Theoretical and Experimental Investigation of Threshing Mechanism for *Tef (Eragrostistef (Zucc.) Trotter)* on the Basis of its Engineering (Physical and Mechanical) Properties

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DECLARATION

I declare that "**Theoretical and Experimental Investigation of Threshing Mechanism for *Tef (Eragrostistef (Zucc.) Trotter)* on the Basis of its Engineering (Physical and Mechanical) Properties**" is my original work and has not been presented for a degree to any other university. Further, all the sources that I have used or quoted have been indicated and acknowledged by means of referencing. It is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering (Mechanical Design) at Addis Ababa University.

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ABSTRACT

Tef *(Eragrostis tef (Zucc.) Trotter)* is a typical crop growing in most areas of Ethiopia, ranking first in area coverage and second in cereal production. Threshing of *tef* is often done by animal trampling which commonly causes quality and quantity loss. Consequently, improving the threshing technique is a priority which requires research intervention. The objective of the current research project was to investigate the theoretical and experimental of threshing mechanisms for designing *tef* threshing unit on the basis of its physical and mechanical properties. The physical and mechanical properties of *tef* namely: diameter, length, modulus of elasticity, shear strength and flexural rigidity were determined. Four major varieties [Local, Dz-Cr-438- (Kora), Dz-Cr-387/RIL-355 (Quncho) and Dz-01-1880 (Guduru)] were considerd for the research. The test varieties were harvested by sickles with a minimum height of cutting 1-1.5 cm from the ground. The panicles were separated from the stem and the stem was divided in three equal lengths. The segments' physical sizes were measured and coded. Texture Analyzer and Universal Testing Machine were used for measuring their mechanical properties. The factors considered were moisture content, diameter and thickness of the *tefs'* stem. Experimental data were analyzed using analysis of variance (ANOVA) linear modeling correlated with multi linear modeling. The means were compared with different range tests and graph construction in **R i386.3.0.1** software. The results indicated that among the *tef* varieties the minimum and maximum values of modulus of elasticity were 1.03 and 3.88 Gpa at moisture levels of 5.5% and 19.70% at upper and bottom positions for Kora and Guduru varieties respectively. The maximum modulus of elasticity and shear strength of *tefs'* stem were applied to determine the power requirements of the threshing unit. Then designing and manufacturing of the threshing units were performed following the standard design procedures. After manufacturing the newly developed threshing unit and establishing the test stands, the design effect of the SG-2000 model and the newly developed (closed type concave and drum) threshing units were evaluated. The three variables: threshing capacity, cleaning efficiency and separation efficiency on feed rate and drum speed with three levels 275, 325 and 400kg.hr^{-1} and 900, 1000 and 1200 rpm respectively. Experimental data were analyzed using analysis of variance (ANOVA) non-linear modeling, correlated with polynomial modeling and spearman methods. The means were compared with different range tests and graph construction and analysis in **R i386.3.0.1, ANSYS 2015** and **MATLAB 2014a** software's were used. The test result revealed that the newly developed (cylindrical type concave) has significant difference under 99% of confidence interval on separation and cleaning efficiency over SG-2000 (the open type concave). The maximum threshing capacities were found to be 70.88 and 52.11 kg.hr^{-1} for newly developed and SG-2000 threshing units respectively. Further, the research compared the design effect along the concave length of two threshing units. The mean values of the cleaning and separation efficiencies were 24.85% and 35.92%; and 85.66% and 93.34% for SG-2000 and newly developed threshing units respectively. Upon comparison of the two threshing units, the mean values of performance increment for newly developed over SG-2000 threshing units were 7.8%, 44.54% and 9.5%. The maximum value increments were 36.4%, 56.19% and 15.4% in capacity, cleaning efficiency and separation efficiency respectively. The effective threshing zone was determined, based on the result it is recommended to minimize the length of both threshing units with respect to the existing features. **MATLAB 2014a** software was used for the evaluation and graphical representation of modeling and simulation. Under mathematical and computational modeling and simulation, the result showed that best fit in optimization of the performance evaluations parameters of *tef* threshing unit. Therefore, the technology is recommended to promote to the end users. It can improve the cleaning efficiency of *tef* threshing mechanisms; increase the quality of *tef* and the drudgery of farmers. To perform closer to 100 % cleaning efficiency, it is recommended to have additional sieves.

Key Words: Cleaning Efficiency, Concave, Design, Drum, Separation Efficiency, *Tef*, Threshing Unit, Trampling.

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NOMENCLATURE

A	Factor accountable to the resistance of bearing from references
A_{cc}	The effective areas of concave (m^2)
a	Cross-sectional area (m^2)
B	Factor accountable to air resistance(kgfm)
C_1	Concentration of grain below straw walkers
C_2	Concentration of grain on straw walker
C_c	Concave cylinder clearance(m)
C_f	Coefficient of friction b/n straw and thresher
C_t	*Tef* threshing unit drum concave clearance
D_t	*Tef* threshing drum diameter
D	Cylinder (rotor) diameter (m)
D_c	Coefficient of diffusion(m^2.min)
D_r	The deformation at rupture point
E	Modulus of elasticity (Gpa)
E_a	The rupture energy(mJ)
E_i	Energy developed per unit area of impacts($J.m^{-2}$)
E_n	Energy needed per area of impacts to detach a unit mass
F	The crop feed rate ($kg.s^{-1}$)
F_r	The rupture force in(N) -
F_{ri}	Flexural rigidity
F_{smax}	Maximum cutting/ shearing/ force, (N)
f_{t1}	Tangential force due to the impact action the crop speed(kN)
f_{t2}	The resistive force experienced by the cylinder due to the compression(kN)
f_{t3}	The resistance against the movement of the crop mass(kN)

F_{tt}	The tangential force (kN)
g	Acceleration due to gravity ($g=9.81 m.s^{-2}$)
I	Moment of inertia(mm^4)
k_t	Threshing factor
K_c	The elasticity of the crop stem(kpa)
L	Cylinder(rotor) length(m)
L_c	Concave length (m)
L_d	Length through which diffusion is occurring(m)
M.C	Moisture content (%)
N	Number of impacts
Q_g	Volumetric grain flow rate ($m^3.min^{-1}$)
q_p	Throughput of MOG($kg.s^{-1}$)
Q_t	Feedrate for stationary thresher ($kg.s^{-1}$)
U	Unthreshed grain mass (kg)
U_{cy}	The peripheral speed of the threshing cylinder ($m.s^{-1}$)
V	Peripheral speed of the rotor ($m.s^{-1}$)
V_{ax}	Crop speed ($m.s^{-1}$)
V_t	Peripheral velocity($m.s^{-1}$)
W	Drum width (m)
w.b	Wet base
W_c	The width of the threshing cylinder (m)
W_t	Width of *tef* threshing cylinder (m)
λ	The threshing rate (m^{-1})
α	Moisture content of crop (%w.b.)
β	The separation rate(m^{-1})
δ_m	Concave clearance(m)

ρ	Bulk density of MOG(kg.m^{-3})
ρ_o	The bulk density of the incoming crop(kg.m^{-3})
ρ_i	The bulk density of the entrapped crop(kg.m^{-3})
ρ_t	The bulk density of *tef* (kg.m^{-3})
μ_c	The coefficient of friction of the crop mass over the concave surface
Ω	Angular speed of the drum(rad.s^{-1})
Δt	Change of crop stems thickness at original and after entrance in concave(m)
θ_m	The current rotation angle of the material around the longitudinal axis(^{o})
τ	Shear stress,Mpa

LIST OF ABBRVIATIONS

AAiT	Addis Ababa Institute of Technology
AARC	Adet Agricultural Research Center
AAU	Addis Ababa University
AMIMTDE	Amhara Metal Industry and Machine Technology Development Enterprise
ANOVA	Analysis of Variance
ARARI	Amhara Region Agricultural Research Institute
ASAE	American Society of Agricultural Engineers
CSA	Central Statistics Agency
DZARC	Debreziet Agricultural Research Center
et al	Et alibi
h	Hour
ha	Hectare
i.e.	That is
m	Meter
mm	Millimeter
mm^2	Millimeter square
MoA	Ministry of Agriculture
MC	Moisture content
MOG	Material other than grain
RTPC	Rural Technology Promotion Center
SG-2000	Sasakawa Global 2000

CHAPTER ONE

GENERAL INTRODUCTION

1.1. Background

Ethiopian economy is much dependent on agricultural production, where crop production contributes largely to the local and export markets. Different types of cereals are grown in almost all regions of Ethiopia. The area coverage out of the total grain crop area, 80.71% (10,232,582.23 hectares) is under cereals. *Tef, maize, sorghum* and *wheat* took up 23.85% (about 3,023,283.50 hectares), 16.79% (about 2,128,948.91 hectares), 14.96% (1,896,389.29 hectares) and 13.38% (1,696,907.05 hectares) of the grain crop area, respectively. As to production, cereals contribute 87.48% (about 267,789,764.02 quintals) of the grain production. *Maize, tef, wheat* and *sorghum* made up 27.43% (83,958,872.44 quintals), 17.26% (52,834,011.56 quintals), 15.17% (46,429,657.12 quintals) and 16.89% (51,692,525.40 quintals) of the grain production, in the same order (CSA, 2018).

Tef (Eragrostistef (Zucc.) *Trotter*) *is* the typical crop and staple food for Ethiopians. *Tef* is a gluten- free crop, which makes it suitable for patients with celiac disease (Dekking *et al*., 2005). *Tef* is likely to remain a favorite crop of the Ethiopian population and the crop is also gaining popularity as a health food in the western world. The straw is used mainly for reinforcing mud for plastering wooden walls of buildings. *Tef*s' straw is the preferred feed for animals and *tef* has a fine stemmed straw which can be firmly stacked in such a way to minimize percolations of rain water and exposures to other inclement weather conditions (Fekede *et al*., 2015). *Tef* is a labour intensive crop; each activity (pre- harvest and post-harvest) is mostly done by traditional practice. It is obvious that productivity of agriculture is strongly related to among other factors, the timely and efficient pre-harvest and post-harvest operations. Most of the farmers in the country usually prepare their land either using human power or draught.

Threshing is a key part of agricultural processing that involves removing the seeds or grain from plants and the plant stalk. This may be accomplished by impact between the heads and a fast moving element, rubbing, squeezing or a combination of these methods. Threshing is breaking grain free from other plant material by applying mechanical force that creates a combination of impact, shear and/or compression (Bill and Bernard, 1999). It is important to avoid damaging grain during threshing, a challenging task under certain crop conditions. Threshing can be performed with different methods. In the case of small farms, threshing is done by beating or crushing the grain by hand or foot and sticks which requires a large amount of hard physical labour. Animal trampling is also the method of threshing in most developing countries. A simple thresher with a crank can be used to make this work much easier for the farmer. The conventional tangential threshing unit threshes mostly by impact; other threshing devices like rotary threshing units act more by rubbing. Rotary threshing units, in which the crop is fed axially or tangentially into the rotor, are becoming more popular (Bill and Bernard, 1999). In most threshing operations the next steps are separation and cleaning seeds from material other than grains. The operation of separation refers to separating threshed grains from bulk plant material such as straw. The cleaning operation uses air to separate fine crop material such as chaff from grain (Christopher, 2011).

In Ethiopia, mostly threshing is performed by animal trampling, separation and cleaning done manually using fork. Threshing of *tef* is done by animal trampling. Cleaning and separation of *tef* seeds from the chaff and straw using the conventional techniques /mostly by air / are impossible, the size of the *tef* seed is very small was reported to vary between 0.71 and 0.87mm and thousand grain mass 0.257–0.421 g (Zewdu & Solomon, 2007). Zewdu (2007) concluded that air separation technique cannot provide complete theoretical separation of *tef* grain from straw; particularly end-node straws have terminal velocities comparable or even greater than that of *tef* grains.

Mechanisms is an assembly of moving parts performing a complete functional motion, and threshing mechanisms are the part of the thresher (drum and concave) which can help to perform rubbing, impact or squeezing. Threshing efficiency is the percentage of the threshed grains calculated on the basis of the total grains entering the threshing mechanism. It increases asymptotically with concave length up to a certain point. Increasing concave length beyond the point does not increase threshing efficiency and might even decrease it under certain conditions (Miu *et al*., 1997). Threshing performance parameters are affected by design factors, operating parameters and crop conditions. To combat the problem of *tef* threshing and cleaning, it required to design/develop/ a new *tef* threshing system. Based on the requirements of the appropriate threshing mechanism, following the design procedures (Pahl *et al*., 2007), a new *tef* threshing unit was developed (designed and manufactured). After development of threshing unit the performance was evaluated with two variables of drum speed and feed rate. The preliminary observation test and the performance of each threshing units were determined following the test standard procedure by Smith *etal. (*1994).

This dissertation focused on development of a new *tef* threshing mechanism including identification of the physical and mechanical properties of different *tef* varieties and on design, manufacture and evaluation of the *tef* threshing units. The new design is expected to increase the cleaning and separation efficiency and capacity of stationary thresher in comparison with the existing stationary threshers (Like, SG-2000 model). The wider application of this mechanism will enhance the quality and quantity of *tef* production by reducing threshing losses and drudgery of the farmers and end users. The system will be as initial point for performance improvements of other threshing units for cereal crops.

1.2. Statement of the Problem

Tef is a unique crop which has the smallest seed compared to other crops. It is an indigenous crop widely consumed in Ethiopia. The production system is traditional and sedimentary with high post-harvest loss which is estimated at 20-30% of the total production. About post-harvest loss of *tef* as Oromo people in the Adaa area said "Had they known how much of me is lost, they would not have grown me, said *Tef*" Bekabil *et al*. (2011). This indicates that the peoples producing *tef knows* about losses, but they couldn't have any alternative rather than using the same way of production. As a researchable issue, the following questions should be answered. Is it possible to combat the *tef* threshing drudgery? By how much could we minimize the threshing loss and increase the cleaning efficiency compared to the existing threshing system?

Despite the increment of interest in consumption and production of *tef* crop in other countries other than Ethiopia, the physical and mechanical properties of this typical crop's stem are not well known. The traditional system of *tef* threshing is rubbing between the grounds and hooks of animals, so, in this research the questions become, what type of threshing system is more appropriate for *tef*, rubbing or impact or squeezing or a combination of each other? To design a new threshing and separation system determination of the physical and mechanical properties of *tef* stem is very important. The current practice of Ethiopian farmers and the experience in threshing systems for cereal crops calls for the development of a new threshing mechanism. The research will focus on determination of the physical and mechanical properties of *tefs'* stem beforehand to analyze the *tefs* threshing power requirements and develop *tef* threshing system which improved and can be easily adapted in any type of threshers.

1.3. Objectives of the Research

1.3.1. General objective

- Theoretical and experimental investigation of a threshing mechanism for *tef* depending on the crop's engineering properties (physical and mechanical properties)

1.3.2. Specific objectives

- Evaluation of the physical and mechanical properties of *tef* stem during the maturity stage, and characterization of *tef* grain straw ratio mixture
- Theoretically analyze and select different types of threshing units and increase the cleaning and separation efficiency by 20-30% and capacity by 10-15% compare to the existing technology (stationary threshers)
- Design and manufacture of *tef* threshing unit in affordable cost
- Evaluation of threshing units' performance with the selected *tef* variety

1.4. Significance of the Research Project

Traditional ways of *tef* threshing and cleaning contribute to the post-harvest loss and decrease of the quality of *tef* production. The *tef* post-harvest loss is estimated at more than 25% (Bekabil *et al*. 2011), which could be minimized by utilizing the modern technology. However, most of the Ethiopian farmers are under subsistence farming and have no opportunity to use modern technology. Therefore, searching for a better and efficient threshing system with minimum (affordable) cost is a timely assignment of researchers. The new threshing unit would solve the existing technology problem (improved stationary *tef* threshers), and the *tef* crop will increase in quantity and quality. In addition to that this technology could be one option of threshing technology for manufacturers and create job opportunity.

1.5. Limitation of the Study

The study focused on basic research to verify the physical and mechanical properties of *tef* stem, though the research was conducted only on four selected varieties (local and newly released varieties). The result could be different if it would be assessed and tested on many different varieties. After development of the *tef* threshing units, the comparisons were performed only on the feed rate and speed of the drum. But, the clearance between concave and drum; and concave hole size and configuration were not considered as variables.

1.6. Originality

The *tef* threshing units' prototype with new shape and configuration was developed and evaluated using the standard design and test procedures. The evaluation was done with comparisons of the existing stationary threshing units' performance (used by Ethiopian farmers). This output will be the first initiation in having a new *tef* threshing unit design with unique profile and could possible to improve the output capacity, separation and cleaning efficiency of stationary threshers. The physical and mechanical properties were determined; it used to determine the force and power requirements of *tef* threshing system.

1.7. Organization of the Paper

The dissertation is divided in five chapters; the first chapter describes the general introduction about the research background and justification; originality; statement of the problem and its objectives. The second chapter includes the literature reviews about the whole issues. The third chapter shows the detail methodology for the whole research. The fourth chapter includes the result and discussions of the research. The fifth chapter summarizes conclusions, recommendations and future works.

CHAPTER TWO

LITERATURE REVIEW

2.1. Physical and Mechanical Properties of crop's Stem

Different researchers determined the physical and mechanical properties of different plants (Yiljep and Mohammed, 2005; Simonyan *et al*., 2009). Identifying the physical and engineering characteristics of cereal crops is very important to optimize the design parameters of agricultural equipment used in harvesting, threshing, production, handling and storage processes.

2.1.1. The physical properties of crop's stem

The physical properties of cellular materials are important in cutting, compression, tension, bending, density and friction (Shaw and Tabil, 2007; Yiljep and Mohammed, 2005). The physical properties are stalk (stem) diameter, maturity, moisture content and cellular structure. Moisture content has a great influence in harvesting, threshing, separation, cleaning and grading operations (Simonyan *et al*., 2009). The *tef* plant has different structure of the stem (compare to other cereals) which has different number of panicles containing different amount of *tef* seeds at each panicle. Lodging is the major problem of *tef* production. Several studies have shown morphological traits that are related to the lodging of *tef* to be related to plant height, stem diameter of lower internodes, panicle length, biomass and seed weight (Seyifu, 1997). In Ethiopia, lodging of *tef* is also a common phenomenon and one of the causes for the current low grain yields. The Ethiopian national average grain yield of *tef* is in the order of 800 kg ha^{-1} (Tulema *et al*., 2005).

Tef's estimated yield loss due to lodging can be as high as 30% (Seyifu, 1997). Lodging resistance related traits, such as plant height and culm thickness, diameters of the stem are related to the physical properties of the plant. Delden *et al.* (2010) studied the lodging cause of the two varieties of *tef* and come up with the conclusion that enhancing the anchorage strength of the roots has priority over stem enhancement. The axial dimensions of agricultural product determine the size while its volume determines the shape (Irtwange and Igbeka, 2002).

Nevertheless, breeding efforts should not only focus on a wider root plate diameter and more rigid horizontally growing roots but also on shorter and thicker stems, that means the breeding study should focus on the morphological behavior of *tef.*

2.1.2. The mechanical properties of crop's stem

Plants are rheological materials whose properties follow non-Newtonian laws as derived their behavior in terms of plasticity and elasticity (Miu, 2016). However, the mechanical properties of plants were studied and determined by different researchers. Bending stress, young's modulus, shearing stress and shearing energy were determined for Alfalfa (Medicago sativa L.) stem by Nazari *et al.* (2008). The alfalfa stems were arranged with the major axis of the cross–section in the horizontal plane and placed on two rounded metal supports 50 mm apart and then loaded midway between the supports with a blade driven by the movable supports. Accordingly, the experiments were conducted at a moisture content of 10%, 20%, 40% and 80% w.b. The bending stress decreased as the moisture content increased. The value of the bending stress at low moisture content was obtained approximately 3 times higher than at high moisture content. The average bending stress value varied from 9.71 to 47.49 MPa. The young's modulus in bending also decreased as the moisture content and diameter of stalks increased. The average young's modulus ranged from 0.79 to 3.99 GPa (Nazari *et al.*, 2008).

Similarly, to measure the shear strength of the stem, an apparatus was constructed to hold the counter shear and canola specimen, so that it would be possible to cut the stem under constant speed. Shearing stress, bending stress and young's modulus were determined for Canola (Brassica napus L.) stem by Bahram and Alireza (2012). They studied three varieties of Canola and the average values for the young's modulus were found to be 1.57, 1.71 and 2.04 GPa for Zarfam, Okapi and Opera varieties respectively. An instron Universal Test Machine (UTM) which equipped with 50 N load cells with an accuracy of ±0.001 N was used to measure the mechanical strength testing and picking force of rose flower stem (Adel *et al.*, 2017).

Egidijus *et al.* (2013) measured the shear strength of the wheat and barley straw by establishment of tension (breaking) force. Tribometer TRM 500 (Wazau GmbH, Germany) was used to establish the breaking force of crop harvest residues. In order to apply it in the experiments with crop harvest residues a special device allowing fixing the examined crop residues from both ends was made.

Measurement of the shear strength of six varieties of wheat straw by O'Dogherty *et al.* (1995) showed mean values in the range 5.4–8.5 MPa. Bending and shearing properties of safflower stalk was studied by Shahbazi and Nazari (2012). The average bending stress value varied from 21.98 to 59.19 MPa. The Young's modulus in bending also decreased as the moisture content and diameter of stalks increased. The average Young's modulus varied between 0.86 and 3.33 GPa. The shear stress and the shear energy increased with increasing moisture content. Values of the shear stress and energy also increased from top to bottom of stalks due to the structural heterogeneity. The maximum shear stress and shear energy were found to be 11.04 MPa and 938.33 mJ, respectively, both occurring at the bottom region with the moisture content of 37.16%. Chattopadhyay and Pandey (1999) found that the bending stress for sorghum stalks at the seed stage and forage stage were 40.53 and 45.65 MPa, respectively.

The shear strength of rice was determined by Tabatabaee and Borgheie (2006) the static and dynamic shearing strength was different among the varieties. They used a pendulum impact testing apparatus which was fabricated and used to measure the cutting energy and shearing stress. The maximum and minimum shearing strengths were related to the varieties Khazar and Hashemi, with an average of 1629 and 1429 kPa for static test and values of 187.4 and 144 kPa for the dynamic test, respectively. Similarly, Mohammad *et al.* (2011) established a pendulum impact type testing apparatus for measuring the cutting energy of rice stem. They conclude that there was a highly significant and positive correlation between the cutting energy and stem wall thickness.

According to Crook and Ennos (1994) lodging susceptibility in cereals depends on three factors: first, the size and dynamics of the forces to which the plant is subjected; second, the bending strength of the shoot and its resistance to buckling; and third, the anchorage strength of the root system. Flexural rigidity (E x I) is not stem strength but is a measure of the stem's ability to bend. It is dependent on the geometry of the stem (stem radius and stem wall width), but is not dependent on the material component of the stem.

Data on physical and mechanical properties are important in the design of a specific machine or analysis of the behavior of products in order to perform various post-harvest operations (Singh *et al.*, 2004)**.** The data obtained from this research could be very essential for designing of *tef* threshing units. The physical properties can influence the mechanical properties such as the tensile strength, shear stress and flexural rigidity of the stem (resistance to lodging). Prior to improvement of the physical properties of *tef*, it is more crucial to determine the mechanical properties of the existing varieties (major varieties). Based on the above references and information’s, it is possible to measure the physical properties of *tef* stem with Micro Meter and Vernier Caliper, the mechanical properties like tensile test with UTM and shear (cutting force) test with Texture Analyzer .

2.2. Development of a Threshing System

Threshing is the process of separating grains from heads, pods, panicles (Kutzbach and Quick, 1999). The first thresher was first invented by Scottish mechanical engineer Andrew Meikle for use in agriculture. It was devised for the separation of grain from stalks and husks. Threshing mechanism is a system composed of rotating part (drum) and stationary concave, used for threshing.

Threshing is detaching the kernels from the ears or pods and is accomplished by a combination of impact and rubbing action. While the conventional tangential threshing unit threshes mostly by impact, other threshing devices like rotary threshing units act more by rubbing. Rotary threshing units in which the crop is fed axially or tangentially into the rotor are becoming more popular (Bill and Bernard, 1999). Additional tasks of the threshing units are the separation of the grain through the concave and transferring the straw to the straw walker or separating section. In rotary combiners, generally, the front part of the one or two rotors threshes and the rear part separates the grain from the straw, making use of higher *g*-forces without the need for gravity-dependent walkers.

The entire harvesting operation may be divided into cutting, threshing, separation and cleaning functions. Threshing is breaking grain free from other plant material by applying mechanical force that creates a combination of impact, shear and/or compression. It is important to avoid damaging grain during threshing–a challenging task under certain crop conditions. For example, at high moisture content it is harder to break grain away from the crop material but easier to damage grain. The operation of separation refers to separating threshed grains from bulk plant material such as straw. The cleaning operation uses air to separate fine crop material such as chaff from grain (Kutzbach and Quick,1999).

2.2.1. Methods of threshing

In agricultural practice, farmers use different methods of threshing: stick beating, animal trampling, stationary threshers and combine harvester. A source of energy includes human power for stick beating, animal power for trampling and motor for stationary thresher and combine harvester.

2.2.1.1. Manual (hand or mechanical assisted) threshing

As a source of power, the human being operates essentially like a heat engine, with built-in overload controls or regulators. Only about 25 percent of the energy consumed when handling relatively easy tasks such as pedaling, pushing or pulling is converted into actual human work output (Bill and Bernard, 1999). On the average, a healthy person in temperate climates consumes energy at a sustainable rate of only about 300 W, while in tropical climates, as a result of heat stress the rate is reduced to only about 250 W (Bill and Bernard, 1999). Manually it is possible to detach grain from stalk or panicle by stick beating (Figure.2.2 and 2.3.) and manual operated thresher (Figure 2.4.).

Figure 2. 1. Animal trampling (for tef threshing and cleaning) in Adet, Ethiopia **(**Authors)

Figure 2. 2. Stick or hand beating (threshing) of crops in Ethiopia

Figure 2. 3. Stick beating (threshing) of sorghum in Nigeria; (Simonyan *et al*.,2008)

Figure 2.4. Human (labour) operated mechanical threshing system or hold-on rice thresher in Ethiopia

2.2.1.2. Animal threshing (trampling)

Threshing of crops by animals is done on special flat ground (*awdma)* that is usually plastered by dried cattle dung. The harvested crop is laid over the ground and cattle/pack animals are trampled over to separate the grain from the straw (Figure 2.1). However, significant yield losses are incurred during this process.

In addition, as the threshing is done on the ground, the quality of the crop is affected as it can become mixed with the soil, sand and other foreign matter. This affects the market value of *tef* significantly as *tef* becomes contaminated by the foreign matter, particularly minute grains of sand and soil. Those foreign materials are difficult to clean and cause discomfort during the consumption of '*Injera*' (Bekabil *et al*., 2011).

2.2.1.3. Motorized stationary threshing

A stationary thresher is a mechanical thresher that uses a threshing cylinder and concave in a localized position. This type of thresher is classified in two distinct methods. The two methods are hold-on and throughput types. The material or crop is fed by throwing in the threshing chamber is called throughput type and when the crop is holding with the operator is called hold on type (Figure 2.4).

In Ethiopia the major threshing system is animal trampling which employs low output and poor quality of produce. To overcome the short comings of animal trampling and hand beatings different threshers developed by Rural Technology Promotion and Research Centers like SG-2000 (Figure 3.5& 3.6) and multi-crop thresher (Figure 2.7) and promoted. The thresher was designed without cleaning mechanism. Some demerits were observed during on farm testing and evaluation of SG-2000 original model.

Poor cleaning efficiency, tedious, time and labour consuming for cleaning, separating straw and grain mixture, especially for threshing and separation of *tef*. To combat these drawbacks, modification was done and tested with different crops by Rural Technology Promotion Centers and Private Companies, but still the problem remains unsolved (Geta *et al.*, 2001). There are few stationary threshers found (developed and modified) in Ethiopia. The thresher operated with the capacity indicated on the (Table 2.1).

Table 2. 1. Capacity of stationary threshers in Ethiopia (Girma and Dawit, 2014)

It	Type of thresher	Type of crops	Unit	Amount
1	Assella Multi crop thresher	Wheat	$Kg.hr^{-1}$	300-500
		Tef	$Kg.hr^{-1}$	200-300
		Barely	$Kg.hr^{-1}$	400-600
		Sorghum	$Kg.hr^{-1}$	1500-2000
2	Bahirdar modified SG-2000 thresher	Wheat	$Kg.hr^{-1}$	300-400
		Sorghum	$Kg.hr^{-1}$	600-700
		Maize	$Kg.hr^{-1}$	1000-1200
3	Bako maize sheller	Maize	$Kg.hr^{-1}$	5000-7000

Figure 2. 5. Bako Maize Sheller and Assela multi-crop stationary thresher in Ethiopia (Girma and Dawit, 2014)

Figure 2. 6. Stationary threshers a) Bahirdar modified SG-2000 b) multi-crop thresher (through put type) in Ethiopia

Figure 2. 7. Internal parts of stationary threshers SG-2000: 1.Drum cover 2. Drum (beater) 3. Concave

Table 2. 2. Stationary threshers in some countries and their performance for threshing grain crop under optimum operating conditions; (Joshua *et al.*, 2010)

s/n	Type of cylinder	Crop	Cylinder Speed	Concave Clearance /mm	Crop Parameter	Cylinder Dimension /mm	Performance Index	Threshing Capacity	Feed Rate Kg/h	Power Source	source
1	Rasp bar	Sorghum	400r/min 10.5m/s	7	Gs=4.33mm G:S-1:3 D=0.22g/cc Ar=33° Ai=32° Mc=32%	D=480 L=640	Te=98.3% Ce=97.2% Gd=1.12% SI=3.8% G= 85.3%	32.2q/h	360	4.95kw Electric Motor	Desta and Mishar
2	Tooth peg	Chickpea	580r/min 14.6m/s	30	Yd=517kg/ha Mc=14.2%	D=480 L=640	Te=93.0% Gd=2.2% Ml=9.1%	190kg/h	430	5.7l/h Gasoline engine	Anwar and Gupta
3	Tooth Peg	Multi crop Wheat, Sorghum Paddy, Maize	12.8m/s 10.5m/s 16.5m/s 15.0m/s	25 35-45 20	Mc=20.2% Mc=16.2% Mc=15.5% Mc=14.8%	D=480 L=480 D=235 L=830	Te=99.0% Gd=2.0% Gd=4.0%	276kg/h Wheat 200kg/h Sorghum 392Kg.hr^{-1}Paddy	500 450 550 500	3.7285 kw Electric motor	Majudar Joshi
4	Tooth Peg	Ground nut	400r/min 6.3m/s	25	Mc=12.0%	D=300 L=1220 61pegs	Ce=95% Gd=3% Sl=6%	264-367 Kg.hr^{-1}		Tractor PTO	Zafar et.al
5	Tooth Peg	Millet	800r/min 9.8m/s	6	Mc=12.0% Ar=13.95° D=798g/cc Gs=3.9mm	D=235 L=830	Te=96.8% Gd=1.3% Sl=4.5%		385	2.24kw Electric motor	Ndirika

Note: Gs = Grain Size; G:S = Grain to Straw Ratio; d = Bulk Density; Ar = Angle of Repose;
Ai = Angle of Internal Friction; D = Cylinder Diameter; L = Cylinder Length;
Te = Threshing Efficiency; Ce = Cleaning Efficiency; Gd = Damaged Grain; Sl = Sieve Loss;
G = Germination Rate; G.nut= Groundnut; Mc = Moisture Content (wet basis);
Bl = Blower Loss; Yd = Yield; Ml = Machine loss; wb = wet basis.

2.2.1.4. Motorized direct combine harvesting

In the direct harvesting method, all functions starting from cutting up to cleaning are performed by one machine called the combine (Figure 2.8). Most major crops can be harvested directly. There are two main kinds of combines, conventional types and rotary types. Either of these types may be self-propelled or pulled by a tractor and powered by the PTO drive. Different manufacturers have different designs, but the functional components are similar. During combine operation the uncut standing crop is pushed by the reel against the cutter bar and onto the platform. The cut crop is conveyed towards the center of the platform from either side by the platform auger and conveyed to the threshing cylinder by the feeder conveyer (Srivastava *et al.*, 2006).

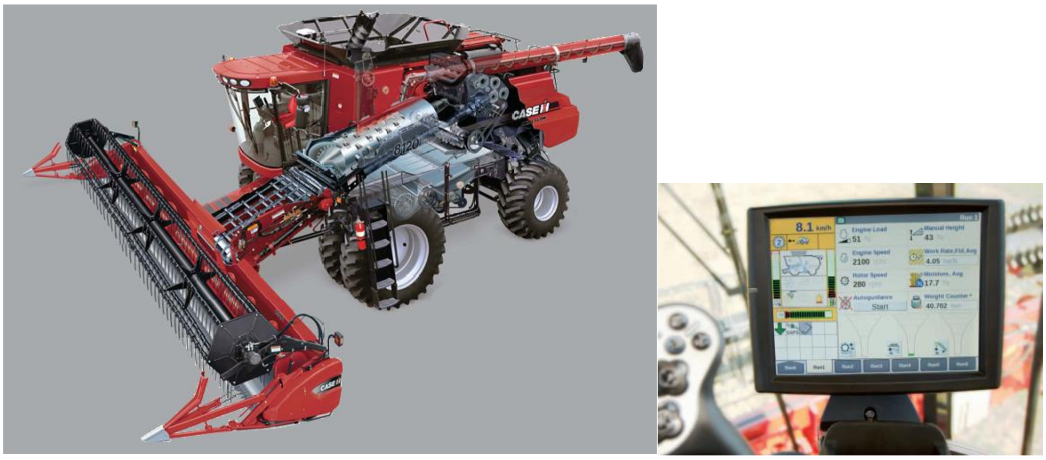


Figure 2. 8. Schematic of the Case IH combine harvester (Axial flow thresher) (Eric,2011)

The crop is threshed by the threshing cylinder. The threshing cylinder rotates at a very high speed (about 30 m/s peripheral speed). About 80% of the grain, along with some chaff and small pieces of straw, is separated through the grate. The bulk of the straw, chaff and the remaining grains pass through the concave-cylinder gap where the beater causes it to slow down. Then this material is delivered to a separator. In a conventional combine the separator is made of oscillating channel sections called the straw walkers. The modern grain harvesters that combine all of the operations (Harvesting, Threshing, Separation and cleaning) in one field-going machine are commonly called combines (Figure 2.8) *(Srivastava et al.*, 2006).

2.2.1.4.1. Functional processes of combine harvester

A modern grain combine performs many functional processes, these are gathering and cutting (or in case of windrows, picking up), threshing, separation and cleaning. In Figure 2.9 shows a process diagram of a combine.

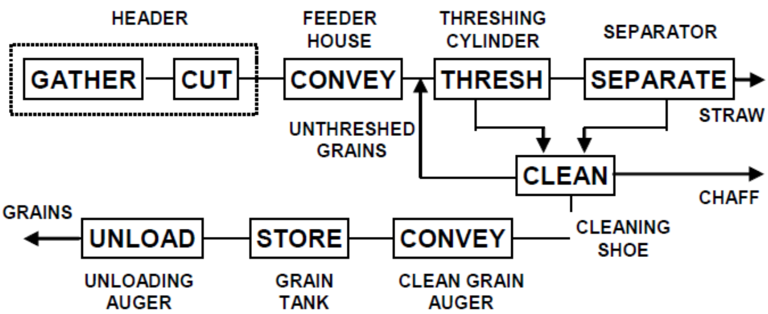


Figure 2.9. Process diagram of a Combine harvester (threshing) (Bill and Bernard, 1999; Srivastava *et al.*, 2006)

General working principles of threshing in threshers

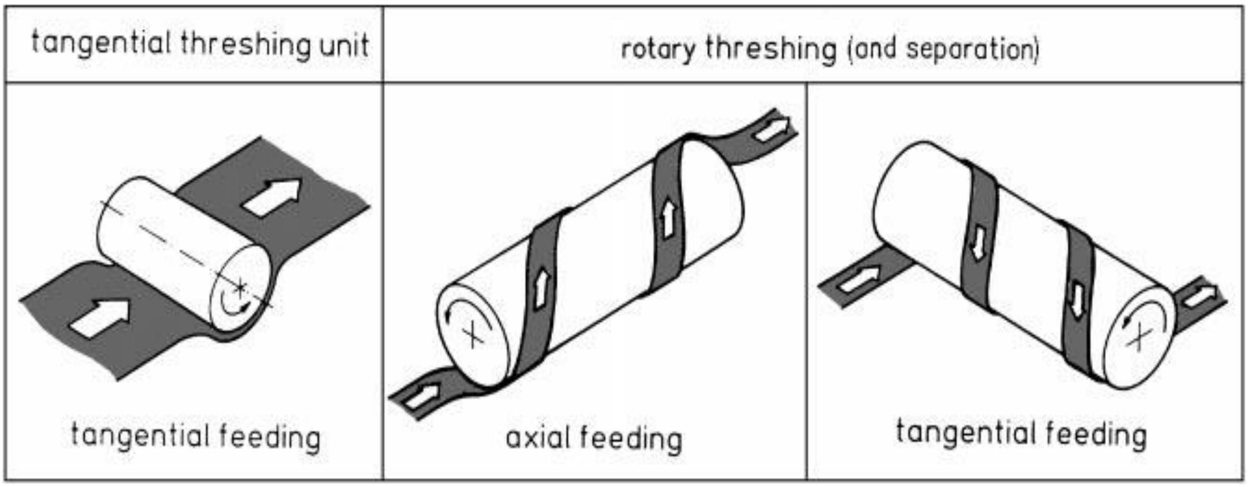


Figure 2. 10. Feeding principles of threshing cylinders (Simonyan *et al*.,2009; Srivastava *et al*.,2006)

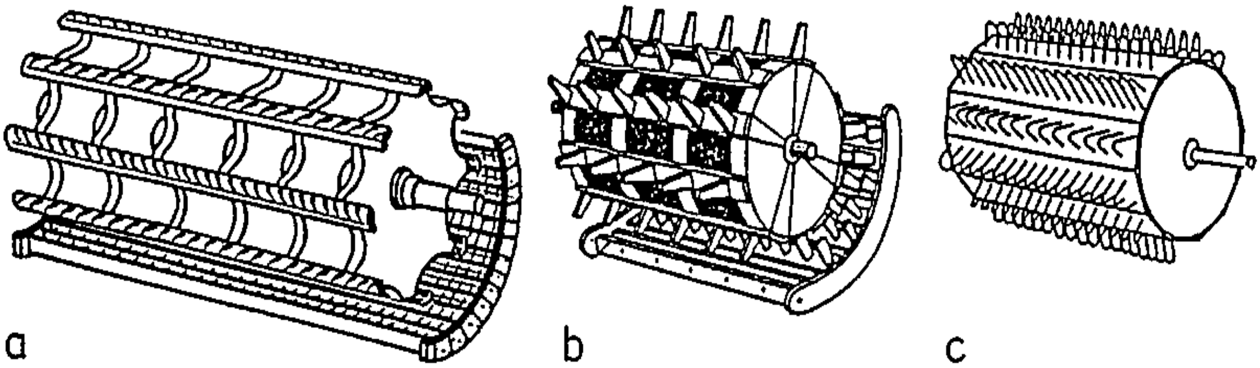


Figure 2. 11. Threshing cylinders type; a) rasp bar; b)spike tooth; c) wire loop (Bill and Bernard, 1999; Srivastava *et al*., 2006)

Tangential threshing units with rasp bars (Figure 2.10) are versatile and can be used for most crops (Bill and Bernard, 1999; Srivastava *et al*., 2006). A spike-tooth threshing cylinder on the other hand (Figure 2.11) offers some advantages for crops having strong stem like rice; wire-loop cylinders are used for hold-on threshers and Japanese rice combines with head feeder systems. The feed elevator, usually a drag chain, supplies the crop to the threshing cylinder at about 2.5–3 m/s.

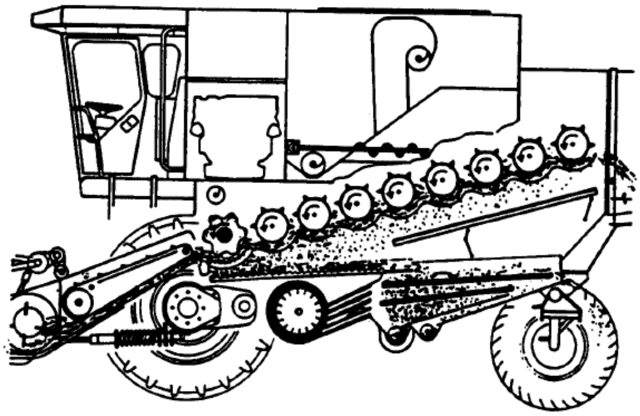


Figure 2.12. A Combine design utilizing a conventional threshing cylinder and multiple separation cylinders (Bill and Bernard, 1999; Srivastava *et al*., 2006)

To thresh different crops, it is possible to get adjustment for varying crop conditions by changing peripheral speed and concave-to-cylinder clearances. With higher cylinder peripheral speeds threshing losses decrease, but grain damage increases (Srivastava *et al*., 2006). Some typical peripheral speeds are shown in Table 2.3 (Bill and Bernard, 1999; Srivastava *et al*., 2006).

Table 2. 3. Typical cylinder peripheral speeds for various crops (Bill and Bernard, 1999; Srivastava *et al*., 2006)

crop	Peripheral speed(rasp-bar or spike-tooth), m/s	Mean clearance (rasp-bar cylinders), mm
Alfalfa	23-30	3±10
Barley	23-28	6-13
Edible beans	8-15	8-19
Beans for seed	5-8	8-19
Clovers	25-33	1.4-6
Corn	13-22	22-29
Flax	20-30	3-13
Grain sorghum	20-25	6-13
Oats	25-30	1.5-6
Peas	10-15	5-13
Rice	25-30	5-10
Rye	25-30	5-13
Soya beans	15-20	10-19
Wheat	25-30	5-13

To adjust speed, the threshing cylinder is driven by a variable-speed power belt drive or hydrostatic transmission, often in association with a reduction gearbox for speed-sensitive crops like peas or soybeans. Asli-Ardeh and Abbaspour (2008) investigated the effects of drum speed and moisture content of crop on threshing loss and damaged grain percent on an auto head feed threshing unit. In some studies, grain separation increases along the length of the concave but at a diminishing rate Srivastava *et al*. (2006), as in Figure. 2.14. Under good conditions, grain separation at the concave can be as high as 90%. It drops down to 50%–60% under worse conditions, with the consequence of a high burden on separator or straw walkers.

