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Effect of moisture content and pulley shaft speed on grinding characteristics of wheat (*Triticum aestivum*)

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Abstract
Experiment was conducted to evaluate grinding characteristics of wheat milled. The treatments of the experiment include three moisture contents of wheat (12.20, 10.90, 9.70%) and three shaft pulley speeds (4000, 3000, 2400 rpm). After milling and sieve analysis the study indicated that the value of fineness modulus was increased with decreasing speed whereas decreased with decreasing moisture content. The maximum fineness modulus 4.650 was found at 2400 rpm speed and 12.20% moisture content whereas minimum fineness modulus 3.383 at 4000 rpm speed and 9.70% moisture content for wheat flour. The average particle size of ground wheat was increased with the increasing moisture content of wheat but decreased with increased speed. The maximum throughput capacity 9.16 kg h^{-1} was observed for treatment T_7 and minimum 6.57 kg h^{-1} for treatment T_3. The maximum and minimum values of size reduction ratio were 10.133, 6.807 value for treatment T_7, and T_3 respectively. The specific energy consumption (23.50 kJ kg^{-1}) was higher for treatment T_1 and the lower (13.50 kJ kg^{-1}) for T_9. The milling yield (88.23%) during wheat milling was higher at 4000 rpm speed and 12.20% moisture content for treatment T_1. Milling loss was found to be higher at lower moisture level and decreased with the increase of moisture content as well as speed. It was observed that the energy requirement for grinding, Rittinger's constant, Kick's constant, Bond's work index and Bond's constant which are the measures of energy uptake got increased with the increased moisture level and pulley shaft speed.

Keywords: Average particle size, fineness modulus, grinding characteristics and energy requirements, wheat milling

Introduction

Cereals such as wheat, rice, oats and barley are utilized as staple foods globally (Das *et al*., 2011; Sheweta *et al*., 2014) [6, 30]. Among these cereals, wheat is a crucial cereal crop that holds immense significance in terms of food globally with the largest producers being China, India, and the United States (Tian *et al*., 2022; Dziki, 2023) [31, 9]. Wheat is grown in a variety of climates and soils and is adaptable to different growing conditions (Zubko *et al*., 2022; Dziki, 2023) [35, 9]. It has played a significant role in shaping human civilization and remains an integral part of our daily lives as a vital food source (Turky *et al*., 2023; Dziki, 2023) [32, 9]. Wheat (*Triticum aestivum*) is an important source of energy and protein in the diets of population in developing countries (Hira *et al.*, 1991) [15]. The grains contain about 8−12% protein, carbohydrates 72−73%, fat 1−2% and fiber 1−2.2%. The most common way of wheat kernel size reduction is a gradual reduction process during the wheat flour milling (Dziki *et al*., 2012) [10]. Kernel moisture also had a significant influence. The initial moisture content influenced such grinding properties as average particle size, particle size distribution, grinding energy, product yield, grinding loss, *etc*. In most grinding results, materials with high moisture content had larger average particle sizes and higher grinding energy consumption than the powder produced by low moisture materials, because foods with high moisture content became difficult to grind since water acts as a plasticizer (Dziki *et al*., 2012a; Lee *et al*., 2013; Lee *et al*., 2014; Balasubramanian *et al*., 2017; Deng and Manthey, 2017; Moon *et al*., 2017; Hassoon and Dziki, 2018; Hwabin *et al*., 2018) [11, 18, 19, 3, 8, 23, 14, 16]. Grinding is an energy intensive process in which a hard matter is broken down (Rozalli *et al*., 2015) [28]. Specific grinding energy was most influenced by crushing before grinding and the moisture content of the kernels.

Crushing of kernels compared to impact grinding resulted in less energy being used. However, the degree of fineness or finer particles produced also was lower (Dziski, 2008) [12].

The main purpose of milling is to completely separate bran and germ from the mealy endosperm and to thoroughly pulverize the mealy endosperm into middling's, semolina and flour. Clean, consistent and well-prepared wheat at the first grinding stage is a key component for the most favourable flour extraction and flour quality (David, 2011; Posner and Hibbs, 2005) [7, 26]. The size of ground wheat flour is the most important parameter judging the quality of the flour as it is directly related with the protein content, digestibility, N-balance as well as the cost. (Majzoobi *et al*., 2013; Muhammad *et al*., 2014) [21, 24]. The reduction in size of agricultural products is brought about by mechanical means without change in chemical properties of the materials. The main advantages of the attrition mills are the relatively high energy utilization, fast and efficient fine grinding, proficient temperature control and simple operation (Russell, 1989) [29]. Stone mills are the oldest attrition mills used for making whole grain flours, which simultaneously use compression, shear, and abrasion to grind wheat kernels between two stones.

The fineness modulus indicates the uniformity of grind in resultant product. It is determined by adding the weight fraction retained above each sieve and dividing the sum by 100. The grade of grinding depends on the fineness within each mill. The size of flour must be in the range of 250 µm and 360 µm to achieve high digestibility from the cooked product (Yawatkar, 2010; Muhammad *et al*., 2014) [34, 24]. Potkins *et al.* (1989) [27] and Alaviuhkola *et al.* (1993) [1] reported that coarse grinding of wheat flour having size more than 350 µm and less than 150 µm may impair essential nutrients like proteins. The aim of these experiments was to study the effect of moisture content and speed on grinding characteristics of wheat milled by attrition mill.

