Zhu et al., 2016). The textural features of the grain with impact force of thresher had been studied by highspeed digital imaging technique (Delwiche et al., 2013). The fungal biological damage occurred due to high moisture at harvesting stage (Delwiche et al., 2011; Singh et al., 2012). Grain crops harvested at physiological maturity reduced grain damage up-to a minimum level (Herrera et al., 2015; Zhou et al., 2015; Baktash & Alkazaali, 2016). The modification of threshing component had reduced grain loss and damaged (Ahmad et al., 2013). The modification of contact condition for wheat threshing enhanced threshing efficiency from 94.8% to 99% than conventional. The seed breakage was found 0.3% than 0.6% which was less than seed damage in conventional method (8.4%) (Mesquita et al., 2000). The strip rotor with rubber blades instead of cutter bar system gave better threshing efficiency (Kalsirisilp & Singh, 2001). The wheat thresher performance based on performance of concave, the experiments on concave clearance and drum speeds showed that the grain breakage was low at concave clearance increased from 29mm to 35mm while it was more when drum rotates from 675 rev./min to 875 rev./min (Sudajan et al., 2005). These empirical techniques reduce grain loss and damage and are applicable in specific threshing conditions.

Evaluation of threshing performance predicts possible modification and provides guidelines towards designing more intelligent thresher for better field operations. The reliable measure of field testing is the rate at which the required agricultural machinery accomplishes intended function (Barger et al., 1972; Noor et al., 2021). The evaluation of machinery also details the deficiencies still present in the performance, durability of components and safety (Yasin and Ansari, 1981). The conservation agricultural system and the mechanized wheat threshing are optimum solutions to overcome the problem in wheat threshing that help to improve threshing performance and reduce grain losses. The main objective of this study was to design, develop and evaluate the threshing performance of a wheat thresher in conservation agriculture system under farmer's fields conditions for wheat varieties Seher 2006 (V1), Faisalabad 2008 (V2) & Lasani 2008 (V3) at early, mid & late harvesting stages (moisture content) and feeding rates (FR1, 41 kg/min, FR2, 47 kg/min & FR3, 52 kg/min) on threshing efficiency, grain cleaning efficiency, grain breakage percentage, grain loss in straw, straw chopping efficiency and fuel consumption. It was also aimed to recommend suitable operating modes under the conservation agriculture system and solve the problem against further adaptation of conservation agricultural technology due to optimized threshing performance.

Materials and Methods

A Wheat thresher with modification in design, fabricated with locally available materials, techniques and standards for wheat threshing under different crop and machine parameters i.e., wheat moisture content, wheat variety, feed rate, concave clearance, and speed of threshing drum. This wheat thresher was tested and consisted of 4 units; feed and threshing, sieving, cleaning and power transmission & transportation (Fig. 1). The thresher components with their salient features and the material used were presented in Table 1.

Description of functional units of wheat thresher

Feeding and threshing unit

The objective of the feeding system was to feed the wheat crop into threshing unit of thresher. This unit consisted of a feed shaft and pulley (70 rev./min) from main shaft (800 rev./min) through feed pulley. The feed shaft connected with 8 feed stars was used to deliver wheat material into the threshing drum. The threshing system comprised of threshing drum, rings and 100 beaters (cutter bars) on the rings of the threshing shaft and concave. The wheat crop was fed into the clearance between rotating drum and circumference. The beaters rotating with high revolving speed stroke wheat crop and detached through impact and rubbing force (Alluvione et al., 2011; Xu et al., 2013; Liang et al., 2017). The wheat material passed through clearance between concave and beaters. The concave clearance optimized the threshing yield (Sudajan et al., 2005). That threshed grain and straw chopped moved into sieving unit through concave grates.

Fig. 1 Wheat thresher and its functional units

Sieving and cleaning unit

The sieving and cleaning unit consisted of Set if round hole sieves, set of blowers. In this unit grain was separated from stalks with the help of main blower connected with main threshing shaft (800 rev./min) for cleaning of grain from straw. The finer chaff was removed through a small blower mounted with cleaning sieves. The main blower consisted of four blades and was used to remove chaff from the grain. The 3 mm thick M.S. sheet was used for blower blades. This central shaft of centrifugal blower was powered through belt and pulley. The designed measurement centrifugal fan blowers were shown in in Table 2.

Main frame and transportation unit

It consisted of a main frame and two driving wheels used to mound accessories and transportation respectively. Main frame was fabricated such strong to withstand the load of thresher parts. Main frame was made up of M.S. sheet formed channel.

Power transmission unit

This system took power through the PTO shaft connected with tractor PTO at one and another end with main shaft of thresher. The accessories installed in this system were fly wheel/balance weight, bearing casing, main multi-grooved pulley, shaft coupling, double groove pulley, feed (tanga) pulley and flat belt pulley. Bearing casings were installed to avoid dust contact and keep smooth movement. The casing was manufactured with cast iron.

The flywheel or balance weight (diameter = 492 mm, 80 kg) fabricated with cast iron was installed at main shaft to absorb inertial force. The main multi-grooved pulley made up of cast iron was installed to connect tractor PTO shaft and rest of the thresher parts. The power was transmitted from large pulley of PTO input shaft to small, grooved pulley connected to threshing cylinder through double V-belt. The revolution of threshing drum was calculated using the expression.

$$N2 = \frac{N1D1}{D2} \text{-------------------------------------}(1)$$

Where

N_1 & N_2 = Number of revolutions of PTO shaft and cylinder shaft (540 and 800 r/min) respectively

D_1 & D_2= Diameter of pullies at PTO and cylinder shaft respectively.

A big feed pulley was used to lower the revolutions of feed shaft required for star wheel shaft (70 r/min). The pully (diameter, 406 mm) was determined using relationship (1). A flat belt pully (305mm diameter) connected at rear end of main shaft was fabricated with cast iron to operate the thresher with flat belt through a pulley run by PTO of shaft if required. The thresher was tested intensively at three farmer fields (Southern Punjab) during wheat season 2017-18 to evaluate the thresher performance for three wheat varieties Seher 2006 (V1), Faisalabad 2008 (V2) and Lasani 2008 (V3) at three different harvesting stages (moisture content) of wheat crop; early harvesting stage, mid harvesting stage and late harvesting stage and Feeding rate (FR_1, FR_2 & FR_3) on threshing efficiency, grain cleaning efficiency, grain breakage percentage, grain loss in straw, straw chopping efficiency and fuel consumption to observe optimum threshing conditions for each variety. The variable level and their description were presented in Table 3.

Table 1 Salient features, component specification and materials of wheat thresher

Feature	Specification
General	
Make	Local made except where different origins are specifically indicated
Type	Automatic with double blower
Tractor requirement	≥ 50 hp
Power input	PTO shaft driven
Main frame & transportation system	
Length	3700 mm
Width	1600 mm
Height	1900 mm
Weight	1400 kg
Main frame	75 × 75 × 6 mm, 62 × 62 × 6 mm M.S. angle or 4.5 mm M.S. sheet formed channel
Hitch	4 mm M.S. sheet formed channel
Number of driven Wheels	2 (6:00-16)
Feeding & threshing system	
Width	1375 mm
Number of cutters/hammers	108
Balance weight	80 kg (2 in Numbers)
Speed	800 r/min
Number of feeding stars wheel	8
Threshing capacity (Theoretical)	1400-1800 kg/h
Drum cover	3 mm M.S. sheet
Threshing drum, Rings, Cutter bars, Cutters	Width 1376 mm, 05 Nos. 50 × 8 mm M.S. steel cast, 08 Nos. 50 × 50 × 6 mm M.S. angle, minimum 100 Nos. 38 × 10 mm M.S. flat with tool tips
Concave	6 × 9 mm rectangular M.S. bar
Feeding hopper/chute	07 Nos. steel cost
Feeder shaft	47 mm M.S. round, cold drawn
Sieving & cleaning system	
Number of Blower	2
Speed	800rpm
No/Size of sieves holes	2, M.S sheet 1.25 thick round hole, (Upper 7 mm & lower 2.4mm)
Grain/chaff outlet	M.S. sheet of 12 gauge
Main blower	3 mm M.S. sheet
Power transmission system	
PTO shaft	47 mm or above M.S. round cold drawn
Balance weight	02 Nos. cast iron (minimum 80 kg each)
Threshing shaft	70 mm M.S. sheet round, cold drawn
Bearings	02 Nos. 6309
PTO shaft	02 Nos. 6313
Threshing shaft	02 Nos. 6209
Feeding shaft wheels	04 Nos. 6207/6208
Cam shaft	02 Nos. 6307/6208, 6215/6212

Table 2 Design calculation of centrifugal fan blower

Component	Dimension
Small blower	
Blade (L × W)	(375 × 171.4) mm
Shaft (L × W), Diameter	(1140 × 377.5) mm, 155 mm
Housing	Split in two sections
Main blower	
Blade (a), (L × W)	(375 × 262.5) mm
Housing (b)	(1505 × 262) mm
Outlet size (c), (W × H)	(282 × 282) mm

Independent parameters

Drum speed and concave clearance

The thresher was operated at designed drum operating speed and concave clearance as 800 rpm and 31 mm respectively (Sudajan et al., 2005). The higher teeth speed that critical speed impact damaged the wheat grain (Xu & Li, 2011).