Large cylinder diameters allow long concaves, but the centrifugal forces needed for good separation decrease with increasing threshing cylinder diameter. Typical diameter is 600 mm. To improve threshing and grain separation with the conventional design for high capacity combines, most manufacturers have turned to multiple cylinder threshing units (Figure 2.12) (Srivastava *et al*., 2006). Additional separation cylinders may be placed behind the beater (New Holland, MF, Fiatagri, Deutz-Fahr) or in front of the threshing cylinder (Class). Between the drums the material is loosened up for improved grain penetration. The performance improvement of any type of threshing units can apply the above multiple cylinder, but for the case of stationary threshers it will be more complicated in manufacture process and costly.

2.2.1.4.2. Comparison of tangential and axial threshing units

The performance criteria of threshing devices are primarily:

- Throughput
- Threshing losses
- Grain separation
- Grain damage
- MOG-separation and power requirements

Threshing loss is defined as the percentage by weight of whole grains not detached from the ears; grain separation as percentage by weight of separated grain at the concave; grain damage as percentage by weight of damaged grain in the sample compared with the total grain entering the threshing unit (ASABE, 2006). Wacker (2003) showed the influence of MOG-throughput, peripheral speed, MOG moisture content and amount of green content on working quality of a rotary threshing unit. These studies compared this threshing unit with a tangential threshing system with walkers.

This type of axial threshing unit had higher power requirements, higher MOG-separation, a lower percentage of grain damage and higher throughput in a given machine envelope. Generally, rotary threshing units have advantages in corn, soy and rice threshing, but they cannot thresh as many kinds of crop as tangential units can. Rotary threshing units are more sensitive to crop moisture content than the tangential threshers. Axial threshing units show no effect of ground surface irregularity (slopes). Grain loss characteristics are also different (Figure. 2.13) (Bill and Bernard, 1999; Srivastava *et al.*, 2006). Hence, for stationary threshers the axial type threshing unit with tangential feeding is preferable in order to have higher separation rate with limited length/or space of concave.

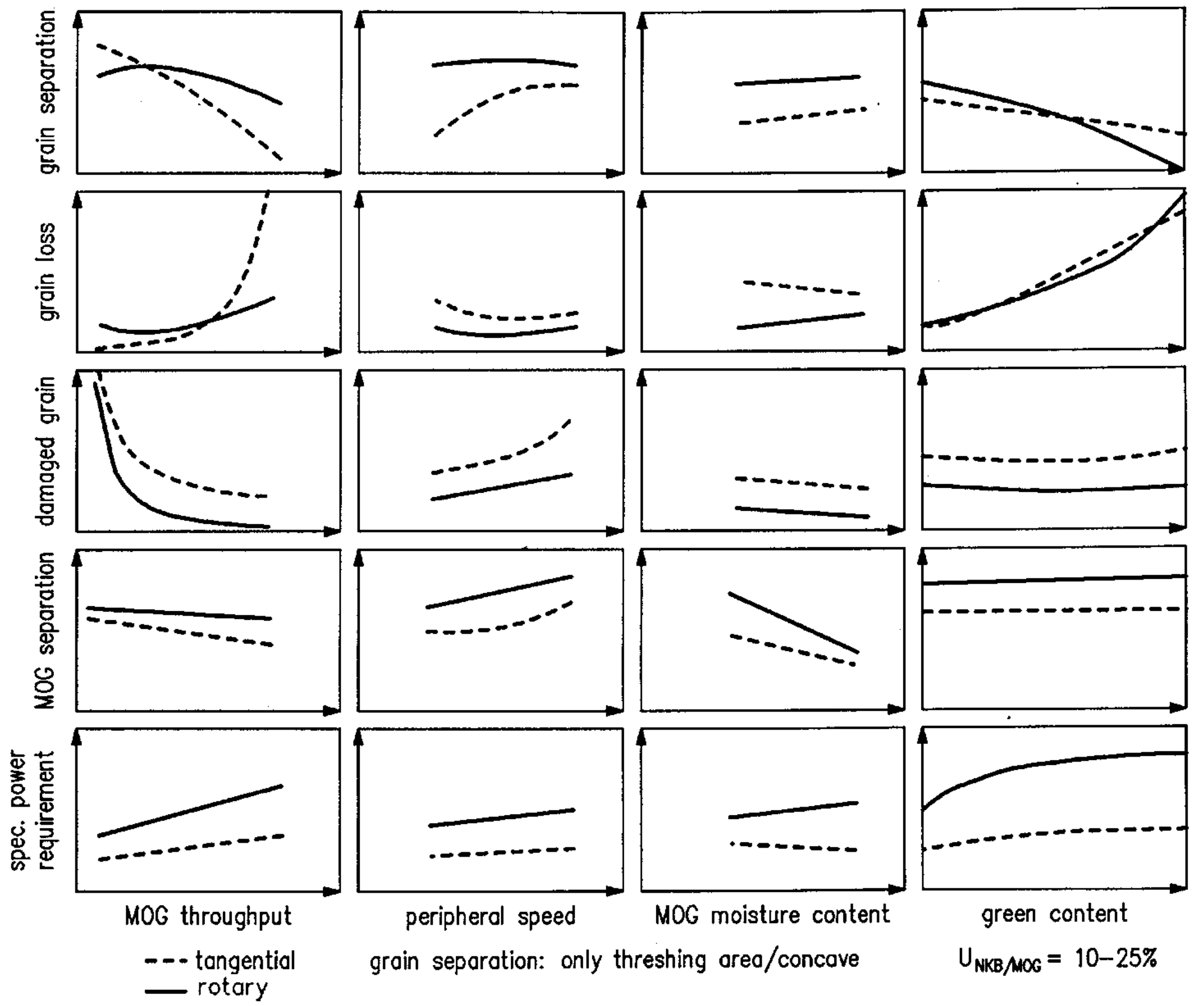


Figure 2. 13. . Performance characteristics of rotary and tangential threshing devices (Bill and Bernard, 1999; Srivastava *et al.*, 2006).

The characteristic grain separation (λ) versus length of the concave *(x)* can best be described with an exponential function by Miu (2016). Detachment of grain from ears can also be described by an exponential function shows by (Bill and Brenard, 1999; Srivastava *et al.*, 2006; Miu, 2016).

$$f_1(x) = \lambda e^{-\lambda x} \tag{2.1}$$

The proportion of unthreshed grain s_n is given by equation 2.2:

$$S_n = 1 - \int_0^x \lambda e^{-\lambda x}\, ds = e^{-\lambda x} \tag{2.2}$$

For a constant throughput, at every cross-section of the threshing unit, the sum of proportion of unthreshed grain S_n, free grain S_f, and separated grain S_S is stated on equation 2.3.:

$$S_n + S_f + S_s = 1 \tag{2.3}$$

With the assumption that the frequency of grain separation S_d is proportional to the amount of free grain in equation 2.4.:

$$S_d = \frac{dSs}{dX} = \beta S_f \tag{2.4}$$

The cumulative proportion of separated grain *Ss* is calculated in equation 2.5.:

$$S_s = \frac{1}{\lambda-\beta}\left[\lambda\left(1 - e^{-\beta x}\right) - \beta\left(1 - e^{-\lambda x}\right)\right] \tag{2.5}$$

and the frequency of grain separation S_d is under equation 2.6.

$$S_d = \frac{\lambda\beta}{\lambda-\beta}\left(e^{-\beta\chi} - e^{-\lambda\chi}\right) \tag{2.6}$$

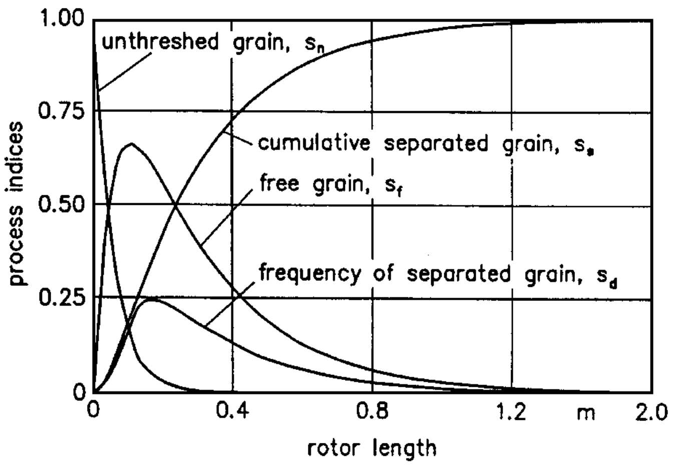


Figure 2. 14. Grain separation versus separation length; (winter barely, total throughput 5 kg/s) (Bill and Bernard, 1999; Srivastava *et al*., 2006).

Figure 2.14 shows unthreshed grain S_n, free grain S_f, cumulative separated grain S_s, and frequency of grain separation S_d plotted against rotor length. For tangential and axial threshing units, there are different values of rotor length (*L*), threshing rate (λ) and separation rate(β).

According to, Miu *et al.* (1997) the linear rate of threshing λ is given by equation 2.7.:

$$\lambda = kt\ (\rho v^2 LD)/(q_p \delta_m V_{\mathrm{ax}}) \tag{2.7}$$

Where:

ρ-bulk density of MOG, (kg/m^3)

V-peripheral speed of the rotor, (m/s)

V_{ax} -crop speed, (m/s)

L -cylinder (rotor) length, (m)

D-cylinder (rotor) diameter, (m)

q_p -throughput of MOG, (kg/s)

δ_m -concave clearance, (m)

k_t -threshing factor

Threshing factor k_t relates to: machine type, crop variety, moisture content, etc. The rate of separation β is proportional to the probability of a kernel passage through an opening in the concave and depends on the ratio of kernel diameter to opening size.

2.2.1.4.3. Separation system in combine harvester

Separation is the isolating of detached seed, small debris and unthreshed material from the bulk. Grain separation in combines refers to the separation of grains from straw after threshing. Large percentages (70% to 90%) of grains are separated during the threshing process. Two types of grain separators are commonly used in combines: conventional combines use straw walkers and rotary combines use rotary separators (Kutzbach and Quick, 1999).

Straw walkers consist of several long channel sections mounted on a crankshaft. As the shaft turns the channel sections follow an elliptical or circular path that causes the straw to bounce on top of the channels and move toward the rear of the combine due to the design of the saw tooth shape of the top of the channel sections. The oscillating action causes the grains and some chaff to be sifted down and be separated from the straw.

Rotary separators, the main force causing the grain to move through a mat of straw is the centrifugal force caused by rotation of the straw mat by the rotor, as compared to the gravity force in the straw walkers. The rotor, which rotates inside of a stationary cylindrical screen, generates a centrifugal force field which is several times that of gravity. The paddles mounted on the rotor surface cause the crop to take a helical path in the annular space defined by the rotor and the screen. In rotary separators the crop motion is forced rather than induced (as in the case of straw walkers). These results in higher capacity per unit grate area, but require higher power. Since the separation is not gravity dependent, irregularity of the ground surface has no effect on the separation process.

Generally, the modern combine harvester is so expensive, complex in manufacture and not economical for small scale farmers like most farmers in Ethiopia.

2.2.2. Design and application

2.2.2.1. General design concept

Design engineering is solving technical problems, finding suitable and preferably optimal solutions for the given task (Eder and Hosnedl, 2008). For product planning, the following differentiation of design tasks is of interest; the first, Original design (new tasks and problems) are solved using new or novel combinations of known solution principles; the second, Adaptive design is the solution principle remains unchanged, only the embodiment is adapted to new requirements and constraints and the third, Variant design is the sizes and arrangements of parts and assemblies are varied within the limits set by previously designed product structures, which is typical of size ranges and modular products (Phal *et al.*, 2007). The engineering design process can range from purely intuitive to systematic and methodical, and prototypes and test rigs may be used to verify parts or complete technical process and/or technical system (Eder and Hosnedl, 2008). Based on the above theory, this research follows the adaptive design and used the design procedures as stated on Figure 2.15.

For any type of product the design specification should consider: purpose, function properties, functionally determined properties, operational properties, manufacturing properties, distribution properties (easy of transportation), liquidation properties (easy disassembly, material recyclable), human system factors (ergonomic..), technical system factors, environmental factors (low energy consumption, high energy efficiency..), management and economic factors (low and affordable cost, delivery time) (Eder and Hosnedl, 2008; Phal *et al.*, 2007) .

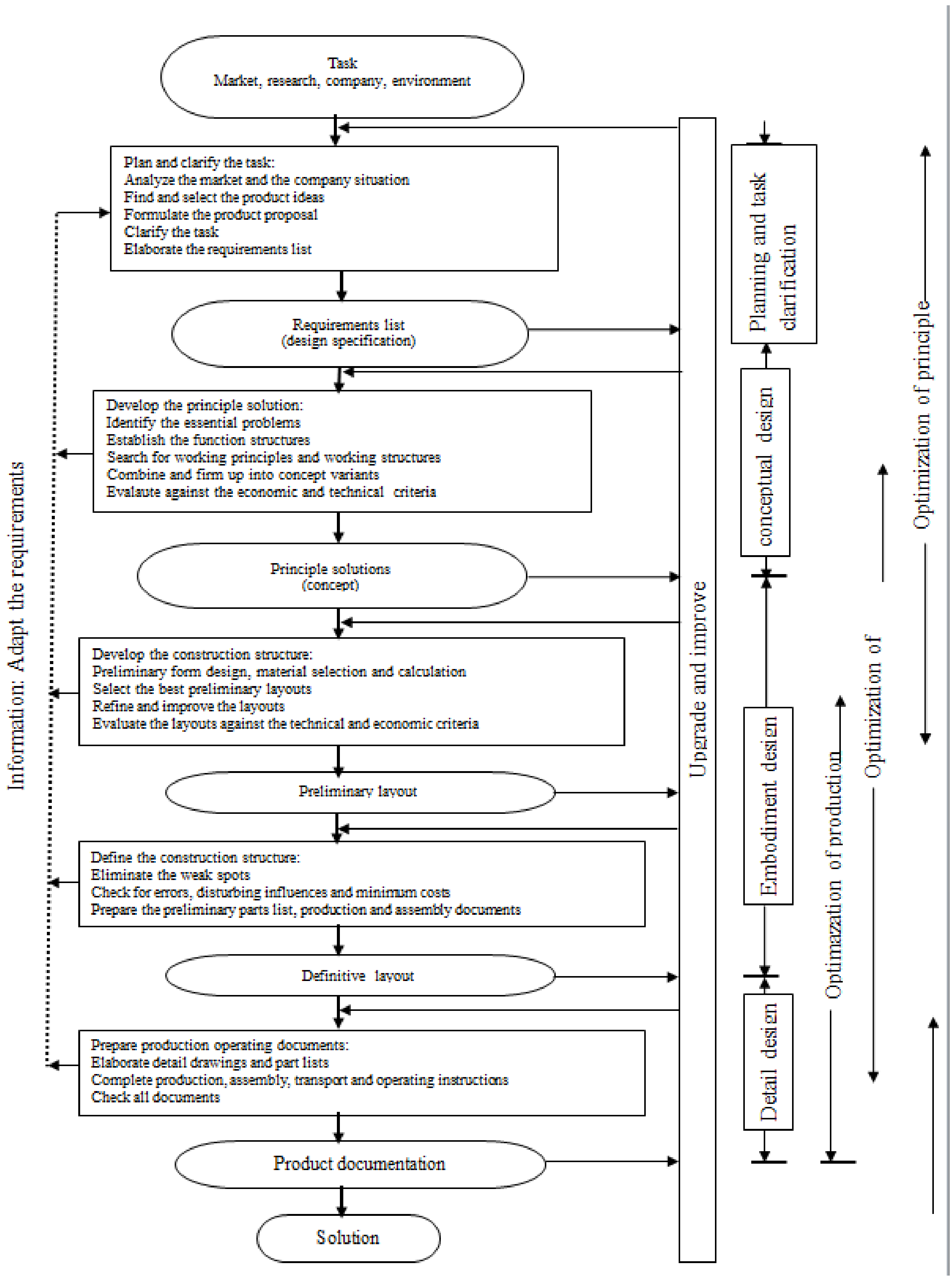


Figure 2.15. Steps in the planning and design process, (Pahl *et al.*, 2007)

2.2.2.2.Theoretical base for designing of threshing units

The conventional threshing units include the rotating drum with different configuration and stationary concave. For this research threshing mechanisms consist of all components and movements of threshing units (cylinder and concave) to perform threshing activities.

Threshing can be performed by impact, rubbing, squeezing and the combination of these actions by hand beating, the animal hoofs and the ground or the rotating parts (drum) and stationary parts (concave) of the machines (Miu, 2016). The impacts can be viewed as random process with some grain being detached by each impact action. The rate of threshing decreases as the probability of hitting unthreshed grain decreases. In equation form this relationship can be expressed as equation 2.8. (Osueke, 2011):

$$\frac{dU}{dN} = -\frac{E_i}{E_n M}U \tag{2.8}$$

Where :

U- unthreshed grain mass

N- number of impacts

E_i- energy developed per unit area of impacts

En- energy needed per area of impacts to detach a unit mass of grain (this variable should vary with the properties of the crop being threshed)

M- Mass of grain to be threshed

This equation can be rearranged and integrated to obtain the following

$$\int_{U_i}^{u_f} \frac{dU}{U} = -\frac{E_i}{E_n M}\int_0^{N_f} dN \tag{2.9}$$

Where:

u_i-initial amount of undetached grain

u_f-final amount of undetached grain corresponding to the final number of impacts N_f

The completion of the above integrations and the conversion from logarithmic to exponential form yields the following equation for the prediction of unthreshed materials.

$$\frac{u_f}{u_i} = e^{\frac{-E_i}{E_n M}N_f} \tag{2.10}$$

The ratio of u_f/u_i is the fraction of material not threshed or the fraction of grain lost due to incomplete threshing. If the material moves through the cylinder concave clearance at a constant velocity, the number of impacts can be evaluated with the following equation 2.11.

$$N_f = \frac{B.L}{V} \tag{2.11}$$

Where:

B-the number of bars (impacting points) on the cylinder that pass a point on the concave in a unit of time.

L-Length of concave (arc length), (m)

V- Velocity of material flow from beginning of concave to the end of concave, ($m.s^{-1}$)

The variable *B* can be evaluated by multiplying the number of bars '*n*' on the cylinder times the '*RPM*'of the cylinder. Both the number of bars and *RPM* are important variables that must be considered in the design of threshing units.

Those formulae can apply for the radial type of threshing drum (unit), where as in the case of tangential (axial) type of threshing unit the impact point (number of impacts) will be more than that of the previous, also its number will be depend on the length of threshing unit.

The equation can be:

$$F_1 = e^{-\left(B/E_n\right)\left(E_i/M\right)\left(L/V\right)} \tag{2.12}$$

The energy per mass term E_i/M**,** can be replaced by the ratio of power per feed rate, *P/R* times the ratio of straw to grain '*r*'. The power rate '*P*' and feed rate '*R*' are very important design and operation variable is given by equation 2.13. As

$$F_1 = e^{-r\left(B/E_n\right)\left(P/R\right)\left(L/V\right)} \tag{2.13}$$

This equation can be rearranged as

$$F_1 = e^{-\left[r\left(P/En\right)\left(L/V\right)n\frac{RPM}{R}\right]} \tag{2.14}$$

For a given threshing design and a given crop material, the quantity within the brackets should be a constant.

2.2.2.3.Threshing performance theory

The performance indices of a threshing unit (composed of one cylinder or rotor) deriving from the threshing and separating processes are shown as in the Figure.2.16.

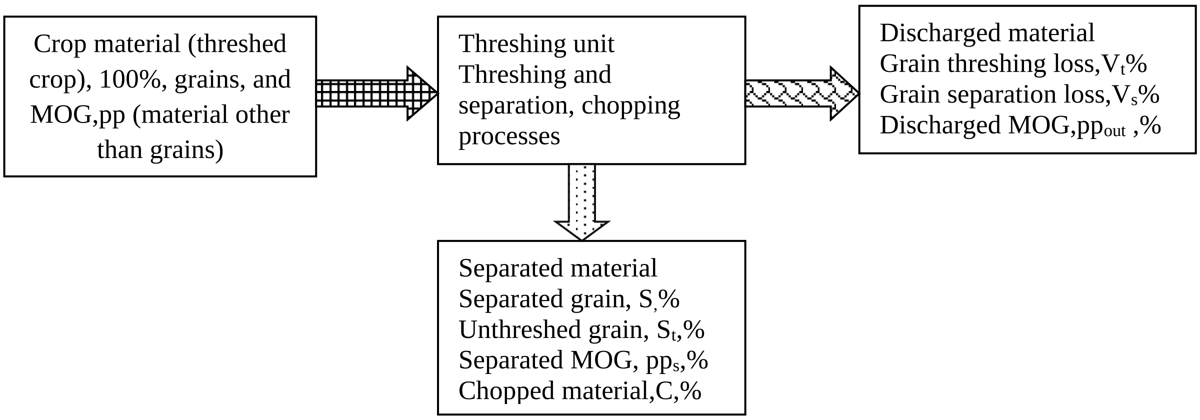


Figure 2.16. Performance indices of a threshing unit (Miu, 2016)

It is possible to consider a threshing unit of a certain design and dimensional parameters that performs a stationary threshing and separating processes that is stochastic processes whose marginal distribution like means, variances do not change when shifted in a certain time. So, the threshing unit performance is characterized by the following performances indices:

- Total material throughput (feed rate), q
- Cumulative percentage, S_s of the grains, relative to S, that separate through the concave openings and cage
- Percentage of unthreshed grains, S_n and threshing loss V_s (which are either separated or discharged)
- Percentage of threshed (free grain that are discharged) and un separated grains (the separation loss, V_s)
- Grain separation efficiency, eff_s, %
- Cumulative percentage, pp_s, of separated MOG, through the concave opening
- Percentage of fragmented, separable MOG, pp_f, relative to the pp 100% through put
- Percentage of damaged grain, S_b
- Specific power consumption, Pts that is the required power per unit of material throughput
- Idle power, Po of the cylinder/rotor that needs to be overcome

These indices are highly depending and has relation in the following variables (parameters)

- Crop: type, variety, maturity, crop yield variation, fraction of green content (weed-to MOG ratio)
- Vegetal material properties: MOG compressibility modulus, MOG bulk density, grain and MOG moisture content, coefficients of friction of material with various surfaces, stem structure and shape
- Feeding-dependent parameters: material cutting height (grain straw ratio), feeding direction (tangential, axial), material velocity and throughput variation
- Threshing unit: Type, design, functional parameters (rotor speed, material feed rate and concave clearance) (Bill and Bernard, 1999; Srivastava *et al*., 2006 and Miu, 2016)

Threshing efficiency is the percentage of the threshed grains calculated on the basis of the total grains entering the threshing mechanism. It increases asymptotically with concave length up to a certain point. Increasing concave length beyond the maximum point does not increase threshing efficiency and might even decrease it under certain conditions. However, Miu *et al.* (1997) experiments show that under easy threshing conditions there is little advantage of increasing the concave length beyond 33 cm. increasing the diameter of the conventional threshing cylinder increases threshing losses at a rate of about 0.9% for each 7.5 cm increase in the diameter.

The number of rasp bars and their spacing do not seem to have any effect on the threshing efficiency. Cylinder speed is one of the most important variables affecting threshing losses. For hard-to thresh crops and/or conditions, threshing losses can be significantly reduced by increasing the cylinder speed. According to Srivastava *et al.*, (2006) one set of experiments increasing the speed from 23 to 33 m/s reduced losses from 8% to 4%. The cylinder-concave gap affects threshing losses adversely. An increase of 1/8 in. increased the unthreshed loss from 0.6% to 2.0%. Changing the concave clearance ratio (the ratio of the gap at the front to that at the rear of the cylinder) is done to facilitate crop feeding into the cylinder, but the effect of this variable on the threshing efficiency is not consistent (Srivastava *et al*., 2006).

Threshing losses increase with material feed rate, which is generally expressed in terms of tons/h of material-other-than-grain (MOG). The other ways of expressing material feed rate are grain feed rate and total feed rate. Threshing losses also increase with the MOG-to-grain ratio. Moisture content also affects threshing efficiency. Generally, the crop becomes hard to thresh at higher moisture content and as a result the threshing losses become higher. Also, if the crop is not fully mature and if there is a lot of green material in the crop, threshing becomes difficult and losses increase.

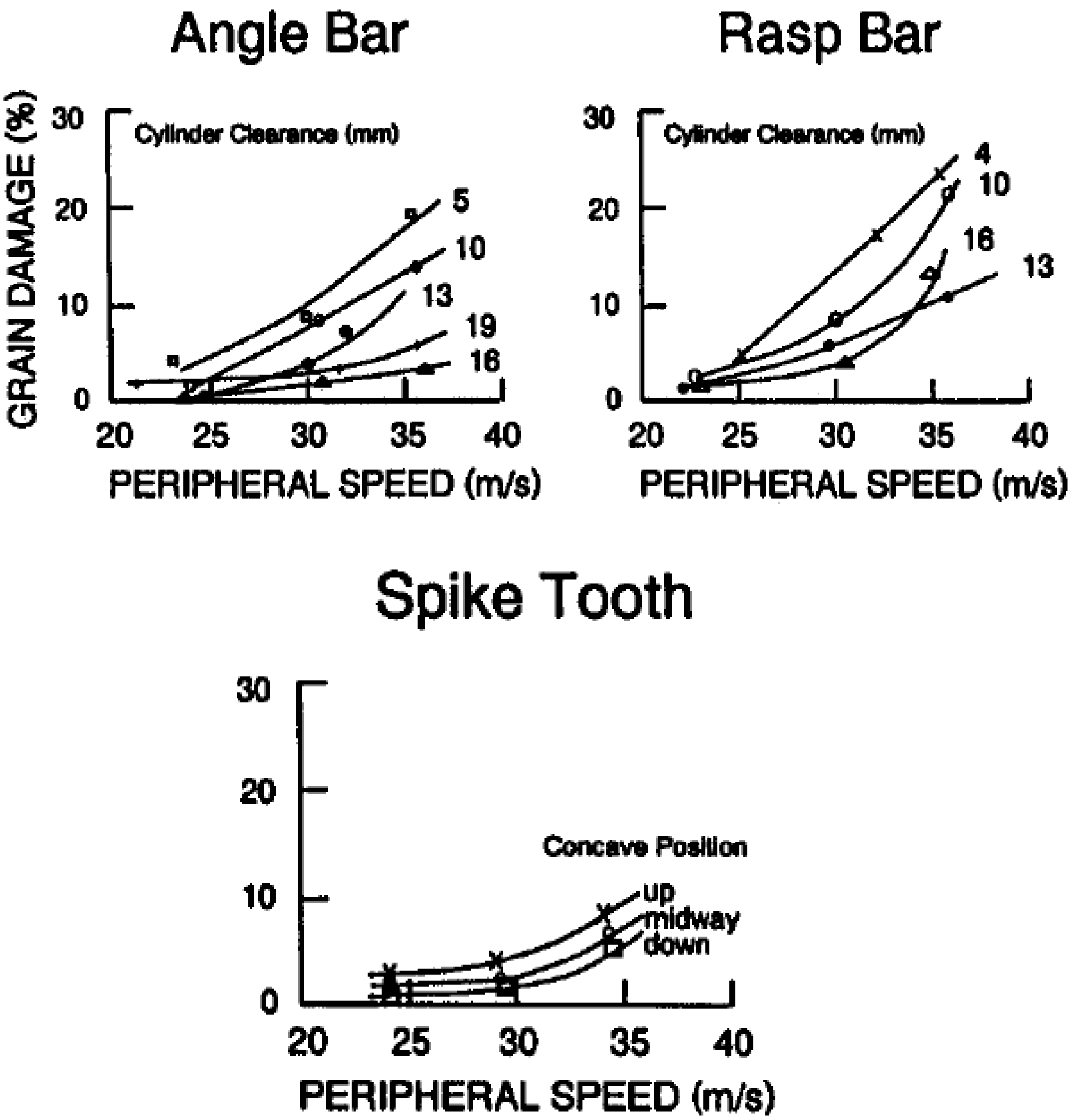


Figure 2.17. Effect of cylinder speed and clearance on visible damage to barely having a moisture content of 12%-15%; (Srivastava *et al.*, 2006).

The separation efficiency of the threshing cylinder is defined as the percent of grains separated through the concave grate of a conventional combine, or at the threshing of a rotary combine, to the total grain in the crop entering the threshing mechanism. A major portion of the total grain separation is done at the threshing (Miu *et al.*, 1997).

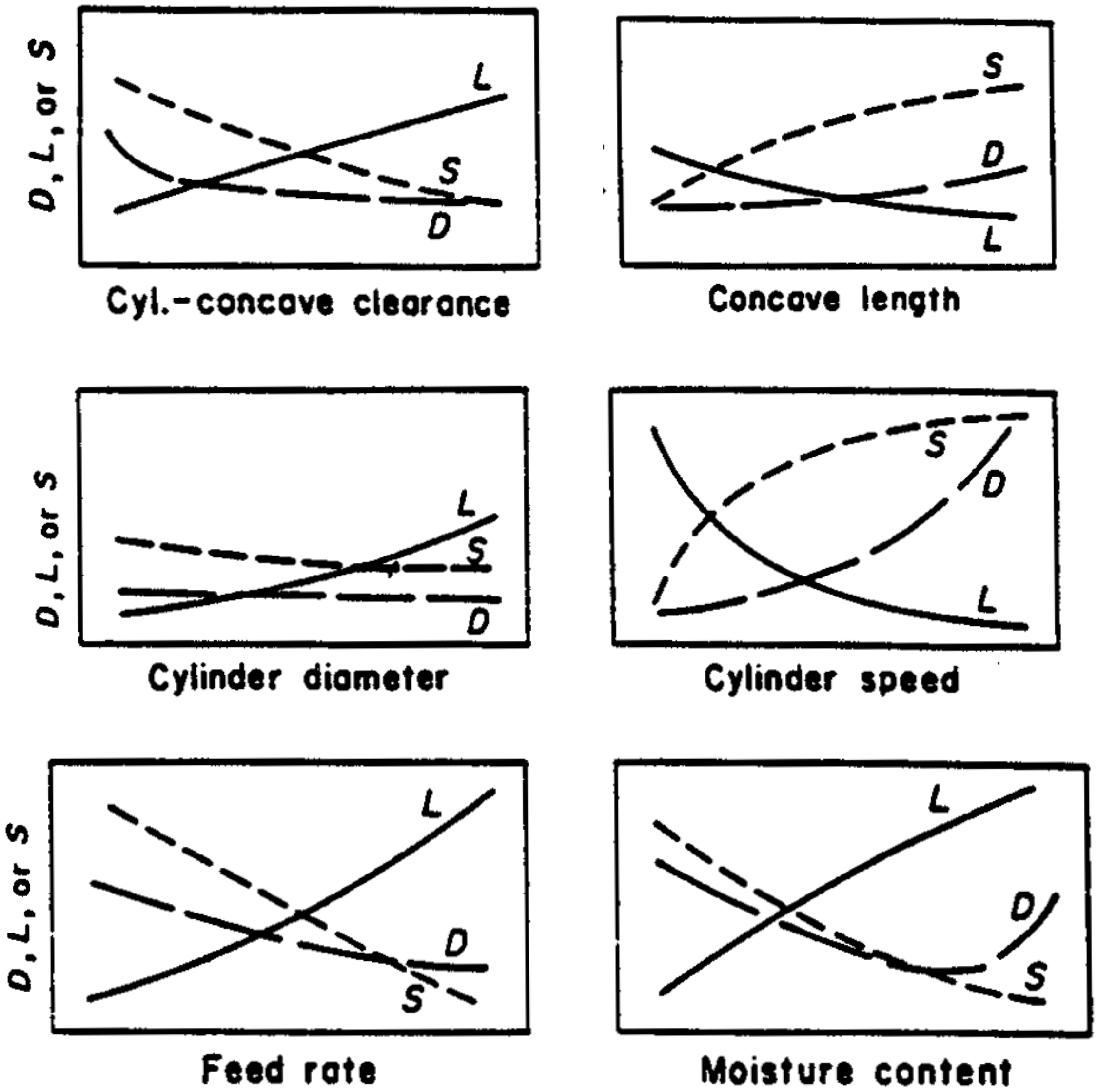


Figure 2. 18. Graphical characterization of some of the performance relations for a rasp-bar cylinder with an open -grate concave; L = cylinder loss; D = grain damage; and S = percent of grain separated through concave grate (Bill and Bernard, 1999; Srivastava *et al*., 2006)

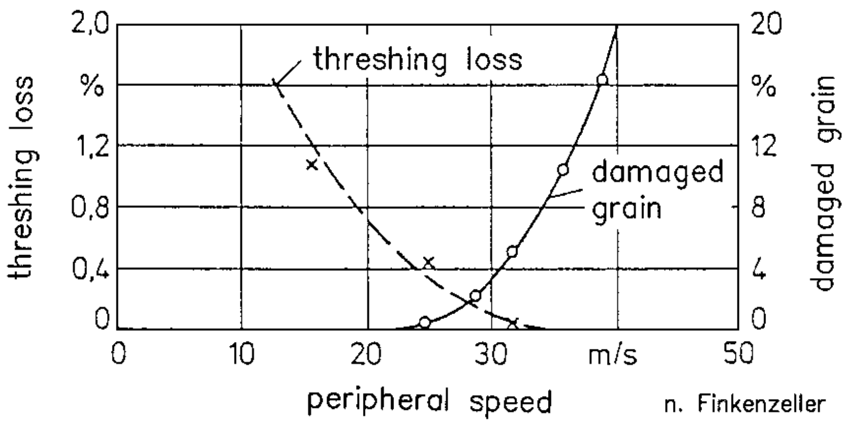


Figure 2.19. Threshing loss and grain damage versus peripheral speed (Srivastava *et al*., 2006)

2.2.2.4. Separation theory

The separation process occurs during the threshing process, means every movement of the threshed material determined the separation and segregation rate of the given crops. The grain separation efficiency represents the probability of separation of the remaining separable grain (seed) in a given area (length x width) of the concave or sieves. Grain separation efficiency is a useful index for comparison of the design versus work of similar threshing units with different sizes (Miu, 2016). Separating efficiency of an axial flow threshing cylinder largely depends on the length and diameter of cylinder (or area of separation) and the peripheral speed of the cylinder (Chimchana *et al*., 2008).

The major determinant factors for separation rate of the threshing units studied by different researchers, in some studies the common conclusions draw the separation theory in the following forms. The separation rate β_t is given by relating the separated grain fractions additionally to the length of the individual sample collecting boxes:

$$\beta_t = \frac{m_{ti}}{m_{tto}\Delta l_i} = \frac{m_{ti}}{\Delta t \cdot m \cdot_{tto} \Delta l_i} \tag{2.15}$$

Where:

β_t-the separation rate of crop

m_{ti}-the whole collected mass of crop with its length of individual sample boxes,(gr)

m_{tto}- the total grain collected in the samples box,(gr)

Δl_i- length (width) of each box towards the length of sieve(concave),(m)

Based on Miu (2016) the coefficient of β and λ bear an exponential relationship with the rotor speed.

$$\beta = \frac{aV}{ebv}$$

$$\lambda = \frac{v^2}{k_e mv}$$

Where:

a,*b*,*k*,*m* are the coefficients of the threshing units

V -the rotor(drum) speed, ($m.s^{-1}$)

β- the separation rate, (m^{-1})

λ- the threshing rate, (m^{-1})

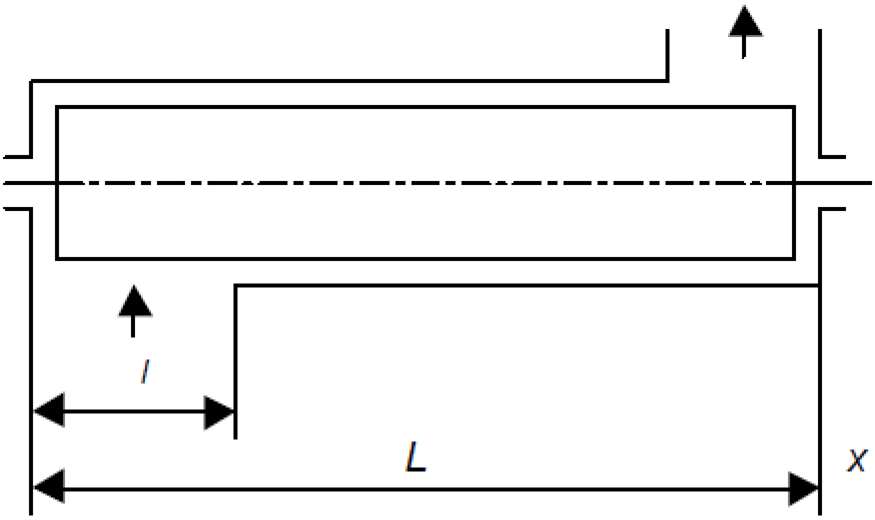


Figure 2.20. Schematic representation of axial threshing unit with tangential feeding (Miu, 2002)

The frequency of unthreshed grain in to the threshing space is a continuous variable. The fraction of unthreshed grain S_{n1} *(x)* equation 2.16 in the feeding zone, $0 \leq x \leq l$ is (Figure 2.20).

$$S_{n1}(x) = \frac{1}{L}x\left(1 - \int_0^{x<L} \lambda e^{-\lambda s}\, ds\right) = \frac{1}{L}xe^{-\lambda x} \quad (2.16)$$

Making the first derivative

$$\frac{ds_{n1}(x)}{dx} = 0$$

We find that $S_{n1}(x)$ has a maximum at $x = \frac{1}{\lambda}$.

The fraction of unthreshed grain $S_{n2}(x)$ over the length $l \leq x \leq L$ is equal to as equation 2.17:

$$S_{n2}(x) = 1 - S_{n1}(l) \int_0^x \lambda e^{-\lambda(s-l)}\, ds = e^{-\lambda x} \quad (2.17)$$

At the end of the threshing space it is possible to use *(x=L)*, the unthreshed grain becomes the threshing loss V_l and in the empirical form it has effect on the length of the threshing units.

$$V_l = S_{n2}(L) = e^{-\lambda L} \quad (2.18)$$

Separation of free grain kernels or seeds through the straw mat and openings of the cage and concave occurs due to independent and successive random events. According to the probability theory, the joint density $S_d(x)$ of the sum independent steady random variables equals the convolution of their densities. Therefore, we get the joint density that is the separation frequency:

$$S_d(x) = f(x) * g(x) = \int_0^x f(z)g(x)dz = \frac{\lambda\beta}{(\lambda-\beta)}\left(e^{-\beta x} - e^{-\lambda x}\right) \quad (2.19)$$

The cumulative distribution function $S_{s1}(x)$ of separated grain over length *[0,l]* is found by integrating the density function $S_d\ (x)$ equation 2.19, and then multiplying by proportionality factor *x/l*, Hence

$$S_{s1}(x) = \frac{1}{(\lambda-\beta)}\frac{x}{l}\left[\lambda\left(1-e^{-\beta x}\right)-\beta\left(1-e^{-\lambda x}\right)\right] \tag{2.20}$$

For $l \leq x \leq L$, the cumulative distribution function $S_{s2}(x)$ of separated grain is found by integrating the above equation only (i.e., the proportionality factor equals 1), as equation 2.21:

$$S_{s2}(x) = \frac{1}{(\lambda-\beta)}\left[\lambda\left(1-e^{-\beta x}\right)-\beta\left(1-e^{-\lambda x}\right)\right] \tag{2.21}$$

It can be noted

$$S_{s2}(l) = S_{s1}(l) \tag{2.22}$$

Therefore, the cumulative distribution function $S_s(x)$ over length *[0,x]* is

$$S_s(x) = \begin{cases} S_{s1}(x)_{0\leq x\leq l} \\ S_{s2}(x)_{0\leq x\leq l} \end{cases} \tag{2.23}$$

In the cross section of threshing space (Figure 2.20), at position *x*, the balance equations can be written as equation 2.24 and 25:

$$S_{n1}(x) + S_{f1}(x) + S_{s1}(x) = \frac{x}{l}, x \leq l \tag{2.24}$$

$$S_{n2}(x) + S_{f2}(x) + S_{s2}(x) = 1, l \leq x \leq L \tag{2.25}$$

Where $S_{f1}(x)$ and $S_{f2}(x)$ represent free, separable grain proportion corresponding to different position *x* over the rotor length. Consequently, we get equation 2.26 and 27:

$$S_{f1}(x) = \frac{\lambda}{(\lambda-\beta)}\frac{x}{l}\left(e^{-\beta x}-e^{-\lambda x}\right) \tag{2.26}$$

$$S_{f2}(x) = \frac{\lambda}{(\lambda-\beta)}\left(e^{-\beta x}-e^{-\lambda x}\right) \tag{2.27}$$

It can be noted that

$$S_{f2}(l) = S_{f1}(l)$$

At the end of the threshing unit space, the free grain becomes segregation separation loss V_{gs}. Hence the equation can be written on equation 2.28.

$$V_{gs} = S_{f2}(L) = \frac{\lambda}{\lambda-\beta}\left(e^{-\beta L} - e^{-\lambda L}\right) \quad (2.28)$$

In different research out puts notice that the fraction of unthreshed grain decreases with rotor (drum) length, but reaches the maximum within the feeding zone, and then decreases exponentially.