Materials and Methods

Raw Materials and Sample Preparations

Good quality and freshly harvested, firm, mature, dazzling in color wheat (local variety *Sharbati Tukdi*) without any blemishes were purchased from local market of Dediapada. Cleaning of wheat was done by hand picking. The impurities present in wheat like stones, foreign seeds and chaff were removed from wheat. Tray dryer and grain moisture meter were used for maintaining the required grain moisture for milling of wheat.

Treatments Details

Table 1: Treatment details of wheat (local variety Sharbati Tukdi)

Sr. No.	Moisture Content	Speed	Treatments (MS)	Sample Code
1.	M_1	S_1	M_1S_1	T_1
2.		S_2	M_1S_2	T_2
3.		S_3	M_1S_3	T_3
4.	M_2	S_1	M_2S_1	T_4
5.		S_2	M_2S_2	T_5
6.		S_3	M_2S_3	T_6
7.	M_3	S_1	M_3S_1	T_7
8.		S_2	M_3S_2	T_8
9.		S_3	M_3S_3	T_9

M_1 = Initial moisture content of wheat (12.20%, w.b)
M_2 = Moisture content after drying in tray dryer (10.90%, w.b)
M_3 = Moisture content after in tray dryer (9.70%, w.b)
S_1 = Speed of pulley (4000 rpm)
S_2 = Speed of pulley (3000 rpm)
S_3 = Speed of pulley (2400 rpm)

Attrition Machine Parameter

The machine parameters for existing attrition mill were given

Speed of Motor (N_1) =1483 rpm (given)
Diameter of motor's pulley (D_1) = 20.10 cm (given)

For changing the speed of shaft pulleys, using three different diameters of pulleys (Plate 1) *i.e.* 7.41 cm, 9.88 cm, 12.35 cm and corresponding belts are used in attrition mill according to their length *i.e.* B_{59}, B_{61}, B_{62} respectively. The formula used for calculation of speed of shaft pulley in rpm, as under,

$$\frac{D_1}{D_2} = \frac{N_2}{N_1}$$

Where,
D_1 = Diameter of motor's pulley, cm
D_2 = Diameter of shaft pulley, cm
N_1 = Number of revolution per minutes of motor pulley, rpm
N_2 = Number of revolution per minutes of shaft pulley, rpm

Speed of shaft pulley (S_1)

Now, calculation of speed of shaft pulley (S_1) in rpm
Diameter of shaft pulley (D_2) = 7.41 cm

$$\frac{D_1}{D_2} = \frac{N_2}{N_1}$$

Putting the values of D_1, N_1, and D_2 in this equation, we get the values of N_2

$$\frac{20.1}{7.41} = \frac{N2}{1483}$$

N_2 = 4022 rpm
$N_2 \approx$ 4000 rpm

Speed of shaft pulley (S_2)

Now, calculation of speed of shaft pulley (S_1) in rpm
Diameter of shaft pulley (D_2) = 9.88 cm

$$\frac{D_1}{D_2} = \frac{N_2}{N_1}$$

Putting the values of D_1, N_1, and D_2 in this equation, we get the values of N_2

$$\frac{20.1}{9.88} = \frac{N_2}{1483}$$

$N_2 = 3000$ rpm

Speed of shaft pulley (S_3)
Now, calculation of speed of shaft pulley (S_1) in rpm

Diameter of shaft pulley (D_2) = 12.35 cm

$$\frac{D_1}{D_2} = \frac{N_2}{N_1}$$

Putting the values of D_1, N_1, and D_2 in this equation, we get the values of N_2

$$\frac{20.1}{12.35} = \frac{N2}{1483}$$

$N_2 = 2400$ rpm

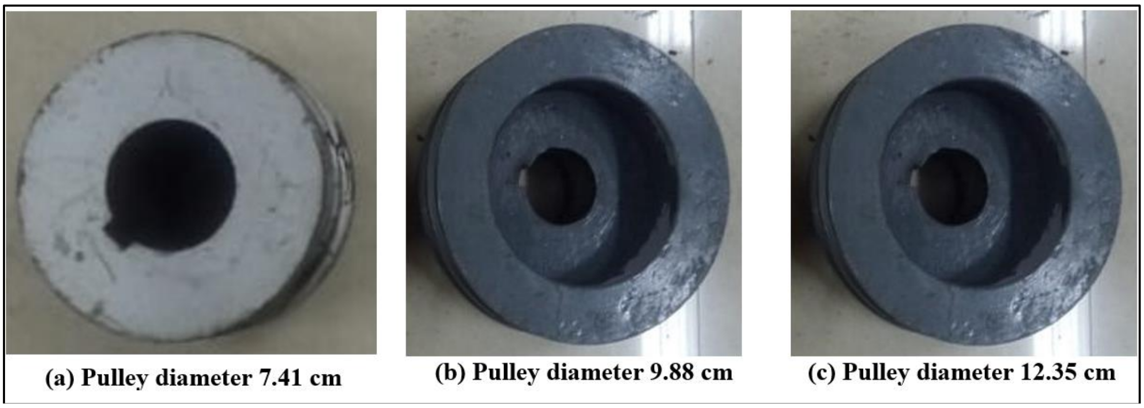

Plate 1: Three different diameters of shaft pulleys

Attrition Machine and Milling Operation
An attrition mill (Plate 2) made of mild steel consist of hopper, milling chamber, induction motor, hammers, two pully and belts and cotton cloth for collecting wheat flour. Single phase induction motor of 3 hp having 1440 rpm. The speed of pulley was varied by adding two different diameters pulleys and belts. An energy meter was used to measures the amount of electric energy (kWh) consumed during milling. One kg of clean, graded and dried samples of wheat (local variety *Sharbati Tukdi*) at three different moisture content were milled in attrition mill with three varying speed of shaft pulleys. After milling the HDPE plastic bags were used for packaging of wheat flour samples (Plate 3) to prevent loss of nutritional quality and protect from contamination by atmospheric microorganisms.