Moisture content

Moisture content of wheat crop is essential for good quality wheat threshing. The moisture content of wheat crop majorly influenced threshing performance. The moisture content of wheat crop was calculated by oven dry method (130˚C for 19 Hours, ASAE, 2002).

$$GMC = \frac{Wgw-Wgd}{Wgw} \times 100 \quad (2)$$

$$SMC = \frac{Wsw-Wsd}{Wsw} \times 100 \quad (3)$$

Where

GMC, SMC = grain and straw moisture content respectively, % (Wb).

(Wgw, Wgd) and (Wsw, Wsd) = Wet and dry weight of grain and straw respectively, (g)

Grain straw ratio

Grain straw ratio was measured by separating grain from straw.

$$GSR = \frac{Wg}{Ws} \quad (4)$$

Where

GSR = grain straw ratio

Wg and Ws = weight of grain and straw, (kg)

Feeding rate

Feeding rate affects threshing performance of thresher and measured by collecting 15kg, 20kg, and 25kg weights of wheat crop into the threshing unit for known time as discussed by (Ukatua, 2006).

$$FR = \frac{Qmf}{T} \quad (5)$$

Where

FR = Feeding rate, (kg/h)

Qmf = quantity of crop material, (kg)

T = feed time, (h)

Dependent parameters

Threshing efficiency

Threshing efficiency was determined by taking three samples of threshed grains, weight of sample was measured excluding un-threshed grain (Mahmoud et al., 2007).

$$TE = \frac{Qt}{Qnt} \times 100 \quad (6)$$

Where

TE = threshing efficiency, %

Qt, Qnt = weight of threshed and un-threshed grains, g

Grain breakage percentage

The grains are required to be in their original form as the broken grains are more liable for the attack of insects or pests. The three samples of threshed grain were taken, and grain breakage was calculated by expression given below (Ukatua, 2006).

$$GBP = \frac{Wb}{Wt} \times 100 \quad (7)$$

Where;

GBP = grain breakage percentage, %

Wb = weight of broken grain, g

Wt = Total weight of sample, g

Cleaning efficiency

Cleaning efficiency is vital because of value addition with respect to agricultural machinery. Three weights of three samples of threshed grains were measured. The weight was measured again after cleaning the grain samples. The cleaning efficiency was calculated by the equation (Ukatua, 2006).

$$CE = \frac{g}{g+s} \times 100 \quad (8)$$

Where

CE = cleaning efficiency %

g, s = number of grain and foreign matter in sample

Grain loss in straw

The number of grains were calculated in three samples of straw during wheat threshing and weighted. The expressions used were given below.

$$GLS = \frac{Wgs}{FR} \times 100 \quad (9)$$

Where
GLS = grain loss in straw, %
Wg_s = weight of grain in straw, g/min
FR = Feeding rate, kg/min

Straw chopping efficiency

Straw chopping efficiency of thresher for different wheat varieties were measured. The three samples of variable chaff length to measure the length of chaff. The average length was measured and recorded (Tavakoli et al., 2009).

Fuel consumption

The economical operation and feasibility of agricultural machinery is based on its fuel consumption. The fuel consumption of wheat thresher and energy consumed were observed for all feed rates of three wheat varieties. The parameters level and their descriptions are given in Table 3.

Table 3 Variables level and their description

Wheat varieties	Parameters
	M_1 = early harvesting stage (Maximum moisture content)
V_1 = Seher 2006	M_2 = mid harvesting stage (Medium moisture content)
V_2 = Faisalabad 2008	M_3 = late harvesting stage (low moisture content)
V_3 = Lasani 2008	FR_1 = Low feed rate
	FR_2 = Medium feed rate
	FR_3 = Maximum feed rate

Results and Discussion

Independent parameters

The independent parameters used to evaluate the performance of wheat thresher were wheat varieties, wheat feeding rate into the threshing drum of wheat thresher and moisture content of wheat crop at three harvesting stages as presented in Table 4. The wheat thresher was intensively tested for Seher 2006 (V1), Faisalabad 2008 (V_2) and Lasani 2008 (V_3). The wheat feed rates 41, 47 and 52kg/min were determined and the crop moisture content of each wheat variety at three harvesting stages was also measured. The Table 3 showed that the maximum wheat crop moisture 22.2% and 17.4% were observed at early harvesting and mid harvesting stages of Seher 2006 (V1) while Lasani 2008 (V_3) gave 11.6% at late harvesting stage. The average wheat crop moisture 21.4%, 16.6% and 11.2% were measured at early harvesting, mid harvesting, and late harvesting stages respectively.

Table 4 Description and observation of independent parameters

Independent parameters	Observation		
Feeding rate (kg/min)			
FR_1	41		
FR_2	47		
FR_3	52		
Moisture content (%)			
Wheat varieties	Early harvesting stage	Mid harvesting stage	Late harvesting stage
Seher 2006 (V1)	22.2	17.4	11.2
Faisalabad 2008 (V_2)	20.6	15.9	10.8
Lasani 2008 (V_3)	21.3	16.4	11.6
Average moisture contents	21.4	16.6	11.2

Dependent parameters

Threshing efficiency

The effect of wheat crop moisture and wheat feed rate into the threshing drum of thresher on threshing efficiency of wheat thresher presented in Fig. 2 indicated that the threshing efficiencies of wheat thresher both for wheat moisture content and wheat feed rate were significantly highest at mid harvesting stage of wheat and feed rate of 52kg/min followed by late harvesting stage and feed rate of 47kg/min while the minimum threshing efficiencies were found at early harvesting stage and feed rate of 41kg/min. Fig. 2 also depicted the analysis of moisture content of wheat crop and threshing performance for three different wheat varieties and all these varieties gave maximum threshing efficiency at mid harvesting stage of crop while lowest at early harvesting stage. The wheat varieties Faisalabad 2008 (V_2) showed maximum threshing efficiency followed by Seher 2006 (V_1) while the wheat variety Lasani 2008 (V_3) gave lowest threshing efficiency at all harvesting stage of wheat crop. It depicted that the beater gave maximum threshing efficiency in threshing unit for threshing of wheat ears with concave and the detaching grain efficiency with minute damage. Wheat thresher had 97.47%, 98.48% and 97.94% average threshing efficiencies at early harvesting (21.4%), mid harvesting (16.6 %) and late harvesting (11.2%) respectively. The decrease in moisture content from early harvesting stage (21.4%) and increased from late harvesting stage (11.2%) resulted in increased threshing efficiency. The findings are in line with (OAEC, 2007) that the best suited moisture content for wheat thresher is 14-18%. It could be concluded that the brittle nature of grain with decrease in moisture content withstand against impact of beaters fixed at threshing drum.

The result of wheat threshing in response of feeding rate were presented in Fig. 2. It is clear from the figure that the mean threshing of wheat was more with increase in feeding rate from FR_1, 41 kg/min to FR_2, 52 kg/min. Wheat variety Faisalabad 2008 (V_2) had significantly maximum threshing efficiency than Seher 2006 (V_1) and Lasani 2008 (V_3) at all levels of feeding rates. The wheat variety Faisalabad 2008 (V_2) had maximum threshing efficiencies than other wheat varieties were 97.72%, 98.12% and 98.38% at feeding rate 41kg/min, 47kg/min, and 52kg/min respectively. The average threshing efficiencies of Seher 2006 (V1), Faisalabad 2008 (V_2) and Lasani 2008 (V_3) were 97.58%, 98.02% and 98.21% respectively. It was observed that more the feeding rate less were the threshing efficiency and grain breakage, therefore one feeding quantity must be selected for good threshing performance and economically. The wheat thresher produced less grain breakage and maximum threshing efficiency at feeding rate FR_3 (52 kg/min). It would be good to use thresher at FR_3 (52kg/min) for better threshing efficiency otherwise select medium feed rate FR_2 (47 kg/min). The results are same as Noor et al. (2020a).