The continuity equation of the process quality indices over the length of threshing space is

$$\frac{1}{\beta}\frac{\partial^2 S_s}{\partial x^2} + \frac{\partial S_s}{\partial x} = \lambda S_n \quad (2.29)$$

The grain separation frequency $S_g(x)$ depends on the fraction of separable, segregated grain $S_g(x)$ that reaches the concave (cage) surface, by a coefficient that is the linear segregation rate λ. Thus, the fraction of separable, segregated grain $S_s(x)$ is given by the following equations 2.30.

$$S_g(x) = \frac{\beta}{(\lambda-\beta)}\frac{x}{l}\left(e^{-\beta x} - e^{-\lambda x}\right) \quad \textit{for } x \leq l \text{ for Tangential threshing unit} \quad (2.30)$$

$$S_g(x) = \frac{\beta}{(\lambda-\beta)}\left(e^{-\beta x} - e^{-\lambda x}\right) \quad \textit{for } l \leq x \leq L \text{ for axial threshing unit (Figure 2.20)}$$

At the end of the threshing space, the separable, segregated grain $S_g(x)$ becomes pure separation loss V_s on the following equation 2.31:

$$V_s(L) = \frac{\beta}{(\lambda-\beta)}\left(e^{-\beta L} - e^{-\lambda L}\right) \quad (2.31)$$

Consequently, the fraction of free, unsegregated grain $S_{ng}(x)$ can be calculated with the following equation 2.32:

$$S_{ng}(x) = S_f(x) - S_g(x) \quad (2.32)$$

That leads for the following equations 2.33 and 34.

$$S_{ng1}(x) = S_{f1}(x) - S_{g1}(x) = \frac{x}{l}\left(e^{-\beta x} - e^{-\lambda x}\right) \quad (2.33)$$

$$S_{ng2}(x) = S_{f2}(x) - S_{g2}(x) = \left(e^{-\beta x} - e^{-\lambda x}\right) \quad (2.34)$$

At the end of the threshing space, the unsegregated grain becomes segregation loss V_{ng} and the equation becomes

$$V_{ng}(l) = \left(e^{-\beta l} - e^{-\lambda l}\right) \quad (2.35)$$

The continuous separation efficiency $eff_s(x)$ at the current position x of the separation length is defined as the ratio between the separated grain mass on the differential interval dx and the available grain mass that could be separated at the rear of the threshing unit. The separation efficiency on the rotor length is composed of two formulas corresponding to the feeding and threshing zones respectively

$$eff_s(x) = \begin{cases} eff_{s1(x)/0\le x\le l} \\ eff_{s2(x)/0\le x\le L} \end{cases}$$

Consequently, for feeding and threshing zones, these equations can be mathematically expressed as the following equations 2.36 and 37.

$$eff_{s1}(x) = \frac{S_{d1}(x)}{1-(V_t+S_{s1}(x))} \quad (2.36)$$

$$eff_{s2}(x) = \frac{S_{d2}(x)}{1-(V_t+S_{s2}(x))} \quad (2.37)$$

These equations realize and approved by different researcher test result and most of the research outputs agree with the equations. According to Miu *et al*. (1998b) the specific rates β and λ have been determined using multiple nonlinear regression analysis of the cumulative separated grain fraction, threshing and separation losses and the generalized functions that describe the influence of crop properties the functional and design parameters of the axial unit. According to the test result the dry winter wheat has β=3.03-3.95m^{-1}; λ=3.95-5.06m^{-1} with regression R^2=0.981-0.996.

2.2.2.5. Mathematical modeling for designing a threshing unit

The mathematical equations developed to explain the threshing, separation and damage processes. According to Simonyan *et al*. (2009), the mean threshing rate *(λ)* describes on equation 2.38:

$$\lambda = K_t(\rho v^2 wD)/(QC) \quad (2.38)$$

Threshing loss explains on equation 2.39:

$$TN_L = e^{-0.5K_t[(\rho(1-\alpha)VWDL)/(QC)]} \quad (2.39)$$

Grain damage, threshing efficiency and threshing capacity describes under equations 2.40-2.42 :

$$GD = e^{-K_d\left(\frac{(1-\alpha)VWDL}{Q}\right)} \quad (2.40)$$

$$\text{Efficiency} \quad E_{ff} = 1 - e^{-0.5K_T[(\rho(1-\alpha)VWDL)/QC]} \quad (2.41)$$

$$\text{Threshing capacity} \quad CAPTH = E_{ff} * Q * r \quad (2.42)$$

Where:

D-drum diameter, (m)

C-concave clearance, (m)

ρ-bulk density of the crop, (kg.m^{-3})

V_2- peripheral speed of the drum, (m.s^{-1})

W- width of the thresher (threshing unit), (m)

Q-mass feed rate of the threshed crop, (kg.s^{-1})

K_T –threshing factor

According to Miu (2016) or integrating of process model, the threshing and separation can be characterized on the following parameters:

$$y = [S_s, L_s, PP_s, P_{ts}, S_v, L_t, S]$$

Where:

Ss - cumulative percentage of separated grain

Ls - grain separation loss percentage

PPs - cumulative percentage of separated material other-than-grain (MOG)

Pts - specific power requirement

Sv -grain damage percentage

Lt - grain threshing loss percentage

S - material slip (cinematic condition, unpublished yet).

The continuity equations of the process quality indices on the threshing length can be written:

$$\frac{1}{\beta}\frac{\partial^2 S_s}{\partial x^2} + \frac{\partial S_s}{\partial x} = \lambda s_n \tag{2.43}$$

$$\frac{1}{a}\frac{\partial^2 PP_s}{\partial x^2} + \frac{\partial PP_s}{\partial x} = abpl_n \tag{2.44}$$

Where:

x - threshing length (concave or rotor length), (m)

S_n - percentage of unthreshed grain, (%)

pl_n - percentage of undetached chaff, (%)

According to Joshua *et al.* (2010) the mean rate of threshing kernels can be calculated using the empirical formulas equation 2.45.

$$\lambda = k_c \frac{C^3(1 - M_{cwb})}{\delta t_{max}} \tag{2.45}$$

Where:

λ - mean rate of threshing kernels, (m^{-1})

V_t - peripheral speed of the cylinder, (m.s^{-1})

M_{cwb} - moisture content (wet basis) of the crop, (%)

δt_{max} - maximum distance between the threshing drum and the concave, (mm)

C - concave clearance, (mm)

K_c - constant associated with duration of grain crop within the overall length of the concave

The other research group Simonyan *et al.* (2008) developed model**,** is one type of model which is useful for comparison of required power and verify the power with available one.

$$P_{av}=P_{req}$$

Where:

P_{av}- power available at the threshing cylinder

P_{req}-power required detaching grains from their panicles

$$P_{av} = QK_E\left[V^2\left(\frac{Q^2}{VC^2\rho}\right)\right] \quad (2.46)$$

Where:

K_E- constant depending on the grain (crop) type

V-peripheral velocity of cylinder by substitution

$$\lambda = K_T\left(\rho {V_2}^2 WD\right)/(QC) \quad (2.47)$$

Where:

$$K_T = \frac{K_p}{K_E} \qquad \rho = \rho_d(1-\alpha)$$

ρ- bulk density at a given moisture content of crop, (kg.m^{-3})

ρ_d- bulk density at 10% moisture content, (kg.m^{-3})

α- moisture content of crop, (%w.b.)

W - width of the threshing cylinder, (m)

D-diameter of the rotor(cylinder), (m)

Q- feed rate, (kg.s^{-1})

C- concave drum clearance, (m)

Then finally the formulas will be derived as equation 2.48.

$$\lambda = \frac{K_T\rho_d(1-\alpha)V^2WD}{QC} \quad (2.48)$$

For each threshing unit it is a must to know the threshing rate with the help of each empirical formula.

When the operation (threshing) starts the feed material in the immediate vicinity of the drum (rotor) gets a velocity whose value is close to the peripheral velocity of the rotor. For the tangential threshing units, the rotor (cylinder) with the radius R and z rasp bars rotates with the angular speed **ω** thus the peripheral speed V_c of the rotor is:

$$V_c = \omega R$$

Where:

V_c - the speed of the feed crop (feed material), (m.s^{-1})

Whereas for axial or rotary threshing units the velocity of the feeding material at the beginning or entrance of the feeding zone is V_0 and has the axial V_{0a} and tangential V_{0t} components. The value has the vector and scalar values.

$$\overline{V}0 = \overline{V}_{0a} + \overline{V}_{0ft}$$

Then, it drives from the geometry of the projectile motion and the interpretation of the derivative of the function $f(x)$ on the angle $\gamma(x)$ at any point x.

tan $\gamma(x) = f'(x) = abx^{b-1}$

Therefore, the relation between the components of the material is describing as equation 2.49:

$$v_{mt} = v_{ma} abx^{b-1} \quad (2.49)$$

Where:

v_{mt} -the tangential velocity of the material, (m.s^{-1})

v_{ma} -the axial velocity of the material, (m.s^{-1})

The absolute velocity of feed material v_m on its axial path can be calculated on equation 2.50.

$$v_m = v_{ma}\sqrt{1 + (abx^{b-1})^2} \quad (2.50)$$

The twisting of the bars (angle γ) on the axial drum can be used to compute the probability of the seeds passage through the concave hole (cage opening) and to design the subassemblies (Miu *et al.*, 1997).

The axial pitch p_{am} of the material trajectory is given by the following equation 2.51.

$$\gamma a_m = 2\pi R_s \frac{v_{ma}}{v_{mt}} = 2\pi R_s \frac{1}{abx^{b-1}} \quad (2.51)$$

Where:

R_s -the equivalent rotor radius,(m)

a - the coefficient that helps to realize the angular trajectory

b - the exponent (a and b are the coefficients from the experiment result or mathematical modeling coefficients).

2.2.3. Designing of threshing and separation unit

To design an efficient threshing and separation system there are different factors which has to be considered. Crop factors (mechanical and physical parameters), operating factors (feed rate, speed of the machine and moisture) and machine factors (type, material, shape, size and friction).

2.2.3.1. Friction

The friction that occurs at the contact surface of the crop and the beater is an integral part of threshing. The friction is as a result of the rubbing action which leads to the detachment of grains from their panicle and hence threshing occurs (Bill and Bernard, 1999). To properly produce a frictional model for grain threshing, the friction factor alongside all other parameters based on physical characteristics of the crop and machine specification need to be incorporated in the modeling process. A total comprehension of the threshing chamber is necessary because the frictional modeling of the cereal thresher is based on what transpires within the chamber which is as a result of crop (panicle) and cylinder movement. Crop properties of the harvested crop, such as moisture content, external friction behavior, angle of repose, structure of straw, grain dimensions and attachment strength in the ears, have essential and complex effects on combine performance as general threshing performance of any crop. Crop properties depend on crop type, crop maturity, crop variety, process of crop growth, nutrition and water status during growth, etc. (Bill and Bernard, 1999).

According to Simonyan and Oni (2001) report on Lablab Purpurusin grain, the grain mass, size and volume increased with increasing moisture content at a range of 9.7 to 29% wet basis (w.b) for "rongai" variety and 10.2 to 22.6% (w.b) for "high worth" variety. They also reported that there was a decrease in bulk density with increasing moisture content at this same range. Bolufani (2001) considered some physical and mechanical properties like moisture content, major and minor diameters, bulk density and angle of repose and grain/straw ratio.

To design compatible threshing chamber friction, between the crop, the cylinder and concave is one of the decisive parameters, but it is not easy to determine. Christian (2011) studied and developed an actual (true) model, that was developed based on friction which occurs within the threshing chamber and between the threshing cylinder and crop. The model was made feasible by establishing sub models to characterize performance. This sub-model goes a long way to tell the efficiency of the thresher, losses in threshing and capacity of the thresher.

2.2.3.2. Rapture force and power requirements

Olaoye and Oni (2001) found that the average threshing moisture content is 10.2% for millet and its average rupture force of 7.54N. This force is differing from detachment force; it is the breakage of seeds in pieces or fine grain. The energy absorbed by the sample at rupture can be determined by calculating the area under the force-deformation curve from the relationship Christian (2011):

$$E_a = \frac{F_r D_r}{2} \tag{2.52}$$

Where:

E_a - the rupture energy, (mJ)

F_r -the rupture force, (N) and D_r - the deformation at rupture point

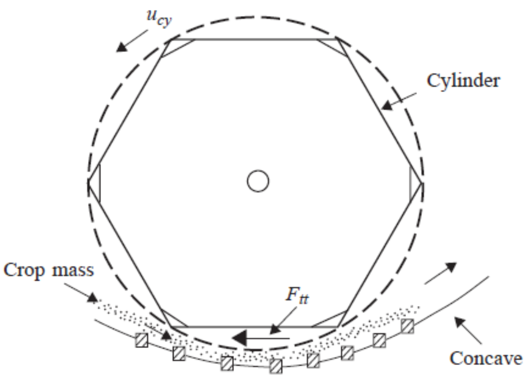


Figure 2.21. Cylinder-concave arrangement of force across flow type threshing cylinder (Baruah and Panesar, 2004)

The value of the material trajectory pitch angle is very essential for the designing of the cylinder or the concave in either tangential or inclined feeding section of the threshing unit in order to ensure that the feed material does not return back to the entrance after one complete revolution.

According to Baruah and Panesar (2004) the cylinder needs to be powered to provide the tangential force at cylinder periphery which comprises the forces of (f_{t1}) impact of threshing member on crop mass, (f_{t2}) compression of crop mass and (f_{t3}) resistance against movement of crop mass.

The following expression is written for estimation of the power P^t_{cy} in kW to overcome tangential force (Figure 2.21):

$$P^t_{cy} = F_{tt} u_{cy} \tag{2.53}$$

Where:

F_{tt} - the tangential force,(kN)

u_{cy} -the peripheral speed of threshing cylinder (rotor),(m.s^{-1})

The tangential force F_{tt} is the sum of the three component forces due to impact, crop compression and crop movement resistances, respectively, as given by

$$F_{tt} = f_{t1} + f_{t2} + f_{t3} \tag{2.54}$$

$$f_{t1} = \left[\frac{25\Delta t}{324.W_c \rho_o C_c t_c} F^2\right] \tag{2.55}$$

$$f_{t2} = \left[K_c \frac{\Delta\rho}{\rho_i} C_c W_c\right] \tag{2.56}$$

$$f_{t3} = \left[K_c \frac{\Delta\rho}{\rho_i} A_{cc} W_c + g\rho_i C_c A_{cc} \mu_c\right] \tag{2.57}$$

And the whole equation expressed as the tangential force due to impact action f_{t1} in kN. The resistive force experienced by the cylinder at its periphery f_{t2} and the resistance against the movement of the crop mass f_{t3} in kN is estimated based on the frictional resistance over the concave surface with an area.

2.2.3.3. Size of cylinder (drum) and concave

In most type of threshing system, the versatile size of these parts is recommended, but different studies reported as common size and types like rasp bar and axial flow. Capacity of a conventional combine increases approximately linearly with increasing threshing cylinder width, if walker and cleaning shoe areas are in the right proportions. Maximum width limitation for the threshing cylinder of about 1.7 m is set by the given total combine body width of 3–3.5 m governed by road and rail transport regulations.

Cylinder or rotor threshing or separating length can be determined based on the length of the cylindrical volume generated by the outermost points of the cylinder or rotor elements, as the cylinder or rotor rotates about its own axis, and as appropriate to its threshing or separating section, dimension (length) (ASABE, 2006) . Single or multiple cylinders or rotors may be disposed laterally (Figure 2.22) or longitudinally (Figure 2.23) within the combine. If multiple cylinders or rotors are used, the number shall be stated and the dimensions given as in Figure 2.22 and Figure 2.23.

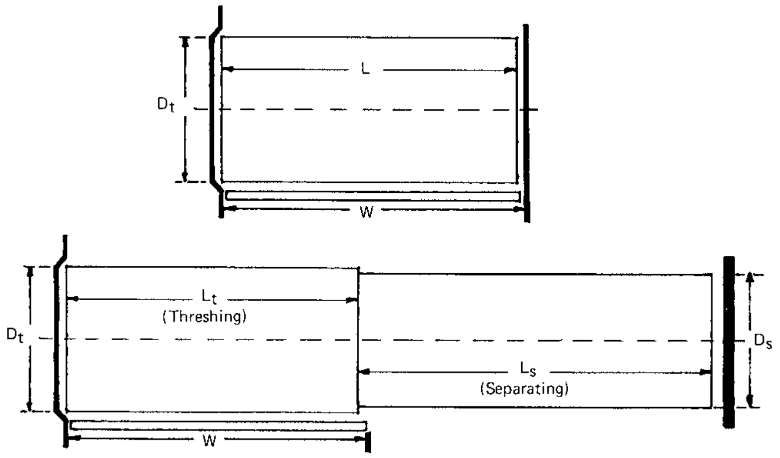


Figure 2. 22. Cylinder, rotor and concave dimensions; (ASABE, 2006)

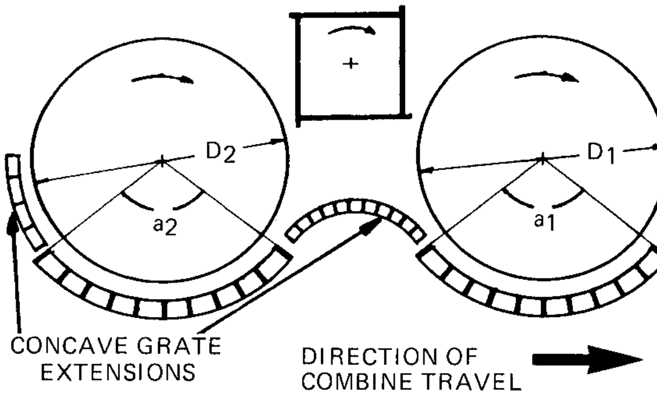


Figure 2. 23. Laterally-disposed cylinders or rotors and wrap angles (ASABE, 2006)

2.2.3.4. The effect of concave design

The concave performs two functions. It must support the threshed material in order to maintain the rubbing or impact action. The concave must allow the maximum possible amount of threshed material or mixture with grains. Miu (2016) reported that, increasing concave length increased concave separation, for unit increase in concave length the proportion of grain separated is equal to 1- e^{-k} , where e is the natural logarithms and k is the rate of constant. With crops that are easily threshed a longer concave produced little increase in threshing efficiency, however crops which were difficult to thresh the increase was not that much.

The amount of grain damage increased with concave length since the grain which was not separated through the concave was subjected to a greater number of impacts before leaving the threshing crescent. For the case of very small grains like *tef* it is not much suspicious for damage and the length of concave is not affecting, rather the length of concave may affect the separation rate of *tef* threshing.

There were comparison studies in regard of concave openness, the two concave types, open and closed type was studied on wheat crop and they come up with the result that there were four times as many damaged kernels in the samples produced using closed concaves. For small grains where the grain damage is not series problem, there is a possibility to use both types. The concaves area is very important for separation the increment in the area will directly proportional with the separation rate. So, based on all test results and assumptions the closed type concave will be one option for *tef* threshing unit.

2.3. Modeling and simulation

Computational modeling: the process is iterative by its nature, meaning that some of the procedures are repeated based on the results obtained at a current stage. The following figure shows processes leading to fabrication of advanced engineering systems (Liu and Quek, 2003).

The processes are:

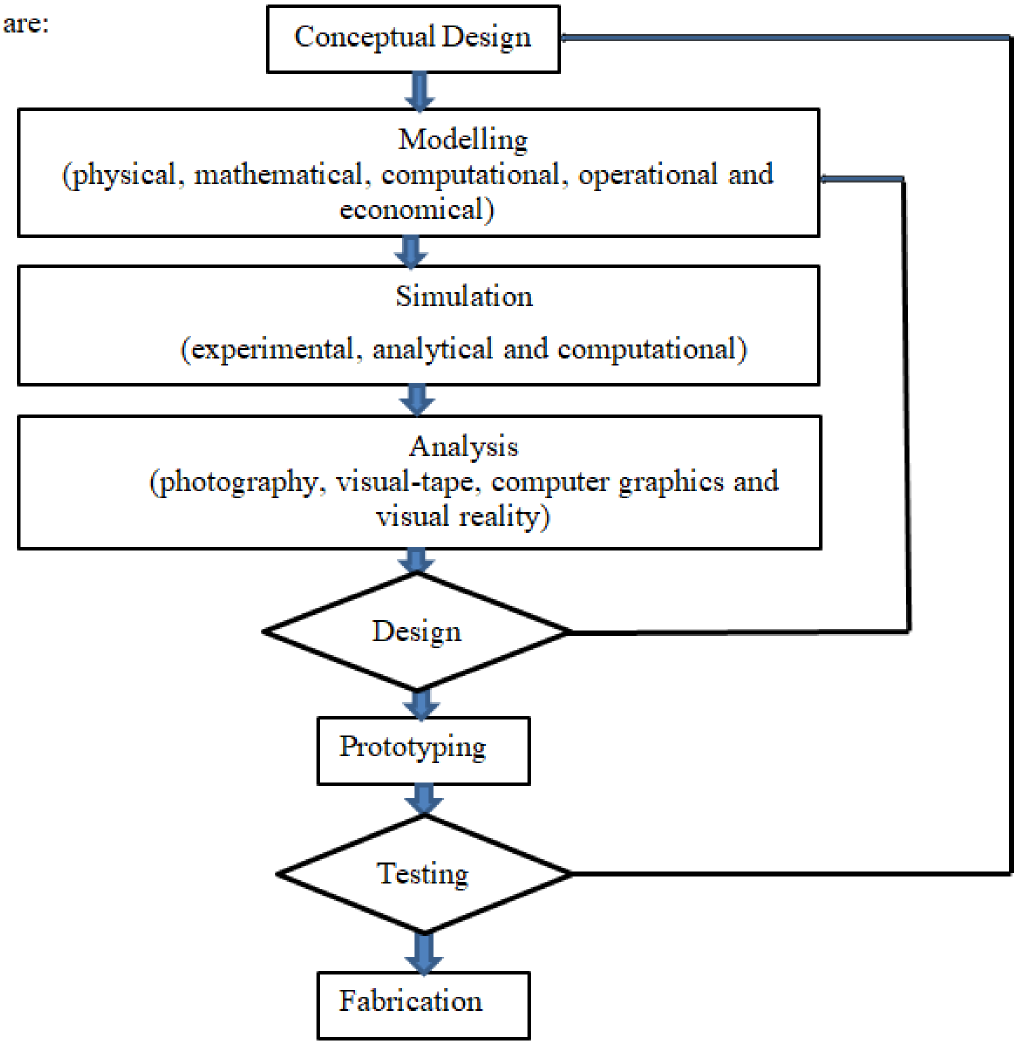


Figure 2. 24. Processes leading to fabrication of advanced engineering systems

System modeling and simulation are extensive techniques for investigating, evaluating and improving the process, design and functional parameters of the system that performs the process (Velten, 2009). Mathematical model of a system consists of one equation or an assembly of equations, inequalities and data employed to describe the behavior of the system in quantitative values of its process performance indices (Miu, 2016).The mathematical model may be linear or nonlinear, with single, double, or multiple inputs and outputs. In a deterministic model, the output is precisely quantified through known mathematical relationships derived from physical laws among input, state and output variables.

A stochastic model based on probability theory for quantifying the probability distributions of potential outputs of a process or a system. This type of model could describe in detaching of grain, threshing and separation of grain from material other than grain. According to Miu (2016) stochastic models of physical phenomena are essentially mathematical relationships between random variables of the process and parameters of the system that performs that process. Simulation uses the mathematical model to determine the response of the system in different situations.

2.3.1. Material kinematics in rotary (axial) threshing units

There is a relation and direct connection between the engineering designs, the movement of threshed material through the threshing chamber and the overall performance of an axial threshing unit. In this research it was observed the stochastic probabilities of the material movements from the feeding table to the straw outlet including the threshing, separation and cleaning process. Published studies indicate the material kinematics in axial threshing units by Miu and Kutzbach (2008), who analyzed on the influence of a few parameters like feed rate, rotor speed material moisture and spiral angles of the rotor on the material movement. Miu (2002a); Miu and Kutzbach (2008) studied the movement of vegetal material through the feeding zone and threshing and separation zones of an axial threshing units. They elaborated the kinematics equations based on nonlinear law governing the non-uniform movement of the material on an even helical path between the rotor and the concave cage assembly.

The kinematics of the material through the threshing space is mainly influenced by:

I. Material properties: type, variety stem size, MOG moisture content, grain to MOG ratio
II. Threshing unit design: feeding direction, design of helical spirals, concave and cage openings design
III. Functional (process) parameters: material feed rate, rotor speed and concave clearance.

In developing the kinematic theory, the following specific assumptions have been made:

a) At the beginning of feeding zone of the threshing unit, the material feeding velocity has no tangential component (due to the starting motion of the material)

b) Once the material getting in to the threshing space, it moves as continuum stratum without any interruptions (due to the auger shape of the axial threshing drum)

c) Material velocity is a continuous function of material position over the length of the threshing space

d) The radial reactive forces due to grain separation do not influence the material movement

Let us consider that the velocity of the feeding material at the entrance (feed chute) of the feeding zone is V_f with the components.

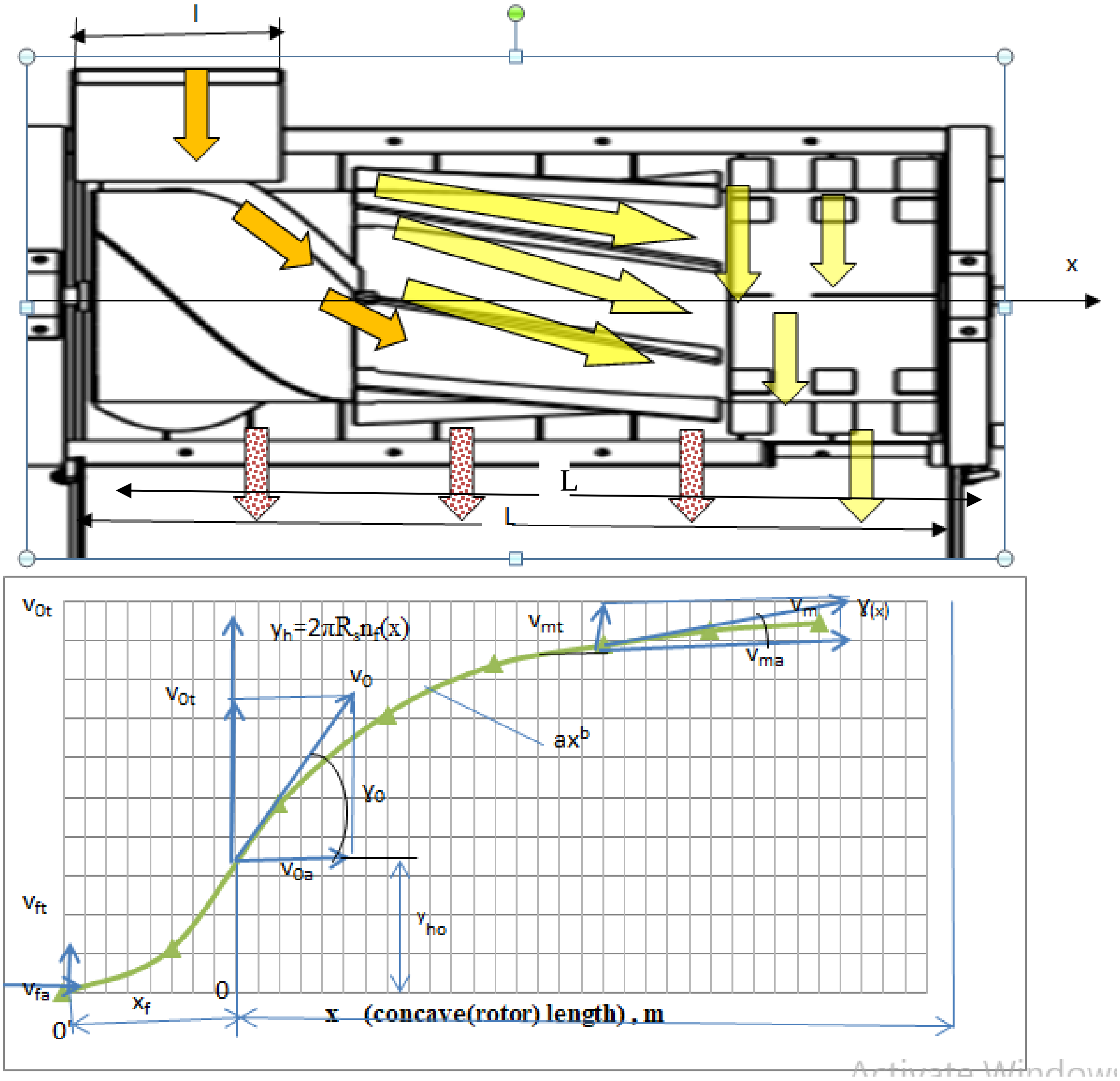
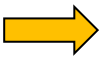


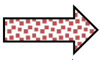
Figure 2. 25. Representation of an axial unit (developed) with tangential feeding
(Graph from the authors research outputs)

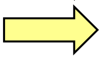
Where:

L- length of the threshing unit, (m)

l- length of the feeding opening, (m)

 - flow of unthreshed crop

 - flow of threshed crop(grain and chaff)

 - flow of threshed crop (straw and chaff)

In the research the velocity at different concave length considered as the velocity of the feeding material at the entrance of the feeding zone V_f with the components of V_{fa} and V_{ft} . At the end of the feeding zone where the threshing process is beginning, the fed material velocity V_0, has also the tangential and axial components (V_{0t} and V_{oa}) (Figure 2.25).

The vector and scalar values are under equation 2.58. and equation 2.59

$$\overline{V}_0 = \overline{V}_{oa} + \overline{V}_{ot} \qquad (2.58)$$

$$|\overline{V}_0| = \sqrt{|\overline{V}_{oa}{}^2| + |\overline{V}_{ot}{}^2|} \qquad (2.59)$$

As indicated in the (Figure 2.25), the threshing process starts from the inlet (feeding) zone and continue up to the straw out let (the end of the threshing). The shape of the trajectory with respect to **x** (concave length) is ultimately determined by the magnitude of material speed $V_m(x)$ as well as the angle $\gamma_{(x)}$, where x is the current position over the rotor length$(x \geq 0)$. The material speed $V_m(x)$ depends on the feeding speed and rotor speed, while the angle $\gamma_{(x)}$ depends on the threshing unit design (rasp bar angle, spiral angle etc..).

The material movement through the threshing unit on the helical path with the variable pitch angle can define by equation 2.60.

$$\theta_m = \theta_m(t) \qquad (2.60)$$

$$x = x(t)$$

Where:

t- time, (s)

θ_m- the current rotation angle of the material around the longitudinal axis of the threshing unit

by eliminating the time, it is possible to calculate

$$\theta_m = \theta_m(x) \qquad (2.61)$$

By assumption $n_r(x)$ be the number of revolutions with radius R that have been completed by the material over the length x, where nr (x) is not necessarily an integer value.

So, by substituting the rotation angle

$$\theta_m(x) = 2\Pi n_r, (t) \tag{2.62}$$

The radius R, can be expressed as

$$R_s = R + \frac{\delta}{2} \tag{2.63}$$

Where :

δ - the weighted average clearance between the rotor and concave, respectively the rotor and cage

R - the rotor (cylinder) radius, (m)

2.3.2. The mathematical modeling

In the research and development of the product (technology) like the threshing units there could have opportunity to get an output (single or multi) from the single input or multi input through algorithms. The threshing and separation of the axial threshing units was studied by Miu (1997). The mathematical modeling for his research was calculated linear rate of threshing λ and linear rate of separation β for winter wheat and barley.

Use of genetic algorithms coupled with fuzzy logic software find greater and potential applications in the contemporary computer age. Design and operation parameters in connection with physical properties of certain crop are expressed as variables of a complex constrained, nonlinear multi-objective problem. Solving the problem requires finding the setting of above-mentioned decision variables so that an evaluation function based on process quality criteria is maximized.

Mathematical modeling of the threshing stage describes at the stage of threshing as that of impact which detaches a grain from straw mat binding Ndirika, (1994). This is actually the most important stage of threshing and must be modeled properly. Considering firstly the energy transferred to the panicle from the beater, if the mass flow rate of panicle (feed rate) Q kg. sec^{-1} and rise in kinetic energy of panicle with each impact per unit mass of panicle is equal to $1/2\ V^2$, Then the rate of transfer of kinetic energy to the panicle by the threshing drum is $\frac{QV^2}{2}$.

Using the energy to dislodge grain (seed) from panicle as E_g the rate of detachment of grain or threshing rate *(λ)* can be calculated by equation 2.64.

$$\lambda = \frac{Q{V_b}^2}{2E_g} \quad (2.64)$$

To model the grain threshing and separation process, the following general assumptions of Miu (1994, 1999, 2001a,b); Miu *et al*., (1997, 1998a, b) and Miu &Kutzbach (2000) were taken into consideration:

(a) The material throughput is constant, where material moves through the threshing space as a continuous stream

(b) The material to be processed is homogeneous, i.e., the panicles are uniformly distributed within the straw mass

(c) In the tangential feeding unit, the material is homogeneous in any cross-section (perpendicular on the longitudinal axis direction), of the threshing space

(d) The mass of the material is continuously distributed throughout the threshing space and its volumetric density is a continuous function of position and time.

For developing mathematical model for stationary thresher Enaburekan (1994) developed mathematical and optimization models for thresher using wheat and sorghum. The model describes the following threshing efficiency model:

$$E_t = 1 - e^{\frac{-Kt\rho g(1-M)VWDL}{2FC}} \quad (2.65)$$

Where:

E_t- threshing efficiency, (%)

K_t-threshing constant

ρ_g-crop bulk density, (kg.m^{-3})

M-crop moisture, (%, dry basis)

V-velocity of threshing cylinder, (m.s $^{-1}$)

W- width of thresher, (m)

D - effective drum diameter, (m)

L - concave length, (m)

F - Crop mass feed rate, (kg.s^{-1})

C -concave clearance, (m)

Simonyan (2006) developed cleaning efficiency model for sorghum thresher:

$$\eta c = 0.4\frac{\rho gM}{\rho s\theta s} - 10.21\frac{\rho pL.Vc.Va}{\alpha s.Fr} + 93.09 \quad (2.66)$$

Where:

ηc -Cleaning efficiency, (%)

ρg-Grain bulk density, ($kg.m^{-3}$)

M- Grain moisture content, (%)

ρs-Straw bulk density, ($kg.m^{-3}$)

Ms-Straw moisture content, (%)

ρ_p-Particle density, ($kg.m^{-3}$)

Vc-Threshing speed, ($m.s^{-1}$)

Va-Air velocity, ($m.s^{-1}$)

α_s-Sieve oscillating frequency, (t^{-1})

F_r -Feed rate, ($kg.h^{-1}$)

CHAPTER THREE

RESEARCH METHODOLGY

3.1. Methods for Determination of the Physical and Mechanical Properties of the Crop *Tef's (Eragrostistef (Zucc.) Trotter)* Stem

3.1.1. Material, methods and test conditions

3.1.1.1.Selected test materials (samples)

In Ethiopia, there are a lot of *tef* varieties, but for this research test material varieties namely Dz-Cr-387/RIL-355- local name Quncho, Dz-Cr-438- local name Kora, Dz-01-1880- local name Guduru and Local variety /from farmers' hand/ were selected based on their productivity, quality of grain, acceptance among the farmers and dissemination rate in Ethiopia, in consultation with *tef* researchers from Debreziet and Adet Agricultural Research Centers.

The samples were planted on individual plot at Adet Agricultural Research Center compound (test site, farm), on the main crop season in 2016/2017. The crops were planted by broadcasting on July and harvested by sickles on November /after 120 days of planting/. Adet Agricultural Research Center is located at $11^0 17$` N latitude and $37^0$ 43`E longitude at an altitude of 2240 m a.s.l. It is situated in West Gojjam zone, Ethiopia, 43-km southwest of Bahirdar town (Amhara Region's capital) along the high way to Addis Ababa via Mota Town. The type of soil is clay loam.

3.1.1.2.Experimental methods and test conditions

The test crops were harvested manually (by sickles) with minimum height of cutting 1-1.5 cm from the ground as it was a common rate when harvesting by sickles and counted 60 stems in each variety. The stems were packed with long plastic bags and cartoons to avoid breakage of the stem. Then, the samples were transported to the controlled lab in Bahirdar University, Institute of Textile and Fashion Technology and Institute of Technology, School of Chemical and Food Engineering.

The variables were moisture content, diameter of the stem, variety and position of the stem (segments where the measurements were performed). Because of the morphological shape, the diameter of the *tef* stem decreases from the bottom of the plant to the top (upper); therefore, stem shows different physical and mechanical properties at different heights due to the variable cross-sectional area. Then, prior to test the samples, stems (the panicles lengths were excluded) were divided at three equal sections (measuring position) at bottom; middle and upper (Figure 3.1.). The segments' length was 170-200 mm (because of the plant height difference); hence the segment lengths were different. But, the test was performed at the center of each segment and avoided to measure near to the nodes (measurement at the node and near the nodes had better strength to the shear and elasticity properties). The local variety has short stem length and the samples were prepared with two segments**.** The grain straw ratio of the *tef* were 1:2.31, 1:3.59, 1:4.26 and 1:6.4 for Local, Kora, Quncho and Guduru varieties respectively.

The moisture content of the stems was measured immediately after test of each segment using the Infrared Moisture Genis Photometer (Figure 3.2.) in wet basis. To determine the mechanical properties of the *tef* stem within different moistures of the specimens, it was important to vary the amount of moisture in the stem. The measured amount of water was sprayed by a syringe on the stem, which was packed with polyethylene material and reserved for three days at controlled lab and refrigerator. During the test, moisture differences were observed within the same stem at different position, so the measurements of moisture were performed on the individual specimens. Before starting each test, in order to distribute and obtain equal moisture at the specimen (stem), the required numbers of stems were allowed to warm up to the room temperature.

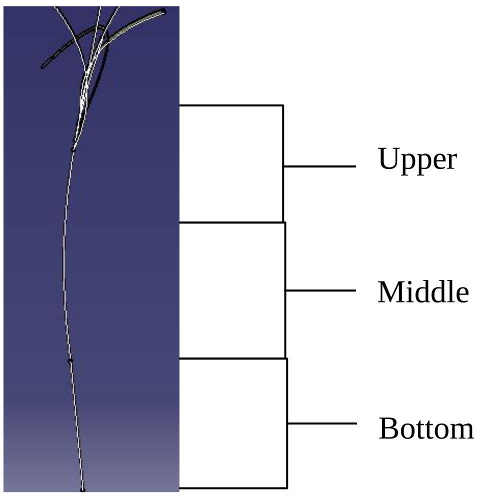


Figure 3. 1. Specimens prepared at different position (segments) of the samples (stem sketch)

Figure 3. 2. Infrared Moisture Genis Photometer (Direct Moisture Tester)

The specimens had different moisture levels from 5% - 35 % (w.b.). Upon the common agricultural practice, during the harvesting and threshing of *tef* crop the M.C. is expected to rise from 18%-25% (w.b.). The test represents the maximum and minimum range of the moisture. For each test, the samples were tagged and coded; the physical parameters like the diameter, thickness and length of the specimen were measured by appropriate equipment (Micrometer and Vernire Caliper).

Instruments used for the measurements were Sensitive Balance Electronic Scale. 2000g/0.1g, England; Micrometer / Moore Wright Sheffield (0-0.045) mm (0-2.5) cm, 0.01, England; Vernire Caliper (0-150) cm, 0.01scale**;** Infrared Moisture Genis Photometer (Direct Moisture Tester)**;** Texture Analyzer TA.XTPlus with force capacity**:** 50kg.f (500N), force resolution**:** 0.1g, speed range: 0.01-40mm/s, maximum aperture**:** 370mm/590mm, distance resolution**:** 0.001mm and Tensile Force Measurements Bench Type Universal Testing Machine THE-Hounsfield England with 5kN.

3.1.1.3.Statistical analysis

In this study the following four factors were studied: moisture, diameter, thickness and variety. The effects of stem moisture content, diameter and thickness of the *tef* stem, stem regions' at three segments (upper, middle and bottom regions) and variety of *tef* (Dz-Cr-387/RIL-355 – Quncho, Dz-Cr-438- Kora, Dz-01-1880- Gudru and Local) shows the mechanical properties (modulus of elasticity, shear strength (shear modulus), flexural rigidity) of *tef* stem. A factorial test with four factors and twenty replications based on completely randomized experimental design was used. Experimental data were analyzed using analysis of variance (ANOVA) linear modeling, correlated with multi linear modeling. Means were compared with different range tests and the graph construction was done by **R i386.3.0.1** software.

3.1.1.4.Test conditions

3.1.1.4.1. Tensile test conditions

The tensile measurements were performed using Universal Testing Machine THE-Hounsfield England (Figure 3.3.) The speed of the test was 75mm/min. The specimens were measured with constant length of segments. To avoid the skidding and squeezing of the stem, the stem ends were plastered (rolled) with the drawing scotch tape at each end and tightened on the upper and lower jaw of the instrument. The breakage of the specimens was not performed exactly at the center of the specimen. It happened because of the rheological properties of the stem, and the breakage acts at any position of the specimens. To avoid the jaws' effect, the breakage distance from the upper and the lower jaws was decided to be from 30-40mm, the specimens which had breakage lower than the specified gap were discarded. The test result data and graphs were recorded as Figure 3.4. The moisture of each specimen was measured immediately after performing each test using the Infrared moisture Genis Photometer (Figure 3.2.).