Plate 2: Attrition machine and milling operation

Plate 3: Packed wheat flour sample in HDPE polythene bags

Sieve Shaker and Sieve Analysis

In order to perform the sieve analysis test a sieve shaker (Plate 4) was used. In sieve shaker the different sieves in different sizes (IS 100, 70, 60, 40, 30, 20, 15 and pan) were arranged in vertically from top to bottom. The last sieve in bottom was called pan. Thoroughly mixed 250 g aggregates samples were obtained from the milling machine and used for sieve analysis in sieve shaker.

Plate 4: Sieve Shaker

Grinding Performance of Wheat Milling

The details procedures, methodology and formula used for determinations of grinding performance of wheat milling as given in subsequent headings.

Throughout capacity (kg h^{-1})

Throughout capacity is the amount of material fed to per unit time. It is generally expressed in kg/h. The throughput capacity was determined using the following equation.

$$\text{Throughput capacity (kg h}^{-1}) = \frac{\text{Total mass of wheat grain fed in attrition mill(kg)} \times 60}{\text{Milling time (min)}}$$

Specific energy consumption (SEC) (kJ kg^{-1})

The specific energy consumption (kJ/kg) was calculated by using the following equation:

The specific energy consumption (kJ kg^{-1})

$$= \frac{\text{Total energy consumed by energy meter for milling of fed wheat sample in attrition mill (kWh)} \times 60}{\text{Total mass of wheat grain fed in attrition mill(kg)}}$$

Milling yield (%)

The milling yield was determined using the following equation.

$$\text{Milling yield (\%)} = \frac{\text{Mass of ground wheat flour obtained (kg)}}{\text{Total mass of wheat grain fed in attrition mill(kg)}} \times 100$$

Milling loss (%)

The milling loss was determined using the following equation.

$$\text{Milling loss (\%)} = \frac{\text{Total mass of wheat grain fed in attrition mill(kg)} - \text{Mass of ground wheat flour obtained (kg)}}{\text{Total mass of wheat grain fed in attrition mill(kg)}} \times 100$$

Analysis of Wheat Flour

Calculation of fineness modulus

The sieve shaker consists of series of eight sieve are standard I.S. sieves of 100, 70, 60, 40, 30, 20, 15 and pan. The samples were placed on the top of eight sieves and vibrated for 5 minute at 140 rpm speed. A 250 g of ground wheat flour sample were tested in sieve shaker. After 5 minutes vibrating of sieve, the wheat flour collected in each sieve was weighed and data were recorded for analysis. The material remaining on each sieve was weighed and the percentage of material on each sieves were calculated. The percentage of ground feed accumulated on each sieve is multiplied by appropriate number from eight to zero and the product added. The added product is then divided by 100 to give a fineness modulus.

Average particle size

The relationship between the fineness modulus average particle sizes, D in mm can be estimated by the following equation

$$D = 0.135\ (1.366)^{FM}$$

Where,
FM = Fineness modulus

Size reduction ratio

The size reduction ratio is the ratio of initial to final particle size. The size reduction ratio was estimated according to (Perry, R.H. and Green, D.W., 1984) [25] as follows from equation:

$$S_R = \frac{X_f}{X_p}$$

Where,
S_R = Size reduction ratio,
X_f = Average size of the wheat grain, mm
X_p = Average size of the ground wheat product, mm

Energy Requirements for Size Reduction

The energy required to produce change dL in particle of a typical size dimension L is as simple power function of L:

$$\frac{dE}{dX} = C\,X^n \;\ldots\ldots\; \text{(eq.1)}$$

Where,
dE = differential energy required
dx = change in typical dimension,
X = magnitude of a typical length dimension and
C and n = constant

The energy-size reduction principles were formulated for designing the grinding operation and predicting the performance of a grinding process by Kick, Rittinger and Bond. The following equations to determine Bond's (work index), Kick's and Rittinger's constants are based on the initial and final particle sizes:

Kick's law

Kick assumed that the energy required to reduce a material in size was directly proportional to the size reduction ratio dX/X. This implies that n = −1 in eq.1. Therefore, the energy requirements are

$$E = K_k \ln\left(\frac{X_f}{X_p}\right)$$

Where
E = Energy requirement for grinding (kWh kg^{-1})
K_k = Kick's constant
X_f = Average initial size of wheat (mm)
X_p = Average size of ground particle of wheat (mm)

Rittinger's law

Rittinger's assumed that the energy required for size reduction is directly proportional to change in surface area. Therefore n = −2 in eq.1 gives the energy requirements are

$$E = K_R\left[\frac{1}{X_p} - \frac{1}{X_f}\right]$$

Where
E = Energy requirement for grinding (kW)
K_R = Rittinger's constant
X_f = Average initial size of pieces (mm)
X_p = Average size of ground particle (mm)