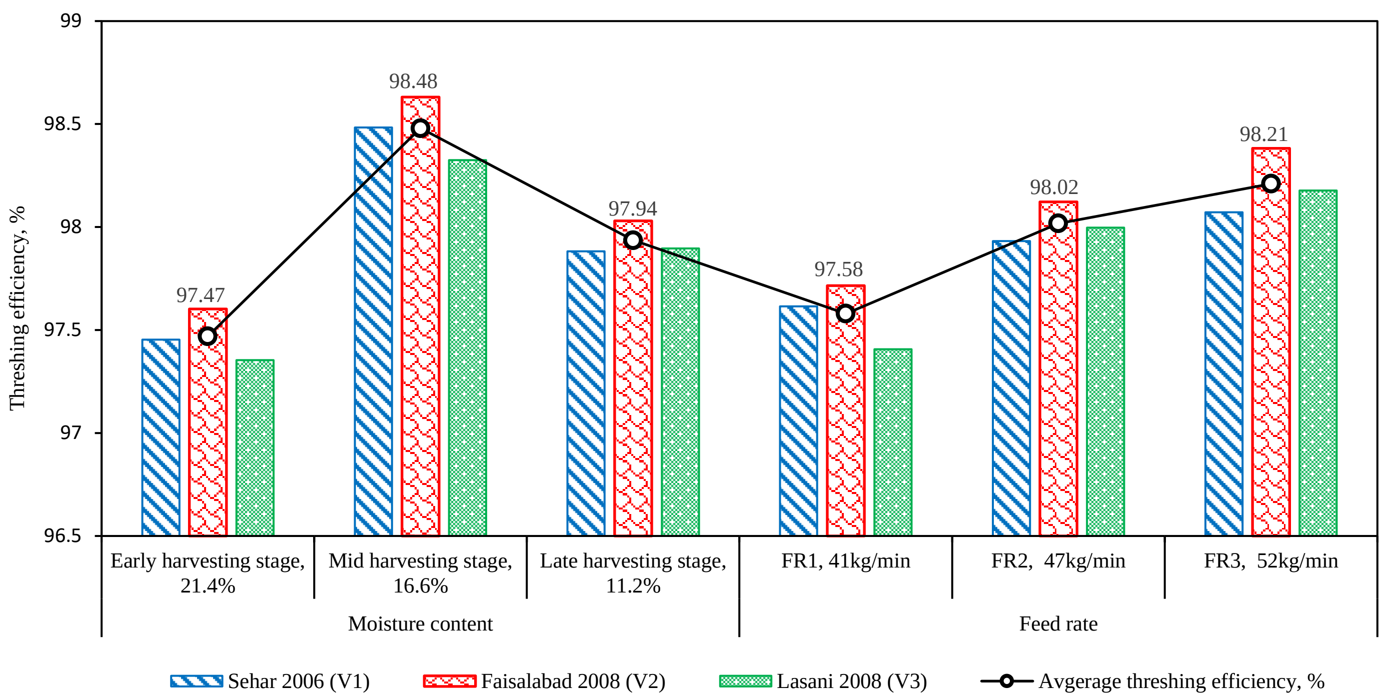

Fig. 2 Effect of wheat moisture content and feeding rate on threshing efficiency of different wheat varieties

Fig. 3 showed the simultaneous effect of moisture content and feed rate on threshing efficiencies of different wheat varieties. Fig. 3 indicated that thresher showed maximum threshing efficiency at mid harvesting stage of wheat crop followed by late harvesting stage while the threshing efficiency was lowest at early harvesting stage of wheat crop. The wheat thresher with FR_3 (52 kg/min) produced maximum threshing efficiency at mid harvesting stage (16.6%) than late harvesting (11.2%) and early harvesting (21.4%) respectively. The mean threshing efficiencies of wheat thresher were 97.32%, 98.40% and 97.87%, respectively.

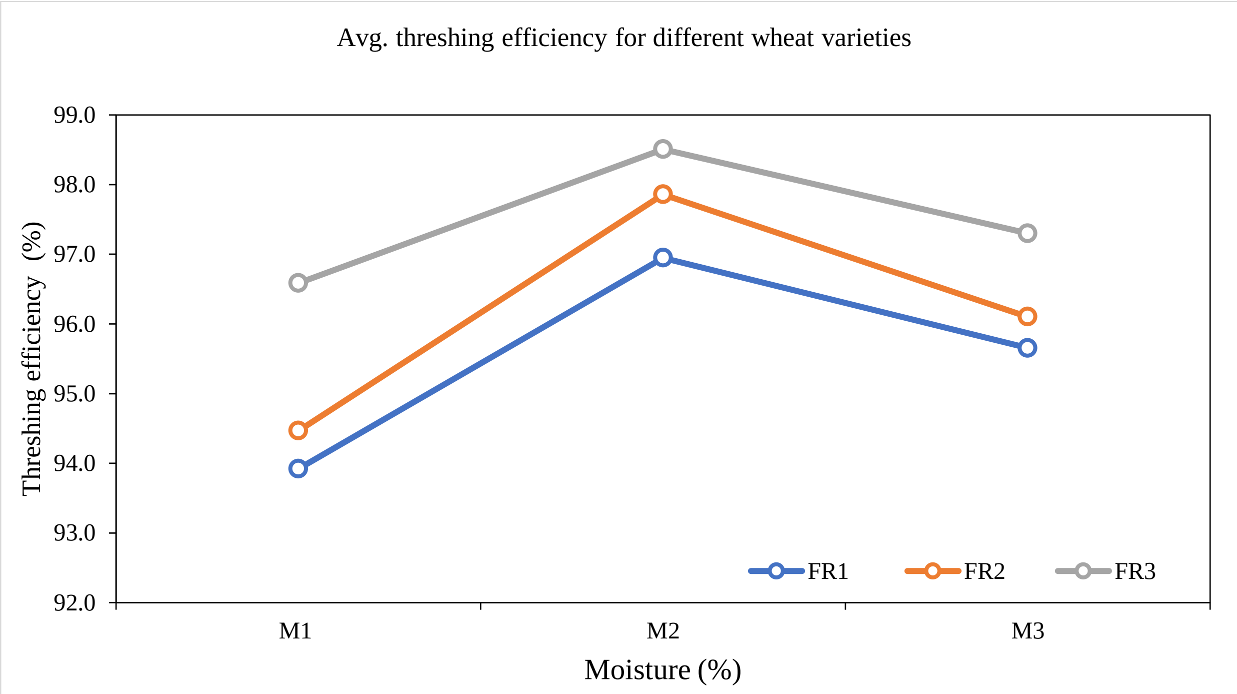

Fig. 3 Effect of moisture content and feed rate on threshing efficiency of wheat crop

Grain breakage percent

The grain breakage produced by wheat thresher during the threshing of three different wheat varieties was presented in Fig. 4 indicated that wheat thresher produced the significantly lowest wheat grain breakage at mid harvesting stage of wheat and feed rate of 52 kg/min. The wheat thresher showed maximum grain breakage at late harvesting stage and feeding rate FR_1 (41 kg/min). The average grain breakage over crop moisture and wheat varieties was shown in Fig. 4 that the thresher gave lowest grain breakage at mid harvesting stage of wheat and feed rate of 52 kg/min. The wheat variety Faisalabad 2008 (V_2) had significantly lowest susceptibility to grain breakage than other two varieties Seher 2006 (V1) and Lasani 2006 (V_3). In Fig. 6, it is clearly reflected that Seher 2006 (V_1) had more grain breakage than other varieties at all moisture content levels. It could be concluded that the wheat variety Faisalabad 2008 (V_2) had optimum resistance against threshing impact of beater than Lasani 2006 (V_3) & Seher 2006 (V1) respectively. The wheat varieties Seher 2006 (V_1), Faisalabad 2008 (V_2) and Lasani 2006 (V_3) had 1.24%, 1.15% and 1.17% grain breakage at late harvesting stage & 1.13%, 1.07% and 1.12% at early harvesting stage while lowest grain breakage 0.83%, 0.74% and 0.82% at mid harvesting stage. Fig. 4 also showed the average breakage was found maximum (1.19%) at late harvesting stage as compared to mid harvesting stage (0.8%) and early harvesting stage (1.11%). This showed that the grain breakage was directly affected by grain moisture. These results are similar as reported by (Arnold, 1964; Noor et al., 2020b) who reported the grain breakage increases as the wheat crop moisture is reduced from 14% and increased from 18%. The effect of feed rate and wheat varieties on grain breakage were presented in the Fig. 6 indicated that grain breakage was found lowest at feeding rate FR_3 52 kg/min and maximum grain breakage at FR_1 41 kg/min. the wheat variety Faisalabad 2008 (V_2) had significantly lower grain damage (0.89%, 0.86% and 0.88%) than other two wheat varieties at all selected feeding rates. The average grain breakage of thresher was lowest (0.88%) at feed rate of FR_3 52 kg/min than 1.12 and 1.23 at FR_2 47kg/min and FR_1 41kg/min respectively. The results were in line as reported by Noor et al. (2019).

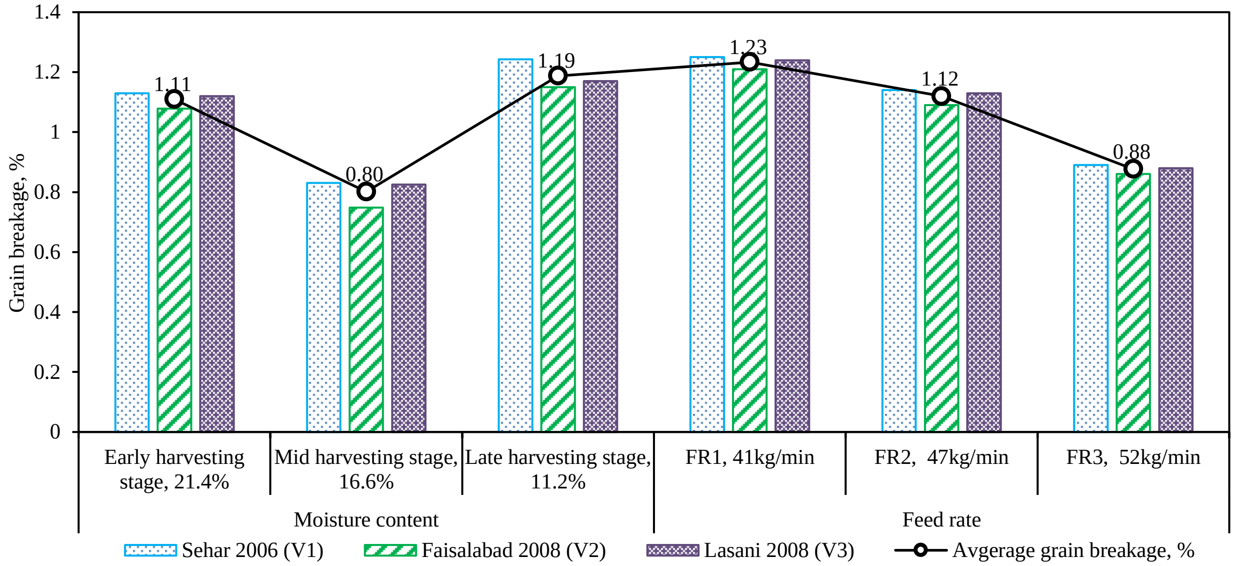

Fig. 4 Effect of wheat moisture content and feeding rate on threshing of different wheat varieties