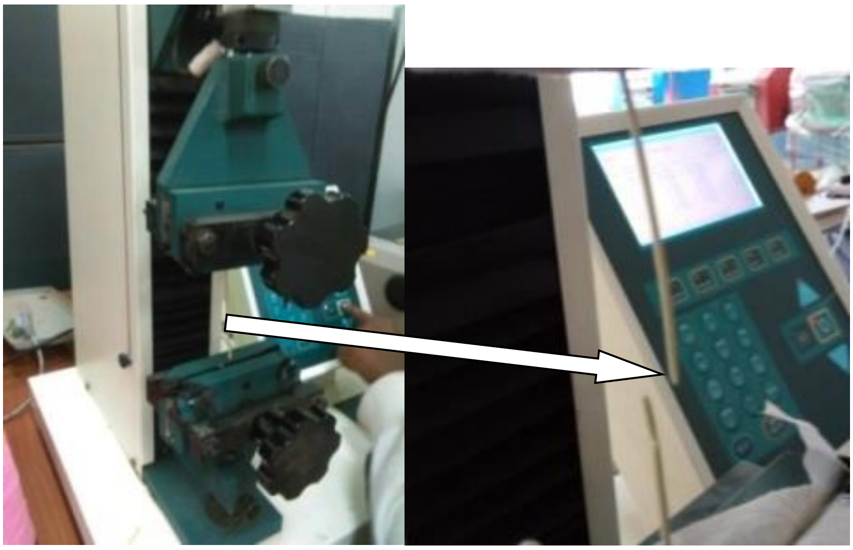


Figure 3. 3. The Universal Test Machine (UTM) THE-Hounsfield

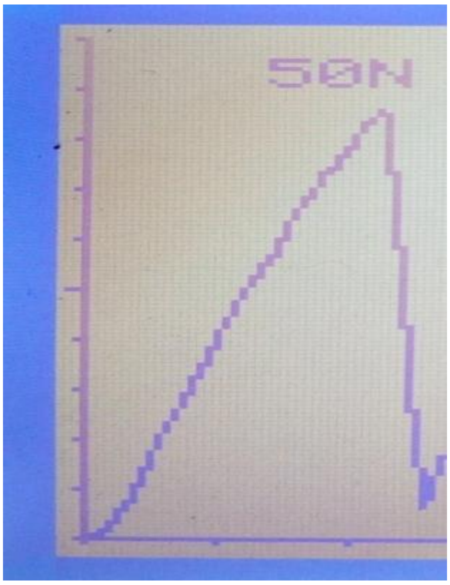


Figure 3. 4. A typical load-deformation curve of *Tef* stem under vertical tension load (tensile test) from UTM

It is possible to determine the modulus of elasticity of different varieties of *tef* from the tested and /or measured parameters using the following empirical and derived formulas.

Area of each variety was calculated

$$A = \frac{{d_1}^2 - {d_2}^2}{4}\pi \quad (3.1)$$

Modulus of elasticity was calculated with the following formula as:

$$E = \frac{PL}{A\Delta l_{max}} \quad (3.2)$$

Where:

A- cross section area of the stem, (mm^2)

d_1 - outer diameter of the stem, (mm)

d_2- inner diameter of the stem, (mm)

P- the maximum tensile force measured by the testing instrument, (N)

L- the length of the specimens (stem to be tested) from the upper jaw to the lower jaw of the instruments, (mm)

Δl_{max}-the maximum elongation of the specimens, (mm)

Flexural rigidity (F_{ri}) of the stem was calculated using equations derived from standard beam theory for specimens with circular cross-sections by Gere and Timoshenko (1990):

$$F_{ri} = EXI \quad (3.3)$$

$$I = \frac{\pi}{4}\left|d_1 {d_2}^3 - (d_1 - t)(d_2 - t)^3\right| \tag{3.4}$$

Where:

I- moment of inertia, (mm^4)
d_1- major diameter of the stem, (mm)
d_2- minor diameter of the stem, (mm)
t-thickness of the stem, (mm)

3.1.1.4.2. Shear force test conditions

The shear force measurements were performed using texture analyzer TA-XTPlus (Figure 3.5). The blade was knife type with sharp edge (0.1 mm). The test mode was compression; pretest and test speed was 2 mm/sec, the target mode was displacement with trigger type auto, break mode rate and break detect auto. The specimen was plastered on the table of the analyzer without squeezing the stem and lied on the center of the knife (blade) and applies the cutting force using proper setup of the Texture Analyzer (Figure 3.5.).

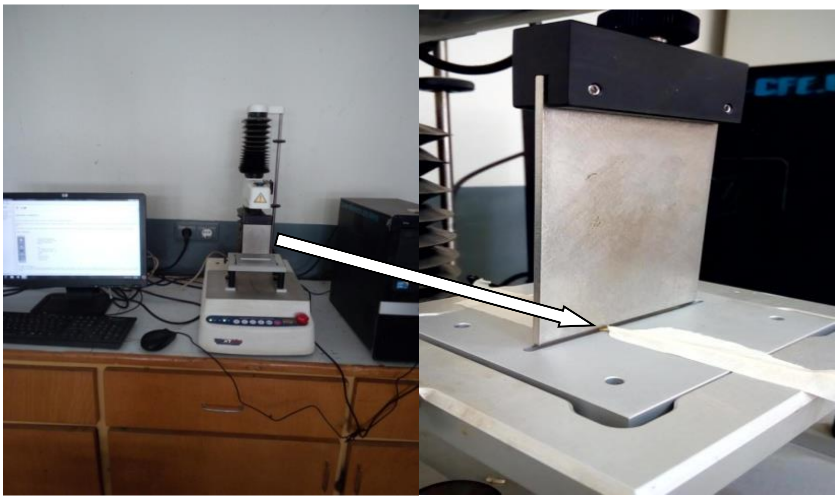


Figure 3. 5. Texture Analyzer TA.XTPlus with full computer accessories

The moisture of each specimen was measured immediately after performing each test, using the Infrared Moisture Genis Photometer. The shear stress with its force and displacement graphs were registered by the testing instruments (Texture Analyzer attached with computer& accessories) (Figure 3.5).

It is possible to determine the shear stress of different varieties of *tef* from the tested and /or measured parameters using the following empirical and derived formulas (equation 3.5).

Shear stress calculated as:

$$\tau = \frac{F_{smax}}{A} \tag{3.5}$$

Area of each variety can be calculated using equation 2.1

Where**:**

A- cross section area of the stem, (mm^2)

F_{smax}-maximum cutting/ shearing/ force, (N)

τ-shear stress, (Mpa)

3.2. Material and Methods for Design and Manufacture of *Tef* Threshing Mechanisms

An output of the first research (determination of the physical and mechanical properties of *tef* 's stem) was used to determine the force analysis and power requirements of the newly design threshing unit. The design started by defining the design requirements and applying the design procedures of Pahl *et al.*, (2007), and followed by the conceptual design using the standard material selection then embodiment and detailed technical (manufacturing) drawing (Appendix IV…). The selected material and its size were analyzed using the **ANSYS 2015 and Solid work 2018** software. The manufacturing process was done in the well-equipped and facilitated work shop in AMIMTDE.

3.2.1. Design method (process)

The design process starts from customers (end user) need up to the manufacturing, following the adaptive design procedure as indicated on Figure 2.15 . The design engineering was applied to the progress toward defining an object with attachment of the process that fulfills a purpose of *tef* threshing.

3.2.1.1. Design requirements for *tef* threshing units

To start designing a new unit, the overall size or dimensions of the threshing units are considered from the existing threshers (stationary threshers available in the country i.e. SG-2000).

For developments a new threshing mechanism the major requirements are listed as follows by considering design steps from literature (Eder and Hosendl, 2008; Phal *etal*., 2007):

- Increase the cleaning and separation efficiency by 20-30% from stationary thresher
- Increase the capacity by 10-15% from stationary model thresher
- The *tef* straw should be chopped properly

- Easy for manufacturing and maintenances
- Should be manufactured from easily available raw materials
- The size of threshing unit should be equal with the SG-2000 model thresher

3.2.1.2.Theoretical base for designing of threshing units

The conventional threshing units include the rotating drum with different configuration and stationary concave. For this research threshing mechanisms include all components and moving parts of threshing units which perform the threshing activities. Among different models this research focused on Simonyan (*et al.*, 2009) model.

$$P_{av} = P_{re} \quad (3.6)$$

Where:

P_{av}- power available at the threshing cylinder

P_{req}-power required detaching grains from their panicles

$$P_{av} = QK_E\left[V^2\left(\frac{Q^2}{VC^2\rho}\right)\right] \quad (3.7)$$

Where:

K_E- constant depending on the grain (crop) type

V-peripheral velocity of cylinder by substitution

$$\lambda = K_T\left(\rho V_2{}^2 WD\right)/(QC) \quad (3.8)$$

$$K_T = \frac{K_p}{K_E} \qquad \rho = \rho_d(1-\alpha) \quad (3.9)$$

Where:

λ- is threshing rate

ρ- bulk density at a given moisture content of crop, (kg.m^{-3})

ρ_{d}- bulk density at 10% moisture content, (kg.m^{-3})

α- moisture content of crop, (%w.b.)

Then finally the formulas will be derived

$$\lambda = \frac{K_T\rho_d(1-\alpha)V^2WD}{QC} \quad (3.10)$$

For each threshing unit it is a must to know the threshing rate with the help of each empirical formula, for this case we have information from the research output (physical and mechanical properties of *tef*) and it helps to predict the threshing rate using equation 3.10. The following parameters are from the research out puts, assumptions and the size of the existing SG-2000 threshing units dimensions.

The bulk density of *tef* (ρ_t) =35 kg.m^{-3}(1-0.12)=35 x 0.88=31 kg.m^{-3}(from own research output)

W_t - width of *tef* threshing cylinder = 0.83m

K_t-threshing factor =0.00092 (Sharma and Mukesh, 2010)

α- moisture content of crop (%w.b.)=12%

Q_t-federate=0.13kg.s^{-1}

V_t-peripheral velocity =27m.s^{-1}

D_t-drum diameter=0.48m

C_t-drum concave clearance=0.02m

$$\lambda = \frac{K_T \rho_d (1-\alpha) V^2 W D}{QC} = \frac{0.00092x35x(1-0.12)x27^2x0.83x0.48}{0.13x0.02} = 3.49$$

The threshing efficiency of the proposed *tef* threshing unit can be

$$E_{ff} = 1 - e^{-0.5K_T\left[\frac{(\rho(1-\alpha)VWDL)}{QC}\right]} = 1 - e^{-0.5\lambda} = 1 - e^{-3.491} = 0.96$$

Threshing capacity $CAPTH = E_{ff} * Q * r$

Then the thresher will have the following theoretical capacity.

$$CAPTH = E_{ff} * Q * r = 0.96x0.13x0.24 = 0.02995 kg/s = 1.07 q/h$$

The separation probability p is defined as the ratio of effective mean separation surface which depend on geometric mean diameter of the grain kernel to the mean surface of an opening.

$$P = \eta\left(1 - \frac{\pi de^2}{4 s_o}\right)$$

Where :

η- opening ratio;

de – geometric mean diameter of grain kernel,(mm)

s_o – mean surface of an opening ($s_o = a_o^2$),(mm^2)

a_o – width of a square opening, (mm)

Power requirements

It is very important to know and determine the required amount of power which is essential for the designing of *tef* threshing unit. The power required for threshing is calculated based on Baruah and Panesar (2005) equations 2.53-2.57 :

$$P_{cy} = F_{tt}.U_{cy} + p^{w}{}_{cy} \qquad [\text{ KW}]$$

$$F_{tt} = f_{t1} + f_{t2} + f_{t3}$$

$$f_{t1} = \left[\frac{25\Delta t}{324.W_c\rho_o C_c t_c}F^2\right]$$

$$f_{t2} = \left[K_c\frac{\Delta\rho}{\rho_i}C_c W_c\right]$$

$$f_{t3} = \left[K_c\frac{\Delta\rho}{\rho_i}A_{cc}W_c + g\rho_i C_c A_{cc}\mu_c\right]$$

Power required to overcome the air resistance can be calculated using equation 2.53

$$p^{w}{}_{cy} = K_{cy}\left(U_{cy}\right)^3$$

$$p_{cy} = \left[\frac{25\Delta t}{324.W_c\rho_o C_c t_c}F^2 + K_c\frac{\Delta\rho}{\rho_i}C_c W_c + K_c\frac{\Delta\rho}{\rho_i}A_{cc}W_c + g\rho_i C_c A_{cc}\mu_c\right]U_{cy} + K_{cy}\left(U_{cy}\right)^3$$

Where:

F_{tt}- the tangential force,(kN)

U_{cy}- the peripheral speed of the threshing cylinder,(m.s^{-1})

f_{t1}- tangential force due to the impact action the crop speed,(kN)

f_{t2}-the resistive force experienced by the cylinder due to the compression of the entrapped crop between cylinder and concave, (kN)

f_{t3}-the resistance against the movement of the crop mass, (kN)

K_c- the elasticity of the crop stems (mass), (kpa)

A_{cc}-the effective areas of concave, (m^2)

F-the crop feed rate, (kg.s^{-1})

ρ_o-the bulk density of the incoming crop, (kg.m^{-3})

ρ_i-the bulk density of the entrapped crop, (kg. m^{-3})

C_c-concave cylinder clearance, (m)

W_c-the width of the threshing cylinder, (m)

g- acceleration due to gravity, (g=9.81m.s^{-2})

μ_c-the coefficient of friction of the crop mass over the concave surface

U_{cy}-the peripheral speed of the threshing cylinder, (m.s^{-1})

Δt-change of crop stems thickness at original and after entrance in concave,(m)

K_{cy}-a proportionality coefficient considered to estimate the power requirements to overcome air resistance

In order to use the above empirical formulas, it is essential to know the values of the parameters.

3.2.2. Manufacturing process

The manufacturing process is the part of design and development. For manufacturing of *tef* threshing units with its test stand, was considered the above procedures and select suitable manufacturing process based on the resource availability, cost and type of parts to be manufacture.

3.3. Material and Methods for Performance Evaluation of Tef Threshing Units

3.3.1. Materials

The two threshing units were made from sheet metal and solid shaft as described in Chapter 3. and shows as Table 3.1 and 3.2.; Figure 3.6 and 3.7.The materials are annexed in Appendix VI. The test procedure was based on Smith *et al.* (1994) and adopted as annexed in Appendix V.

Table 3. 1. Technical specifications of the two concaves

It.no	Parameters	unit	Type and Size of concaves	
			Open (SG-2000)	Closed (developed)
1	Length	mm	830	830
2	Diameter	mm	240 (half circle)	480
3	Wrap angle	o	119	360
4	No of bar	pcs	53(8mmdia.)	Perforated sheet
5	Gap b/n rods or openings (diameter)	mm	15	5
6	Area of contact	m^2	0.79	1.44

Table 3. 2. Technical specifications of the two drums (cylinders)

It.no	Parameters	unit	Type and Size of drums	
			SG-2000	developed
1	Shaft Length	mm	1100	1100
2	Diameter	mm	440	440
3	Drum length	mm	800	800
4	No of threshing bar	pcs	8	6
5	No of straw blade	pcs	8	20
6	No of pegs	pcs	56	No
7	No of auger plate	pcs	No	4
8	No of finger	pcs	4	no

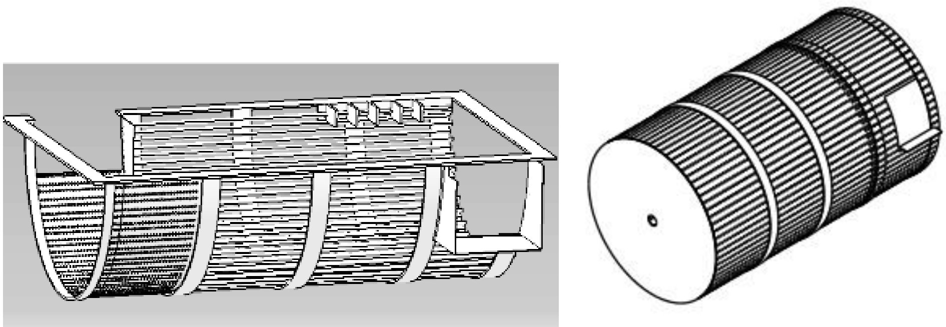


Figure 3. 6. a) SG-2000 concave (open) b) Cylindrical (closed) concave

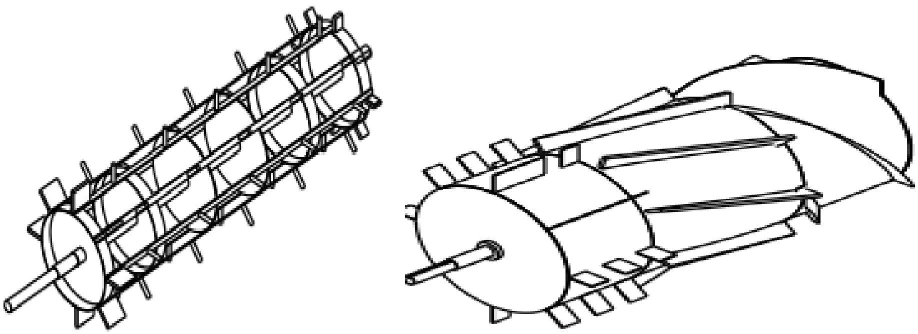


Figure 3. 7. a) SG-2000 thresher drum b) Newly developed *tef* threshing drum

3.3.2. Methods (test conditions and experimental set up)

The threshing unit had 0.83m concave width and the drum diameter was 0.44 m. The newly developed threshing unit consists the round (cylindrical) concave and drum with three parts

(Figure 3.6b.). The test material *tef* (Dz-Cr-387/RIL-355)/Quncho/ were planted and harvested in Adet Agricultural Research Center. The following tests were performed at Adet Agricultural Research Center. The 10 kg bulk of *tef* was prepared for each test and fed manually. The test material parameters were measured and depicted in the Table 3.3. For the experiments the threshing test stand was developed with equal boxes which were mounted below the threshing and separating system. The concave area was partitioned perpendicular to the rotor axis in seven equal sections with the size of 120 mm width, using similar test stand construction (Miu *et al*.,1998b; Chimchana *et al*., 2008 and Xu and Li, 2011). The separated masses of the new threshing unit were caught in the boxes 1 to 7 (*tef* with mixture of straw and chaff) sack as box 8 for straw collection (Figure 3.8). For the SG-2000 model threshing unit the separated mass were caught in the boxes 1 to 6 (*tef* with mixture of straw and chaff) the 7th box was under the straw out let /due to its original construction, was covered with sheet metal/ and sack as box 8 for straw collection.

Table 3. 3. The test crop parameters

	Sample			
	1	2	3	Average
Variety /crop	Tef (Dz-Cr-387/RIL-355) quncho	Tef (Dz-Cr-387/RIL-355)/quncho	Tef (Dz-Cr-387/RIL-355)/quncho	Tef (Dz-Cr-387/RIL-355)/quncho/
Moisture content /w.b/ %	11.16	9.78	13.60	11.51
Grain/straw ratio	1:8.1	1:6.4	1:4.2	1:6.25
Length of the stem average, mm	430	590	520	513.33
Length of the panicle average, mm	250	320	510	360
Bulk density of the *Tef*, kg.m^{-3}	32.81	37.80	34.06	34.96

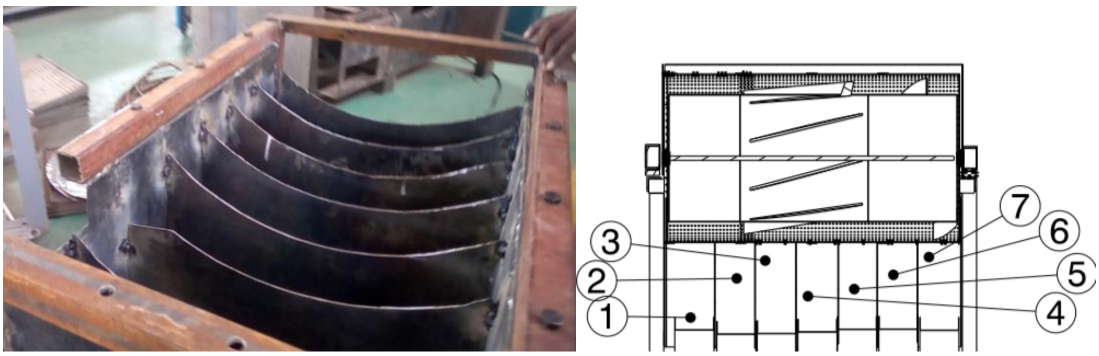


Figure 3. 8. Sample (*tef*, straw and chaff mixture) collectors' box 1-7

The test procedures were started from test sample selection, collection and transporting from the field to the test site. Then, the samples weighed based on the test procedure. The whole evaluation processes were as shown on Figure 3.9.

Figure 3. 9. Test procedures (from unthreshed sample preparation up to manual cleaning and separation of threshed samples (straw, chaff and *tef* mixture) from each sample box)

The gathered materials in the boxes were weighed and cleaned to quantify the part of grain, chaff and the part of MOG in each box. The dimension of each sample box had 120 mm width and its height was attached with the concave bottom i.e.400mm. The overflow was caught in the other sacks. Separation and cleaning were performed manually (Figure 3.9.). Grain samples from the threshing and separating section were drawn for measuring the part of clean grain (*tef*), chaff and straw with sensitive (digital) balance. The test was done manual feed (controlled feed), the speed of the drum was measured with optical tachometer (model C- compact Advent Optical Tachometer), and time of operation recorded with stopwatch and other observation around the threshing units were recorded. There were two independent variables (feed rate and rpm), feed rate in three level (400, 325 and 275 $kg.hr^{-1}$) and rpm in three level (1200, 1000 and 900 rpm) with three replications and three dependent variables (threshing capacity, cleaning efficiency and separation efficiency) used for comparison of two threshing units.

The separation rate β_{ti} was given by relating the separated grain fractions additionally to the length of the individual boxes. The grain mass m_{Gi} of each collection box was measured and related to the total grain m_{Gtot}. This could be mathematically expressed on equation 3.11.

$$\beta_{ti} = \frac{m_{Gi}}{m_{Gtot}\ x\ \Delta li} \tag{3.11}$$

The grain distribution, which was the separation rate over the separation length, greatly characterizes the separation process. The cumulative sum of the separated grain S_G was given by addition of the individual related grain quantities on equation 3.12. The difference to 1 (100%) is the remaining unseparated grain R_G.

$$R_{Gi} = 1 - S_{Gi} \tag{3.12}$$

$$S_{Gi} = \sum \delta_{Gi} \Delta li$$

The separation efficiency η_G denotes the grade of separation in equation 3.13. The separated grain quantity for each section was related to the amount of grain delivered to this section.

$$\eta_G = \frac{\beta_{ti}}{R_{G(i-1)}} \tag{3.13}$$

Where:

β_{ti}- separation rate, (m^{-1})

S_G- cumulative sum of the separated grain, (gr)

Δl_i- length of each box, (m)

R_G- remaining unseparated grain, (gr)

m_{Gi}- grain mass of each collection box, (gr)

η_G - separation efficiency, (%)

The grain output capacity, expressed in $Kg.hr^{-1}$, was the amount of grain threshed per unit time. Cleaning efficiency can be determined the ratio of whole grain and the whole threshed material. Mathematically it was possible to write in the formula equation 3.14.

$$Cl.eff = \frac{K}{L} x100 \tag{3.14}$$

Where:

Cl.eff - cleaning efficiency, (%)

K - weight of whole grain at main grain outlet per unit time, (gr)

L- weight of the whole material at main outlet per unit time, (gr)

The output capacity was measured by weighing the grains collected from the boxes with the time given in the threshing operation. The sensitive balance with 0.005 gr calibration was used for weighing clean grain and chaffs, for measuring the *tef* bulk used the dial spring balance with the 0.1 gr scale.

Damaged grain *(D)* in percent could be calculated using the formula as equation 3.15:

$$D = \frac{E}{A} x100\% \qquad (3.15)$$

Where:

D- Damaged grain in percent, %

E-Weight of damaged grain collected at outlets per unit time, (gr)

A-Weight of whole grain collected in all grain outlets per unit time, (gr)

Time was measured using a stopwatch. Moisture content of crop was determined by oven dry method at a temperature of 103°C for 24 hr. (Smith *et al*., 1994). The bulk density was found by weight – volume method under natural filling condition. Bulk density of the crop could be determined by weighing the crop packed in a container of known volume. The crop was densely packed by gently tapping the container to allow the settling of crop in the container (Ndirika *et al.,* 2006). The volume of the container (sack) was estimated by taking the dimensions of the container (sack) and then the volume was then computed and recorded. The damaged grain of *tef* was empty (due to its small size damaged of *tef* grain is not expected in *tef* threshing).

Figure 3. 10. Comparison of threshing units a) newly developed b) SG-2000 threshing unit

Figure 3. 11. Well chopped *tef* straw by newly developed threshing unit

3.3.3. Statistical analysis

A 2X3X3 factor factorial was employed in CRD statistical design with three replications to evaluate the effect of two threshing units, SG-2000 and newly developed. As comparison variables Feed rate and RPm were selected with three level of feed rate (F_1, F_2 and F_3; 400, 325 and 275 kg.hr^{-1}. respectively), at three drum speed (R_1, R_2 and R_3; 1200, 1000, 900 rpm respectively). Experimental data were analyzed using analysis of variance *(ANOVA)* linear modeling, correlated with multi linear modeling, polynomial modeling with spearman methods and the means were compared with different range tests and graph construction and analysis in **R i386.3.0.1, ANSYS 2018** and **MATLAB 2014a** software.

3.3.4. Experimental layout and design:

A 2X3X3 factor factorial was employed in CRD statistical design with three replications, three levels of feed rate (F_1, F_2 and F_3; 400, 325 and 275 kg.hr^{-1}. respectively), at three- drum speed (R_1, R_2 and R_3; 1200, 1000,900 rpm, respectively).

Experimental data were analyzed using analysis of variance (ANOVA) linear modeling, correlated with multi linear modeling, with Spearman methods and the means were compared with different range tests and graph construction in **R i386.3.0.1** software.

3.4.Methodology for Modeling and Simulation of *Tef* Threshing Unit

3.4.1. Methods

The threshing unit threshed grain probability could be described in the formula equation 3.10. For determination of the *tef* threshing and separation rate the study consider equation 3.16 and equation 3.17., which can predict easily for the axial type threshing units by Miu (2016); Miu and Kutzbach (2000) and Zhong *etal.*(2014). The research focused on optimization of threshing capacity of *Tef*.

$$\lambda = \frac{f(x)}{[1-F(x)]} \tag{3.16}$$

$$\beta = \frac{g(x)}{[1-F(x)]} \tag{3.17}$$

Where:

λ- threshing rate

β - separation rate

x- one point of the axial threshing unit

F(x) - the cumulative total rate of threshed and separated grain through the concave openings

f(x) and *g(x)* - the threshed and separated crop per unit length

Using the above formula and the values from the experimental result of *tef* threshing units obtained the threshing and separation rates as indicated with different values and intervals.

3.4.2. Conditions

In the computational modeling of *tef* threshing units the feed rate and rpm of the drum were selected as evaluating parameters. The material flow along the threshing units is distributed uniformly with continuous flow. The pressure exerted on each area of the concave is uniform. The threshed mixtures are uniformly distributed within the concave. The test considers all treatment combinations. The test results (from the Table 3.4.) were used for this modeling.

CHAPTER FOUR

RESULT AND DISCUSSIONS

4.1. Results on Characterization and Determination of the Physical and Mechanical Properties of *Tef's* Stem

4.1.1. Results on characterization and determination of the physical and mechanical properties

Using the proper set up of the testing equipment and the empirical formulas for determination of the physical and mechanical properties four *tef* varieties stem at three segments (bottom, middle and upper position) data were collected and analyzed as indicated in Table 4. 1- Table 4. 6. The summary of results for modulus of elasticity and flexural rigidity of each variety is presented on Tables 4.1-4.3 and the summary results for the shear stress of each varieties is depicted Tables 4.4-4.6.

Table 4. 1. Summary of measured and calculated data of *tef* stem for the 4 varieties at bottom position of the stem; (Means± SD)

Variety	Moisture content (wb),(%)	Diameter (mm)	Thickness (mm)	Modulus of elasticity E, (Gpa)	Flexural rigidity (E x I)
Local	15.42± 6.23	1.87± 0.17	0.30± 0.07	0.65±0.38	2.99±2.43
Guduru	17.86±4.18	2.01±0.28	0.38±0.10	0.69±0.31	6.41±4.36
Kora	17.51±7.64	1.98±0.29	0.35±0.09	1.75±1.19	7.69±5.13
Quncho	16.65±5.67	2.31±0.37	0.47±0.09	0.95±0.27	9.83± 4.61

Table 4. 2. Summary of measured and calculated data of *tef* stem for the 4 varieties at middle position of the stem; (Means± SD)

Variety	Moisture content (w.b), (%)	Diameter (mm)	Thickness (mm)	Modulus of elasticity E, (Gpa)	Flexural rigidity (E x I)
Local	26.94±12.65	1.58±0.17	0.28±0.08	0.98± 0.53	2.27± 1.38
Guduru	16.47±5.69	1.74±0.30	0.32± 0.09	0.53± 0.29	3.03± 2.77
Kora	22.13±8.96	1.67±0.22	0.26±0.04	0.72± 0.52	1.62± 1.51
Quncho	17.16±8.36	2.36±0.42	0.29± 0.05	1.07± 0.84	12.39± 12.58

Table 4. 3. Summary of measured and calculated data of *tef* stem for the 3 varieties at upper position of the stem; (Means± SD)

Variety	Moisture content (wb),(%)	Diameter (mm)	Thickness (mm)	Modulus of elasticity E, (Gpa)	Flexural rigidity (E x I)
Guduru	19.18± 3.88	1.71±0.23	0.23± 0.06	0.65± 0.25	1.40± 0.68
Kora	19.80±5.94	1.28±0.17	0.28± 0.06	0.94± 0.42	1.45± 0.72
Quncho	19.65±7.71	1.79±0.37	0.31± 0.08	0.72± 0.37	2.11± 1.96

(* local variety has only two segments i.e. bottom and middle)

Table 4. 4. Summary of measured and calculated data of *tef* stem for the 4 varieties at bottom position of the stem; (Means± SD)

Variety	Moisture content(wb), (%)	Diameter (mm)	Thickness (mm)	Shear stress (Mpa)
Local	19.21± 3.60	1.91± 0.14	0.32± 0.04	27.77± 7.78
Guduru	19.44±8.25	2.05± 0.41	0.280±.08	23.19± 8.23
Kora	15.55±10.05	1.79±0.41	0.29±0.06	20.24± 8.65
Quncho	15.01± 8.18	2.23± 0.39	0.37± 0.08	18.40± 11.40

Table 4. 5. Summary of measured and calculated data of *tef* stem for the 4 varieties at middle position of the stem; (Means± SD)

Variety	Moisture content(wb), (%)	Diameter (mm)	Thickness (mm)	Shear stress (Mpa)
Local	14.16± 7.37	1.91±0.37	0.26± 0.08	22.07± 7.86
Guduru	14.54± 3.25	1.85±0.33	0.27± 0.07	18.27± 6.82
Kora	10.54±6.0	1.61±0.39	0.25± 0.11	17.47± 6.11
Quncho	13.90±7.24	2.11±0.40	0.33± 0.08	19.62± 7.22

Table 4. 6. Summary of measured and calculated data of *tef* stem for the 3 varieties at upper position of the stem; (Means± SD)

Variety	Moisture content(wb(%)	Diameter (mm)	Thickness (mm)	Shear stress (Mpa)
Guduru	15.04± 5.83	1.74±0.31	0.25± 0.06	19.06± 5.26
Kora	12.82± 4.69	1.56±0.28	0.20± 0.06	19.41± 6.24
Quncho	14.22± 6.95	1.73±0.37	0.25± 0.07	17.19± 8.55

(* local variety has only two segments i.e. bottom and middle)

4.1.2. Discussion

4.1.2.1.The effect of moisture, stems' diameter and thickness, and variety on Shear stress

The statistical analysis with multi linear regression showed that the thickness of the stem has no significant effect in shear (Table 4.7.). However, the moisture content and diameter were the most dominant factors influencing the shear stress. For comparison of the shear stress at the bottom segments of each stem with the range of all moistures was indicated: the Local (check) is 1st, Guduru (Dz-01-1880.) 2nd, Kora (Dz-Cr-438)3rd and Quncho (Dz Dz-Cr-387/RIL-355) 4th value (Figure 4.2.). Most of the *tef* varieties have very small thickness of stem and their diameter decreases from bottom towards upper position with minimum difference. The measured and calculated shear stresses were 8.58-32.12 Mpa, 10.2-29.60 Mpa, 6.30-28.40 Mpa and 5.10-26.30 Mpa for Local, Guduru, Kora and Quncho *tef* varieties, respectively.

When comparing the *tef* varieties' of shear stress, the Local variety has higher value, which has compacted fibers and many nodes with limited length of the stem. It helps to have strong and dense fiber than that of other varieties. The *tef* shear stress is better than some cereal crops like wheat (3.8-6.8 Mpa), barely (7.2-9.2 Mpa), rice (5.4- 10.2 Mpa) (Miu, 2016). The shear stress of safflower stalk was studied by Shahbazi1 and Nazari (2012) and in the bottom region the shear stress increased from 5.48 to 11.04 MPa with an increase in moisture content from 8.61% to 37.16%.

The position of the *tef* stem has considerable effect on the shear stress within the same moisture content for each variety. Comparison of each variety with the maximum, average and minimum values of shear stress through the measured moisture content, diameter and thickness was plotted by R-software and shown in Figures 4.2-4.6. The figure shows the test result at bottom, middle and upper segments of each variety.

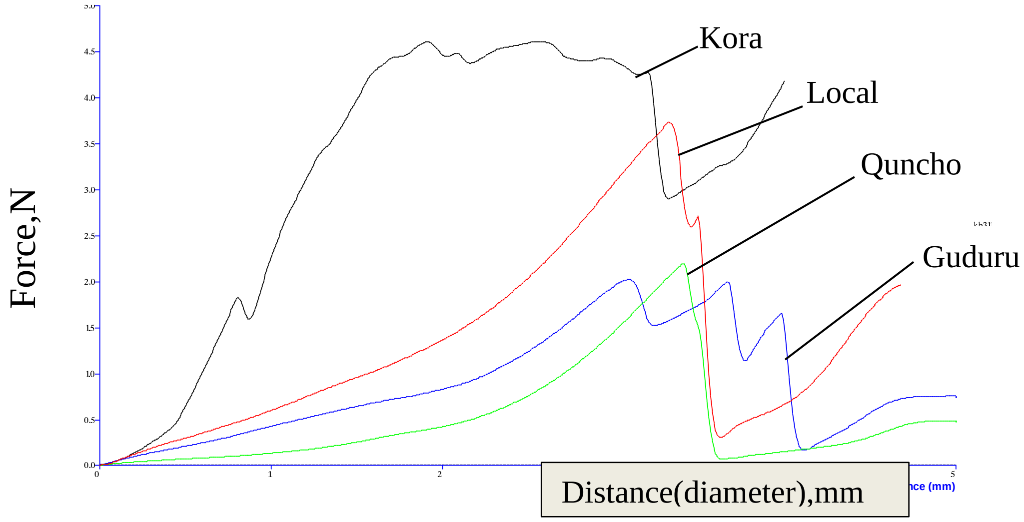


Figure 4. 1. A typical shear (cutting) curve (graph) on the shearing strength test from texture analyzer

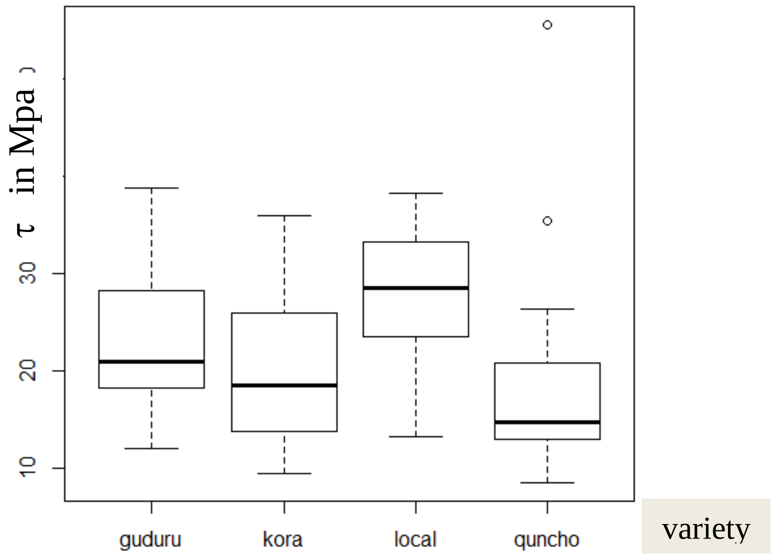


Figure 4. 2. Comparison of *tef* varieties on their max., min. and mean values of shear stress at bottom position (segments)

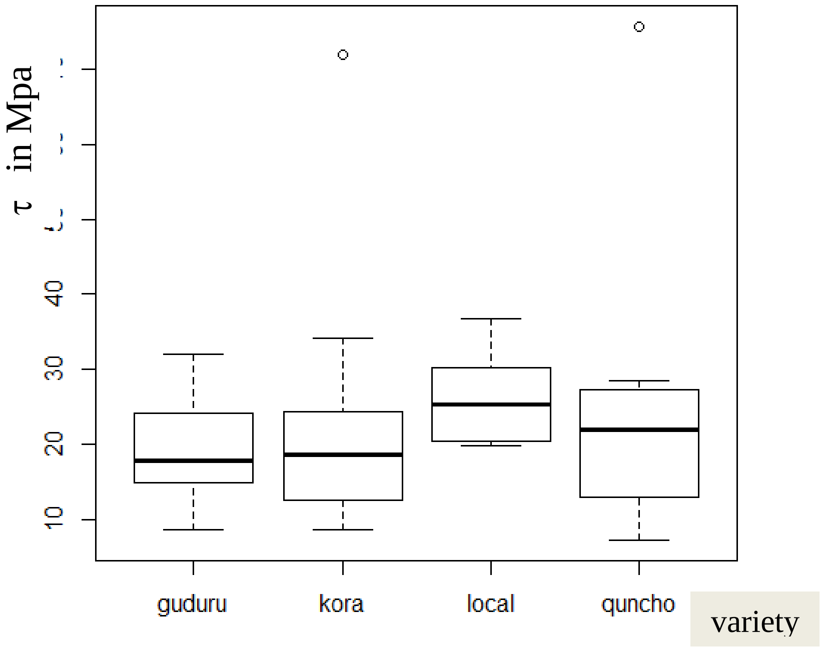


Figure 4. 3. Comparison of *tef* varieties on their max., min. and mean values of shear stress at middle position

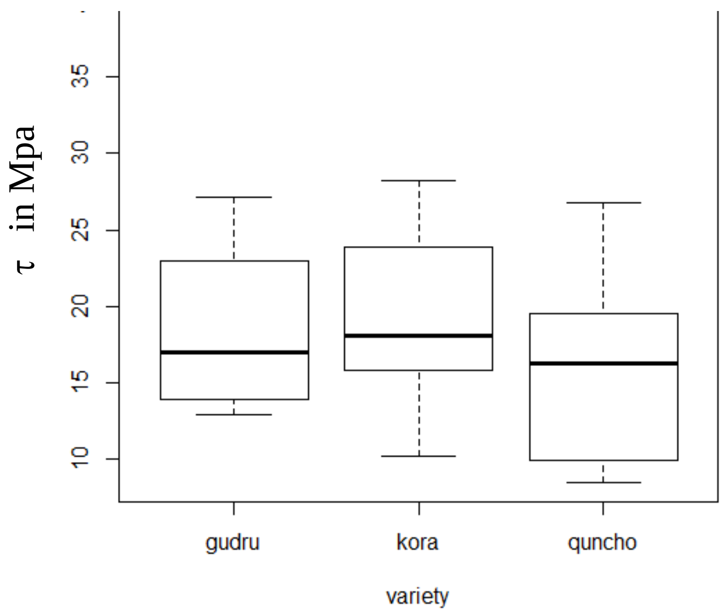


Figure 4. 4. Comparison of tef varieties on their maximum, minimum and mean values shear stress at upper position (* local variety has only two segments i.e. bottom and middle)

The relation between the moisture contents and diameters of each variety on shear stress at different positions is indicated on the (Figure 4.5.) (It is particularly meant for the variety of Kora (Dz-Cr-438) and the same condition was applied for all varieties of *tef*).

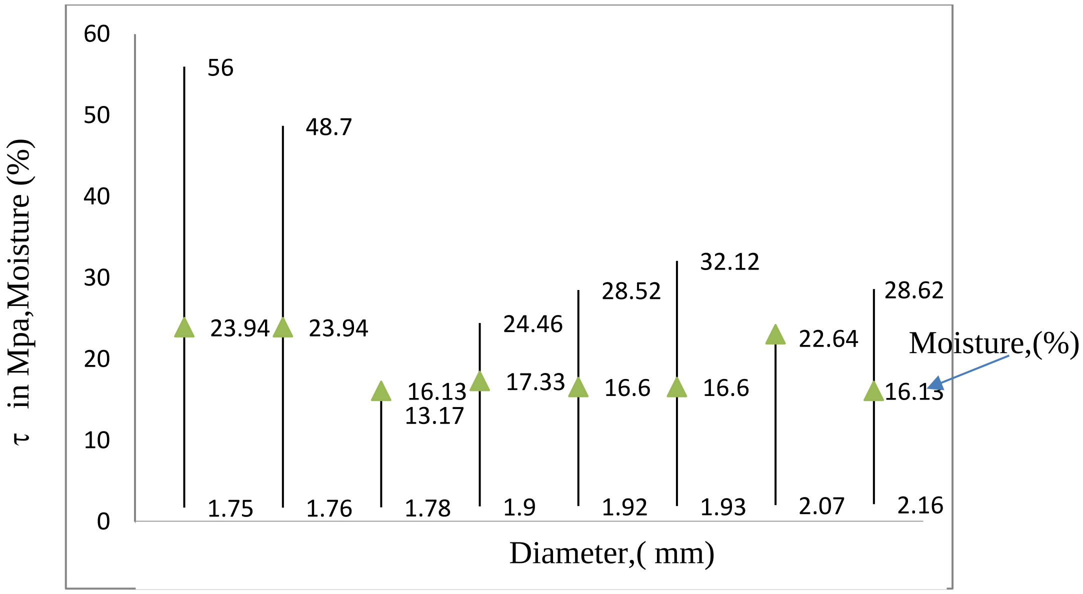


Figure 4. 5. Moisture, diameter of specimen's vs shear stress for Kora variety at bottom position

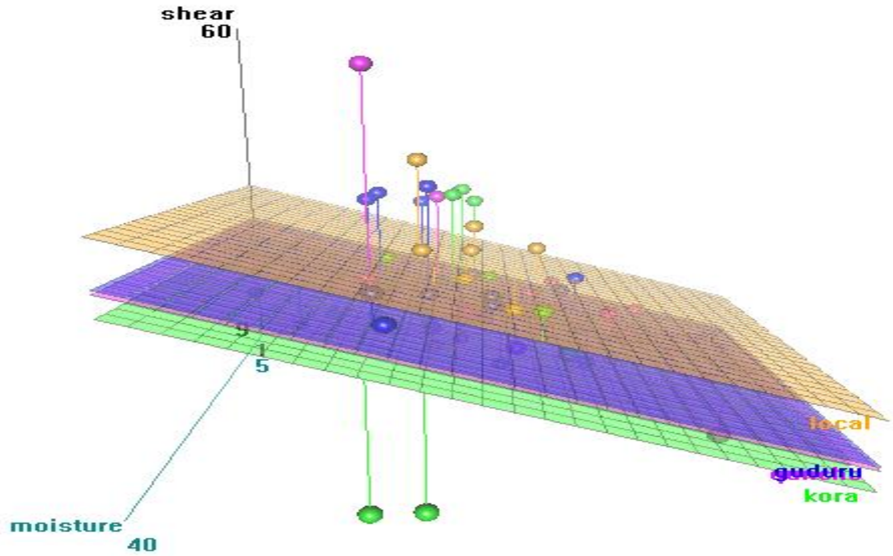


Figure 4. 6. The effect of moisture and diameter of each variety on shear stress at bottom position /3-D plot/

The 3-D plot (Figure 4. 6.) shows that the shear stress is increasing with increase in moisture content, and the local variety has the greatest values of shear stress than from all the other three varieties. The colors are differentiating the varieties, green is Kora, light brown is Quncho, blue is Guduru and the brown (the upper) is Local variety. The graph shows the linearity trend and correlation of two variables (diameter and moisture) of the specimens on the shear stress. At most diameter of the stem, when the moisture increases the shear stress increase, so the moisture is the dominant factor for shear strength.