Bond's law

$$E = K_b\left[\frac{1}{\sqrt{X_p}} - \frac{1}{\sqrt{X_f}}\right]$$

The work index is represented as Wind that is defined as the energy requirement for grinding bulky particles to a size that can penetrate through a 100 µm sieve (McCabe *et al*., 1993) [22].

$$\text{Bond's work index, } W_{ind} = \frac{K_b}{0.3162}$$

Where
E = Energy requirement for grinding (kWh kg^{-1})
K_b = Bond's constant (kWh kg^{-1})
W_{ind} = Bond's work index (kWh kg^{-1})
X_f = Average initial size of wheat (mm)
X_p = Average size of ground particle of wheat (mm)

Results and Discussion

Particle Diameter and Sphericity of Wheat Grain

The particle dimensions *i.e.* length, width and thickness of cleaned whole wheat (local variety *Sharbati Tukdi*) were measured with help of vernier caliper in three replications. The average values of length, width, thickness, particle diameter and sphericity of wheat were found 4.50 mm, 4.10 mm, 3.40 mm, 3.92 mm and 0.87 respectively.

Grinding Performance of Wheat Milling

Throughput capacity of attrition mill, specific energy consumption, milling yield and milling loss were calculated and presented Table 2.

Table 2: Grinding performance of wheat milling

Treatment	Throughput capacity (kg h^{-1})	Specific Energy Consumption (SEC) (kJ kg^{-1})	Milling Yield (%)	Milling loss (%)
T_1	7.76	23.50	88.23	11.77
T_2	7.26	21.00	87.43	12.57
T_3	6.57	19.50	83.83	16.17
T_4	8.27	21.00	87.30	12.70
T_5	7.52	19.00	85.23	14.77
T_6	6.80	17.50	83.70	16.30
T_7	9.16	19.00	86.47	13.53
T_8	7.86	16.50	84.73	15.27
T_9	7.13	13.50	83.40	16.60
S.Em ±	0.381	0.928	0.431	0.431
CD at 5%	NS	NS	NS	NS
CV%	8.70	8.48	0.87	5.18

Effect moisture content and speed on throughput capacity of attrition mill

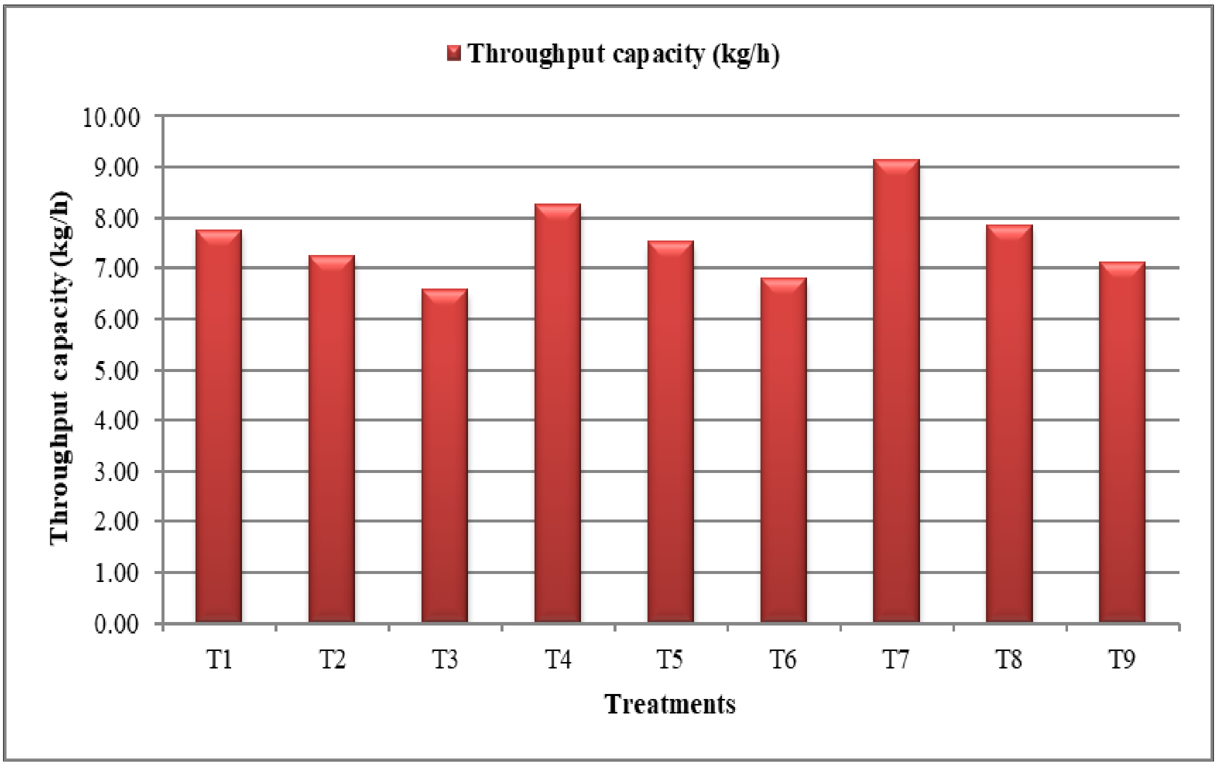

Fig 1: Throughput capacity for all treatment of wheat during milling

The maximum throughput capacity 9.16 kg h^{-1} was observed for treatment T_7 and minimum 6.57 kg h^{-1} for treatment T_3 (Table 2, Fig. 1). The throughput capacity for wheat at 12.20% moisture was significantly less than at the other moisture contents for all treatments. This trend indicates the longer time and higher energy required to grind wheat at higher moisture levels.