Fig. 5 showed the simultaneous effect of moisture content and feed rate on grain breakage of different wheat varieties. Fig. 5 indicated that thresher showed least grain breakage at mid harvesting stage of wheat crop followed by early harvesting stage while the grain breakage was maximum at late harvesting stage of wheat crop. The wheat thresher with FR_3 (52 kg/min) produced maximum average grain breakage at late harvesting stage (1.19%) than early harvesting stage (1.08%) while the least were at mid harvesting stage (0.98%). The grain breakage in thresher with feed rate FR_3 52 kg/min had 0.92%, 0.75% and 0.99% at early harvesting, mid harvesting, and late harvesting stages, respectively.

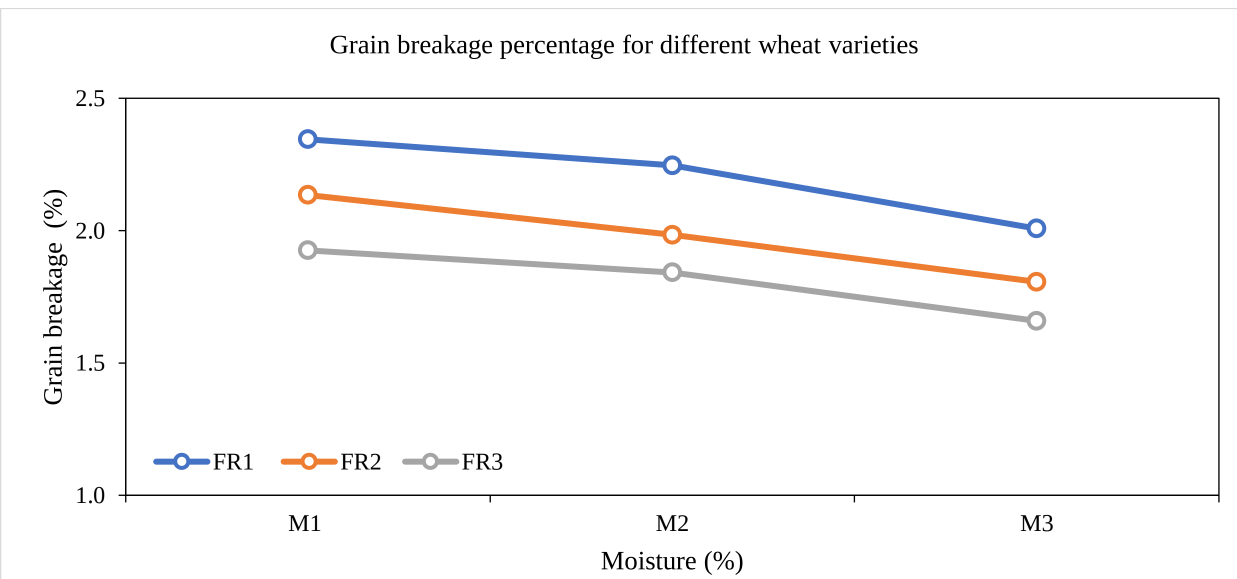

Fig. 5 Effect of wheat moisture content and feeding rate on grain breakage during threshing

Cleaning efficiency

The analysis of grain cleaning efficiency of newly designed and developed wheat thresher presented in Fig. 6 indicated that the wheat thresher produced the significantly highest cleaning efficiency at mid harvesting stage of wheat and feed rate of 52 kg/min. The wheat thresher showed lowest cleaning efficiency at initial harvesting stage and feeding rate FR_1 (41 kg/min). Fig. 6 depicted the correlation between crop moisture and cleaning efficiency for different wheat varieties, the average cleaning efficiencies was observed maximum (98.54%) when threshed wheat crop at mid harvesting stage

(16.6%) than (97.91%) at late harvesting stage (11.2%) while the thresher operated at early harvesting stage (21.4%) of wheat crop gave lowest (97.41%) cleaning efficiency. This could be evaluated that more threshing efficiency better would be the cleaning efficiency. The wheat variety Faisalabad 2008 (V_2) had maximum cleaning efficiency 97.48%, 98.67% and 98.01% followed by Lasani 2008 (V_3) had cleaning efficiency 97.45%, 98.50% and 97.85% while the Seher 2006 (V_1) had lowest cleaning efficiency 97.29%, 98.46% and 97.87% at moisture content (21.4%), (16.6%) and (11.2%) respectively. The static and dynamic balance was considered during the design and development of the blowers. It could be predicted that at early harvesting stage (21.4%) the weight of chopped straw and damaged grain was more separated from clean grain than that at mid harvesting stage (16.6%). It agreed with the discussed above about even threshing efficiency measured for developed wheat thresher with beater of high carbon steel. The effect of feeding rate on grain cleaning efficiency for wheat varieties was presented in Fig. 6 which showed that grain cleaning was significantly better for more feeding rate from FR_1, 41kg/min to FR_3, 52 kg/min. The average cleaning efficiency at FR_1 41 kg/min, FR_2 47 kg/min and FR_3 52kg/min were found 97.71%, 98.37% and 98.48%. The trend of the cleaning efficiency was same as threshing efficiency discussed above. It would have been due to the more straw chopping at less feed rate. The wheat variety Faisalabad 2008 (V_2) showed greater cleaning efficiency among all wheat varieties at all feeding rates.

Fig. 7 indicated that thresher showed highest grain cleaning efficiency at mid harvesting stage of wheat crop followed by late harvesting stage while the grain cleaning efficiency was minimum at early harvesting stage of wheat crop. The wheat thresher with FR_3 (52 kg/min) produced maximum average grain cleaning efficiency at mid harvesting stage (98.47%) than late harvesting stage (97.99%) while the least was at early harvesting stage (97.73%). The grain cleaning efficiency in thresher with feed rate FR_3 52 kg/min had 98.20%, 98.93% and 98.57% at early harvesting, mid harvesting, and late harvesting stages respectively.

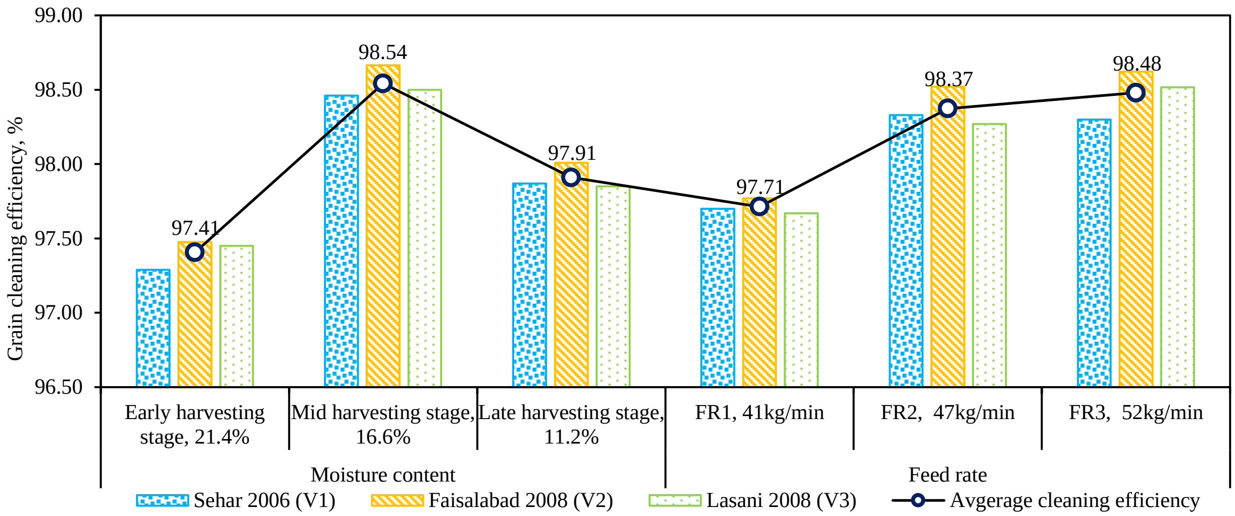

Fig. 6 Effect of wheat moisture content and feeding rate on grain cleaning efficiency of different wheat varieties