Table 4. 7. Results of ANOVA (mean square error) for the shear properties of *tef* stem at bottom position

Source	Df	Sum sq	Mean sq	F value
Variety	3	590.35	196.78	3.7374 *
Diameter	1	533.57	533.57	10.1337 **
Thickness	1	76.42	76.42	1.4514
Moisture	1	49.56	49.56	0.9412 **
Variety x diameter	3	627.66	209.22	3.9735 *
Variety x thickness	3	496.52	165.51	3.1433 *
Diameter x thickness	1	24.44	24.44	0.4642
Variety x moisture	3	435.62	145.21	2.7578 .
Diameter x moisture	1	507.50	507.50	9.6386 **
Thickness x moisture	1	15.84	15.84	0.3008
Variety x diameter x thickness	3	205.67	68.56	1.3020
Variety x diameter x moisture	3	274.19	91.40	1.7358
Variety x thickness x moisture	3	153.91	51.30	0.9744
Diameter x thickness x moisture	1	166.73	166.73	3.1665.
Variety x diameter x thickness x moisture	3	39.22	13.07	0.2483
Residuals	32	1684.90	52.65	

---Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’

Table 4. 8. Results of ANOVA (mean square error) for the shear properties of *tef* stem at middle position

Source	Df	Sum sq	Mean sq	F value
Variety	3	242.3	80.77	0.4170*
Diameter	1	233.8	233.84	1.2074
Moisture	1	62.2	62.22	0.3213*
Thickness	1	115.3	115.33	0.5955
Variety x diameter	3	224.0	74.67	0.3856*
Variety x moisture	3	354.6	118.21	0.6104
Diameter x moisture	1	207.3	207.29	1.0703
Variety x thickness	3	150.1	50.04	0.2584*
Diameter x thickness	1	495.9	495.89	2.5604
Moisture x thickness	1	206.5	206.46	1.0660
Variety x diameter x moisture	3	122.2	40.72	0.2103*
Variety x diameter x thickness	2	915.1	457.55	2.3624
Variety x moisture x thickness	2	60.5	30.25	0.1562*
Diameter x moisture x thickness	1	65.3	65.26	0.3370.
Variety x diameter x moisture x thickness	2	1.7	0.86	0.0045
Residuals	25	4841.9	193.68	

---Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The ANOVAs result (Table 4.7- Table 4.9) indicated the correlation of all factors to the shear stress at different positions of the *tef* stem. The interactions of all factors on shear stress at bottom position are depicted on the ANOVA Table 4.7. Among the factors, the diameter and moisture content are highly significant for the shear stress under the 99% confidence interval, where as the variety and the thickness of the segments had significance for the shear stress under 95% confidence interval at bottom position of the stem. With regard to the interaction effect, diameter with moisture is highly significant for the shear stress at the 99% confidence of interval; the interaction between variety with diameter and varieties with thickness had significance effect for the shear stresses under 95% confidence of intervals.

Table 4. 9. Results of ANOVA (mean square error) for the shear properties of *tef* stem at upper position

Source	Df	Sum sq	Mean sq	F value
Variety	2	25.30	12.65	0.2670
Moisture	1	338.36	338.36	7.1397*
Diameter	1	162.68	162.68	3.4328.
Thickness	1	17.43	17.43	0.3677
Variety x moisture	2	7.56	3.78	0.0798
Variety x diameter	2	54.56	27.28	0.5756
Moisture x diameter	1	25.07	25.07	0.5290
Variety x thickness	2	135.58	67.79	1.4304
Moisture x thickness	1	36.52	36.52	0.7706
Diameter x thickness	1	0.02	0.02	0.0005
Variety x moisture x diameter	2	40.31	20.15	0.4252
Variety x moisture x thickness	2	51.75	25.88	0.5460
Variety x diameter x thickness	2	45.90	22.95	0.4842
Moisture x diameter x thickness	1	82.52	82.52	1.7412
Variety x moisture x diameter x thickness	1	44.10	44.10	0.9306
Residuals	9	426.52	47.39	

---Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The ANOVAs Table 4.8 and Table 4.9 show the interaction of all four factors at middle and upper segments of *tef* stem. The results indicated that the independent variables (variety and moisture) had significance for the shear stress under 95% confidence of interval. Under the interaction of variety with diameter and variety with thickness, it shows significance for the shear stress under 95% confidences at the middle position of the *tef* stem. The other factors interaction has no significant effect on the shear strength.

At the upper position of the stem only moisture content has significance effect for the shear stress under 95% confidence of interval, whereas the diameter has significance for the shear stress under 90% confidence of interval. The effect of the moisture and diameter of the stem on the shear stress at all segments were depicted on the 3-D plot similar to Figure 4.7 ; and it shows moisture content is the most dominant factor in shear strength of the stem in all varieties of *tef*. Multi linear regression analysis was used to find and fit the best general models to the experimental data. Results showed that the *tef* stem shear stress was a linear function of the stem moisture content, diameter and thickness. The linear equations for all segments are as follows:

$\tau = 31.143 + 0.41X_1 - 5.78X_2 - 12.43X_3$ $R^2=0.76$ --for upper segments (position)

$\tau = 43.64 + 0.154X_1 - 3.82X_2 - 15.56X_3$ $R^2=0.71$ --for middle segments (position)

$\tau = 47.16 + 0.144X_1 - 8.13X_2 - 9.29X_3$ $R^2=0.56$ --for bottom segments (position)

Where:

τ-shear stress, (Mpa)

X_1- moisture content, (%) (w.b.)

X_2-diameter of the stem, (mm)

X_3-thickness of the stem, (mm)

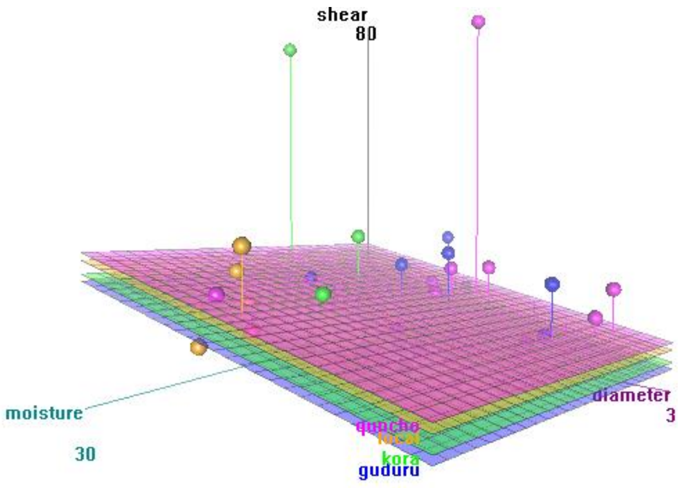


Figure 4. 7. The effect of moisture and diameter of each variety on shear stress at middle position /3-D plot/

4.1.2.2. The effect of moisture, stems' diameter and thickness; and variety on modulus of elasticity

The modulus of elasticity for each variety and the typical tensile graphs are depicted on the Figure 4.8-10. and Figure 2.4. respectively. The varieties have maximum and minimum values of elasticity 0.13 and 2.6 Gpa at moisture levels of 8.82% and 16.6%, 1.02 and 3.6 Gpa at moisture level 10.32%and 13.79%, 0.85 and3.22 Gpa at moisture levels of 7.65% and 12.72%,1.28 and 3.88 Gpa at moisture levels of 5.5% and 19.70% at upper and bottom position for Local, Kora, Quncho and Guduru varieties respectively. The modulus of elasticity at harvesting moisture was: for wheat (2-6.7 Gpa), barley (11.06 Gpa), rye (11.50 Gpa) and rice (0.39-1.2 Gpa) (Miu, 2016). The bending stress and Young's modulus of the barely straw decreased from 9.26 to 7.77 MPa, and 508.59 to 446.38 MPa, respectively, towards the third internode position. A similar effect of the stem level on the bending stress and Young's modulus for sunflower stalk was also reported by Ince *et al.* (2005).

Shahbazi1 and Nazari (2012) studied the modulus of elasticity for safflower stalk and they concluded that the average value was between 0.86 and 3.33 GPa. Bahram and Alireza (2012) found the young's modulus of the canola stem were 1.57, 1.71 and 2.04 GPa for Zarfam, Okapi and Opera varieties, respectively. Amer *et al.* (2008) determined the average tensile strength for cotton stalks at different moisture contents (11.15%, 16.22% and 21.92%) was (26.5, 18.79 and 11.54 MPa). The mechanical properties (average tensile strength) for sugar cans bagasse at different moisture contents 8.1%, 15.31% and 24% were recorded as 4.38, 9.5 and 11 MPa respectively. Based on the test results, all varieties of *tef* stem had better modulus of elasticity than some other cereals like Rice and Barely. The values of the Young's modulus for barley straw were found to be lower than those of wheat straw (4.76 to 6.58 GPa) and of alfalfa stems (0.63 to 4.60 GPa) (Nazari *et al.*, 2008).

The number of nodes per segments in *tef* stem was directly proportional to the elasticity properties. When the segment had two nodes, the module of elasticity was better than the segment which has one node, so the number of nodes on the stem is a very important property of *tef* for strength.

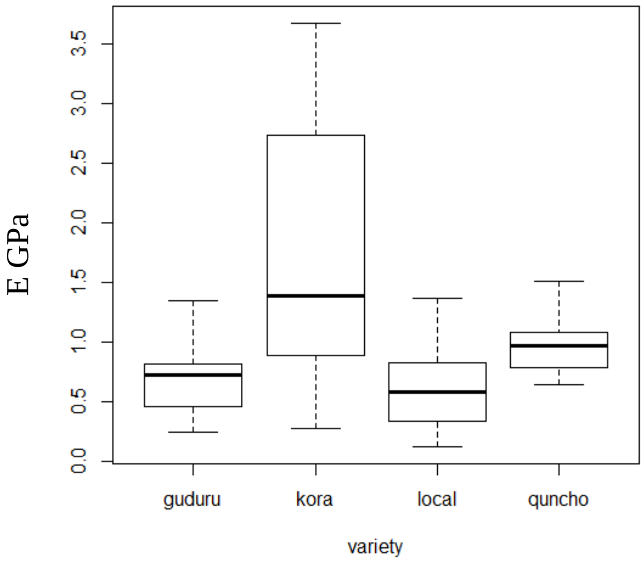


Figure 4. 8. Comparison of *tef* varieties on their max., min. and mean values modulus of elasticity at bottom position

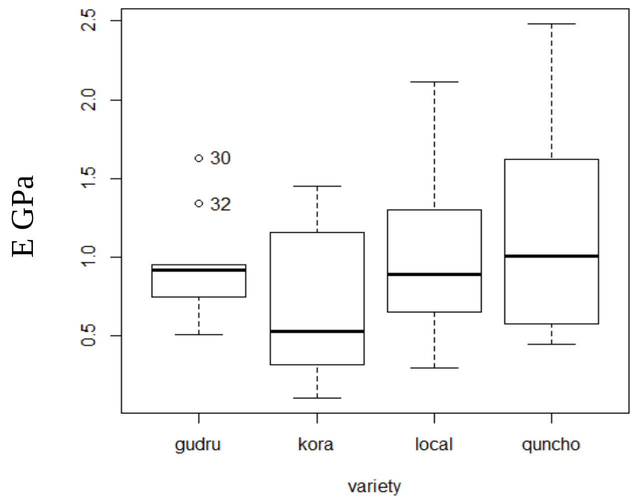


Figure 4. 9. Comparison of *tef* varieties on their max., min. and mean values of modulus of elasticity at middle position

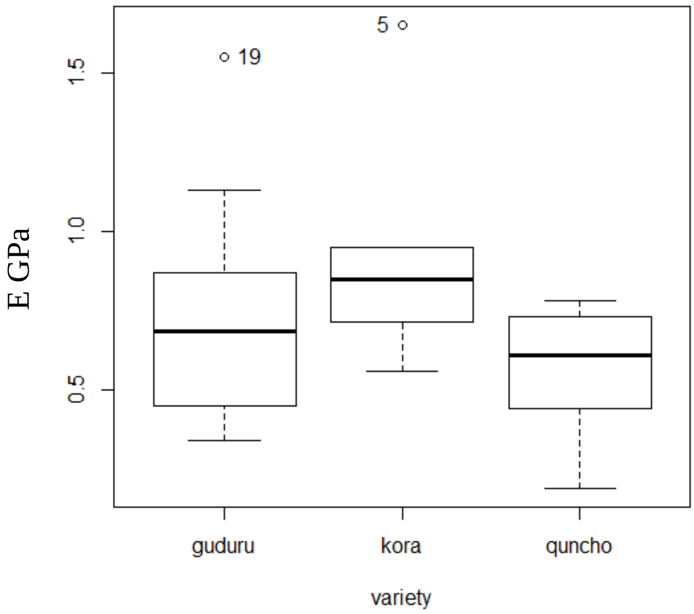


Figure 4. 10. Comparison of tef varieties on their max., min. and mean values tensile strength at upper position (* local variety has only two segments i.e. bottom and middle)

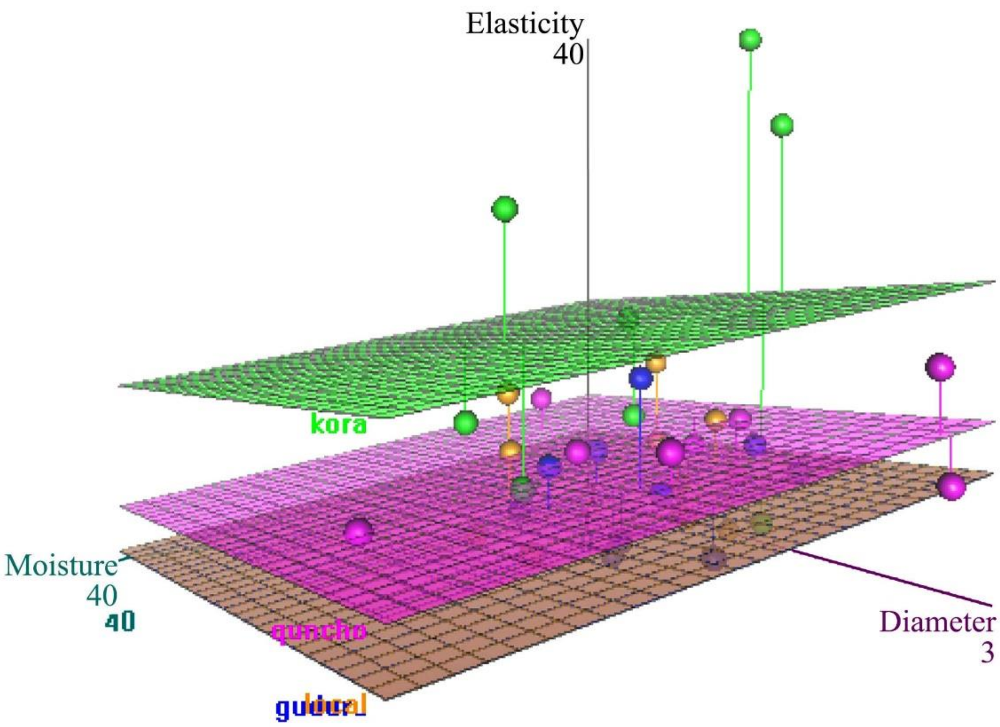


Figure 4. 11. The effect of moisture and diameter of each variety on elasticity at bottom position / 3-D plot/

On 3-D plot Figure 4.11 shows different colors, the colors are differentiating the varieties, green (kora), purple (quncho), light brown (guduru) and the brown (local). The graph shows the linearity trend and correlation of two variables (diameter and moisture) of the specimens on the elasticity and the diameter is the dominant factor.

Table 4. 10. Results of ANOVA (mean square error) for the tensile properties of *tef* stem at bottom position

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	1.5824	1.58243	5.9598 *
Moisture	1	0.4691	0.46915	1.7669
Thickness	1	0.5507	0.55071	2.0741
Variety	1	0.5578	0.55776	2.1007
Diameter x moisture	1	0.1710	0.17103	0.6441
Diameter x thickness	1	0.1153	0.11533	0.4344
Moisture x thickness	1	0.3648	0.36477	1.3738
Diameter x variety	1	0.0052	0.00521	0.0196
Moisture x variety	1	0.0371	0.03709	0.1397
Thickness x variety	1	0.4599	0.45992	1.7322
Diameter x moisture x thickness	1	0.0399	0.03991	0.1503
Diameter x moisture x variety	1	0.0061	0.00614	0.0231
Diameter x thickness x variety	1	0.0107	0.01074	0.0405
Moisture x thickness x variety	1	0.5095	0.50952	1.9190
Diameter x moisture x thickness x variety	1	0.1100	0.11004	0.4145
Residuals	1	8	4.7793	0.26551

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘

Table 4. 11. Results of ANOVA (mean square error) for the tensile properties of *tef* stem at middle position

source	Df	Sum Sq	Mean Sq	F value
Diameter	1	1.5824	1.58243	2.9949
Moisture	1	0.4691	0.46915	0.3893
Thickness	1	0.5507	0.55071	1.0423
Variety	3	0.80701	0.26900	0.5091
Diameter x moisture	1	0.18986	0.18986	0.3593
Diameter x thickness	1	0.12084	0.12084	0.2287
Moisture x thickness	1	0.34429	0.34429	0.6516
Diameter x variety	3	0.47654	0.15885	0.3006
Moisture x variety	3	0.39270	0.13090	0.2477
Thickness x variety	3	0.34358	0.11453	0.2168
Diameter x moisture x thickness	1	0.00042	0.00042	0.0008
Diameter x moisture x variety	3	0.42184	0.14061	0.2661
Diameter x thickness x variety	3	1.16833	0.38944	0.7371
Moisture x thickness x variety	3	0.25950	0.08650	0.1637
Residuals	5	2.64184	0.52837	

---Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The ANOVAs Table 4.11 and Table 4.12 show the interaction of all four factors at middle and upper segments of *tef* stem. The results indicated that the independent variables (variety, moisture and thickness) had significant effect for the modulus of elasticity under 95% confidence of interval at bottom position. Among the factors, diameter and thickness, the interaction between variety with diameter and variety with thickness showed significant effect on the elasticity under 90% confidence of interval at the middle position of the *tef* stem. The other factors interaction has no significant effect on the modulus of elasticity.

Table 4. 12. Results of ANOVA (mean square error) for the tensile properties of *tef* stem at upper position

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	0.42733	0.42733	112.3194**
Moisture	1	0.00074	0.00074	0.1933
Thickness	1	0.36486	0.36486	95.8992*
Variety	2	0.72654	0.36327	95.4806*
Diameter x moisture	1	0.12432	0.12432	32.6752 *
Diameter x thickness	1	0.01046	0.01046	2.7504
Moisture x thickness	1	0.08453	0.08453	22.2181*
Diameter x variety	2	0.05620	0.02810	7.3859
Moisture x variety	2	0.37849	0.18925	9.7412*
Thickness x variety	2	0.07914	0.03957	10.4000
Diameter x moisture x thickness	1	0.16738	0.16738	43.9927*
Diameter x moisture x variety	2	0.19603	0.09802	25.7621*
Diameter x thickness x variety	1	0.03173	0.03173	8.3401
Moisture x thickness x variety	1	0.5095	0.50952	1.9190
Diameter x moisture x thickness x variety	1	0.01950	0.01950	5.1261
Residuals	2	0.00761	0.00380	

-----Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '

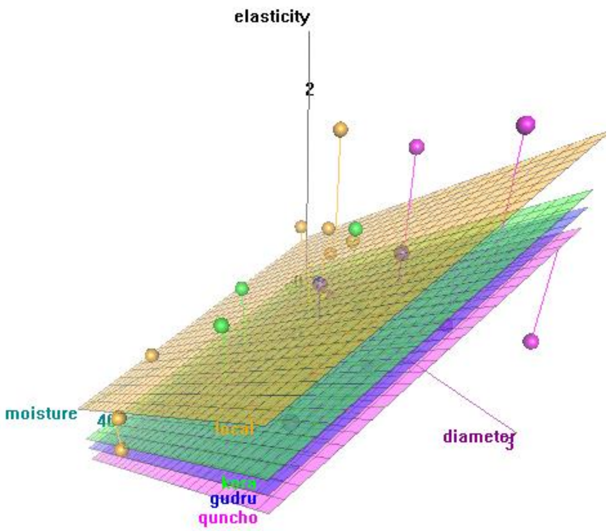


Figure 4. 12. The effect of moisture and diameter for each variety on modulus of elasticity at middle position /3-D plot/

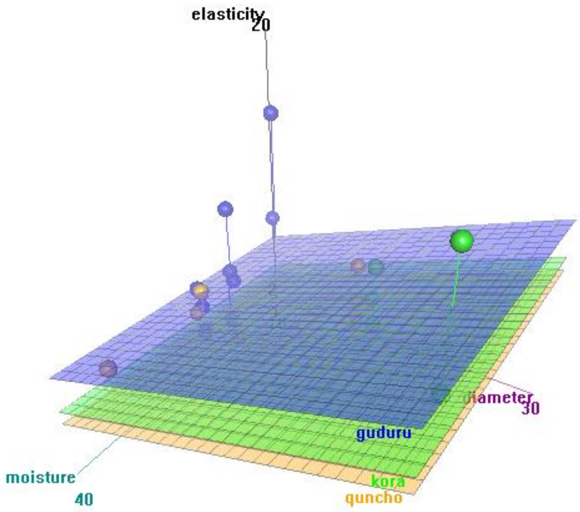


Figure 4. 13. The effect of moisture and diameter of each variety on modulus of elasticity at upper position /3-D plot/

The graphical relation of the moisture and diameter of the stem at all segments were depicted on the 3-D plot (Figure 4.11 -Figure 4.14.); and it shows that diameter is the most dominant factor in modulus of elasticity of the stem in all varieties of *tef*.

The modulus values for wild type Barley crop with the variety of Bowman and Fragile stem was studied and come up with the result that differences in part shows due to the difference in fiber density between the varieties (Christopher *et al.*, 2005). Hence, as general overview the difference of modulus elasticity of each *tef* varieties could have the fiber density difference in each stem.

Multi linear regression analysis was used to find and fit the best general models to the experimental data. Results showed that the *tef* stem modulus of elasticity was a linear function on the stem moisture content, diameter and thickness. The linear equations for all segments are as follows:

$E = -1.117 + 0.904X_1 + 0.940X_2 - 0.007X_3$ R^2=0.64 --for bottom segments (position)

$E = 0.142 + 0.256X_1 + 1.820X_2 - 0.012X_3$ R^2=0.73 ----for middle segments (position)

$E = -0.468 + 0.337X_1 + 2.49X_2 + 0.0004X_3$ R^2=0.67 --for upper segments (position)

Where:

E-modulus of elasticity, (Gpa)

X_1- diameter of the stem, (mm)

X_2- thickness of the stem, (mm)

X_3- moisture content, (%) (w.b)

4.1.2.3. The effect of moisture content, diameter and thickness of the stem on flexural rigidity

The lodging effect is highly related to the flexural rigidity of the stem. Flexural rigidity was calculated using the equation 2.3 and value of modulus elasticity by equation 2.2. It is directly proportional to the modules of elasticity and moment of inertia. The value of flexural rigidity on a heterogeneous cross-section based on bending theory regarding an elastic behavior was reviewed, and also a calculation method of flexural rigidity for materials with heterogeneous cross-section was observed. Based on the ANOVAs result variety has significant effect for the flexural rigidity.

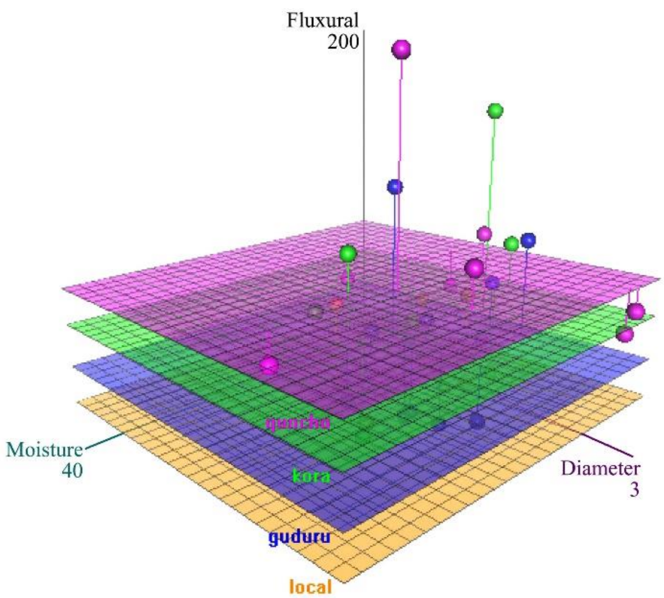


Figure 4. 14. The effect of moisture and diameter of each variety on flexural rigidity at bottom position / 3-D plot/

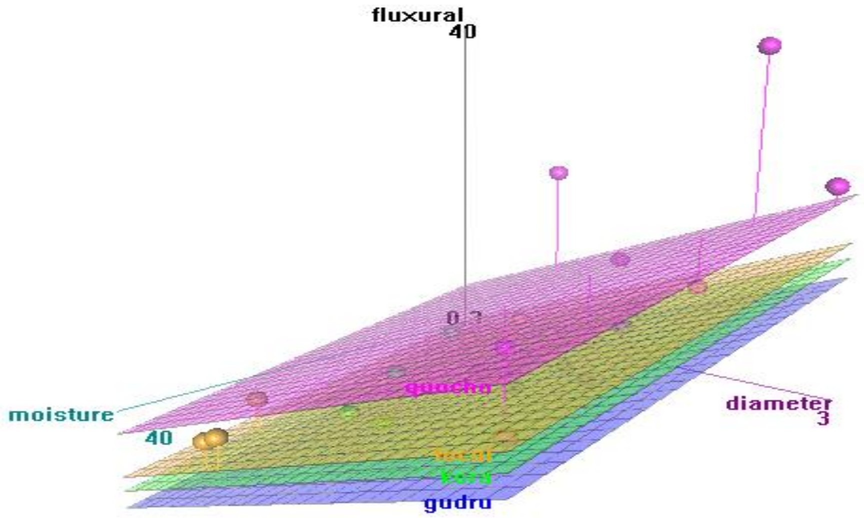


Figure 4. 15. The effect of moisture and diameter of each variety on flexural rigidity at middle position

Hirai *et al.* (2002) studied the mechanical properties and showed the flexural rigidity of rice under the moisture content of 59.3% and wheat under the moisture content 46.7% w.b were 30 and 28.8 kN.mm^2 respectively. These values give relatively similar result with the *tef* stem flexural rigidity (maximum 26-38.8KN.mm^2). The graphical relation of the moisture and diameter of the stem at all segments are depicted on the 3-D plot similar as Figure 4.15 ; and it shows that diameter is the most dominant factor in flexural rigidity of the stem in all varieties of *tef*.

The effect of moisture and diameter at flexural rigidity at all positions is depicted in Figure 4. 16-Figure 4.18. At bottom and upper positions, the increment of all factors increased the flexural, while in middle position the increment of diameter and thickness increased the flexural rigidity and increment of moisture decreased the flexural rigidity. This happened at certain level of moisture increment (after 35%) which decreased the tensile force.

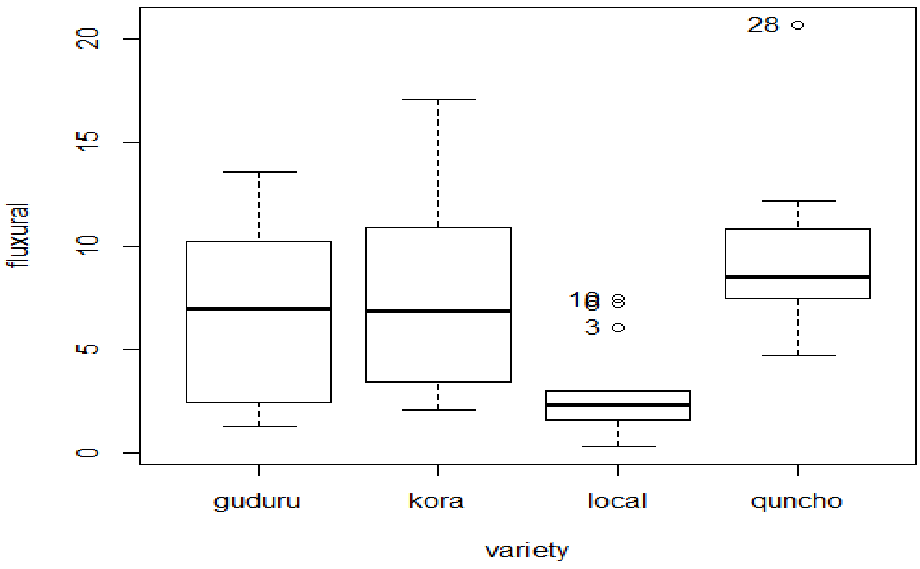


Figure 4. 16 Comparison of *tef* varieties on their max., min. and mean value of flexural rigidity at bottom position

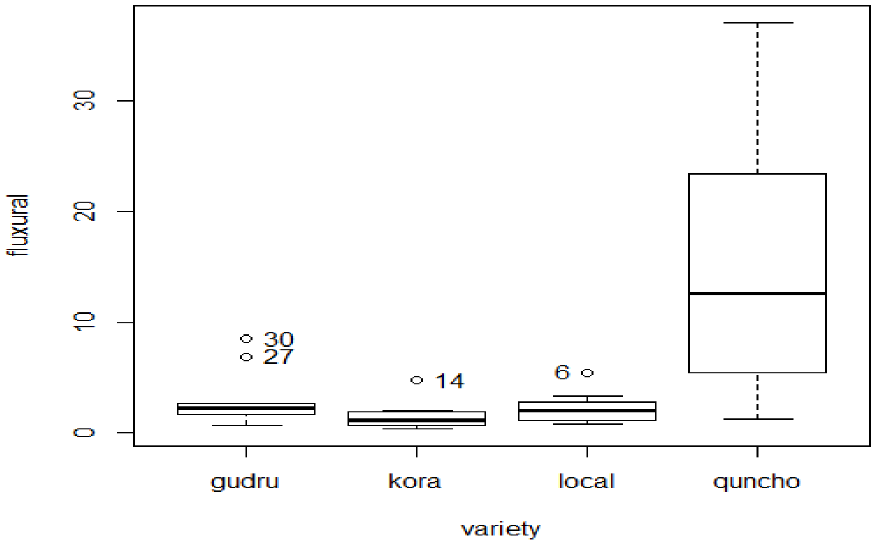


Figure 4. 17. Comparison of *tef* varieties on their max., min. and mean value of flexural rigidity

at middle position

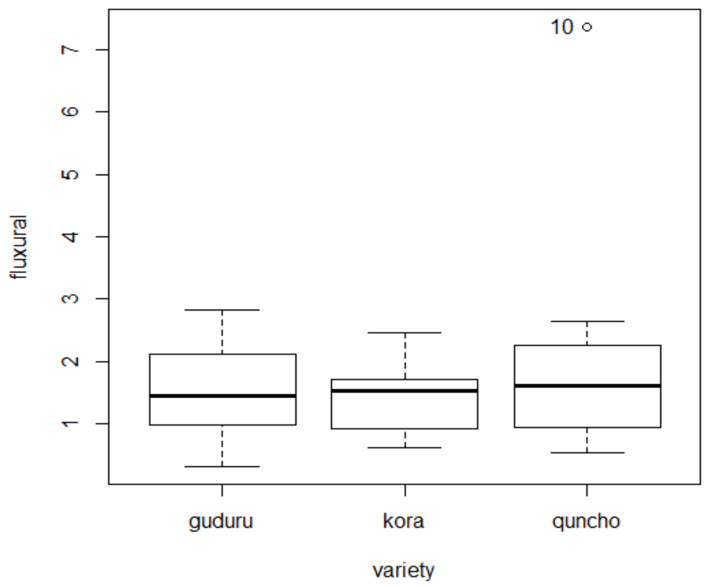


Figure 4. 18. Comparison of tef varieties on their max., min. and mean value of flexural rigidity at upper position **(* local variety has only two segments i.e. bottom and middle)**

Regarding the value depicted on Table 4.13-Table 4.15, the flexural rigidity is directly proportional to elasticity. All relations and value comparison among each variety were similar to the modulus of elasticity. The varieties have maximum and minimum values of flexural rigidity: 1.3 and 26 kNmm^2 at moisture levels of 8.82% and 16.6%, 10.18 and 36 kNmm^2 at moisture levels of 10.32%and 13.79%, 8.48 and 32.2 kNmm^2 at moisture levels of 7.65% and 12.72%,12.78 and 38.84 kNmm^2 at moisture levels of 5.5% and 19.70% at upper and bottom positions for Local, Kora, Quncho and Guduru varieties respectively.

Table 4. 13. Results of ANOVA (mean square error) for the flexural properties of *tef* stem at bottom position

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	252.918	252.918	16.7255**
Moisture	1	2.922	2.922	0.1933
Thickness	1	126.543	126.543	8.3683*
Variety	3	51.896	17.299	1.1440
Diameter x moisture	1	9.082	9.082	0.6006
Diameter x thickness	1	11.093	11.093	0.7336
Moisture x thickness	1	2.750	2.750	0.1819

Source	Df	Sum Sq	Mean Sq	F value
Diameter x variety	3	99.677	33.226	2.1972
Moisture x variety	3	42.714	14.238	0.9416
Thickness x variety	3	22.901	7.634	0.5048
Diameter x moisture x thickness	1	4.897	4.897	0.3238
Diameter x moisture x variety	3	18.011	6.004	0.3970
Diameter x thickness x variety	3	63.542	21.181	1.4007
Moisture x thickness x variety	3	30.321	10.107	0.6684
Diameter x moisture x thickness x variety	3	5.807	1.936	0.1280
Residuals	8	120.973	15.122	

---Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 4. 14. Results of ANOVA (mean square error) for the flexural properties of *tef* stem at middle position

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	869.61	869.61	34.7958**
Moisture	1	139.25	139.25	5.5719.
Thickness	1	22.78	22.78	0.9115
Variety	3	336.08	112.03	4.4825
Diameter x moisture	1	117.30	117.30	4.6934.
Diameter x thickness	1	106.49	106.49	4.2608.
Moisture x thickness	1	5.70	5.70	0.2280
Diameter x variety	3	68.58	22.86	0.9147
Moisture x variety	3	30.95	10.32	0.4128
Thickness x variety	3	31.93	10.64	0.4259
Diameter x moisture x thickness	1	165.90	165.90	6.6382*
Diameter x moisture x variety	3	50.82	16.94	0.6778
Diameter x thickness x variety	3	32.97	10.99	0.4397
Moisture x thickness x variety	3	14.96	4.99	0.1996
Residuals	5	124.96	24.99	

---Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 4. 15. Results of ANOVA (mean square error) for the flexural properties of *tef* stem at upper position

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	17.1912	17.1912	35.4526*
Moisture	1	0.4270	0.4270	0.8806
Thickness	1	4.1931	4.1931	8.6473.
Variety	2	0.3463	0.1731	0.3571
Diameter x moisture	1	11.1136	11.1136	22.9190*
Diameter x thickness	1	5.0245	5.0245	10.3618.
Moisture x thickness	1	0.9148	0.9148	1.8865
Diameter x variety	2	0.6353	0.6550	0.60422
Moisture x variety	2	1.3563	0.6781	1.3985
Thickness x variety	1	0.4572	0.2286	0.4715
Diameter x moisture x thickness	1	0.2622	0.2622	0.5408
Diameter x moisture x variety	2	1.1829	0.5915	1.2197
Diameter x thickness x variety	1	0.0001	0.0001	0.0001
Moisture x thickness x variety	1	0.0334	0.0334	0.0688
Residuals	2	0.9698	0.4849	

--Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The ANOVAs in Table 4.13 – Table 4.14 show the interaction of all four factors at bottom, middle and upper segments of *tef* stem. The result indicated the independent variables (variety, moisture and thickness) had significant effect on the flexural rigidity under 95% confidence of interval at bottom position. The interaction of variety with diameter and variety with thickness showed significant effect for the flexural under 90% confidence of interval at the middle position of the *tef* stem. The other factors interaction has no significant effect on the flexural rigidity. On the upper position of the segments, the diameter is the most dominant factor for the flexural rigidity. Table 4.15 showed that diameter has significant effect on the flexural rigidity under the 95% confidence of interval.

Multi linear regression analysis was used to find and fit the best general models to the experimental data. Results showed that the *tef* stem flexural rigidity *(ExI)* was a linear function on the stem moisture content, diameter and thickness. The multi linear equations for all segments are as follows:

$$Fr = ExI = -10.343 + 3.363X_1 + 20.946X_2 + 0.0091X_3$$ R^2=0.79 --for bottom segment

$$Fr = ExI = -13.721 + 10.511X_1 + 11.712X_2 - 0.219X_3$$ R^2=0.55 --for middle segments

$$Fr = ExI = -4.88 + 2.495X_1 + 8.439X_2 + 0.02X_3$$ R^2=0.53 --for upper segments

Where:

E-modulus of elasticity, (Gpa)

I-moment of inertia, (mm^4)

X_1- diameter of the stem, (mm)

X_2- thickness of the stem, (mm)

X_3- moisture content, (%) (w.b)

4.2. Results on Design of Threshing Mechanisms

4.2.1. Conceptual design

"Everything should be made as simple as possible, but not simpler" **(Albert Einstein).**

In this research the meaning of mechanisms is an assembly of moving parts performing a complete functional motion. So, the threshing mechanisms are the part of the thresher which can help to perform rubbing, impact or squeezing and it consist the rotating drum and the stationary concave. Based on the design requirements the overall dimensions of the threshing units should be equivalent with the existing stationary threshers (SG-2000).

To select the proper shape and configurations of the threshing units, the research depends on the design procedure (process) (engineering design) (Pahl, *et al.*, 2007) and the following concepts were generated. As back ground the research focus on the different studies results, basically among others the study results by Miu (2016) conclude in threshing and separation process, to get better cleaning efficiency, the concave should have better active area (the area where the separation is performed). This concept applied for this particular research.

The other concept is to perform threshing and separation within one movement (action of the operation) of the threshing units upon the existing platform (concave and drum length). The theory of separation was modeled and further developed by Miu and Kutzbach (2000), the stochastic grain movement through the material other than grain layer on the top of sieve is the result of convolution (by constant sinking) and diffusion (due to random scattering). These theories apply in developing *tef* threshing and separation units. As the literature reviews indicated the tangential feed with rotary threshing unit is versatile and has a lot of advantages (like: increasing feed rate and output capacity, easy of separation...), with that axial threshing is selected for *tef* threshing units.

For the improvement of the cleaning efficiency the different studies proved that it is recommended to have better concave and sieves area, this implies to have more space for the passing through the hole with the movement of the whole bulk, there are different options to increase the area of the concave, by increasing the width and length or increasing one of this parameters or other ways, in our case it was predetermined that the length is already fixed and decided to have the same length with the SG-2000 threshers. So, to increase the area of the existing threshers' concave the other options could be increasing the width, in this case the width means increasing the wrap angle.

There were also studies in comparison of closed and open types of concave and came up with conclusions that the closed concave shows more grain damages (due to repeatedly impact of the threshed material inside the threshing units within the same dwell time) than that of open Simonyan (*et al.*, 2009). However, in the case of *tef* threshing the grain damage is not expected (due to the very small size of *tef* seeds). So, conceptually the closed concave will be an option in order to have a better cleaning efficiency and separation with increasing the concave area.

4.2.1.1. Establishing the function and components

Establishing the function structure initially involved, formulating the overall function which was extracted directly from the problem statement. The overall function is developed as seen in (Figure 4.21.) by using the requirement list as a base.