Effect moisture content and speed on specific energy consumption, milling yield and milling loss during wheat milling

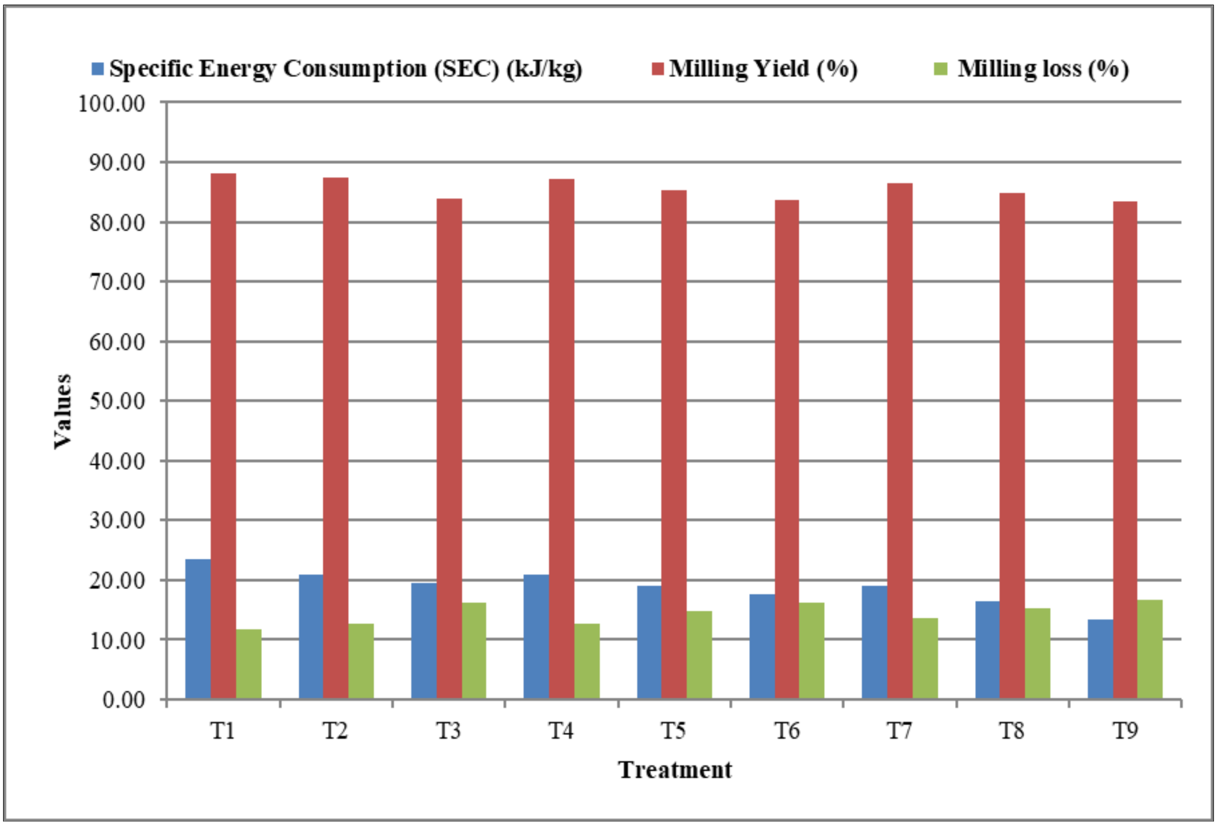

Fig 2: Specific energy consumption, milling yield and milling loss during wheat milling

It was observed from the Table 2 and Fig. 2 that the specific energy consumption (23.50 kJ kg^{-1}) was higher for 4000 rpm speed and 12.20% moisture content for treatment T_1 than other treatments. Thus at increasing speed and moisture content, the specific energy consumption was found increased. The minimum specific energy consumption (13.50 kJ kg^{-1}) was found for T_9. This may be due to the fact that the increase in moisture content causes increase in kernel plasticity therefore increases the shear strength of the wheat grain, which leads to higher energy consumption for grinding (Glenn and Johnston, 1992; Annoussamy *et al.* 2000; Mabille *et al*., 2001; Dabbour *et al*. 2015) [13, 2, 20, 5]. The milling yield (88.23%) during wheat milling was higher at 4000 rpm speed and 12.20% moisture content for treatment T_1 than other treatment. Generally, the efficiency of the food grinding process increases as the moisture content of the material decreases because material with less moisture is more brittle (Laskowski and Lysiak, 1999; Walde *et al.*, 2002; Lee *et al*., 2013) [17, 33]. Milling loss was found to be higher at lower moisture level and decreased with the increase of moisture content as well as speed. The loss at lower moisture content might be due the formation of more fine powdered material that gets easily lost in the form of dust particles during the grinding process. The minimum milling loss 11.77% was found for treatment T_1.

Fineness Modulus, Particles Diameter of Wheat Flour and Size Reduction Ratio

The milled wheat flour for different treatments was analyzed in sieve shaker and ground product quality *i.e.* fineness modulus, particles diameter and size reduction ratio were calculated and presented in Table 3.