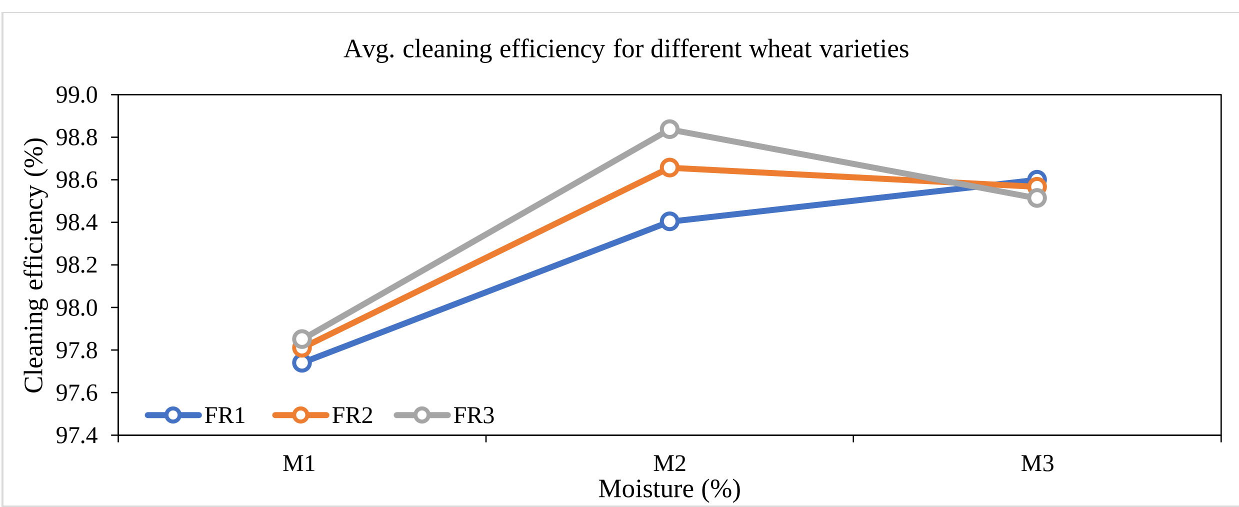

Fig. 7 Effect of wheat moisture content and feeding rate on grain cleaning efficiency

Grain loss in straw

Fig. 8 depicted the analysis carried out for crop moisture content and feeding rate on grain lost in straw by wheat thresher. Fig. 8 showed that the wheat thresher produced the significantly lowest grain loss in straw at mid harvesting stage of wheat and feed rate of 52 kg/min. The wheat thresher showed maximum loss of wheat grain in straw at late harvesting stage and feeding rate FR_1 (41 kg/min). Fig. 8 also depicted the effect of wheat varieties and moisture content on grain loss in straw, the mean grain loss in straw over wheat varieties was significantly low (0.16%) of thresher threshed wheat crop at mid harvesting stage (16.6%) than (0.21%) at early harvesting stage (21.4%) while the thresher operated at late harvesting stage (11.2%) of wheat crop gave highest (0.22%) grain loss in straw. This could be evaluated that more the threshing and cleaning efficiency less would be the grain loss in straw. The wheat variety Lasani 2008 (V_3) had maximum loss of grain in grain 0.23%, 0.16% and 0.24% followed by Seher 2006 (V_1) had grain loss in straw 0.20%, 0.16% and 0.21% while the Faisalabad 2008 (V_2) had lowest loss of grain in straw 0.21%, 0.15% and 0.22% at early harvesting stage (21.4%), mid harvesting stage (16.6%) and late harvesting stage (11.2%) respectively. It could be predicted that at mid harvesting stage (16.6%) the threshing efficiency was more, grain damaged were less than that at other harvesting stages. The effect of feeding rate and wheat varieties on grain loss in straw of wheat thresher revealed that the higher was the feeding rate from FR_1 41 kg/min to FR_3 52kg/min less grain lost in straw. The average grain loss in straw at FR_1 41kg/min, FR_2 47 kg/min and FR_3 52kg/min were found 0.21%, 0.20% and 0.18%. The trend of the grain loss in straw was same as grain breakage discussed above. The wheat variety Faisalabad 2008 (V_2) showed less grain loss in straw (0.18% and 0.17%) at feed rates FR_2 47 kg/min to FR_3 52 kg/min respectively while at feeding rate FR_1 41kg/min, the wheat variety Seher 2006 (V_1) showed lowest (0.19%) grain loss in straw.

Fig. 9 indicated that thresher showed lowest grain loss in straw at mid harvesting stage of wheat crop than early harvesting stage and late harvesting stage of wheat crop. The wheat thresher with FR_2 (47kg/min) showed lowest average grain loss in straw at mid harvesting stage (0.17%) than early harvesting stage (0.20%) and at late harvesting stage (0.22%). The grain loss in straw in thresher with feed rate FR_2 47 kg/min had 0.19%, 0.16% and 0.21% at early harvesting, mid harvesting, and late harvesting stages, respectively.

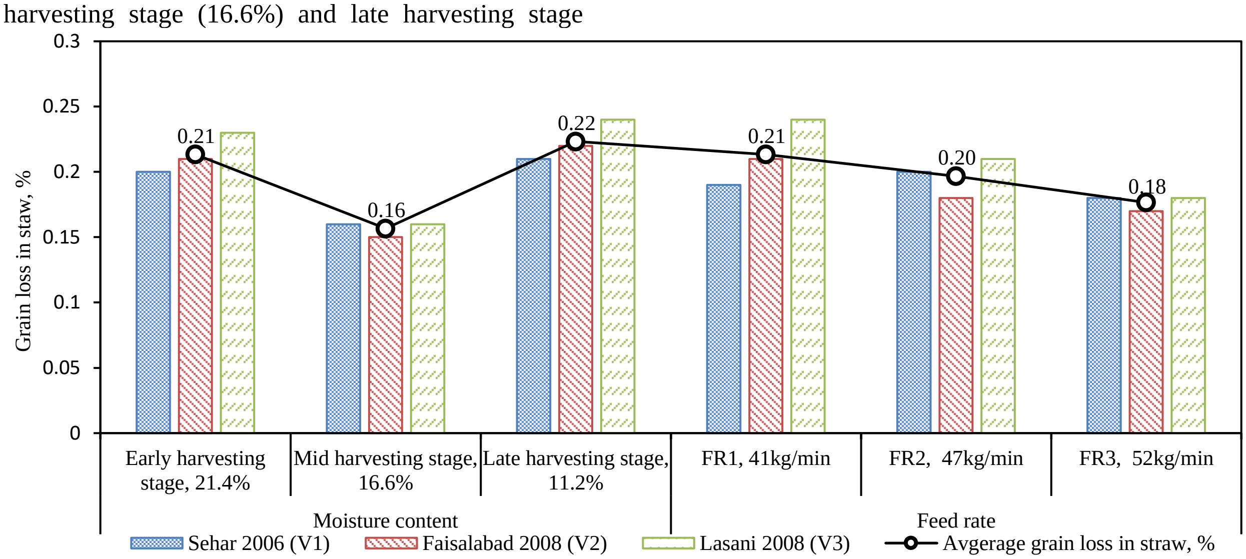

Fig. 8 Effect of wheat moisture content and feeding rate on grain loss in straw of different wheat varieties

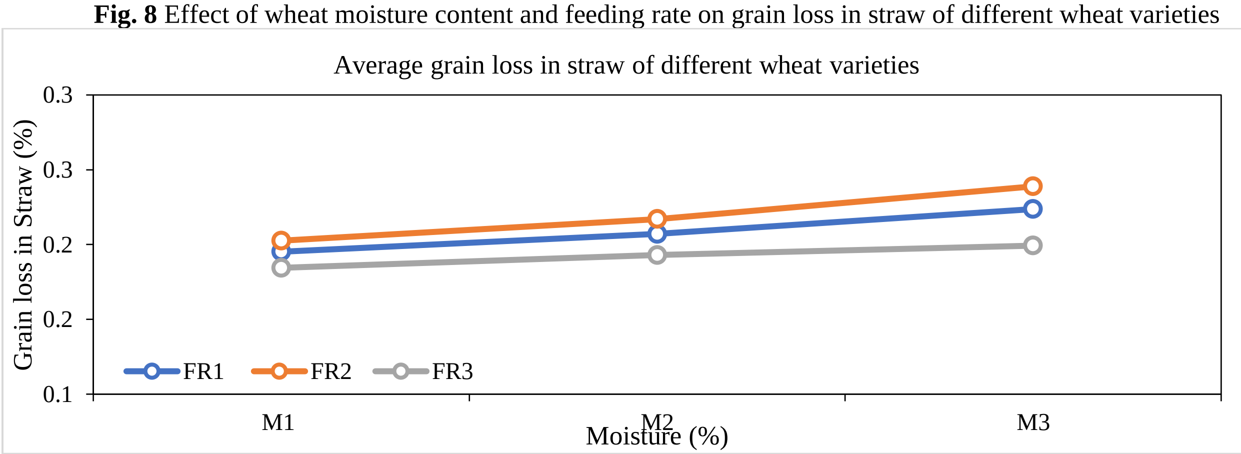

Fig. 9 Effect of wheat moisture content and feeding rate on grain loss in straw for wheat threshing