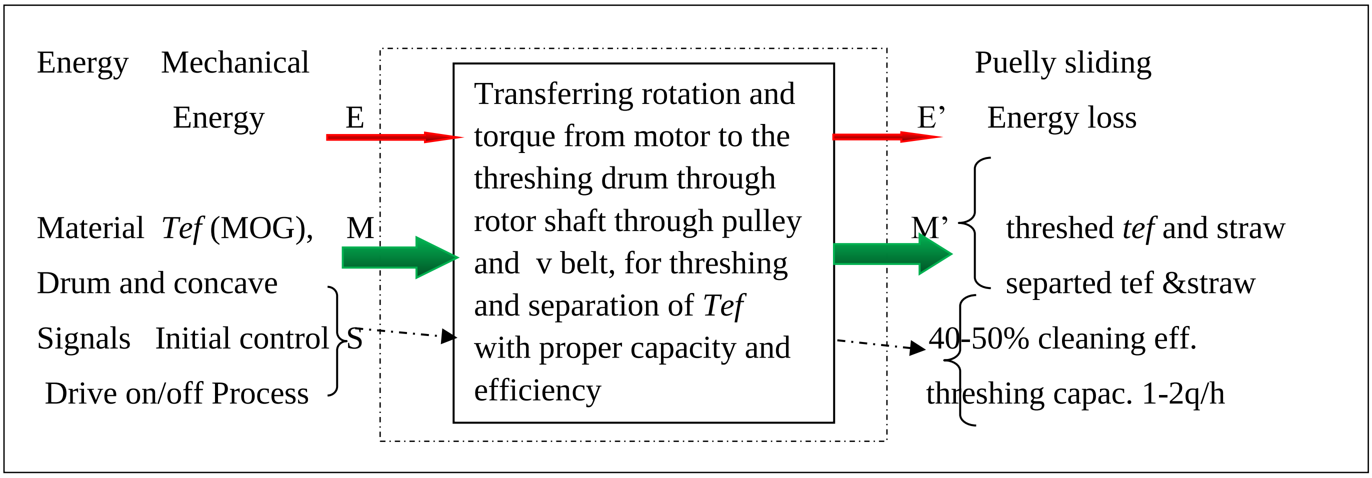
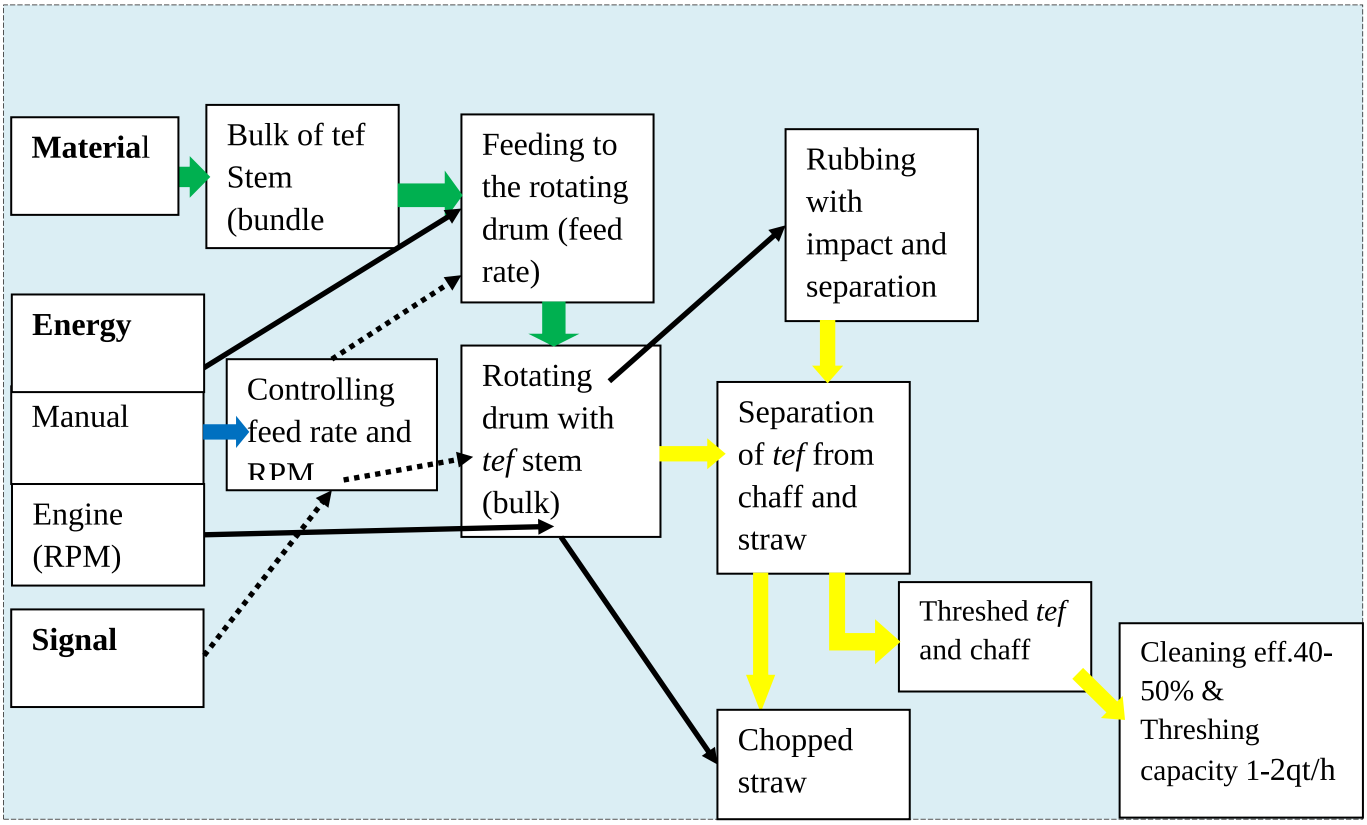


Figure 4. 19. Main function of the structure (Pahl, *et al.*, 2007)

Sub function structure



Legend:

Material [Unthrshed bulk of *tef (*flow *bundle of tef)]*

Applied energy (flow of energy)

Threshed and separated (flow of *tef* and chaff)

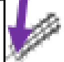
Controlling (operators controlling)

Flow of signals

The essential sub-functions result from the energy flow, signal and material flow:

- *Tef* as abundle prepare and feed manually to the rotating drum and stationary concave
- Motion for rotating parts deliver from diesel engine through pulley and v-belt
- Threshing by rotating drum and stationary concave perform the rubbing and impact actions on the bulk of *tef*, then perform detaching, separation of *tef* from chaff and straw, the mixture fallen with the help of gravity through perforated concave, the chopped straw throw away by the drum end plate through the starw out let.
- *Tef* and chaff collected on the outlets; and chopped straw throw through straw outlets

Table 4. 16. Combining working principles (morphological matrix) (Pahl *et al.*, 2007)

No	Sub function	Solution	Solution principles 1	2	3	Remark
1	Energy	Power /material/	Human	Animal	Motor (tractor)	
		Mechanical energy ↓ Power Transmission (shaft,)	With key	With bolt	Force fit	I-option (blue arrow) II-option (black arrow) III-option (red arrow) IV-option (green arrow) . . . X-option (purple arrow)
		Pulley	single groove	Double groove		
2	Feeding	Human (manual)	direct	Indirect(conveyor assisted)		
3	Threshing	Rubbing	rasp bar(flat iron) 	Spike tooth 	Wire 	
		Impacting	rasp bar(f.Iron)	Spike tooth	Wire(pegs)	
		Chopping	rasp bar/flat iron	spike tooth	Wire(pegs)	
		Concave type	open 	Closed 		
4	Separation	Concave	Stationary (gravity)	External force movement	Internal force movement	
		Shacking	With arm	Shaft	Rocker	
5	Cleaning	Sieving	With out sieve	With sieve		
6	Chopping	Withen bulk (mass) flow	multi blade	Single blade	External chopping unit	
7	Delivery system (discharging system)	Mixture (tef and chaff)	Gravity	Mechanical assisted	Pneumatic	
		Straw	Blade	Blower	Chain	

1 2 3 4 10

Combination solution principles for different variants

4.2.1.2. Selection criteria for each system and select the appropriate one using pair wise comparison

1. **Source of power** - our design requirement is based on the land holding, capacity and the affordability of the technology, ease of operation for most farmers and better quality of work. Hence, there are different options:

- Human power
- Animal power
- Motor or tractor

Selection criteria are:

1. Low cost
2. Easy for operation
3. Quality of work (threshed crop quality)
4. Appropriate for small scale farmers and small land holding

$N = n(n-1)/2$ (Dieter and Schmidt, 2013)

If $n = 4$, $N = 6$

Where:

N- The total number of possible comparison

n- The number of criteria under consideration

Table 4. 17. Evaluation criteria for selecting power source

Criteria	1	2	3	4	mi.	Wi.
1	X	1	0	1	2	0.33
2	0	X	1	0	1	0.167
3	1	0	X	1	2	0.33
4	0	1	0	X	1	0.167

Table 4. 18. Weighted evaluation criteria for selecting power source (Dieter and Schmidt, 2013)

Design criteria Option	1	2	3	4	Sum M*V
Human	95	82	85	80	
V*W power source	31.35	13.69	28.05	13.36	86.45
Animal	85	95	70	80	
V*W power source	28.05	15.86	23.10	13.36	80.37
Motor/Tractor	80	90	93	95	
V*W power source	26.40	15.03	30.69	15.86	**87.98**

Based on the selection criteria **Motor/Tractor power** is selected

2. **Power transmission** - since it is mechanical power transmission, the power will transfer from the motor to the rotating drum through drum shaft and pulley with the help of key (or bolt). For this purpose, there are options:

- Shaft and pulley with force fit
- Shaft and pulley with key
- Shaft and pulley with bolt

Selection criteria are:

1. Minimum power loss
2. Low (minimum) slippage
3. Easy for transport and production
4. Cost

$N = n (n-1)/2$

If $n = 4$, $N = 6$

Table 4. 19. Evaluation criteria for selecting power transmission

Criteria	1	2	3	4	mi.	Wi.
1	X	1	0	1	2	0.33
2	0	X	1	1	2	0.33
3	1	0	X	0	1	0.167
4	0	0	1	X	1	0.167

Table 4. 20. Weighted evaluation criteria for selecting power transmission (Dieter and Schmidt, 2013)

Design Criteria Option	1	2	3	4	Sum M*V
Shaft and pulley with force fit	80	75	95	90	
V*W power transmission	26.4	24.75	15.86	15.03	82.04
Shaft and pulley with key	95	90	80	85	
V*W power transmission	31.35	29.7	13.36	14.19	**88.60**
Shaft and pulley with bolt	90	92	85	80	
V*W power transmission	29.70	30.36	14.19	13.36	87.61

Based on the selection criteria **Shaft and pulley with key** is the best solution and is selected.

3. **Feeding system** – Feeding of the crop to the threshing unit should be very simple and could be appropriate for small scale farmers and ergonomically fit for operators. Different feeding techniques options are available:
    - Human (manual) direct fed
    - Human assisted with chain(belt) drive
    - Auger

    Selection criteria are:

1. Easy for feeding, no needs of additional assistance
2. Easy for operation
3. Easy for production
4. Cost

$$N = n(n-1)/2$$

If $n = 4$, $N = 6$

Table 4. 21. Evaluation criteria for feeding system

Criteria	1	2	3	4	mi.	Wi.
1	X	1	0	1	2	0.33
2	0	X	1	0	1	0.167
3	1	0	X	1	2	0.33
4	0	1	0	X	1	0.167

Table 4. 22. Weighted evaluation criteria for feeding system

Design Criteria Option	1	2	3	4	Sum M*V
Human (manual)	95	92	95	90	
V*W feeding system	31.35	15.36	31.35	15.03	**93.09**
Human assisted with chain(belt) drive	95	90	75	80	
V*W feeding system	31.35	15.03	24.75	13.36	84.49
Auger	85	75	75	80	
V*W feeding system	28.05	12.52	24.75	13.36	78.68

Based on the selection criteria **Human (manual) feeding** system is the best solution and is selected.

4. **Threshing units** -there are three types of threshing units based on the feeding methods i.e. tangential threshing unit with tangential feeding, rotary threshing units with axial feeding and rotary threshing units with tangential feeding. So, from the different alignments and construction of the threshing units the following are mentioned as options and evaluated based on the design criteria. Options are:

- tangential threshing unit with tangential feeding
- rotary threshing units with axial feeding
- rotary threshing units with tangential feeding

Selection criteria are:

1. Efficient for threshing and increased capacity
2. Easy of production
3. Easy for feeding
4. Easy of operation and maintenances
5. Cost

$N = n(n-1)/2$

If $n = 5$, $N = 10$

Table 4. 23. Evaluation criteria for selecting threshing units

Criteria	1	2	3	4	5	mi.	Wi.
1	X	1	0	1	1	3	0.3
2	0	X	1	0	0	1	0.1
3	1	0	X	0	1	2	0.2
4	0	1	1	X	0	2	0.2
5	0	1	0	1	X	2	0.2

Table 4. 24. Weighted evaluation criteria for selecting threshing units

Design Criteria Option	1	2	3	4	5	Sum M*V
tangential threshing unit with tangential feeding	80	85	75	80	95	
V*W threshing unit	24	8.5	15	16	19	82.5
rotary threshing units with tangential feeding	93	95	92	90	94	
V*W threshing unit	27.9	9.5	18.4	18	18.8	**92.6**
rotary threshing units with axial feeding	95	93	90	92	90	
V*W threshing unit	28.5	9.3	18	18.4	18	92.2

Based on the selection criteria **rotary threshing units with tangential feeding** is the best solution and is selected.

5. **Threshing drum** –commonly, there are three types of threshing drum i.e. rasp type, spike tooth type and wire loop type. So, from the different perspective and type of crop to be threshed and construction of the threshing drum, the following are mentioned as options and evaluated based on the design criteria.

- Rasp bar (flat iron)
- Spike tooth
- Wire loop

Selection criteria are:

1. Efficient for threshing (rubbing and impact)
2. Increased capacity
3. Efficient for separation and chopping
4. Easy of production and maintenances
5. Cost

$N = n(n-1)/2$

If n =5, N = 10

Table 4. 25. Evaluation criteria for selecting threshing drum

Criteria	1	2	3	4	5	mi.	Wi.
1	X	1	0	1	0	2	0.2
2	0	X	1	0	1	2	0.2
3	1	0	X	1	1	3	0.3
3	0	1	0	X	1	2	0.2
5	1	0	0	0	X	1	0.1

Table 4. 26. Weighted evaluation criteria for selecting threshing drum

Design Criteria Option	1	2	3	4	5	Sum M*V
Rasp bar (flat iron)	94	90	95	93	92	
V*W threshing drum	18.8	18.0	28.5	18.6	9.2	**93.1**
Spike tooth	90	85	92	90	95	
V*W threshing drum	18.0	17.0	27.6	18.0	9.5	90.1
Wire loop	85	88	90	92	93	
V*W threshing drum	17.0	17.6	27.0	18.4	9.3	89.3

Based on the selection criteria **rasp bar (flat iron) threshing drum** is the best solution and is selected.

6. **Concave**- there are different types of concaves in terms of openness, number of bars, configurations and soon, here, the research concept deals only in terms of openness i.e. closed type and open (with different angles (arcs). So, from the different research out puts the above type of concave are mentioned as options and evaluated based on the design criteria.

- Open (with 119°)
- Closed (round 360°)

Selection criteria are:

1. Efficient for threshing (rubbing and impact)
2. Increased capacity
3. Efficient for separation and chopping
4. Easy of production and maintenances
5. Cost

$N = n(n-1)/2$

If $n = 5$, $N = 10$

Table 4. 27. Evaluation criteria for selecting concave

Criteria	1	2	3	4	5	mi.	Wi.
1	X	1	0	1	0	2	0.2
2	0	X	1	0	1	2	0.2
3	1	0	X	1	1	3	0.3
4	0	1	0	X	1	2	0.2
5	1	0	0	0	X	1	0.1

Table 4. 28. Weighted evaluation criteria for selecting concave

Design Criteria Option	1	2	3	4	5	Sum M*V
Closed type	96	90	95	91	90	
V*W concave	21.12	19.80	20.90	20.02	9.90	**92.04**
Open type	90	85	92	93	95	
V*W concave	19.80	18.70	20.24	20.46	10.45	89.65

Based on the selection criteria **closed type concave is** the best solution and is selected.

7. Selecting Suitable Combinations of Concept:

Combination scheme showing 10 combinations of solution principles in accordance with following formulations:

7.1. Motor →Shaft with key and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

7.2. Motor →Shaft with key and pulley→ Manual feed → spike tooth with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

7.3. Motor →Shaft with key and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with shaking sieves → discharging straw with plates (blades at the end of drum)

7.4. Motor →Shaft with key and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum → closed (cylindrical) type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

7.5. Motor →Shaft with key and pulley→ Manual feed → spike tooth with multi blade end threshing drum → closed (cylindrical) type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

7.6. Motor →Shaft with forced fit and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with shaking sieve → discharging straw with plates (blades at the end of drum)

7.7. Motor →Shaft with forced fit and pulley→ Manual feed → spike tooth with multi blade end threshing drum → closed (cylindrical) type concave →Stationary concave→ threshed material delivery with shaking sieve → discharging straw with blower

7.8. Motor →Shaft with bolt and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

7.9. Motor →Shaft with bolt and pulley→ Manual feed → spike tooth with multi blade end threshing drum → closed (cylindrical) type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

7.10. Motor →Shaft with bolt and pulley→ Manual feed → spike tooth with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with shaking sieve → discharging straw with blower

Table 4. 29. Parts of selection chart (Dieter and Schmidt, 2013)

AAU,AAiT	Selection chart	Page 1	
	Solution variants (SV), evaluated by Selection criteria (+) Yes (-) No (?) Lack of information (!)Check requirements list	Decision (+) pursue solution (-) eliminate solution (?)collect information (re-evaluate solution) (!) check requirements list for change	

A: Compatibility assured
B: Fulfills demands of requirements lists
C: Realizable in principle
D: Within permissible cost
E: Incorporate direct safety measures
F: Prefers by designers' company
G: Adequate information

Variant	A	B	C	D	E	F	G	Remarks (indications, reasons)	Decision
7.1	+	+	+	+	-	-	+	low threshing performance, poor separation	-
7.2	+	+	+	+	-	+	+		+
7.3	+	+	-	-	-	-	+	Incur additional cost, poor threshing and separation rate	-
7.4	+	+	+	+	+	+	+		+
7.5	+	+	-	+	+	-	-	Power loss, inefficient separation, less output capacity	-
7.6	+	+	+	+	+	+	+		+
7.7	+	+	-	-	-	-	+	Power loss, Complexity in production, incur additional cost	-
7.8	+	+	+	+	-	-	+	Difficult in separation, low capacity /output/, low feeding rate	-
7.9	+	+	+	+	-	+	-	Poor separation and threshing efficiency	-
7.10	+	+	+	-	-	+	-	Complexity in production, incur additional cost	-

4.2.1.3. Selected variants for further evaluation

1. **Variant 7.2**- Motor →Shaft with key and pulley→ Manual feed → spike tooth with multi blade end threshing drum → open type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

2.**Variant 7.4**- Motor →Shaft with key and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum → closed (cylindrical) type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

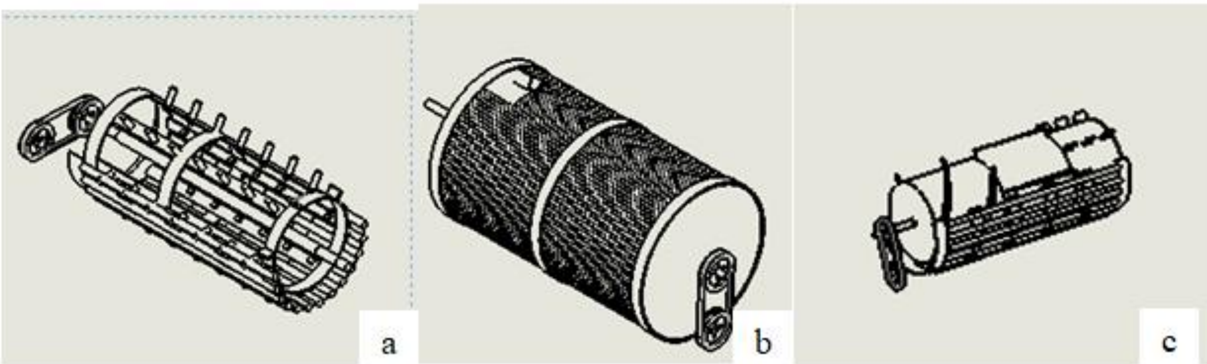


Figure 4.20. Sketches for different variants; a) Variant 7.2 b) Variant 7.4 c) Variant 7. 6

3.**Variant 7.6**-Motor →Shaft with key and pulley→ Manual feed → rasp bar(flatiron) with multi blade end threshing drum →open type concave →Stationary concave→ threshed material delivery with gravity → discharging straw with plates (blades at the end of drum)

Evaluating principle solution variants:

The three variants that were selected in the previous step and firmed up in next step are evaluated using Cost–Benefit Analysis. Important wishes in the requirements list provide a series of evaluation criteria of varying complexity. A hierarchical classification (objectives tree) is drawn up to facilitate closer identification and better assignment of the weighting factors and the parameters of the variants. Figure 4.21.shows an objectives tree for the threshing units. Its lowest objective level provides the evaluation criteria entered into Table 4.30.

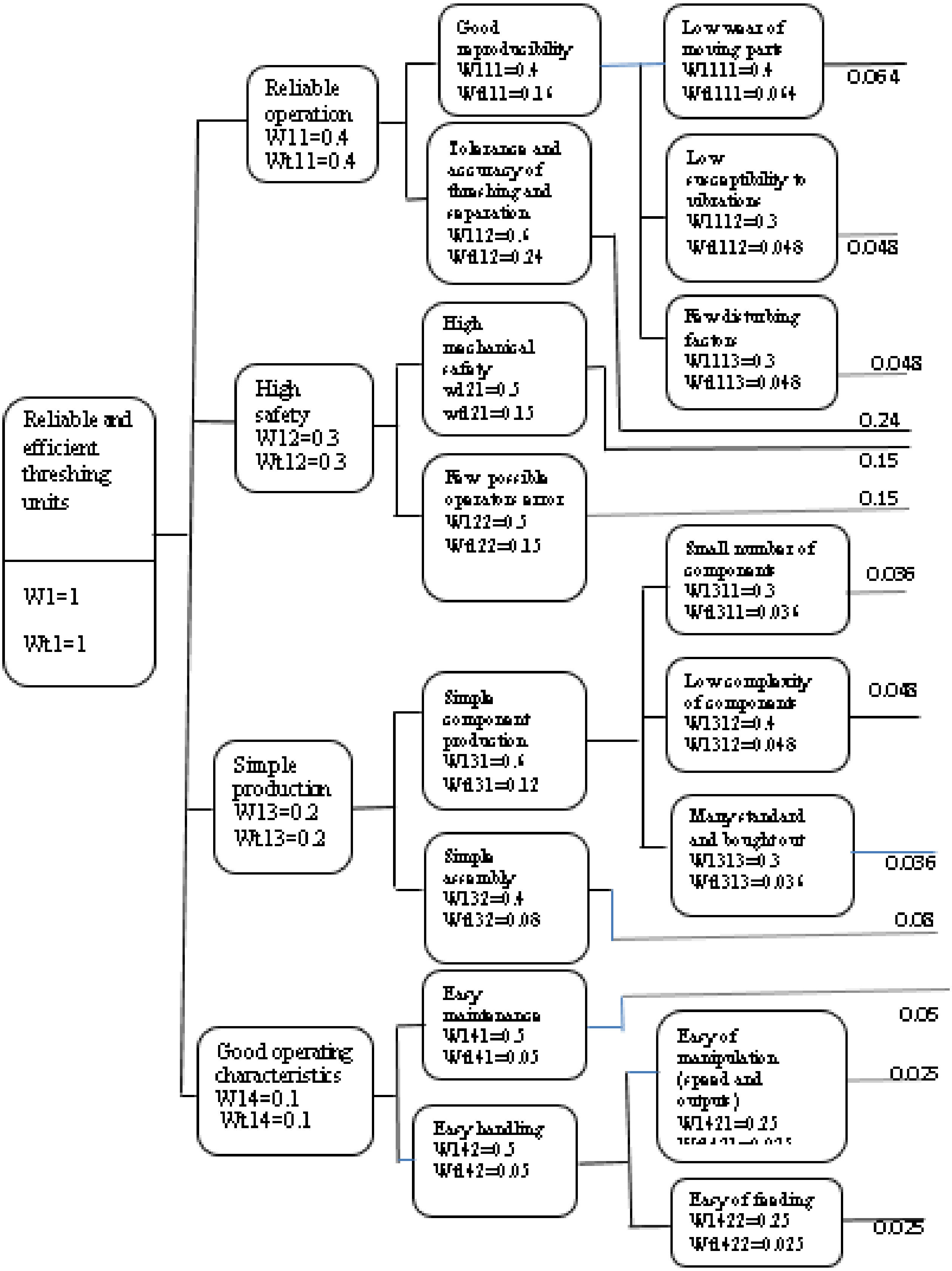


Figure 4. 21. Objective tree for threshing units (Pahl *et al.*, 2007)

4.2.1.4. Searching for working principles

The required working principle desire as simple solution for *tef* threshing units (mechanism) and has to have a better efficiency at the required cleaning and separation rate on comparison to the existing threshing units. It can be proposed that, the selected solution principle must be based on the end users need assessments and recommendation. The overall size of the threshing unit is to be similar that of the previous threshers and fulfilling all safety measures with the simplest production sophistications and maintainability of the system. Among many design procedures this research preferred and followed the Phal *et al.* (2007). This procedure was selected based on its implementation technique and cost effectiveness.

The essential functional requirements of threshing systems are to:

- The *tef* stem (bundle of *tef*) is feeding manually to the threshing unit through the feeding chute
- The torque and RPM of the drum is delivered from the diesel engine through pulley and v-belt, maintain the required rpm of the drum by adjusting the throttle of the engine
- Enable the threshed *tef* and straw to be separated on the surface of perforated concave the mixture (*tef* and chaff) passes through those holes
- The separated *tef* and chaff collect in the outlets
- The straw throws out through straw outlet

In detail study, the threshing units were selected based on the requirements. The result depicted that there was no doubt to choose the best threshing units that is the axial threshing unit. It is the versatile and has the better threshing and separation efficiency than the other one.

Using the above assumption, the following concepts were generated.

Concept one (variant 7.2) – rotary (axial) threshing units and the drum shape is the same as to SG-2000 model (hallow with side, spike tooth) with the end of pegs with helical shape to increase the output capacity, the concave (open) is perforated with 119^0 wrap angle (Figure 4.22.).

Concept two (variant 7.4) -rotary (axial) threshing units and the drum shape is hollow full round with three different parts, the first part is helical for uniform feeding, the second is used for rubbing, the third for chopping the straw, with closed perforated concave (Figure 4.23.).

Concept three (variant 7.6) – rotary (axial) threshing units and the drum shape is hollow full round with three different parts, the first part is helical for uniform feeding, the second is used for rubbing, the third for chopping the straw, and the concave (open) is perforated with 119^0 wrap angle (Figure 4.24.)

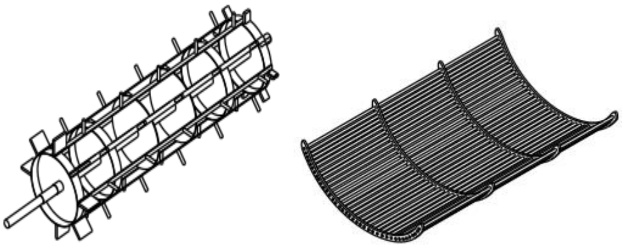


Figure 4. 22. Concept I open spike tooth type drum and open type concave

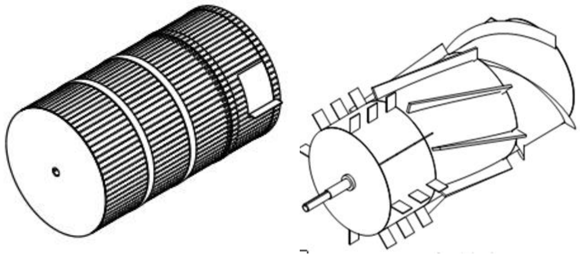


Figure 4. 23. Concept II closed (cylindrical) type concave and rotary drum (new drum)

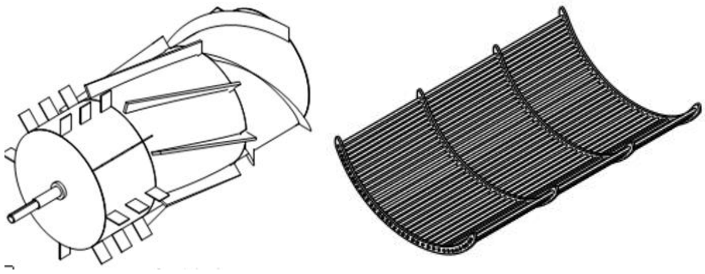


Figure 4. 24. Concept III rotary drum (new drum) and open type concave

After evaluating under evaluation criteria (Table 4.30) variants **concept two** (Figure 4.23.) was selected.

The above conceptual options were evaluated based on the design procedure (Pahl *et al*., 2007) in the following orders:

- Mention the major working principles and different options
- Combining working principles
- List the evaluation criteria for each option
- Selecting Suitable Combinations
- List different combined variants
- Select variants for further evaluation
- Evaluating Principle Solution Variants
- Evaluation criteria for selecting variants

Table 4. 30. Evaluation criteria for selecting variants (Pahl, *et al*., 2007)

It	Evaluation criteria	Weight	Parameters	Variant7. 2			Variant 7.4			Variant 7. 6		
				Magn M2i	Value V2i	Weight Wv2i	Magn. M4i	Value V4i	Weight Wv4i	Magn. M6i	Value V6i	Weight Wv6i
1	Low wear of moving parts	0.096	Amount of wear	High	3	0.288	High	3	0.288	High	3	0.288
2	Low susceptibility to vibrations	0.072	Risk for vibrations	Medium	2	0.144	High	2	0.144	Medium	2	0.144
3	Few disturbing factors	0.072	Risk or disturbing	Medium	2	0.144	medium	2	0.144	Medium	2	0.144
4	Efficient and high rate of threshing and separation	0.16	Effective threshing and separation rate	Medium	2	0.32	High	3	0.48	High	3	0.48
5	Small numbers of components	0.036	Number of components	High	3	0.108	High	3	0.108	High	3	0.108
6	High mechanical safety	0.15	Safety	Medium	2	0.30	High	3	0.45	Medium	2	0.30
7	Few possible operators' error	0.15	Opera ability	Medium	2	0.30	High	3	0.45	Medium	2	0.30
8	Low complexity of components	0.048	Simplicity	High	3	0.144	High	3	0.144	High	3	0.144
9	Many standard and bought up parts	0.036	Proportional bought & standard	Medium	2	0.072	High	3	0.108	Medium	2	0.072
10	Simple assembly	0.08	Simplicity for assembly	High	3	0.24	High	3	0.24	High	3	0.24
11	Ease of maintenance	0.05	Maintainability	Medium	2	0.10	medium	2	0.10	Medium	2	0.10
12	Easy of manipulation (speed and feed rate)	0.025	Controllability	Medium	2	0.050	High	3	0.075	Medium	2	0.050
13	Easy of feeding and ergonomically fit for operator	0.025	Easy of handling	Medium	2	0.050	High	3	0.075	Medium	2	0.05
	Sum	**1**			2.26			**2.81(selected)**			2.42	

4.2.2. Embodiment design

4.2.2.1. Steps of embodiment design

Identifying embodiment-determining requirements and clarifying spatial constraints.

The following items from the requirements list were identified as determining the embodiment features:

Determining layout:

The major components of the proposed threshing unit will have the following components:

- Threshing drum (with three parts)
- Threshing main shaft
- Concave, closed (cylindrical) type concave

The auxiliary components (supporting parts) of the threshing units are threshing test stands:

- Test stand
- Feeding table
- Main frame
- Concave cover and straw outlet
- Crop sample collector
- Bearing house ass.
- Bolt and nuts

Power supplied from the diesel engine (14hp) * by the help of shaft and pulley through v-belt.

*The engine power was used from the existing threshers' power; whereas for our new proposed threshing units the power requirements was calculated in the following sections.

4.2.2.2. Material and size determination of the major components and analysis

According to the requirements, the size of threshing units was determined from the size of the SG-2000 threshers (It is because of the evaluation purpose and avoid the size variation effect on efficiency the threshing units). For new model threshing unit, there is a change in the shape (profile and configuration) of the threshing drum. The new model threshing unit has three parts, part one for accelerating the feed (to increase the overall capacity) is a feeding zone and the feature is similar as auger; the second part is to maintain the rubbing and the separation with one operation as threshing zone and the rasp bars are flat iron twisted to the side of the auger in order to facilitate the speed of the threshed materials (*tef* stem); and the third is for chopping the straw as the same time to throw out the straw as separation and discharge zone and made from sheet metals as a plate.

4.2.2.3. Power requirements

For the *tef* threshing mechanism the main power source is the diesel engine and its power is already predetermined (14hp) from SG-2000 thresher. However, it is very important to know and determine the required amount of power which is essential for the designing of *tef* threshing unit. The power required for threshing is calculated based on Baruah and Panesar (2005) equations as:

$$P_{cy} = F_{tt}.U_{cy} + p^{w}{}_{cy} \qquad [\text{ KW}]$$

$$F_{tt} = f_{t1} + f_{t2} + f_{t3}$$

$$f_{t1} = \left[\frac{25\Delta t}{324.W_c\rho_o C_c t_c}F^2\right]$$

$$f_{t2} = \left[K_c\frac{\Delta\rho}{\rho_i}C_cW_c\right]$$

$$f_{t3} = \left[K_c\frac{\Delta\rho}{\rho_i}A_{cc}W_c + g\rho_iC_cA_{cc}\mu_c\right]$$

Power required to overcome the air resistance can be calculated using equation 3.53

$$p^{w}{}_{cy} = K_{cy}\left(U_{cy}\right)^3$$

$$p_{cy} = \left[\frac{25\Delta t}{324.W_c\rho_oC_ct_c}F^2 + \boldsymbol{K_c}\frac{\Delta\rho}{\rho_i}C_cW_c + \boldsymbol{K_c}\frac{\Delta\rho}{\rho_i}A_{cc}W_c + g\rho_iC_cA_{cc}\mu_c\right]U_{cy} + K_{cy}\left(U_{cy}\right)^3$$

Where:

F_{tt}- the tangential force, (kN)

U_{cy}- the peripheral speed of the threshing cylinder, (m.s^{-1})

f_{t1}- tangential force due to the impact action the crop speed, (kN)

f_{t2}-the resistive force experienced by the cylinder due to the compression of the entrapped crop between cylinder and concave, (kN)

f_{t3}-the resistance against the movement of the crop mass, (kN)

K_c- the elasticity of the crop stems (mass), (kpa)

A_{cc}-the effective areas of concave, (m^2)

F-the crop feed rate, (kg.s^{-1})

ρ_o-the bulk density of the incoming crop, (kg.m^{-3})

ρ_i-the bulk density of the entrapped crop, (kg. m^{-3})

C_c-concave cylinder clearance, (m)

W_c-the width of the threshing cylinder, (m)

g- acceleration due to gravity, (g=9.81m.s^{-2})

μ_c-the coefficient of friction of the crop mass over the concave surface

U_{cy}-the peripheral speed of the threshing cylinder, (m.s^{-1})

Δt-change of crop stems thickness at original and after entrance in concave, (m)

K_{cy}-a proportionality coefficient considered to estimate the power requirements to overcome air resistance

In order to use the above empirical formulas, it is essential to know the values of the parameters. So, the values of the above parameters were identified from the tables of Sharma and Mukesh, (2010) and were indicated in this research output. The threshed crop is *tef* and the mechanical properties were determined in this research project as shown in the text.

K_c=3.6Gpa; A_{cc}=1.47m^2; F=0.20kg.s^{-1}; ρ_o=35kg.m^{-3}; ρ_i=30kg.m^{-3}; C_c=0.02m; W_c=0.83m; g=9.81m.s^{-2}; μ_c=0.8; U_{cy}=25m.s^{-1}; Δt=0.07m; t_c=0.01m

$K_{cy=}$0.68x10^{-6}kgf.m.s^2 for the rasp bar type drum (Sharma and Mukesh, 2010)

Then the exact value of power for new *tef* threshing units was calculated using the above value and

$$p_{cy} = \Big[\frac{25x0.07}{324x0.96x35x0.02x0.01_c}0.2^2 + 3.6x1000\frac{5}{31}x0.02x0.96 + 3.6x1000\frac{5}{31}x1.477x0.83 + 9.81x20x0.02x1.44x0.8\Big]25 + 0.68x10^{-6}(25)^3$$

Then P_{cy}=5.46 kw means the required amount of power is 7.6 hp and to lay on the standard **8**hp diesel engine was selected for the *tef* threshing units. For comparison of the above empirical formulas' result, the required power was calculated using different literatures.

Based on Sharma and Mukesh (2010) the power requirement can be calculated using equation as:

$$P = \frac{q(v_2 - v_1)v}{1 - c_f} + mv + nv^3$$

Where:

p- power required for operation of thresher, (watt)

q-feed rate; (kg.s^{-1})

v_1-intial velocity of plants, (3m.s^{-1})

v_2-velocity of plant mass after impact, (m.s.1)

v-peripheral velocity of threshing drum, (m.s^{-1})

c_f-coefficient of friction b/n straw and thresher, (assumed from table c_f=0.6)

m-a constant 0.85-0.90 N per 100 kg weight of threshing drum

n-a constant 0.065 N.sec^2.m^{-2}

v_2=α.v

Where:

α-0.7 then when the peripheral velocity, *v*=27 m.sec^{-1}

v_2-0.7 x 27=18.9 m.s^{-1}

For determining the power required for *tef* threshing unit, we assume some parameters as we intended to perform in maximum level the above parameters was from the first research outputs and from the design requirements.

q=0.20 kg.s^{-1}; v_1=3m. s^{-1}; v_2=18.8m. s^{-1}; *v*=27m .s^{-1}; *cf*=0.6

m=0.87N x 0.5 =0.435

n=0.065 N.sec^2.m^{-2}

Using these values with the above empirical formulas, the result obtained by substituting the above parameters

$$P = \frac{0.20(18.9-3)27}{1-0.6} + 0.435x27 + 0.065(27)^3$$

P=3.9kw=5.64 hp

With the standard setup the selected power is **6 hp,** this seems not adequate power that may be due to the coefficients and constants applied on the formula, which are considered from their type of crops (references from Sharma and Mukesh, (2010)

From both empirical formulas, the convenient power with the standard and availability was selected **8 hp** engine. This power is similar from the first calculated power on equation 3.57, and it is useful for determination of the size of shaft. The required power for *tef* threshing unit is **8** hp. The diameter of the shaft to transmit a given horse power P_{req} can be determined from the following formulas, the formula applies for the short shafts (Hearn, 2000):

$$P_{req} = \frac{D^3 N}{0.83x10^6}$$

Then $D = \sqrt[3]{\frac{8x0.83x10^6}{N}} = 21.162$ mm

To have the standard items, it is recommended to have 20 or 25 mm diameter, so the shaft diameter D=25 mm was selected.

For safety application, it is possible to evaluate the working stress with the allowable stress of the shaft. The mild steel shaft has the ultimate tensile strength for the main power transmitting shaft σ_u=280 MN.mm^{-2} and for the short small shaft σ_u=590 MN.mm^{-2}. When the safety factor is intended to be 3 the working stress for the short shaft could be σ_w=196.6 MN. mm^{-2}. The shaft could evaluate in torque and moment, torque at belt drive is:

Tension ratio in belt *(R_a)*

$$R_a = T_1/T_2$$

$$R_a = e[\frac{(0.5123)\theta\pi}{180}] \qquad \text{for V-belts}$$

(T_1-T_2)= effective pull

Where:

Ra – allowable tension ratio

θ - arc constant

T_1- tight side tension, (N)

T_2- slack side tension, (N)

P- Power transmitted by belts, (kw)

D_r -drive pulley diameter, (m)

D_n- driven pulley diameter, (m)

V -belt velocity =14.42 m.s^{-1}

P= (T_1-T_2)V/1000

T_1-T_2=1000 x P/v

Torque T_A= (T_1-T_2) Dr/2

Then

$$T_A = \frac{1000\ x\ PxD_r}{2V}$$

$$T_A = \frac{1000\ x\ 12x\ 0.150}{2x\ 14.42}$$

$$T_A\text{=62.42 N.m}$$

The maximum moment M_A generates from the moment diagram and using force analysis. The equivalent (equally distributed along the shaft with the drum) force $\boldsymbol{Q_t}$**=725** $N.m^{-1}$ calculated from the force applied on the shaft due to the threshing (impact and shear) force. Driven pulley has 150 mm diameter.

Q_t- the equivalents weight (force) applied in the drum sub assembly and it is calculated based on the following formulas.

$$Q_t = q_d + q_{ts}$$

Where:

Q_t-the equivalent weight =725 $N.m^{-1}$ by assuming that

q_d-the weight of drum sub assembly=24 kg x 9.81$m.s^{-2}$=236 N

q_{ts}-the threshing force calculated from equation 3.57. and equal to 562.19 N

$$q_{ts} = \left[K_c \frac{\Delta\rho}{\rho_i} A_{cc} W_c + g\rho_i C_c A_{cc} \mu_c\right] = 562.19\ \text{N}$$

For the size of 1.1 meter shaft the force (equivalent weight) is 798.19 N hence for 1 meter the equivalent weight become **725** $\mathbf{N.m^{-1}}$

$$\sum F_Y = 0; R_a + R_b = T_A + Q_t$$

$$\sum M_b = 0; T_A x 0.09 - \frac{Q_t x 0.80^2}{2} + Rax1.02 = 0$$

Then R_a= 221.94 N

From the equation 3.62 R_b= 565.48 N

And M_b = 554.39 N.m

Then the shaft generates with the working condition and applied force and moment at the critical size of the shaft were analyzed and obtained the equivalent moment from the formulas Hearn, (2000):

$$M_e = \frac{1}{2}\left[M_A + \sqrt{M_A{}^2 + T_A{}^2}\right]$$

M_A=554.39 Nm, and T_A=62.42 Nm

M_e=556.28 Nm

The maximum stress applied on the shaft could be

$$\sigma_{max} = \frac{M_e}{Z_p} \qquad Z_p = \frac{\Pi d^3}{16}$$

$$\sigma_{max} = \frac{16x556.14}{\pi d^3}$$

The working stress for the small solid shaft is σ_w=196.6 MN. mm^{-2} with safety factor 3 and the maximum stress obtained in the research working condition was σ_{max}=181.36 MN. mm^{-2}.