Table 3: Calculated fineness modulus and particles diameter of wheat flour for all treatment

M.C. (%), (w.b)	Speed (rpm)	Samples code	Particle diameter of whole wheat, X_f (mm)	Fineness modulus (F.M)	Particle diameter of ground wheat, X_p (mm)	Size reduction ratio $S_R = (X_f/X_p)$
12.20	4000	T_1	3.92	4.063	0.480	8.177
	3000	T_2	3.92	4.450	0.541	7.250
	2400	T_3	3.92	4.650	0.576	6.807
10.90	4000	T_4	3.92	3.893	0.455	8.623
	3000	T_5	3.92	4.233	0.506	7.753
	2400	T_6	3.92	4.460	0.543	7.227
9.70	4000	T_7	3.92	3.383	0.389	10.133
	3000	T_8	3.92	3.680	0.427	9.243
	2400	T_9	3.92	4.203	0.502	7.840
S.Em ±				0.100	0.014	0.282
CD at 5%				NS	NS	NS
CV%				4.20	4.88	6.02

Effect moisture content and speed on fineness modulus

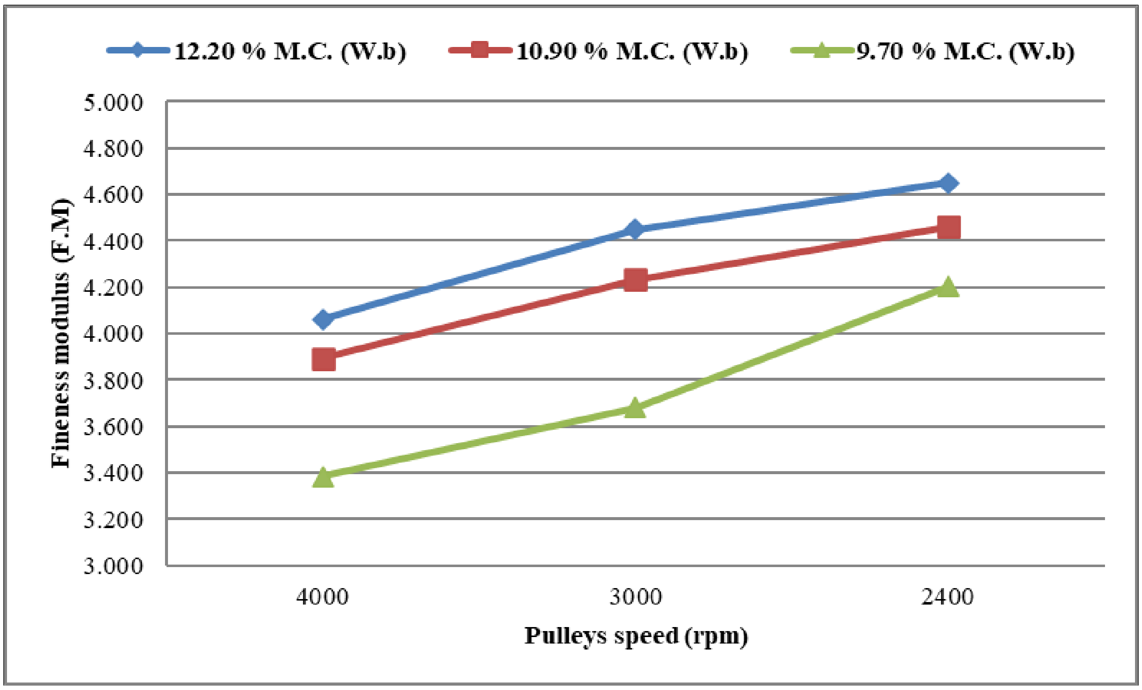

Fig 3: Effect moisture content and speed on fineness modulus

Variations in fineness modulus and average particle size (Table 3, Fig. 3) were seen. It was observed that the fineness modulus was increased with decreasing speed whereas decreased with decreasing moisture content after sieve analysis. The maximum fineness modulus 4.650 was found at 2400 rpm speed and 12.20% moisture content for treatment T_3 whereas minimum fineness modulus 3.383 was observed at 4000 rpm speed and 9.70% moisture content for wheat for treatment T_7. Higher the value of fineness modulus, lower will be the fineness of flour.