Straw chopping efficiency

Fig. 10 showed the results obtained for straw chopping efficiency of wheat thresher at different moisture levels. It is indicated that the wheat thresher gave the significantly highest straw chopping efficiency at early harvesting stage (21.4%) of wheat and third wheat feeding rate of 52 kg/min into the threshing drum of thresher. The wheat thresher showed lowest straw chopping efficiency at late harvesting stage (11.2%) and feeding rate FR_1 (41 kg/min). The Fig. 10 depicted the effect of wheat varieties and moisture content on straw chopping efficiency, the mean straw chopping efficiency over wheat varieties was significantly greater (2.79 cm) at early harvesting stage (21.4%) than (2.18 cm) at mid harvesting stage (16.6%) and (1.75 cm) late harvesting stage (11.2%) of wheat crop. This could be evaluated that more uniform and smooth the threshing efficiency, better would be the straw chopping efficiency and straw size produced at mid harvesting stage were best suited for straw storage and for feed. There was no significant difference of straw chopping of three different wheat varieties, the wheat variety Faisalabad 2008 (V_2) had lower size of chopped straw 2.73 cm, 2.12 cm and 1.66 cm than that of other wheat varieties at moisture content (21.4%), (16.6%) and (11.2%) respectively. It could be predicted that at early harvesting stage (21.4%) the bigger chopped straw size was due to high moisture content in the wheat straw. The effect of feeding rate and wheat varieties on straw chopping efficiency of wheat thresher presented in Fig. 10 showed that the increment in feeding rates from 41 kg/min to 52 kg/min increased straw chopping efficiency significantly. The average straw chopping efficiency at FR_1 41 kg/min, FR_2 47 kg/min and FR_3 52 kg/min were found 2.23 cm, 2.35 cm and 2.55 cm. The trend of the straw chopping efficiency was same as threshing efficiency and cleaning efficiency discussed above. It would have been due to the more straw chopping at less feed rate. The wheat variety Faisalabad 2008 (V_2) showed lower straw chopping efficiency (2.22 cm) at FR_1 41 kg/min and (2.44 cm) at FR_3 52 kg/min while wheat variety Lasani 2008 (V_3) gave lowest (2.30 cm) chopped straw size at feeding rates FR_2 47 kg/min.

The effect of wheat moisture and feeding rate on the threshing drum of wheat thresher was presented in Fig. 11. It is indicated that the highest straw chopping efficiency of all feeding rates were observed at early harvesting stage of wheat crop followed by mid harvesting stage while the straw chopping efficiency was minimum at late harvesting stage of wheat crop. The wheat thresher with FR_1 (41 kg/min) produced minimum straw chopping efficiency at all harvesting stages of wheat crop. The mean straw chopping efficiency at early harvesting stage (2.80 cm), late harvesting stage (2.28 cm) and least was at early harvesting stage (1.93 cm), respectively.

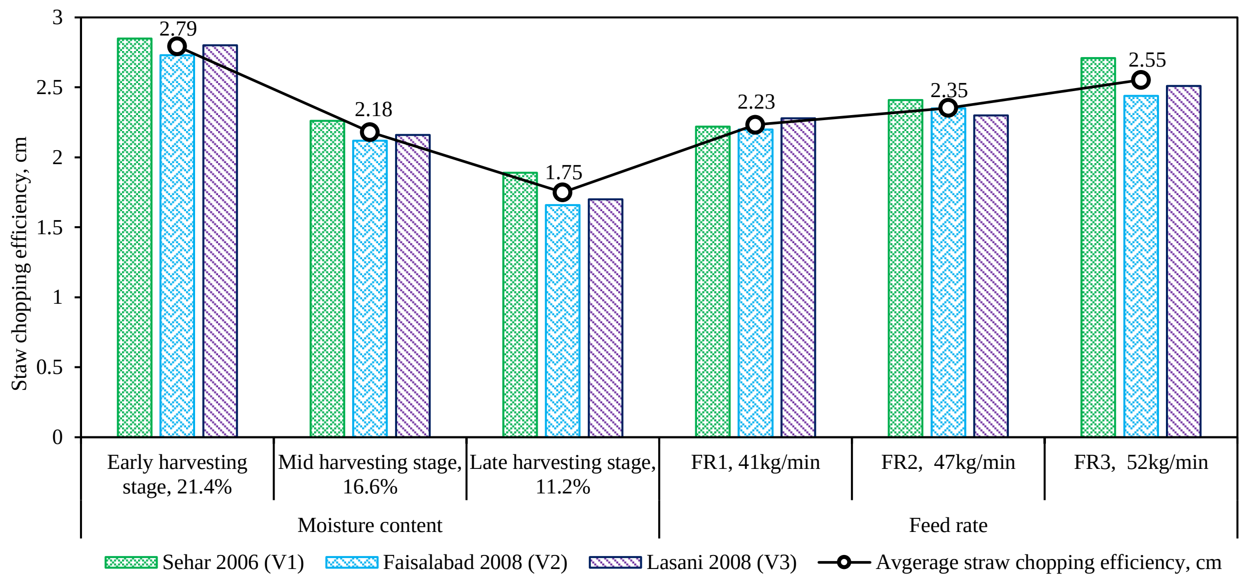

Fig. 10 Effect of wheat moisture content and feeding rate on straw chopping efficiency of different wheat varieties

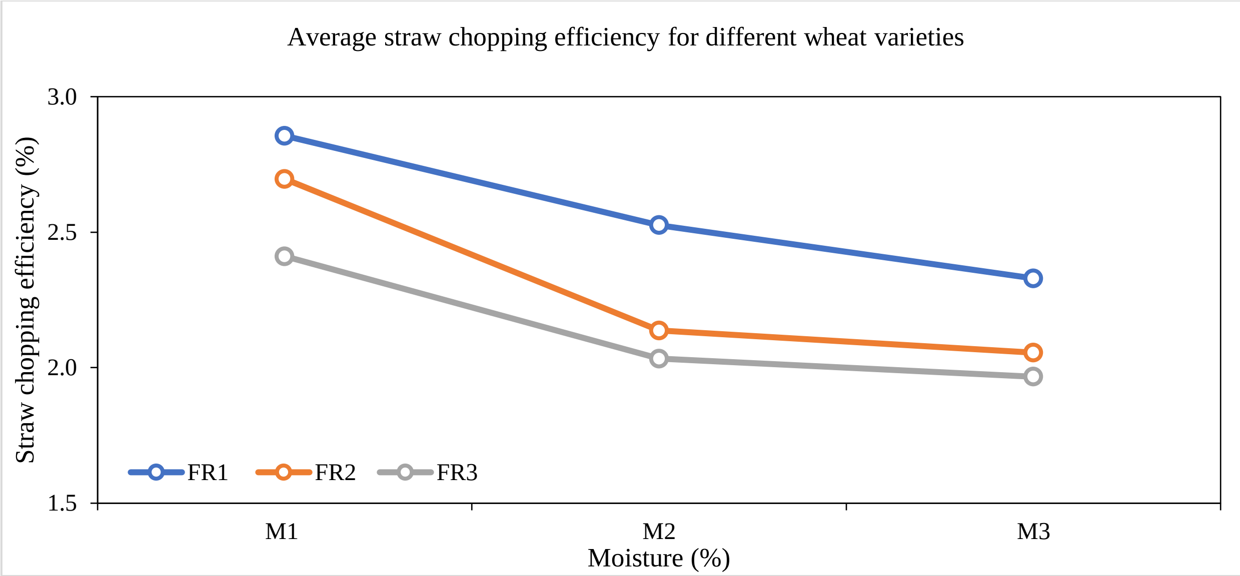

Fig. 11 Effect of wheat moisture content and feeding rate on straw chopping efficiency

Fuel consumption

Table 5 depicted the results obtained for fuel consumed and energy utilized for the threshing of wheat at three different feeding rates. Table indicated that feeding rate FR_1 41 kg/min had lowest fuel consumption 6.41 L/h for Seher 2006 (V_1) and FR_3 52 kg/min had maximum fuel consumption 6.71 L/h for wheat variety Lasani 2008 (V_3). The mean fuel consumed by the wheat thresher were 6.45 L/h, 6.56 L/h and 6.68 L/h at feeding rates FR_1 41 kg/min, FR_2 47kg/min and FR_3 52 kg/min and wheat varieties Seher 2006 (V_1), Faisalabad 2008 (V_2) and Lasani 2008 (V_3) had fuel consumption 6.54 L/h, 6.88 L/h and 6.60 L/h respectively. This was true the more feed material would be the fuel consumption. The energy utilized against the fuel consumed was calculated @ 1-liter diesel = (0.893 kg) (46 MJ/kg) (0.28 kW/MJ) = 11.5kWh. The thresher operated at FR3 52 kg/min showed maximum energy utilization 80.43 kWh while the wheat variety Faisalabad 2008 (V2) had maximum energy utilization 78.91 kWh.