So, $\sigma_{max} < \sigma_w$

181.66 MN.mm^{-2} < 196.6 MN.$mm^{-2}$and the selected mild steel solid shaft is safe for the intended operation.

4.2.2.4. Analysis of drum shaft and concave plate

The power was transmitted from the engine through the pulley to the shaft and rotating drum. The size of the shaft was determined based on the maximum moment and tension forces at the end of the shaft and is calculated manually and checked with the dynamic analysis using the ***ANSYS 2015*** software (Figure 4.25). The result of the analysis shows the shaft is safe for the specified task. The maximum deflection (transitional displacement) of the shaft is 0.21mm.

$\delta = 0.001L - 0.003L \ in \ mm$ (Hearn, 2000)

Where:

δ – deflection or transitional displacement, (mm)

L- the distance (length) between to support (bearing center), (mm)

In our case the length of the shaft is 1000 mm and the δ limit is 1.0-3.0 mm. The actual maximum deflection of the drum shaft i.e. 0.21 mm is less than 1.0 mm. The maximum stress is 1.31 x 10^8 pa and the yield strength of the material is 2.87 x10^{8} pa. The maximum vonmiss stress is on the shoulder (fillet) and key edge of the shaft.

Table 4. 31. Selected material and properties (Hearn,2000)

no	Parameter	description	value
1	Material	Steel(ss)	AIS1035
	Material properties	Elastic modulus	$2.05e^{+11}N.m^{-2}$
		Poisson ratio	0.2
		Tensile strength	$5.8e^{+8}$ $N.m^{-2}$
		Shear modulus	$7.9e^{+10}$ $N.m^{-2}$

Table 4. 32. Conditions for analysis and result for shaft analysis

no	Parameter	Description		Value
1	Connection	Component contact		
2	Fixtures	Bearing supports		2
		Fixed joint		1 at end
3	External loads	Torque		63 N.m
		Moment		557 N.m
4	Mesh	Fine mesh size		
		Mesh type		Solid
		Jacobian point		4
		Max.element size		14.78 mm
		Min.element size		3.94 mm
		Mesh quality		High
		Total nodes		10445
		Total element		5981
		% of distorted element		0
5	Result	Equivalent(von-mises)stress	max	$1.32e^{+08}$ Pa
		Equivalent (von -mises)	min.	$1.02e^{+04}$ Pa
		Total deformation	max.	$2.565e^{-01}$ mm
		Total deformation	min.	$1.01e^{-30}$ mm

With regard to the concave plate analysis, it was made from perforated sheet with 3 mm thick and it was modeled in solid work and applied the force (assume that all pressures are equally distributed on the surface of the concave) with the safety factor 3 and computed its model and mesh as shown on Figure 4.26. For analysis it was partitioned at the size of 100 mm x 100 mm of the perforated sheet and the graphical analysis shows on the Figure 4.27. The maximum stress is 8.723×10^4 pa and the yield strength of the material is 2.827×10^8 pa. The maximum displacement is 1.084×10^{-4} mm, it is very minimum deflection (no deflection). So, based on the analysis result the concave plate is safe for intended purpose.

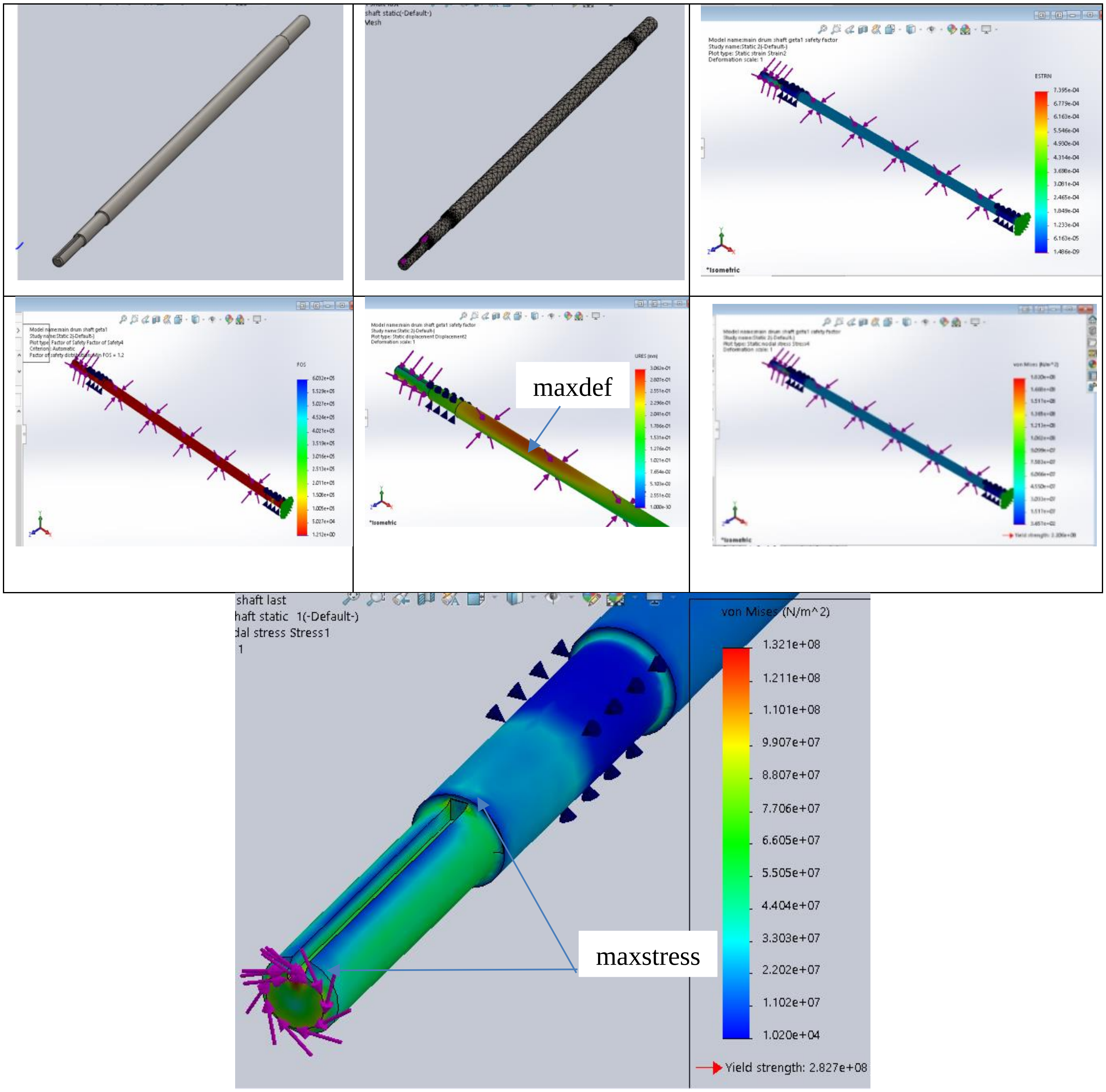


Figure 4.25. The drum shaft maximum stress and displacement analysis

Table 4. 33. Conditions for analysis and result for concave analysis

no	Parameter	Description		Value
1	Connection	Component contact		
2	Fixtures	Fixed joint		all edges at end
3	External loads	Pressure		725 $N.m^{-2}$
4	Mesh	Fine mesh size		
		Mesh type		Solid
		Jacobian point		4
		Element size		4.7818mm
		Tolerance		0.2391mm
		Mesh quality		High
		Total nodes		21090
		Total element		10170
		% of distorted element		0
5	Result	Equivalent(von-mises)stress	max	$3.329e^{+05}$ Pa
		Equivalent (von -mises)	min.	$5.585e^{+03}$Pa
		Total deformation	max.	$4.135e^{-04}$mm
		Total deformation	min.	$1.00e^{-30}$mm

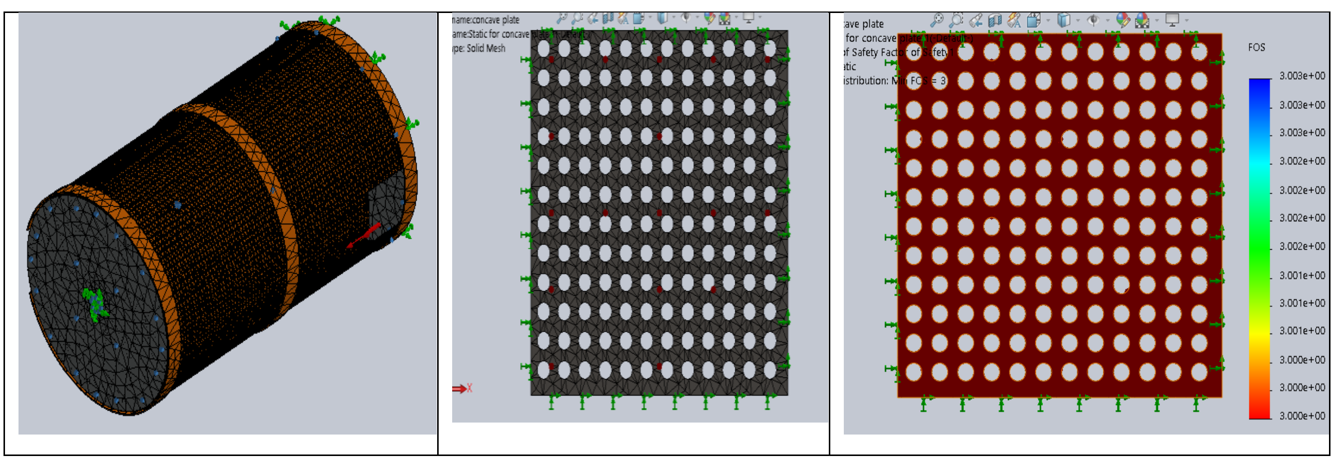


Figure 4. 26. The closed (cylindrical) type concave model and mesh size

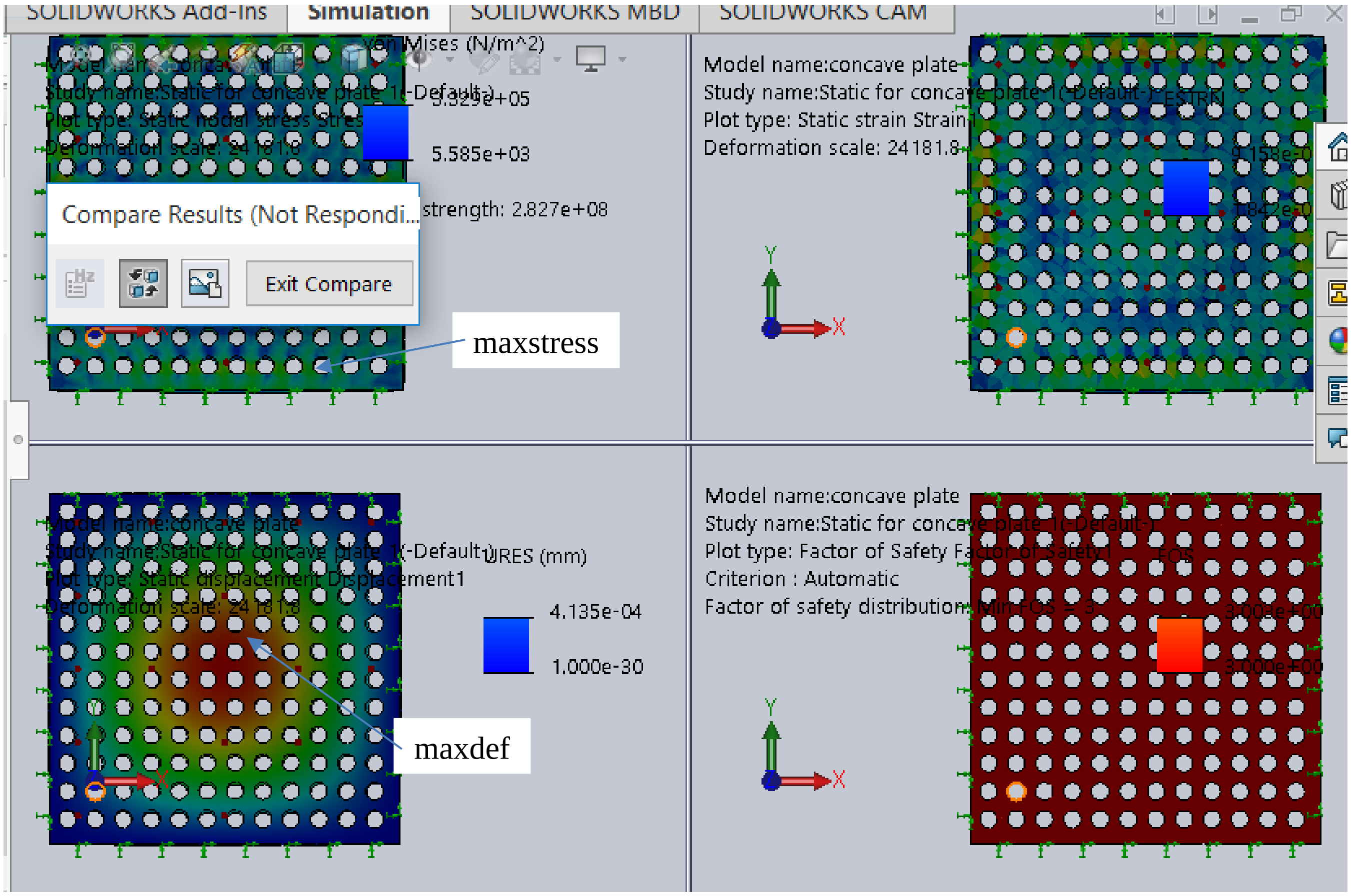


Figure 4. 27. The concave sheet (plate) maximum stress and displacement analysis

4.2.3. The manufacture sequence of the threshing units and testing stands

The manufacture process started after selecting the row materials required for the major parts, i.e. concave and drum, closed (cylindrical) type concave was manufactured from perforated sieve with 3 mm thickness which has the diameter of 5 mm and the drum and other parts made from solid shaft, angle iron, sheet metal and soon (detail parts' drawing are attached at the **Appendix VII**). The manufacturing process and selected machines were as indicated in Table 4.34. The manufacturing was done in AMIMTDE at Bahirdar, it is well equipped with experienced Technicians and Engineers.

Table 4. 34. Selected manufacturing process and machines

It no.	Main parts (manufactured)	Process	Selected machine/equipment
1	Drum sub assembly (shaft, sheet metal, bars, key)	Sawing, turning, drilling, shaping, milling, grinding, cutting, bending, rolling, sheet metal working, welding	Lathe, milling, shaper, grinder, roller, bender, welding, cutter, drilling machines
2	Concave (cylindrical) type and its cover (perforated sheet and sheet metal)	Bending, cold rolling, welding, sheet metal working	Roller, bender, drilling and welding machines
3	Test stand with sample collectors	Cutting, drilling, cold rolling, sheet metal working, welding, grinding	Roller, saw, bender drilling, welding and grinding machines
4	Assembly (finishing)	Welding, bolt and nut, screwing, polishing, sanding, painting	Welding, spanners (wrenches), hammer, painter, sprayers

4.2.3.1.Threshing drum manufacturing

The threshing drum has 440 mm diameter and 1100 mm total length (with drum shaft). The drum consists drum shaft and round (rolled) sheets with three parts (compartments) the first for feeding zone, the second for threshing zone and the third for separation or straw chopping and throwing. The compartments were divided with its advantage and its share of threshing activities, the feeding part took 31% of the total length, the threshing part took 44% and the third (straw chopping and throwing) part took 25 % of the total length. The feeding zone used as inlet auger which has three helical shape blades made from sheet metal, the threshing zone has threshing bar made from 8 sheet metal (flatiron) with thickness of 6 mm and the third parts has blades (made from sheet metal 3 mm thick) as chopper of straw and assist for throwing out the straw (Figure 4.28.).

4.2.3.2.Concave manufacturing

The concave type is closed (cylindrical) with diameter of 480 mm, length 830 mm and made from perforated sheet with thickness of 3 mm. In order to have better separation in the threshing units the concave opening has to be similar as the shape of the *tef* seed that is almost round. The diameter of the opening was determined based on Miu (2016) and the selected value becomes 5 mm with perforated sheet metal. The opening diameter is 5 mm and the space between two holes is 15 mm. As general, the concave is round as cylinder in shape; it has two openings with 180 degrees apart in two opposite end sides. The first opening is for feeding unthreshed material (bundle of *tef* crop) as inlet and the second is for straw out let. The overall size is 480 mm diameter with 830 mm length (Figure 4.29.).

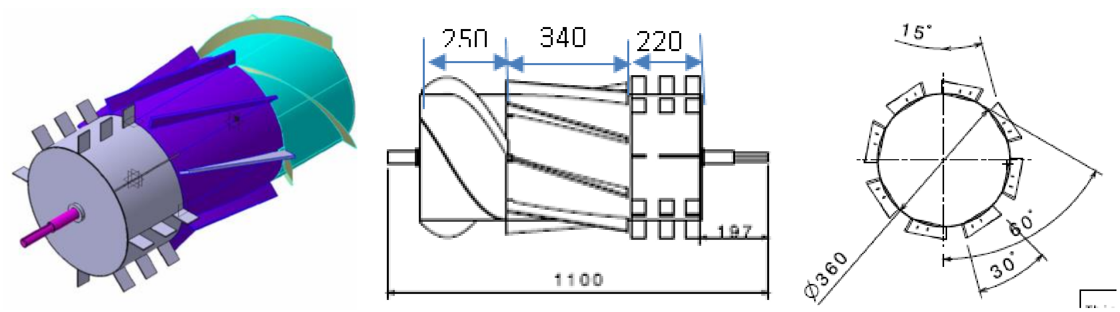


Figure 4. 28. The new developed threshing drum with three compartments, design assembly and front view

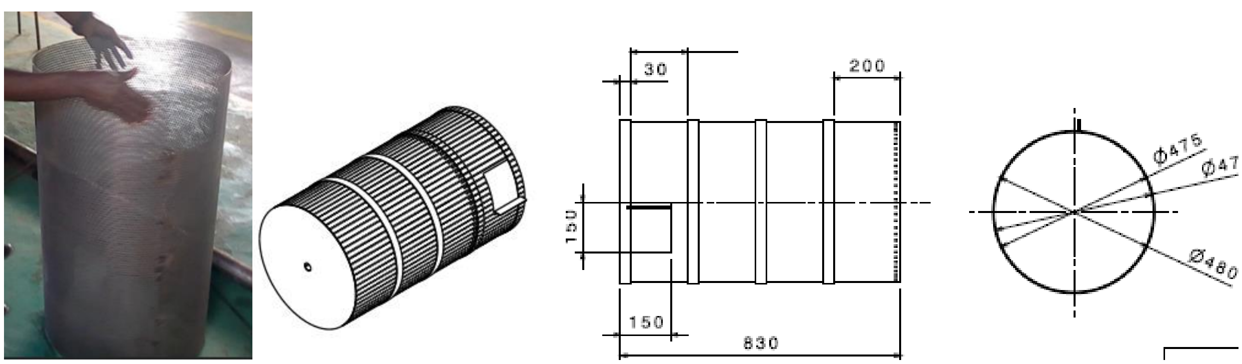


Figure 4. 29. The newly developed (cylindrical) type concave under production and pictorial view

4.2.3.3. Threshed sample (crop mixture) collector manufacturing

The sample (threshed mixture) collector made from a thickness of 1.5mm sheet metal at the length x width of 835 mm x 580 mm.The partition has 7 equal boxes and located perpendicular under the concave. Each box has 120 mm width the depth is 400 mm (Figure 4.30.). All test stand dimensions were considered in ergonomically conditions of an average person (height of a person, length of arm...etc.).

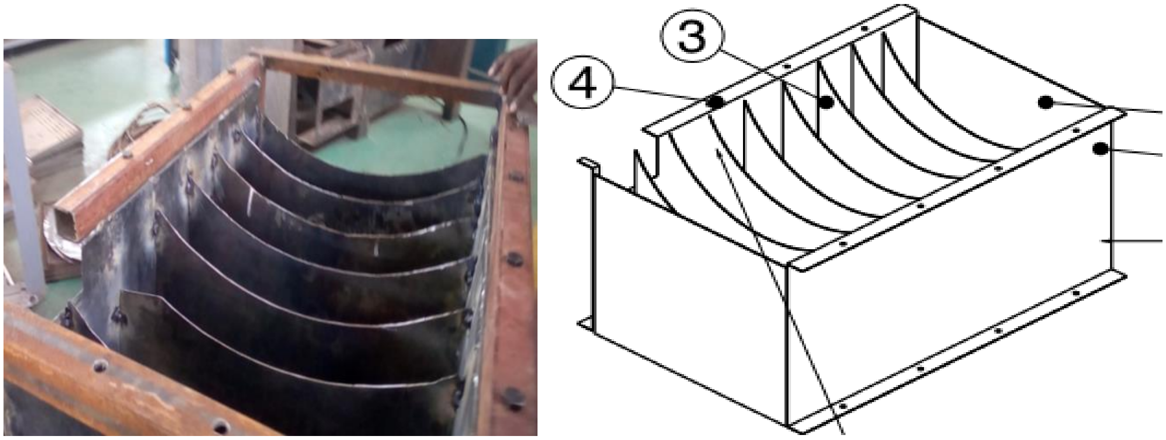


Figure 4. 30. The crop mixture (sample) collector in production and pictorial view

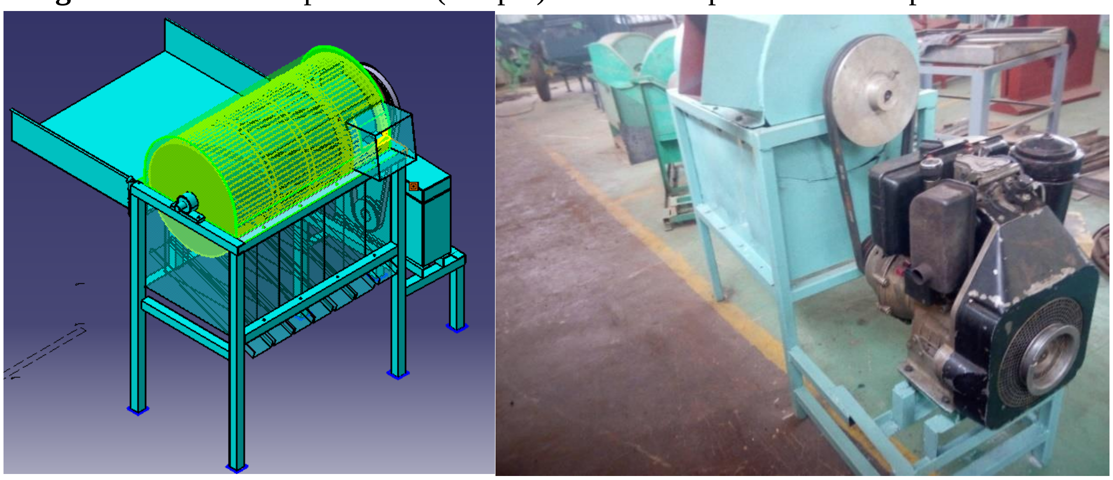


Figure 4. 31. Model and assembled prototype of a newly developed threshing unit with its test stand

4.2.4. Summary of threshing unit manufacture

The design process was performed following the design procedure starting from requirements on conceptual generation through the embodiment design. The new threshing unit with its profiles and partitions were developed by considering the mechanical and physical properties of *tef* crop. The manufacturing process of test stand with *tef* threshing units implemented at AMIMTDE. The testing stand will help not only for evaluation of *tef* threshing units it is possible to use for evaluation of others similar threshing units. The quality of manufacturing process was checked by experts and preliminary observation test was done at the workshop. During the observation the functional units worked properly and there was no any defect. So, the model was ready for further performance evaluation.

4.3. Result and Discussions on Evaluation of *Tef* Threshing Mechanism

4.3.1. Result

The data collected during machine operation was statistically analyzed and the test result and the summary of the Analysis of Variance *(ANOVA)* depicted in the Table 4. 35 and 4. 36 respectively. The newly developed *tef* threshing units showed superior values in all dependent variables. The performance data was shown on Table 4.36. The increment of its mean value in capacity is 10 %, cleaning efficiency is more than 40% and separation efficiency is more than 15%. The parameters (cleaning and separation efficiency) through the length of concave show its graphical representation with nonlinear or polynomial shape.

Table 4. 35. Summary of the result of threshers in response variables

Variables parameter	Capacity ($Kg.hr^{-1}$)			Cleaning efficiency (%)			Separation efficiency (%)		
	mean	Sd	cv%	Mean	Sd	cv%	mean	Sd	cv%
New thresher	45.81	11.32	24.71	35.92	8.36	23.75	93.10	2.06	2.21
SG-thresher	42.30	4.62	10.92	24.85	3.39	13.64	86.33	4.38	5.07

Table 4. 36. ANOVAs table for *tef* threshing units

Variables parameter	Capacity ($Kg.hr^{-1}$)				Cleaning efficiency (%)				Separation efficiency (%)			
	Sum sq.	Df	F value	Pr>F	Sum sq.	Df	F value	Pr>F	Sum sq.	df	F value	Pr>F
Thresher	166.5	1	2.218	0.14	1654.2	1	40	4.86e-08***	9372.6	1	147.6	2.2e-16***
Residuals	3915.2	52			2115.3	52			3301.7	52		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 4. 37. Performance data of *tef* threshing units at different combination of variables feed rate (F) and rpm(R)

Treatment Combination *	Threshing capacity ($Kg.hr^{-1}$)		Cleaning efficiency (%)		Separation Efficiency (%)	
	NT	SG-2000	NT	SG-2000	NT	SG-2000
R1F3T1	48.01	39	39.69	25.85	89.12	86.76
R1F2T1	40.35	42.73	23	24.07	94.35	86.81
R1F1T1	54.44	47.69	44.68	23.7	91.9	87.5
R2F3T1	34.02	37.73	32.13	27.13	95.62	88.12
R2F2T1	41.42	41	24.23	21.67	93.75	90.25
R2F1T1	70.88	44.45	44.08	21.66	92.5	81.5
R3F3T1	36.25	35.72	35.55	26.76	94.5	85.9
R3F2T1	49.95	52.11	44.08	32.54	92.45	91.35
R3F1T1	67.89	37.8	50.06	16.08	94.98	88.24
R1F3T2	47.72	36.51	41.69	29.8	93.5	91.52
R1F2T2	46.17	42.73	34.04	25.42	95.45	86.81
R1F1T2	49.3	49.68	37.58	24.49	90.95	89.4
R2F3T2	40.88	40.96	40.73	26.74	96.53	79.54
R2F2T2	35.88	46.04	20.9	26.73	91.34	79.6
R2F1T2	50.77	41.93	32.61	20.77	92.4	88.6
R3F3T2	35.84	37.92	33.28	24.15	94.55	87.92
R3F2T2	50.01	36	43.76	22.97	93.65	81.3
R3F1T2	47.13	47.74	32.63	22.97	90.33	90.85
R1F3T3	43.3	39.88	39.84	31.16	93	90.94
R1F2T3	36.24	41.03	22.7	25.49	93.36	88.11
R1F1T3	48.92	47.81	35.07	22.76	94.9	88.3
R2F3T3	45.96	43.69	44.91	27.39	96.1	77.07
R2F2T3	46.04	46.71	39.87	27.41	91.5	77.12
R2F1T3	35.15	41.04	18.25	21.04	92.85	88.7
R3F3T3	37.8	38.25	35.05	24.08	94.94	86.82
R3F2T3	49.06	37.55	45.48	23.42	90.24	81.45
R3F1T3	67.47	48.43	33.96	24.72	89.03	90.43

*F1($400kg.hr^{-1}$), F2($325\ kg.hr^{-1}$), F3($275\ kg.hr^{-1}$)- R1(1200rpm), R2(1000rpm), R3(900rpm)

NT -newly developed threshing unit

SG-2000-threshing unit

4.3.2. Discussion

4.3.2.1.The effect of feed rate in the cleaning efficiency (%)

The feed rate was controlled by the operator skill and it was performed after a long trail and accustoming constant feed as much as possible. The shape of the drum highly influence in charging and discharging without additional effort of the operator. The auger type drum assists to pull the bulk of the crop immediately on the touch of the concave leap; in addition of this the inlet chute of the thresher was at the lower side of the drum. As indicated on the (Table 4.38. and Figure 4.38.) the newly developed drum has better cleaning efficiency than the SG-2000 thresher drum in all feed rates. The threshed material could distribute in a better way to the surface of the concave due to the shape of the beater and round concave.

The comparison of result among threshing units shows that it had significant difference of cleaning efficiency under 99% of confidence interval (Table 4.38.). This difference was because of the construction of the concave (round or closed) type (Figure 3.6b.). It has more threshing area of contact than the open type concave. The drum auger on the feeding zone pushes the bulk immediately to the next part of the threshing compartment and it doesn't give time to fallen only at the inlet side of the concave. This facilitates to have a minimum layer of crop and mixture on the grain mat (the next sieve). In this case, it is possible to have additional cleaning mechanisms (shaking sieves) to get clean *tef* seed with a minimum effort on the sieve motions.

On SG-2000 threshing unit, when the feed rate increased, the cleaning efficiency decreased, where as in the newly developed threshing unit after a certain level of feed rate increments the cleaning efficiency increase (Figure 4.32.), this could happen because of the effective area of the concave. The total area of the open concave SG model is 0.77 m^2 and the new closed type is 1.40 m^2.

Table 4. 38. ANOVA table for response variable cleaning efficiency (%)

	df	Sum sq	Mean sq	F value
Federate	1	82.9	82.886	1.1542
Rpm	1	24.2	24.225	0.3373
Residuals	51	3662.5	71.813	

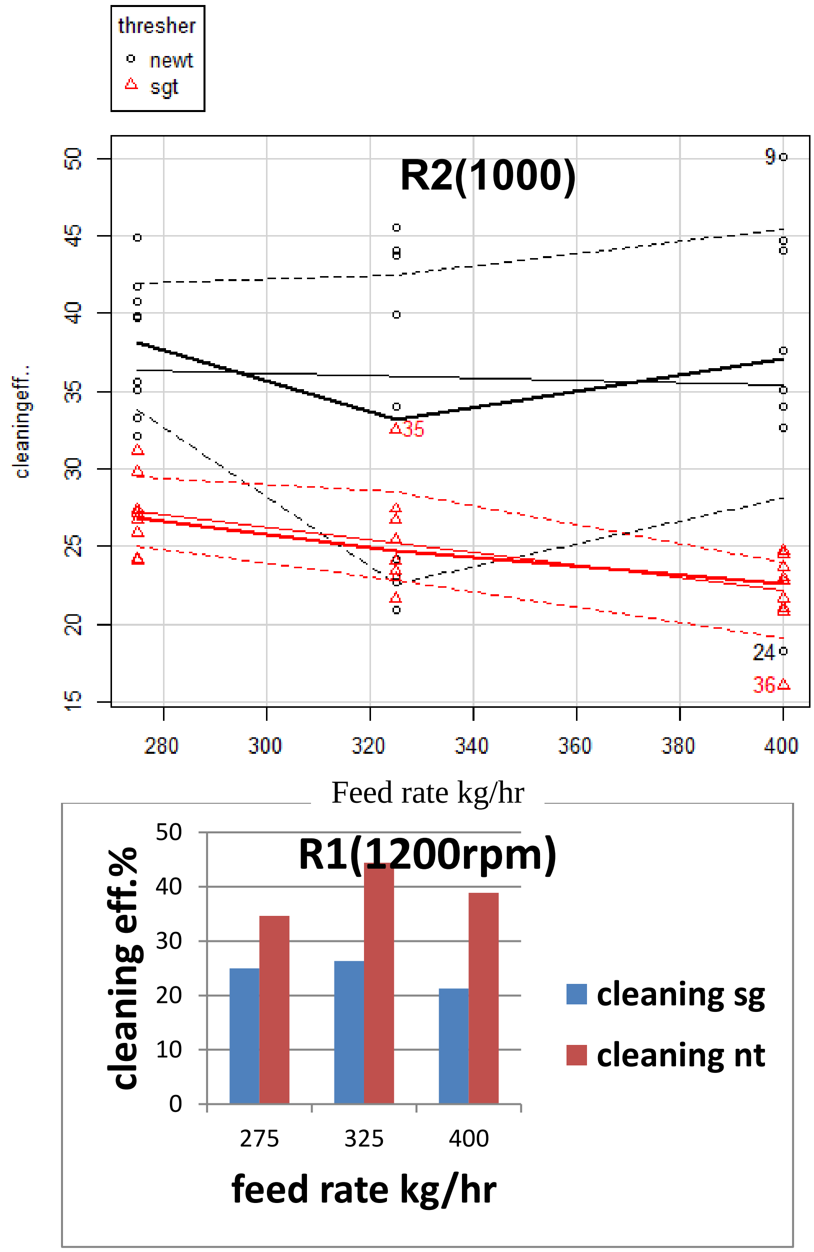


Figure 4. 32. The effect of feed rate ($kg.hr^{-1}$) on cleaning efficiency (%) of two threshing units

4.3.2.2. The effect of feed rate in the capacity of the threshing units

The capacity was directly proportional to the feed rate as the feed rate increases the capacity of both threshing units increase with minimum capacity difference (Figure 4.33.). The threshing capacity was highly influenced by the length and width of drum. Since the threshing units had equal size the result shows that there was no significant difference among the two threshing units. But, for both type of threshing units as indicated in the ANOVAs Table 4.39., the feed rate had significant effect on capacity at the level of 99% confidence interval.

Table 4. 39. ANOVA table for response variable capacity (kg.hr^{-1})

	df	Sum sq	Mean sq	F value
Federate	1	716.1	716.14	10.89**
Rpm	1	11.6	11.63	0.1769
Residuals	51	3354	65.76	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

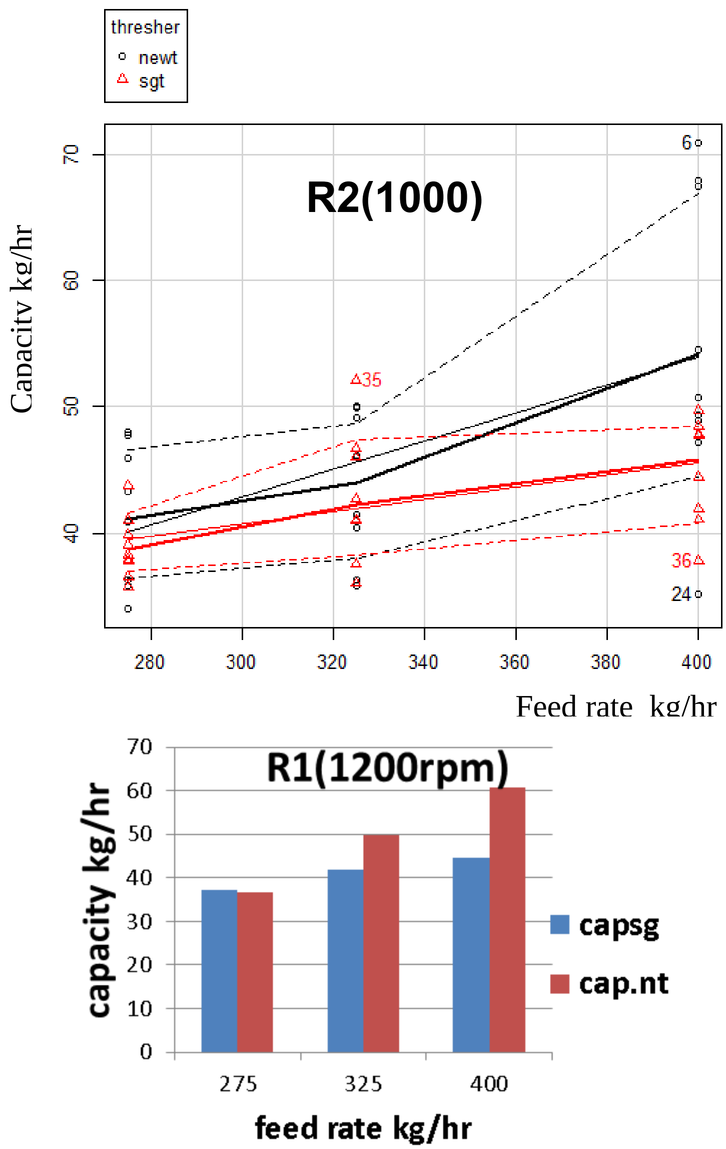


Figure 4. 33. The effect of feed rate on capacity of two threshing units

4.3.2.3.The effect of feed rate on the separation efficiency (%)

The feed rate has negative correlation with the separation of the threshing units for both two type of threshing units. As indicated on Table 4.40 and Figure 4.34. the optimum value of the feed rate can predict around 280 and 300 $Kg.hr^{-1}$. When the feed rate increase from 275 to 325 $Kg.hr^{-1}$and from 325 to 400 $Kg.hr^{-1}$ the separation efficiency decreased from 95.98% to 94.66% and from 86.57% to 81.02%; and from 94.66% to 91.78% and increase from 81.07% to 85.98% for newly dveloped and SG-2000 threshing units respectively.

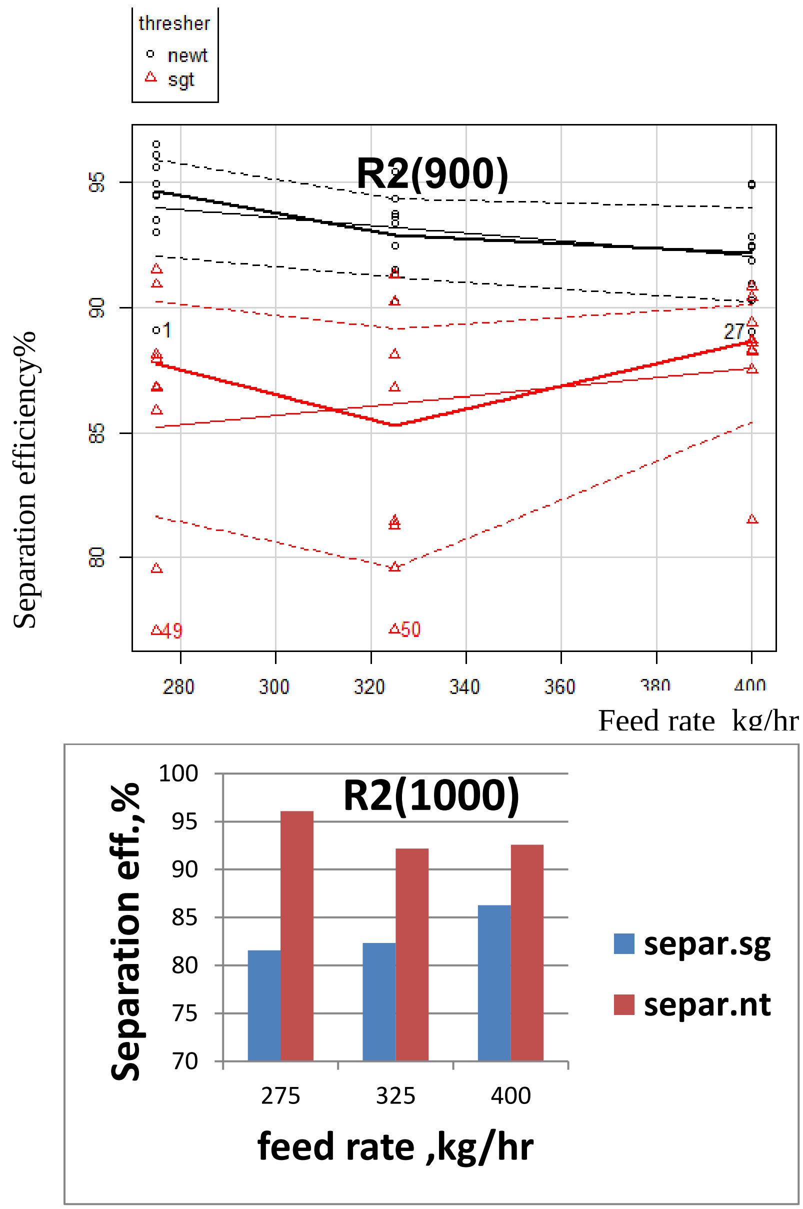


Figure 4. 34. The effect of feed rate on separation efficiency (%) of two threshing units

Table 4. 40. ANOVA table for response feed rate variable on separation efficiency

	df	Sum sq	Mean sq	F value
Federate	1	451.9	451.86	1.8894
Rpm	1	25.2	25.19	0.1053
Residuals	51	12197.2	239.16	

4.3.2.4.The effect of drum speed (rpm) on capacity

The drum speed was correlated for the output capacity of both threshing units, for the SG-2000 it had the negative effect and for the newly developed threshing units had a minmum positive effect (Table 4.40.). In this test at the initial speed 900 rpm the out put were good, on the 1000 and 1200rpm the capacity decline. This could be because of the *tef* stem propertis which had high tensile strength and could be rolled with the drum bars of the SG-2000 thresher (Figure 4.35.). In newly developed threshing unit, after 1000 rpm, again the capacity shows increments and this could happened under the closed type drum and concave where the material got opportunity to contact more than one times for rubbing and cut the *tef* stem in a better way. The optimimum rpm of the threshing process could be 1000rpm.

In some research (Dauda, 2015; Anwar *et al*., 1991; O'Ndirika, 2006 and Enaburekhan, 1994) results, it was shown that the capacity has positive correlation with the drum speed. The speed of threshing unit(drum) could not influnecing the power consumption of the thresher as some studies showd the speed of the drum has no significant effect on the process power (Bjork, 1988 and Harrison, 1991). Vajasit and Solokha (2006) showed that the output capacity rapidly increased with an increase in drum speed for all feed rates and grain moisture content.