Effect moisture content and speed on average particles diameter of wheat flour

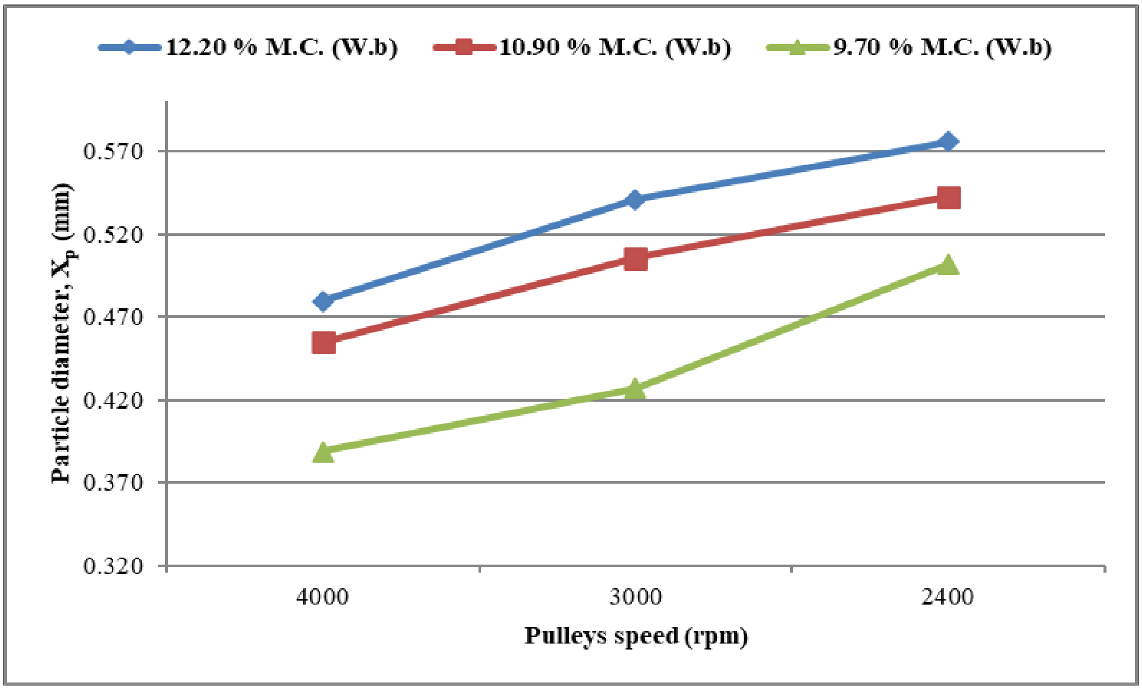

Fig 4: Effect moisture content and speed on average particles diameter of wheat flour

The average particle size increased with the moisture level but decreased with pulley shaft speed. This was due to the reason of lesser grinding effect at higher moisture level and thus less formation of fine material. Similar types of observations were also reported for size reduction of pearl millet, respectively (Balasubramanian *et al.*, 2011) [4]. The maximum average particle size of wheat flour 0.576 mm was found at 2400 rpm speed and 12.20% moisture content for treatment T_3 and minimum 0.389 mm at 4000 rpm speed and 9.70% moisture content for treatment T_7 (Table 3, Fig. 4).

Effect moisture content and speed on size reduction ratio

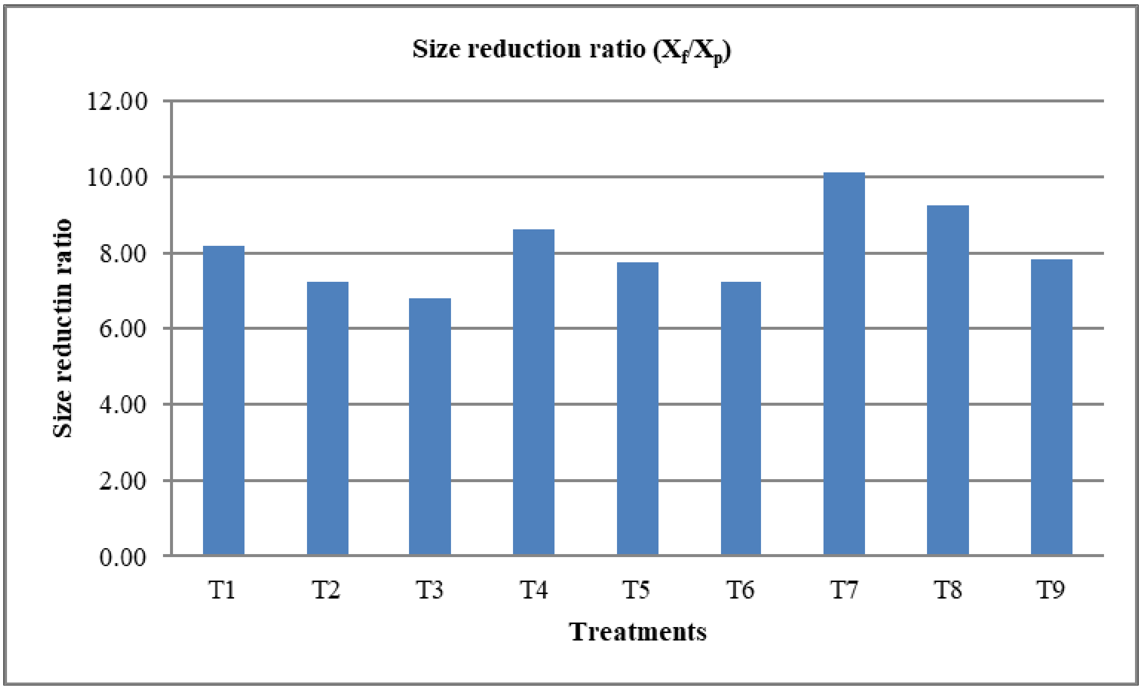

Fig 5: Size reduction ratio of wheat flour

Regarding the size reduction ratio, the results indicated that the size reduction ratio decreased with increasing the moisture content and increased with increasing speed. It was observed that the maximum value 10.133 for size reduction ratio was found for treatment T_7 it may be due to smaller average size of ground wheat particle. And minimum values 6.807 for size reduction ratio was at T_3 it may be due to higher average size of ground wheat particle (Table 3, Fig. 5).

Comparison of Grinding Characteristics for Different Models during Wheat Milling

Energy requirement are depending on throughout capacity of wheat and power consumed during wheat milling. The grinding characteristics *i.e* Rittinger's constant, Kick's constant, Bond's work index and Bond's constant for milling of wheat were studies and calculated using Rittinger's law, Kick's law and Bond's law and presented in Table 4.