Table 5 Effect of feed rate on fuel consumption and energy of wheat thresher

Feed rate	Fuel consumption (L/h)				Energy (kWh)			
	Seher 2006 (V_1)	Faisalabad 2008 (V_2)	Lasani 2008 (V_3)	Mean	Seher 2006 (V_1)	Faisalabad 2008 (V_2)	Lasani 2008 (V_3)	Mean
FR_1, 41 kg/min	6.41	6.44	6.49	6.45	73.48	73.82	74.40	73.90
FR_2, 47 kg/min	6.55	6.53	6.60	6.56	75.08	74.85	75.66	75.20
FR_3, 52 kg/min	6.66	6.68	6.71	6.68	76.34	76.57	76.92	80.43
Mean	6.54	6.88	6.60	6.562	74.97	78.91	75.66	76.51

Conclusion

In conservation agriculture system, it was required to optimize the threshing performance of wheat thresher operated at variable crop moisture & feed rate and to suggest suitable working parameters for threshing. Analysis of dependent parameters observed during the field testing indicated that the performance of wheat thresher was maximum for variety Faisalabad-2008 (V2) than Sehar-2006 (V1) and Lasani-2008 (V3). The maximum mean threshing efficiency and grain cleaning efficiency of wheat thresher were reached up to 98.83% and 98.93%, respectively, when threshing was done at mid harvesting stage (16.6%) and feed rate, 52 kg/min. The grain breakage percentage and quantity of grain lost in wheat straw were found least 0.75% and 0.16%, respectively at feed rate, 47 kg/min and mid harvesting stage (16.6%). The wheat thresher chopped straw (2.28cm) accurate and uniform at moisture content 16.6% (mid harvesting stage) while the straw chopping was non-uniform and irregular at late harvesting stage of wheat crop (1.93cm). The maximum fuel consumption and energy utilized were observed 6.71 L/h and 76.57kWh respectively for wheat variety Lasani-2008 (V3) at feeding rate FR3, 52 kg/min. This study suggested the suitable wheat crop moisture and feed rate for maximizing threshing performance in conservation agriculture system. Further studies will be conducted that aim to reach highest threshing efficiency and minimum grain losses selecting appropriate crop moisture content and feeding rate.

References

Abdi, R., & Jalali, A. (2013). Mathematical model for prediction combine harvester header losses. *International Journal of Agricultural and Crop Sciences, 5*(5), 549-556.

Agelet, L. E., Ellis, D. D., Duvick, S., Goggi, A. S., Hurburgh, C. R., & Gardner, C. A. (2012). Feasibility of near infrared spectroscopy for analyzing corn kernel damage and viability of soybean and corn kernels. *Journal of Cereal Science, 55*(2), 160-165.

Agha, S. K., Oad, F. C., & Saddiqui, M. H. (2004). Gain loss of wheat as affected by threshing timings, PAK. *Pakistan Journal of Agriculture and Biology, 6*(4), 1170-1171.

Agriculture Statistics of Pakistan. (2017-18). Retrieved from http://www.finance.gov.pk/survey/chapters_14/

Ahmad, S. A., Iqbal, M., Ahmad, M., Tanveer, A., & Sial, J. K. (2013). Design improvement of indigenous beater wheat thresher in Pakistan. *Pakistan Journal of Agricultural Sciences, 50*, 711-721.

Alizadeh, M. R., & Bagheri, I. (2009). Field performance evaluation of different rice threshing methods. *International Journal of Natural and Engineering Sciences, 3*(3), 139-143.

Alluvione, F., Moretti, B., Sacco, D., & Grignani, C. (2011). EUE (energy use efficiency) of cropping systems for a sustainable agriculture. *Energy, 36*(7), 4468-4481.

Anser, M. R., Ahmad, I., Shah, S. H., Abuzar, M. K., Raza, M. S., & Malik, M. A. (2018). Weed control measures for controlling the density of Canada thistle (*Cirsium arvense* (L.) Scop. in wheat (*Triticum aestivum* L.). *Pakistan Journal of Botany, 50*(1), 355-363.

Arnold, R. E. (1964). Experiments with rasp bar threshing drums. I: Some factors affecting performance. *Journal of Agricultural Engineering Research, 9*, 99-131.

Audilakshmi, Aruna, S. C., Solunke, R. B., Kamatar, M. Y., Kandalkar, H. G., & Gaikwad, P. (2007). Approaches to grain quality improvement in rainy season sorghum in India. *Crop Protection, 26*, 630-641.

Baktash, F. Y., & Alkazaali, H. A. (2016). Effect of grain moisture of corn at harvesting on some agronomic traits. *The Iraqi Journal of Agricultural Sciences, 47*(5), 1334-1339.

Barger, E. L., Bainer, R., & Kepner, R. A. (1972). Principles of farm machinery (2nd ed.). AVI Publishing Company, Inc., Westport, Connecticut.

Baryeh, E. A. (2003). A simple grain impact damage assessment device for developing countries. *Journal of Food Engineering, 56*, 37-42.

Behnke, W., & Brune, M. (2014). Method for controlling a crop separating process of a combine harvester: U.S. Patent 8,676,453.3-18.

Byerlee, D., & Curtis B. B. (2006). A Crop Transformed, Developing World Agriculture. International Maize and Wheat Improvement Centre (CIMMYT). Mexico.

Callaway, E. (2014). Domestication: The birth of rice. *Nature, 514*(7524), 58–59.

Cerquitelli, T. (2017). Predicting large scale fine grain energy consumption. *Energy Procedia, 111*, 1079–1088.

Chaudhry, M. A. (1979). Wheat losses at the threshing and winnowing stages. *Agricultural Mechanization in Asia, Africa and Latin America, 10*(4), 67-70.

Delwiche, S. R., Kim, M. S., & Dong, Y. (2011). Fusarium damage assessment in wheat kernels by Vis/NIR hyperspectral imaging. *Sensing and Instrumentation for Food Quality and Safety, 5*(2), 63-71.

Delwiche, S. R., Yang, I. C., & Graybosch, R. A. (2013). Multiple view image analysis of freefalling U.S. wheat grains for damage assessment. *Computers and Electronics in Agriculture, 98*, 62-73.

Economic Survey of Pakistan. (2018). Government of Pakistan, Finance Division, Economic Advisor Wing, Islamabad.

Gbabo, A., Gana, I. M., & Amoto, M. S. (2013). Design, fabrication and testing of a millet thresher. *Net Journal of Agricultural Science, 1*(4), 100-106.

Gobbett, D. L., Hochman, Z., & Horan, H. (2017). Yield gap analysis of rainfed wheat demonstrates local to global relevance. *The Journal of Agricultural Science, 155*(2), 282–299.

Hanna, H. M., & Quick, G. R. (2013). Grain harvesting machinery. In Handbook of Farm, Dairy and Food Machinery Engineering (pp. 223–257). Academic Press.

Harrison, H. P. (1992). Grain separation and damage of an axial flow combine. *Canadian Agricultural Engineering, 34*(1), 49-53.

Herrera, J. M., Pizzolitto, R. P., Zunino, M. P., Dambolena, J. S., & Zygadlo, J. A. (2015). Effect of fungal volatile organic compounds on a fungus and an insect that damage stored maize. *Journal of Stored Products Research, 62*, 74-80.

Kalkan, F., Kara, M., Bastaban, S., & Turgut, N. (2011). Strength and frictional properties of popcorn kernel as affected by moisture content. *International Journal of Food Properties, 14*(6), 1197-1207.

Kalsirisilp, R., & Singh, G. (2001). Adoption of a stripper header for a Thai-made rice combine harvester. *Journal of Agricultural Engineering Research, 80*, 163-172.

Karlen, D. L., Birrell, S. J., Johnson, J. M. F., Osborne, S. L., Schumacher, T. E., & Varvel, G. E. (2014). Multilocation corn stover harvest effects on crop yields and nutrient removal. *Bio-Energy Research, 7*(2), 528-539.

Kemanian, A. R., Stöckle, C. O., Huggins, D. R., & Viega, L. M. (2007). A simple method to estimate harvest index in grain crops. *Field Crops Research, 103*(3), 208–216.

Khan, Q., Mumtaz, A. S., Khurshid, H., Jan, S. A., Ahmad, N., Khan, S. A., Saleem, N., Shah, S. H., Ibrahim, M. I., Ilyas, M., & Arif, M. (2016). Exploring durable genetic resistance against leaf rust through phenotypic characterization and Lr34 linked STS marker in wheat germplasm. *Bioscience Journal, 32*(4), 986-998.

Khazaei, J., Shahbazi, F., & Massah, J. (2008). Evaluation and modeling of physical and physiological damage to wheat seeds under successive impact loadings: Mathematical and neural networks modeling. *Crop Science, 48*(4), 1532-1544.

Khir, R., Atungulu, G., Ding, C., & Pan, Z. L. (2017). Influences of harvester and weather conditions on field loss and milling quality of rough rice. *International Journal of Agricultural & Biological Engineering, 10*(4), 216-223.

Krishna, V., Mehrotra, M. B., Teufel, N., & Bishnoi, D. K. (2012). Characterizing the cereal systems and identifying the potential of conservation agriculture in South Asia. Socio-Economics Program Working Paper 5. Mexico, D.F.: CIMMYT.

Kumar, A., Kumar, A., Khan, K., & Kumar, D. (2017). Performance evaluation of harvesting and threshing methods for wheat crop. *International Journal of Pure and Applied Bioscience, 5*(2), 604-611.

Li, H. C., Li, Y. Y., Gao, F., Zhao, Z., & Xu, L. Z. (2012). CFD-DEM simulation of material motion in air-and-screen cleaning device. *Computers and Electronics in Agriculture, 88*, 111-119.

Liang, Z., Li, Y., Xu, L., Zhao, Z., & Tang, Z. (2017). Optimum design of an array structure for the grain loss sensor to upgrade its resolution for harvesting rice in a combine harvester. *Biosystems Engineering, 157*, 24-34.