Table 4: Comparison of grinding characteristics for different models during wheat milling

Treatment	E (kWh kg^{-1})	K_r (kWh. m kg^{-1})	K_k (kWh kg^{-1})	W_i (kWh kg^{-1})	K_b (kWh kg^{-1})
T1	0.392	0.205	0.179	1.264	0.400
T2	0.350	0.204	0.164	1.203	0.380
T3	0.325	0.202	0.156	1.167	0.369
T4	0.350	0.167	0.151	1.051	0.332
T5	0.317	0.159	0.134	0.965	0.305
T6	0.292	0.157	0.127	0.927	0.293
T7	0.317	0.130	0.130	0.863	0.273
T8	0.275	0.120	0.113	0.771	0.243
T9	0.225	0.115	0.098	0.698	0.221
S.Em ±	0.016	0.005	0.002	0.020	0.006
CD at 5%	NS	NS	NS	NS	NS
CV%	8.48	5.11	2.10	3.47	3.46

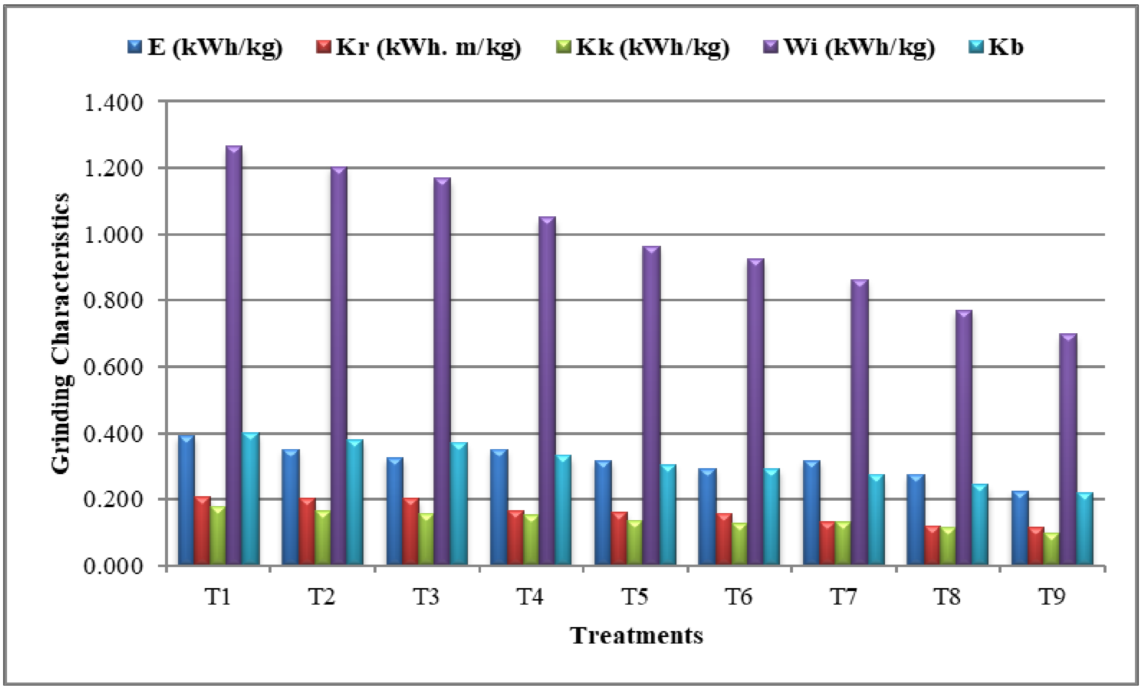

Fig 6: Comparison of grinding characteristics for different models during wheat milling

Table 4 and Fig. 6 describes the effect of moisture content and pulley shaft speed on various grinding characteristics *viz*., energy requirement for grinding, Rittinger's constant, Kick's constant, Bond's work index and Bond's constant. It was observed that the energy requirement for grinding, Rittinger's constant, Kick's constant, Bond's work index and Bond's constant which are the measures of energy uptake got increased with the increased moisture level and pulley shaft speed. This might be attributed to comparatively less grinding time taken to grind the unit mass with the increase of speed. However, with the increase of moisture level, the material becoming soggy/tougher, resulting in more consumption of energy and hence the increase in Rittinger's constant, Kick's constant, Bond's work index and Bond's constant. The total surface area decreased with the increase of moisture level. Similar results were obtained in the studies of Lee *et al*., 2013 [18] and Lee *et al*., 2014 [19] on soybeans and black soybeans with less moisture contents resulted in lower values of the grinding constants associated in the grinding law models and a decrease in the energy requirement.

Conclusion

Milling is adding value to the wheat in terms of its acceptability, marketability and profitability. The initial moisture content influenced such grinding properties as fineness modulus, average particle size, throughput capacity, specific energy consumption, product yield, grinding loss, etc. In most grinding results, wheat grain with high moisture content had larger average particle sizes and higher grinding energy consumption than the powder produced by low moisture materials, because wheat with high moisture content became difficult to grind since water acts as a plasticizer. Least fineness modules of 3.383 were recorded at 9.70% moisture content and 4000 rpm pulley shaft speed for treatment T_7. The milling yield (88.23%)

during wheat milling was higher at 4000 rpm speed and 12.20% moisture content for treatment T_1 than other treatment. The minimum milling loss 11.77% was found for treatment T_1. On the basis of overall studies milling characteristic of milled wheat flour, we found treatment T_1 was best for wheat milling. Thus we can say the optimized operating parameter of attrition mill for wheat milling was at 12.20% moisture content of wheat and 4000 rpm speed of shaft pulley.

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