Lashgari, M., Mobli, H., & Omid, M. (2008). Qualitative analysis of wheat grain damage during harvesting with John Deere combine harvester. *International Journal of Agriculture and Biology, 10*, 201-204.

Mahmoud, M. A., Moheb, M. A., El-Sharabasy, & Khattab, M. A. (2007). Development of feeding device in a Turkish threshing machine. *Misr Journal of Agricultural Engineering, 24*(2), 235-258.

Markowski, M., Żuk-Gołaszewska, K., & Kwiatkowski, D. (2013). Influence of variety on selected physical and mechanical properties of wheat. *Industrial Crops and Products, 47*, 113-117.

Mehmood, K., Arshad, M., Ali, G. M., Shah, S. H., Zia, M. A., Qureshi, A. A., & Qureshi, R. (2020). Drought stress tolerance in transgenic wheat conferred by the expression of a dehydration-responsive element-binding 1a gene. *Applied Ecology and Environmental Research, 18*(2), 1999-2024.

Mesquita, C., Hanna, M., Costa, N., & França, N. (2000). Soya bean threshing by nylon cords on rotating shafts. *Journal of Agricultural Engineering Research, 77*(3), 297-301.

Mirzazadeh, A., Abdollahpour, S., Mahmoudi, A., & Bukat, A. R. (2012). Intelligent modeling of material separation in combine harvester's thresher by ANN. *International Journal of Agricultural Crop Science, 4*(23), 1767-1777.

Nawrocka, A., Stępień, E., Grundas, S., & Nawrot, J. (2012). Mass loss determination of wheat kernels infested by granary weevil from X-ray images. *Journal of Stored Products Research, 48*, 19-24.

Ndirika, V. I. O. (2005). A mathematical model for predicting output capacity of selected stationary grain threshers. *Agricultural Mechanization in Asia, Africa, and Latin America, 36*(2), 9-13.

Noor, R. S., Hussain, F., Abbas, I., Umair, M., Saad, A., Farooq, M. U., & Sun, Y. (2020b). Assessing sustainability of rainfed wheat (*Triticum aestivum*) production under various soil tillage systems: An energy and economic analysis. *Pakistan Journal of Agricultural Research, 33*(4), 810-819. http://dx.doi.org/10.17582/journal.pjar/2020/33.4.810.819

Noor, R. S., Hussain, F., Farooq, M. U., Noor, R., & Waqas, M. M. (2021). Evaluating performance of water seed drill for wheat production: A sustainable technique under rainfed agricultural system. *Big Data in Agriculture (BDA), 3*(1), 21-26.

Noor, R. S., Hussain, F., Saad, A., & Umair, M. (2020a). Performance Evaluation of Wheat Straw Chopper Blower. *Acta Mechanica Malaysia (AMM)*, 3(2), 29-32.

Noor, R. S., Wang, Z., Umair, M., Ameen, M., Imran, M., & Sun, Y. (2019). Performance Evaluation of a Water Seed Drill. *Sustainability, 11*, 137. https://doi.org/10.3390/su11010137

OAEC, 19769-70. (2007). Combines and combining. The Ohio Agricultural Education Curriculum Material Service. USA. Petre I. Miu, HeinzDieter Kutzbach. Mathematical model of material kinematics in an axial threshing unit. *Computers and Electronics in Agriculture*, 58(2), 93-99.

Pishgar-Komleh, S. H., Keyhani, A., Mostofi-Sarkari, M. R., & Jafari, A. (2013). Assessment and determination of seed corn combine harvesting losses and energy consumption. *Elixir Agriculture, 54*, 12631-12637.

Shafqat, N., Ahmed, H., Khan, Z., Shehzad, A., Shah, S. H., Islam, M., & Masood, R. (2023). Characterization of wheat-thinopyrum bessarabicum genetic stock for stripe rust and karnal bunt resistance. *Brazilian Journal of Biology, 83*, e246440. https://doi.org/10.1590/1519-6984.246440

Shafqat, N., Ahmed, H., Shehzad, A., Chaudhry, S. K., Shah, S. H., Islam, M., Khan, W., Masood, R., & Khan, U. (2019). Screening of wheat-Thinopyrum bessarabicum addition and translocation lines for drought tolerance. *Applied Ecology and Environmental Research, 17*(5), 10445-10461.

Shahbazi, F. (2012). A study on the seed susceptibility of wheat (Triticum aestivum L.) cultivars to impact damage. *Journal of Agricultural Science and Technology, 14*(3), 505-512.

Shaheen, A., Shahzad, A., Shah, S. H., Khattak, S. H., Idrees, S., & Khan, S. U. (2023). Molecular and morphological evaluation of salt tolerance genes in advanced wheat lines. *Pakistan Journal of Botany, 55*(3), 813-823.

Shehzad, R. A., Sarwar, G., Shah, S. H., Tahir, M. A., Sabah, N.-U., Muhammad, S., Aftab, M., Manzoor, M. Z., & Shehzad, I. (2022). Efficacy of P enriched organic manures to improve soil health and nutrient acquisition of wheat.

Pakistan Journal of Agricultural Research, *35*(2), 266-273.

Shehzad, R. A., Sarwar, G., Shah, S. H., Tahir, M. A., Sabah, N.-U., Muhammad, S., Aftab, M., Manzoor, M. Z., Shehzad, I., & Saleem, U. (2023). Growth and yield response of wheat to organic manures [Farm yard manure, phospho-compost (PROM) and press mud] alone and in combination with mineral fertilizer. *Pakistan Journal of Agricultural Research*, *36*(1), 1-8. https://dx.doi.org/10.17582/journal.pjar/2023/36.1.1.8

Singh, C. B., Jayas, D. S., Paliwal, J., & White, N. D. (2012). Fungal damage detection in wheat using short-wave near-infrared hyperspectral and digital color imaging. *International Journal of Food Properties*, *15*(1), 11-24.

Spokas, L., Steponavičius, D., & Petkevičius, S. (2008). Impact of technological parameters of threshing apparatus on grain damage. *Agronomy Research*, *6*, 367-376.

Sudajan, S., Salokhe, V. M., & Chusilp, S. (2005). Effect of concave hole size, concave clearance and drum speed on rasp-bar drum performance for threshing sunflower. *Agricultural Mechanization in Asia, Africa, and Latin America*, *36*, 52-60.

Tavakoli, H., Mohtasebi, S. S., Jafari, A., & Mahdavinejad, D. (2009). Power requirement for particle size reduction of wheat straw as a function of straw threshing unit parameters, Tehran, Iran. *Australian Journal of Crop Science*, *3*(4), 231-236.

Ukatua, A. C. (2006). A modified threshing unit for soya beans. Department of agricultural engineering, University of agriculture, PMB 2240, Abeokuta, Ogum state, Nigeria, *95*(5), 371-377.

Wang, G., Jia, H. L., Tang, L., Zhuang, J., & Jiang, X. X. (2016). Design of variable screw pitch rib snapping roller and residue cutter for corn harvesters. *International Journal of Agricultural and Biological Engineering*, *9*(1), 27-34.

Wu, Q., Xia, G. M., Chen, T. T., Chi, D. C., Jin, Y., & Sun, D. H. (2016). Impacts of nitrogen and zeolite managements on yield and physicochemical properties of rice grain. *International Journal of Agricultural and Biological Engineering*, *9*(5), 93–100.

Xu, L. Z., & Li, Y. M. (2011). Finite element analysis on damage of rice kernel impacting on spike tooth. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, *27*(10), 27-32. (in Chinese).

Xu, L. Z., Li, Y. M., Ma, Z., Zhao, Z., & Wang, C. H. (2013). Theoretical analysis and finite element simulation of a rice kernel obliquely impacted by a threshing tooth. *Biosystems Engineering*, *114*, 146-156.

Yang, L., Cui, T., Qu, Z., & Zhang, D. X. (2016). Development and application of mechanized maize harvesters. *International Journal of Agricultural and Biological Engineering*, *9*(3), 15-28.

Yasin, M., & Ansari, A. (1981). Test and Evaluation (necessary components of farm machinery). *The Journal of the Society of Agricultural Engineering*, *1*, 8-12.

Zami, M. A., Hossain, M. A., Sayed, M. A., Biswas, B. K., & Hossain, M. A. (2015). Performance Evaluation of the BRRI Reaper and Chinese Reaper Compared to Manual Harvesting of Rice (Oryza sativa L.). *The Agriculturists*, *12*(2), 142–150.

Zareiforoush, H., Komarizadeh, M. H., & Alizadeh, M. R. (2010). Effects of crop-machine variables on paddy grain damage during handling with an inclined screw auger. *Biosystems Engineering*, *106*(3), 234-242.

Zhou, Q., Ravnskov, S., Jiang, D., & Wollenweber, B. (2015). Changes in carbon and nitrogen allocation, growth and grain yield induced by arbuscular mycorrhizal fungi in wheat (*Triticum aestivum* L.) subjected to a period of water deficit. *Plant Growth Regulation*, *75*(3), 751-760.

Zhu, M., Shabala, S., Shabala, L., Fan, Y., & Zhou, M. X. (2016). Evaluating predictive values of various physiological indices for salinity stress tolerance in wheat. *Journal of Agronomy and Crop Science*, *202*(2), 115-124.