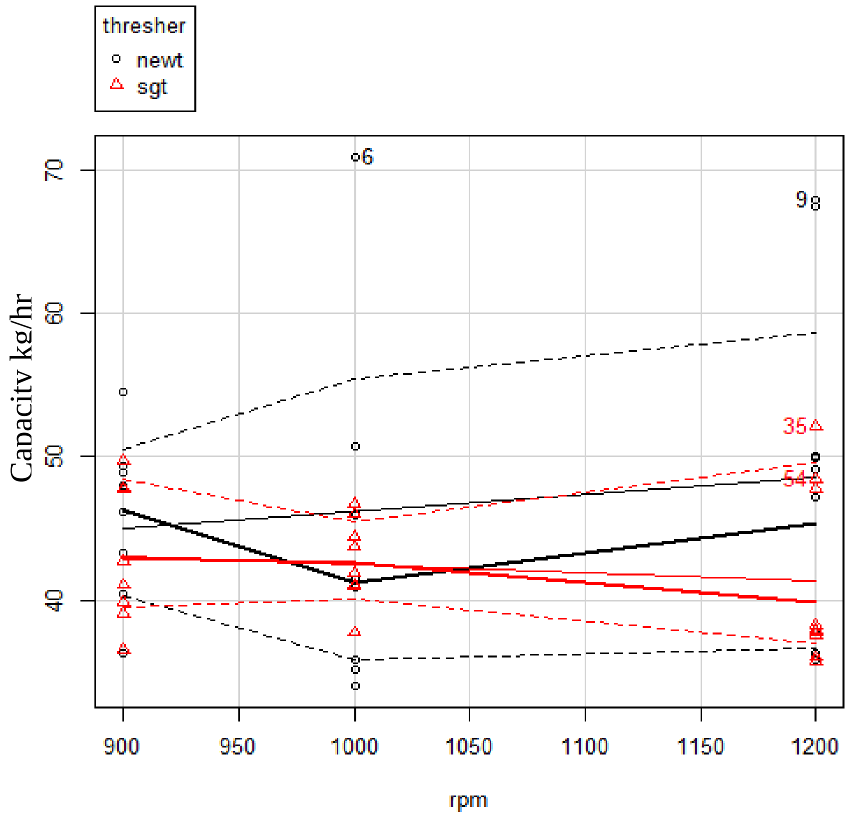


Figure 4. 35. The effect of drum speed (rpm) on capacity (kg.hr-1) of two threshing units

4.3.2.5. The effect of drum speed (rpm) on cleaning efficiency (%)

The effect of drum speed on the perfromance of cleaning had the negative correlation for SG-2000 thresher and a positive correlation for newly developed thresher (Figure 4.36. and Table 4.41.) . When the drum speed increased from 900 to 1000 the cleaning efficency decreased from 35.79% to 33.48% and when the drum speed increased from 1000 to 1200 the cleaning efficency increased from 33.48% to 43.41% for the new threshing units. This could happened beacause of the drum (auger) shape and easily pushing of bulk to the outlet. In the case of SG 2000 threshing unit, when the drum speed increased from 900 to 1000 and 1000 to 1200 the cleaning efficency decreased from 25.82% to 24.50% and 24.50% to 24.15% respectively (Figure 4.36).This could happen due to more impact /rubbing and result more breakage of the bulk in the threshing units and more mixtures passsed under the concave.

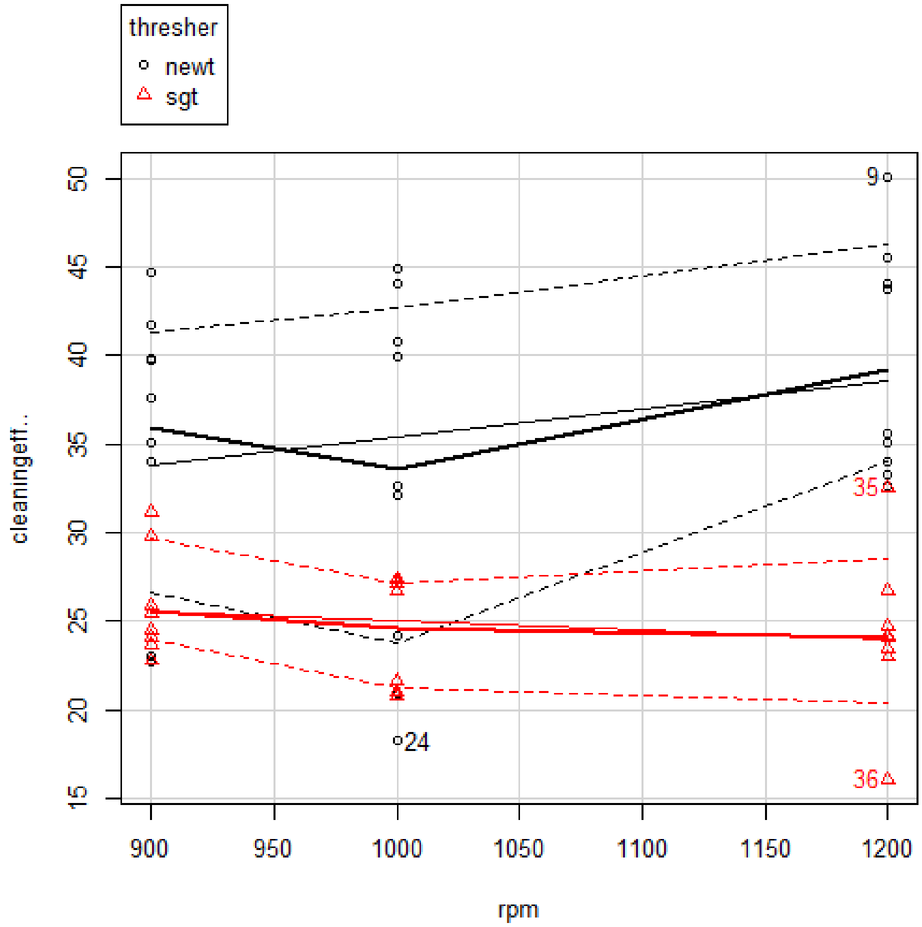


Figure 4. 36. The effect of drum speed (rpm) on cleaning efficiency (%) of two threshing units

4.3.2.6.The effect of drum speed (rpm) on the separation efficiency (%)

The effect of drum speed on the perfromance of separation efficiency had the negative correlation for SG-2000 thresher (Table 4. 42.) and a positive correlation for newly developed thresher (Figure 4.37. and Table 4.42.). As a general trend of the graph,when the drum speed increased from 900 to 1000 the separation efficency increased from 91.66% to 96.66% and when the drum speed increased from 1000 to 1200 the separation efficency decreased from 96.66% to 93.85% for the new threshing unit. When the drum speed increased from 900 to 1000 and 1000 to 1200 the separation efficency of SG 2000 threshing unit decreased from 89.77% to 80.43% and increased from 80.43% to 86.74% respectively.This could happen due to the configuration of the drum and concave.When more chopped material fallen within the sepcified (small) area, then the separation is difficult. As general principle, the separation should be closed to 100%, but there was the overflow of the bulk material and it was beyond the separation rate and could acount as overflow (loss).

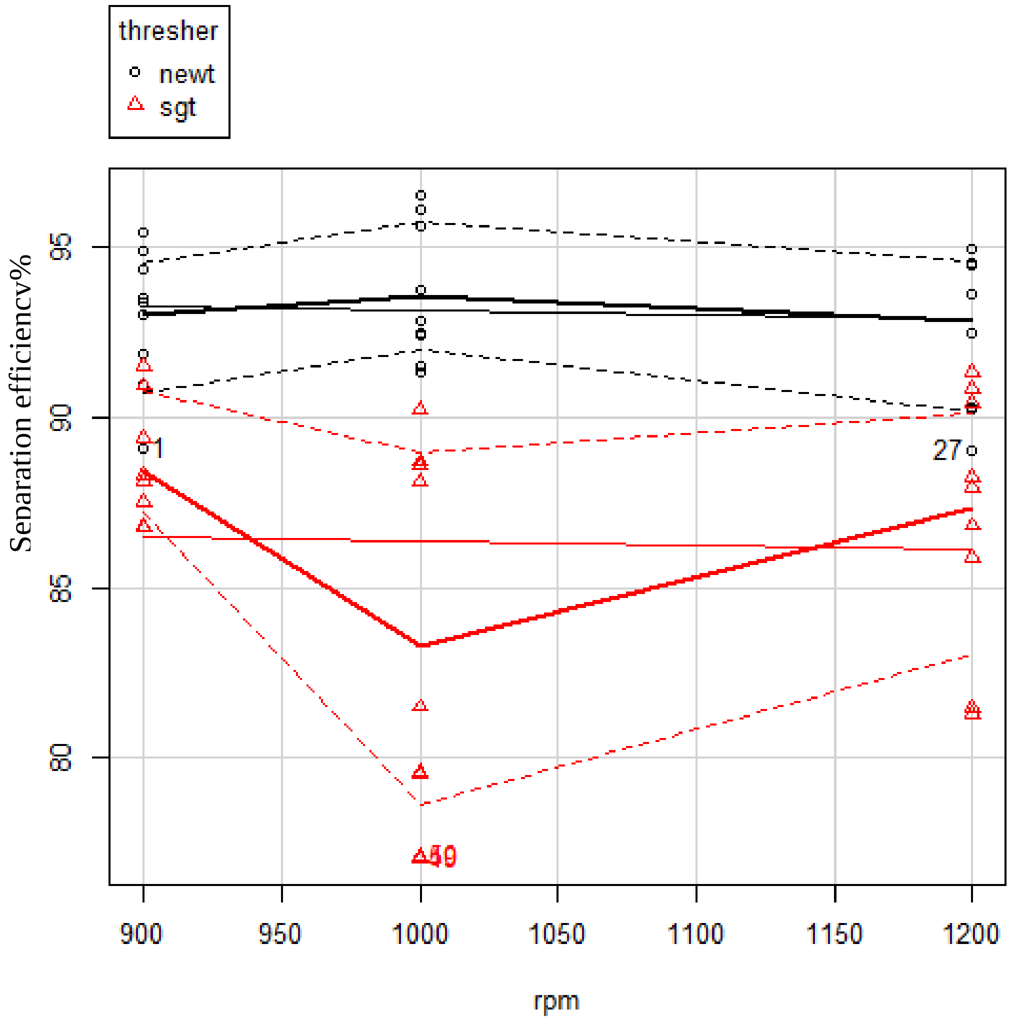


Figure 4. 37. The effect of drum speed (rpm) on separation efficiency (%) of two threshing units

Table 4.41. ANOVA table for response variable separation efficiency (%)

	df	Sum sq	Mean sq	F value
Federate	1	451.9	451.86	1.8894
Rpm	1	25.2	25.19	0.1053
Residuals	51	12197.2	239.16	

Table 4. 42. Summary of the correlation coefficient of variables on the performance indices for new developed threshing unit

	Capacity ($Kg.hr^{-1}$)	Cleaning Eff. (%)	Drum speed. (rpm)	Feed rate. ($Kg.hr^{-1}$)	Separation Eff.(%)
Capacity, $Kg.hr^{-1}$	1.0000000	0.66242601	1.490846e-01	4.273228e-01	0.3549236
Cleaning eff. (%)	0.6624260	1.00000000	2.394266e-01	-4.892809e-02	0.7719110
Drum speed. rpm.	0.1490846	0.23942665	1.000000e+00	1.540297e-20	0.1052052
Feed rate. $Kg.hr^{-1}$	0.4273228	-0.04892809	1.540297e-20	1.000000e+00	-0.2700074
Separation eff. (%)	0.3549236	0.77191096	1.052052e-01	-2.700074e-01	1.0000000

Table 4. 43. Summary of the correlation of variables on the performance indices for SG-2000 threshing unit

	Capacity ($Kg.hr^{-1}$)	Cleaning Eff. (%)	Drum speed. (rpm)	Feed rate. ($Kg.hr^{-1}$)	Separation Eff. (%)
Capacity $Kg.hr^{-1}$	1.0000000	0.1472618	-1.616847e-01	5.543082e-01	-0.1004044
Cleaning eff. (%)	0.1472618	1.00000000	-1.874961e-01	-6.238472e-01	0.7420157
Drum speed (rpm)	-0.1616847	-0.1874961	1.000000e+00	1.540297e-20	-0.3640085
Feed rate. $Kg.hr^{-1}$	0.5543082	-0.6238472	1.540297e-20	1.000000e+00	-0.5252806
Separation eff. (%)	-0.1004044	0.7420157	-3.640085e-01	-5.252806e-01	1.0000000

4.3.2.7. The effect of feed rate, rpm and concave length on the cleaning efficiency

Cleaning efficiency is dominantly depending on the length of the concave and the area where the threshed material could fall. The general relation and modeling were related on the parabolic shape as indicated on Figure 4.38. The cleaning of *tef* performed at different length of the concave as shown in the graph, the SG-2000 threshing units had got the maximum cleaning efficiency at the distance of concave from 0.1- 0.2 m and the total area is 0.16 m^2, which was closer to the inlet chute and the newly developed threshing units indicated in between 0.1- 0.4 m of concave length and the total area was 0.6 m^2 within the range of this distance the maximum cleaning efficiency occurred at the distance of 0.3 m from the inlet chute.

The privilege of increment in area of concave and length from the inlet chute where the mixture lays gives the amount of grain or mixture to pass through the concave holes and uniformly distribute on length of concave which allows a better cleaning performance.

The amount of mixture per unit area of concave, influence the probability of fallen grain through the opening of the concave. The shape of the graph (Figure 3.38.) was similar with the mathematical model and its graph derived by Miu (2016). The effect of rpm and concave length on the cleaning rate distribution is depicted on the Appendix III. Fig.5. The effect of feed rate and concave length on the cleaning rate distribution was shown on Appendix III.Fig. 6-7.

Different research showed the cleaning efficiency and loss had correlation with the feed rate. The increase in cleaning loss with feed rate may be due to load intensity on the sieve, which resulted in matting on the sieve with material other than grain blocking sieve holes, thereby increasing cleaning loss. Wacker (2003) showed an increase in grain loss with increasing throughput of MOG.

The cleaning rate distribution along the concave length on the effect of feed rate and drum speed (rpm) was shown on Appendix III.Fig.6. The maximum and minimum rate were 13.71% at the concave length of 0.1 m at F1R2 and 0.12% at 0.6 m concave length on F1R2; and 14.91% at length of 0.2 m at F2R1 and 0.28% at 0.7 m concave length with the F2R3 testing parameters for SG-2000 and newly developed threshing units respectively.

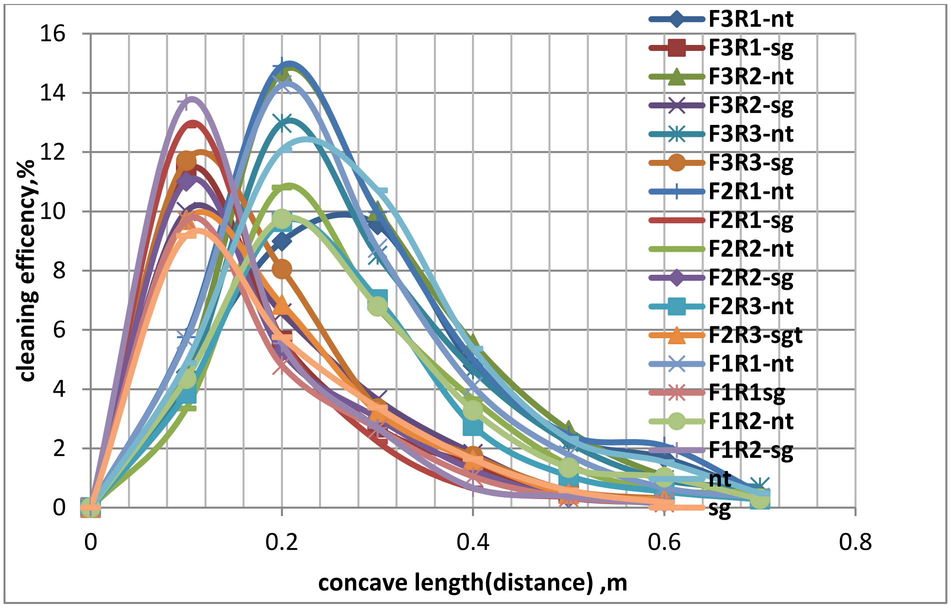


Figure 4. 38. The effect of feed rate and rpm on cleaning efficiency distribution along the concave length of the tef threshing units (nt-new threshing unit and sg-SG-2000 threshing unit)

When the feed rate was constant with 400 $Kg.hr^{-1}$and different rpm (Appendix III.Fig.1.), the maximum magnitude of cleaning rate was 14.27% at 0.2 m concave length with 1200 rpm and 13.71% at 0.1 m concave length with 1000 rpm; and minimum to be 0.29% at 0.7 m length with 1000 rpm and 0.12% at 0.6 m concave length for newly developed and SG-2000 threshing units respectively. The whole trend was similar for 325 $Kg.hr^{-1}$ feed rates (Appendix III.Fig.2.).

When the rpm is increasing, the cleaning efficiency smoothly distributed along the concave length and the peak efficiency was at the center, this could facilitate by the assistance of auger shape of the drum part which was designed at the feeding zone of newly developed threshing unit. Under feed rate 275 $Kg.hr^{-1}$ (Appendix III.Fig.3.), the maximum cleaning efficiency 14.19% obtained on 1000 rpm at 0.2 m length of concave and 12.92% at the initial (0.1 m) concave length for newly developed and SG-2000 threshing units respectively. This could happen due to the uniform distribution of the material to be threshed and it was the optimum level of rpm for the system, but the output capacity could be less.

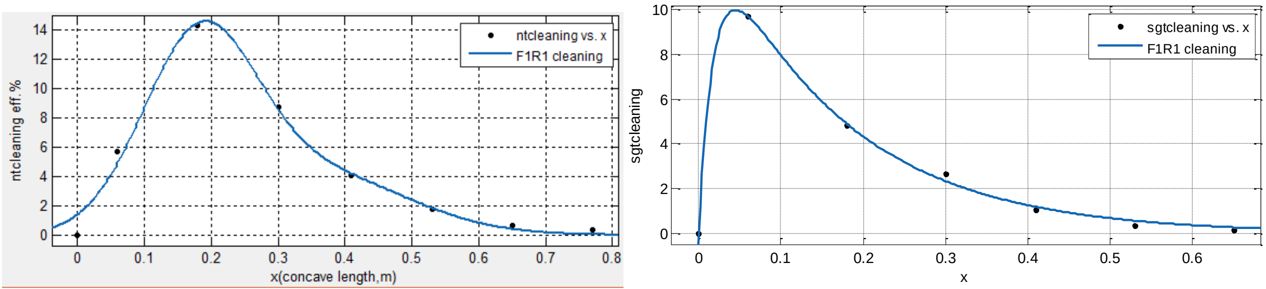


Figure 4. 39. Varation of the cleaning efficiency distribution along concave length for new threshing and SG-2000 threshing units under F1R1

In this study the individual paramaters like rpm and feed rate through the concave and rotor length could generate the same trend and function as shown in Figure 2.14. and studied by different researchers (Bill and Bernard, 1999; Srivastava *et al*., 2006 and Miu and Kutzbach, 2000**).** It was concluded that the separation and threshing rates described on the polynomial function**.** In general, under this research and its result, the *tef* threshing units described and the best fitting graphical representation was on the Gaussian function. The graph depicted as in Figure 4.39.

4.3.2.8. The effect of feed rate and rpm on the separation rate of threshing units

The effect of feed rate and rpm on the separation rate as general trend was shown on Figure 4.40.The different separation rate under different feeding rates (400, 325 and 275 $Kg.hr^{-1}$) is depicted in Appendix III. Fig.7-9. The maximum separation rate is under 1200 rpm and 1000 rpm between the concave length of 0.1- 0.2 m and 0.1- 0.3 m for SG-2000 thresher and newly developed threshing units respectively (Figure 4.39.). When the separation increase on the minimum concave distance then the cleaning efficiency of the system may got even difficulty to clean with additional sieves, this could occur because of the smaller concave area. Since, the area of concave where the seaparation performed is directly proportional to the separation and segragation rate of the threshing units.The mass of threshed mixture per unit area should be optimum with proportinonal of separtion ratio (separation area/openning).

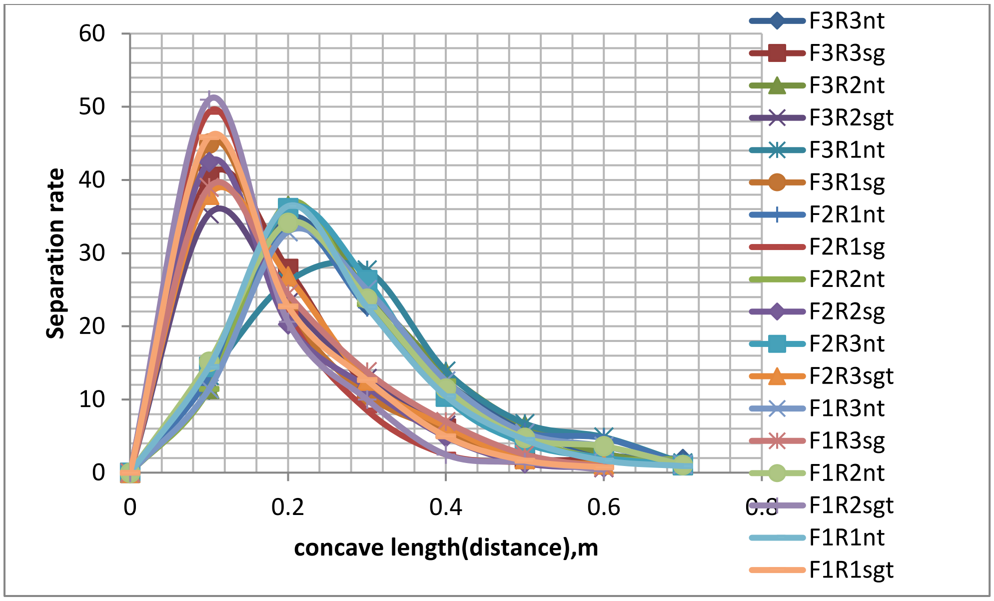


Figure 4. 40. The effect of rpm and feedrate on the separation distribution along the concave length

4.3.2.9.The effect of feed rate on the separation rate

The grain separation efficiency shows the probablity of separation of the remaining avaliable (separable) of *tef* and mixture within the concave length.The grain separation efficency is a useful index for the comparsion of the design and feature work of the similar threshing units with the same or different size. As shown in the Appendix III.Fig.7-9. with in different feeding rates the separation probablity of *tef* threshing process and trends seems similar at the initial part of threshing part, it increased up to the half of the concave length and then the probablity of separation decreased, finally was minimum (closer to zero) and was become the threshing loss.

But, when comparing the two threshing units, on SG-2000 threshing unit the separtion rate goes very fast upto the conacve length of 0.2m.That means, the fallen crop could got minimum area of concave or sieves, where as in the newly developed unit the increasing goes smoothly and also the separation rate goes gentily with the quadartic shape upto the concave length of 0.4m. That means, the fallen crop mixture could get enough space for cleaning. In all graphical relation of cleaning and separation with the concave length shows that, the effective concave length was from 0.1m upto 0.5m. This indicated the possiblity of reducing the length of both evaluated threshing units. The grain can pass through the concave opennings, this openning describes under the formula (Miu *et al.*, 1998b).

$$\eta = \frac{S_a}{S}$$

Where :

η - is the opening ratio

S_a- is the mean surface of the concave opening

S- is the mean surface that contains an opening with the surfaces S_a

The general relation and modeling is described by quadratic equation and the relationship between the grain separation *(S)* in % and length of concave *(x)* in meter is given by the following equations under Table 4.44:

Table 4. 44. General relation and modeling of feed rate and rpm vs length of concave on separation

Feed rate Kg.hr^{-1}	rpm	Equation	Threshing unit	R^2
275	900	$S = -244.7x^2 + 277.4x$	newly developed	0.973
275	900	$S = -395.9x^2 + 397.4x$	SG-2000	0.981
275	1200	$S = -213.3x^2 + 261.3x$	newly developed	0.978
275	1200	$S = -423.1x^2 + 418.4x$	SG-2000	0.939
325	900	$S = -125.7x^3 - 37x^2 + 262.2x$	newly developed	0.977
325	900	$S = 561.9x^3 - 879.1x^2 + 472.6.4x$	SG-2000	0.999
325	1000	$S = -776.9x^3 - 943.1x^2 + 294.9x$	newly developed	0.893
325	1000	$S = 1590x^3 - 1747x^2 + 426.2x$	SG-2000	0.705
400	1200	$S = 834.2x^3 - 994.7x^2 + 305.5x$	newly developed	0.868
400	1200	$S = 1742x^3 - 1909.1x^2 + 465x$	SG-2000	0.716

Similar graphical representations in all feed rate and rpm combinations are presented in Figure 4.15. The separation rate distribution along the concave length was shown on Appendix III.Fig.8. The maximum and minimum separation rates were 49.36% at the concave length of 0.1 m at F1R2 and 0.40% 0.6 m concave length on F1R2; and at 36.87% at length of 0.3 m at F2R2 and 0.9 % at 0.7 m concave length with the F1R1 testing parameters for SG-2000 and newly developed threshing units respectively. At the initial of threshing zone, it is expected to detach the grain from the stalk immediately at the moment of feeding, but the amount of fallen mixture at the limited area of the mat or sieve influence in separation and cleaning rate of the thresher. When the fallen grain mixture through the concave to the mat (sieve) at per unit area is maximum (or much) then the cleaning of that mixture could be very difficult, this situation was observed on the SG-2000 threshing units, hence the improvement of this unit should consider this condition.

Dauda (2015) and Chimchana *et al*. (2005) shown on their study that 50 % of the crop was detaching up to the quarter of the concave length. However, the threshing drum construction facilitate to give impact or assist to transport the threshed material before getting more impacts within the same threshing units. In the case of SG-2000 threshing drum, there are bars with sharp edge at the tip of the drum and at the first contact it could facilitate more impacts and release the grain at the initial zone which gave the maximum separation and cleaning rates at the initial stage of threshing Figure 4.39 and 4.40.

In the newly developed threshing unit, the threshing starts at the initial of concave edge and go gently up to the half-length of the concave and then decline up to the end of concave length. This happened with the help of the helical shape of the drum, it could distribute the mixture across the area of the concave and facilitate easy of cleaning. Uniform threshed material (mixture) distribution across the concave length implies better separation and cleaning rate. At high material feed rate, the thicker layer of crop makes grain separation more difficult. Therefore, with increasing of material feed rate, the linear rate separation rate *(β)* decreases and threshing rate *(λ)* increases, it can be seen in the Figures 4.39 and 40.

4.3.2.10. The effect of drum speed (rpm) on the separation rate

The drum speed was one of the process parameters and had effect on the separation distribution along the concave length. The kinematics of the material through the threshing space is influenced by different factors such as material properties, threshing unit design and process parmeters (Miu, 2016). As depicted in the Figure 4.41-4.43 the threshing unit design and drum speed variation had effect in the separation efficiency. When the rpm increased the kinematics of material increased, so in both threshing units the separation rate distribution increasing very fast and gentily for SG-2000 and newly developed threshing units respectively.

This reality is related with the study of Miu (2002a) that stated the detachment of the grain from panicles and grain separation mainly takes place at the threshing unit, due to the beating energy (impact force) of the drum (rotor). The grater the rotor speed the stronger is the action of the active elements (rasp bar) and the greater are the centrifugal force and grain separtion.

It could imply for all types of the threshing units, especially for axial threshing unit (like the design of *tef* threshing unit) which has auger shape at the inlet part of the unit, at higher rpm of the drum, the stationary time of the material in the axial threshing unit become shorter and shorter. Miu and Kutzbach (2008) showed the coefficient of λ and β bears an exponenetial relation ships with the rotor speed .

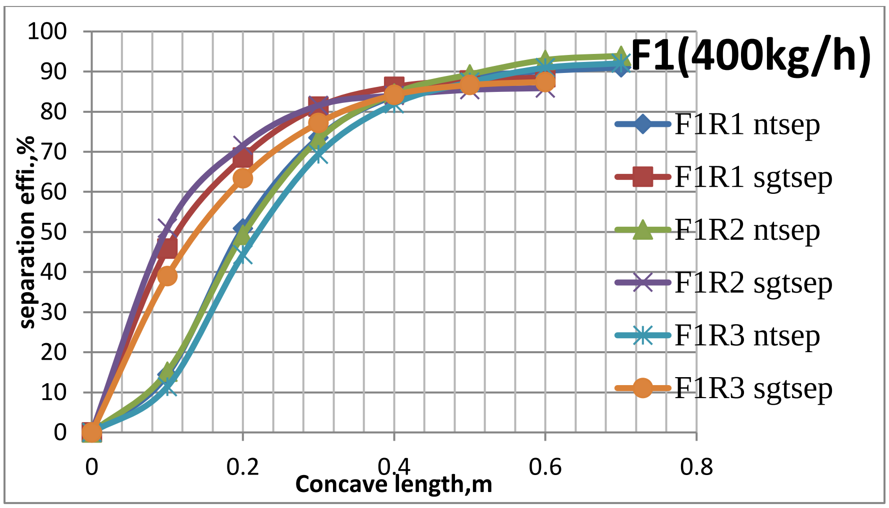


Figure 4. 41. The effect of rpm on the separation efficiency(%) along the concave length

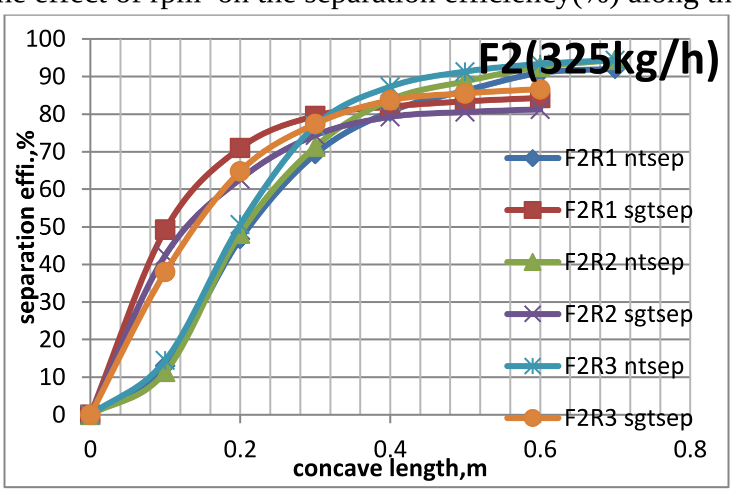


Figure 4. 42. The effect of rpm on the separation efficiency(%) along the concave length

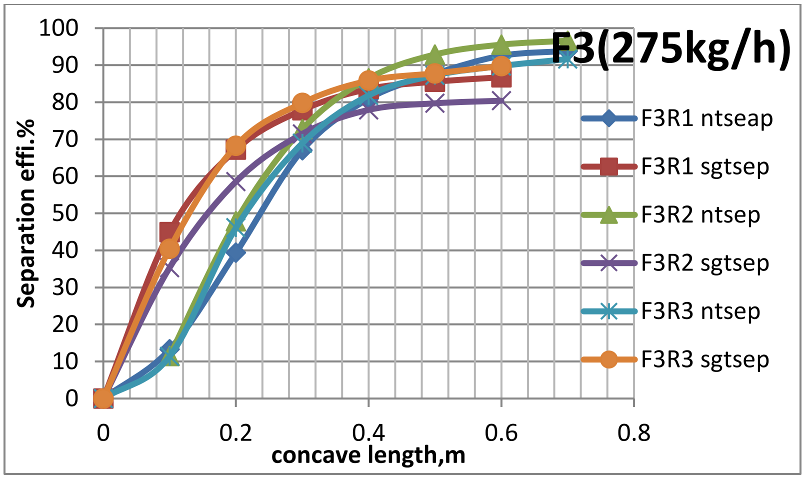


Figure 4. 43. The effect of rpm on the separation efficiency(%) along the concave length

4.3.2.11. The relation of concave length on the separation efficiency (%) for different threshing unit

The separation rate and the summation of separation efficiency distribution along the concave length are shown in Figure 4.44 and 4.45. For the rest of variables, the whole trend was similar as described in the above Figures. Miu (2002a) noted that the greatest quantity of grain is separated through the central part of the concave. The research output, especially in the newly developed threshing unit, the maximum separation occurs at the center of the concave and this situation agreed with Miu (2002a) test result.

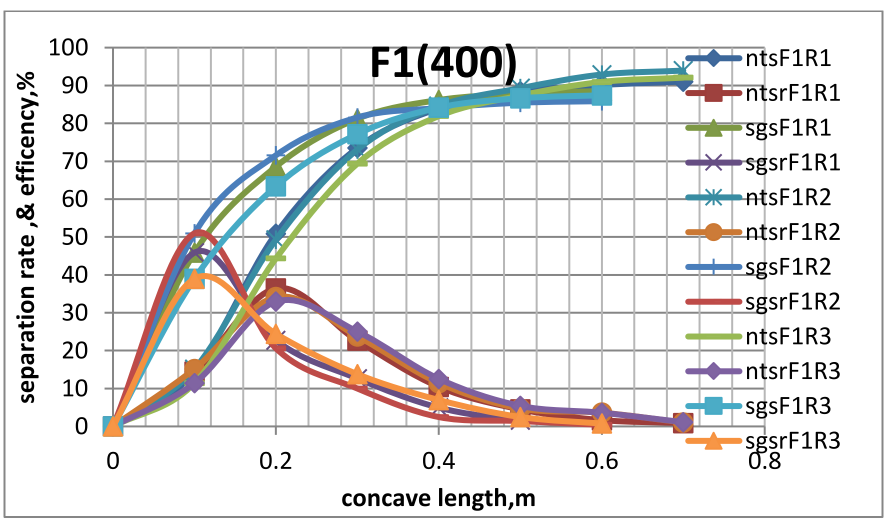


Figure 4. 44. The rpm effect on grain separation rate and separation efficiency (%) distribution along concave length

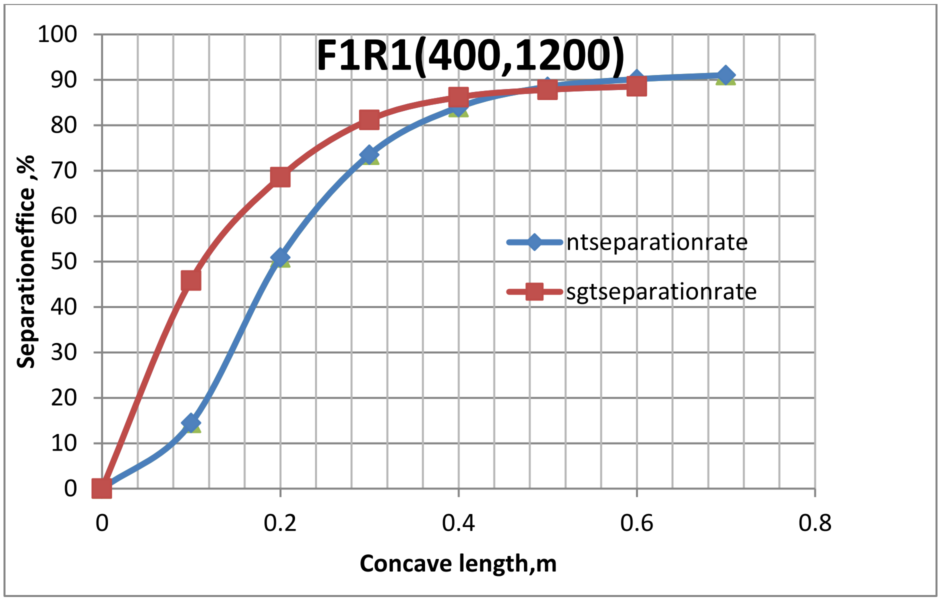


Figure 4.45. The feed rate and rpm combination effect on grain separation efficiency (%) and distribution along concave length

The coefficient of determination R^2 for the separation rate and efficiency was from 0.644 to 0.999 and 0.829 to 982 for SG-2000 and newly developed threshing units. The effect of feed rate of the materials to cleaning efficiency is given in Appendix III.Fig.7-Fig.9.

As a general observation, the grain separation over the length of the concave differs from one threshing unit to the other one (Figure 4.38). The reason for the differences could be first attributable to the fact that the SG-2000 threshing drum has more pegs as bar could give more impact than facilitate transporting while the other one (newly developed threshing drum) has an axial feeding and implicitly different values of crop axial velocity in the intake zone. It could increase the uniform distribution of material to be threshed in the concave and fallen mixture in the second phase of cleaning system.

4.4. Result and Discussion on Modeling and Simulation of *Tef* Threshing Unit

4.4.1. Result

Table 4. 45. The experimental result of this research for threshing rate and separation rate for tef threshing unit (from Chapter 4.3)

It	Threshing units	Parameters(rates)	
		Threshing rate(λ)	Separation rate(β)
1	New threshing unit	1.5-10.5	3.2-6.8
2	SG-2000	0.5-8.4	2.8-5.7

The best fit of the function could be described using the **MATLAB R2014a** and obtained under the Gaussian function and the Exponential functions with the mathematical model and the best fit for the performance of *tef* threshing mechanisms along the concave (rotor) length. The performances are cleaning and separation efficiency.

The Gaussian function with the 95% of confidence bounds and

The equation is

$$a_1 * e\left(-\left((x - b_1)/c_1\right)^\wedge 2\right) + a_2 * e\left(-\left((x - b_2)/c_2\right)^\wedge 2\right) \tag{4.1}$$

The exponential function is

$$a_1 * e(b * x) + c * e(d * x) \tag{4.2}$$

Where the value of each coefficient is determined as:

x- the concave length interval from the inlet to the outlet in meter

a-the height of the curves peak

b-the position of the center of the peak

c-the standard deviation

In accordance with this research the values are different for each variable and for instance, the result under the feed rate (400 Kg.hr^{-1}) and rpm (1200) (F1R1) and F1R3 (400,900) of each threshing units obtained as indicated on Table 4.46.

Table 4. 46. Model validation in different variables (feed rate and rpm) for two threshing units

Variables	Parameters	Coefficients									function
		a1	b1	c1	d	a2	b2	c2	R^2	Ad. R^2	
F1R1 (400, 1200)	ntcl.ef	32.36	0.198	0.105					0.998	0.993	Gaus.
	sgclea.eff	32.21	0.14	0.036		2.81	0.26	0.14	0.99	0.99	Gaus.
	ntsep.ef.	31.59	0.20	0.106		10.33	0.348	0.173	0.99	0.99	Gaus.
	sgsep.ef.	56.97	0.13	0.07					0.89	0.83	Expo.
	ntsep.ef	97.47	0.55	0.38					0.99	0.98	Expo.
	sgsep.ef	94.95	0.46	0.37					0.88	0.83	Expo.
F1R3 (400, 900)	ntcle.ef	11.45	0.23	0.13		3.03	0.40	0.21	0.99	0.98	Gaus.
	sgcle.ef	27.94	-7.183	-27.94	-18.3				0.997	0.995	Expon.
	ntsep.ef	28.26	0.215	0.11		10.36	0.36	0.199	0.99	0.99	Gaus.
	sgsep.ef	98.2	-7.229	-118.2	-18.5				0.998	0.996	Expo.
	ntsep.ef	97.14	0.56	0.37					0.99	0.99	Expo.
	sgsep.ef	94.2	-0.59	-142.1	-4.072				0.999	0.999	Expo.

- nt-new threshing unit and ntclea.eff-cleaning efficiency; ntsep.ef.-separation efficiency
- sg-SG-2000 threshing unit and sgcle.ef-cleaning efficiency;sgsep.ef.-separation efficiency

4.4.2. Discussion

4.4.2.1.The computational model and optimization of newly developed *tef* threshing unit

The computational simulation is the process of emulating and experimenting with a physical system through development of a computer application using a mathematical model. Under different variables as input and output of the *tef* threshing units the three output variables of capacity in kg.h^{-1}, cleaning efficiency in %, and separation efficiency in % are determined using with the input variables feed rate in kg.h^{-1} and speed of the drum in rpm, analyzed with the **MATLAB 2014a** coding and graphical representation. In terms of modeling the threshing units refer the stochastic modeling which belongs on the probability theory for quantifying the probability distribution of potential outputs of a threshing process. For the process of *tef* threshing units the input from the physical model incorporated with computational model and obtains the functions as indicated in Figure 4.46. and Table 4.47.

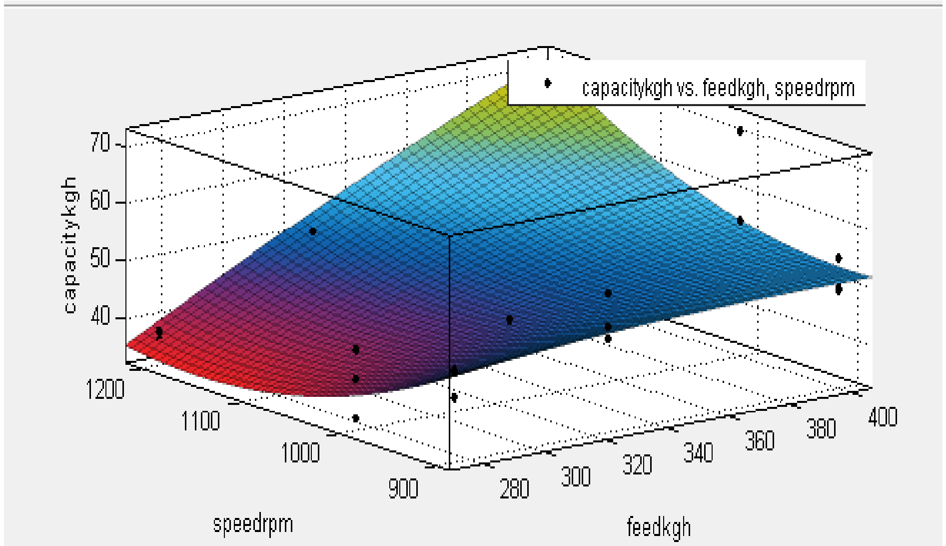


Figure 4. 46. The Computational model validation of capacity in Kg.hr-1with feed rate (Kg.hr-1) and drum speed (RPM) for new threshing unit

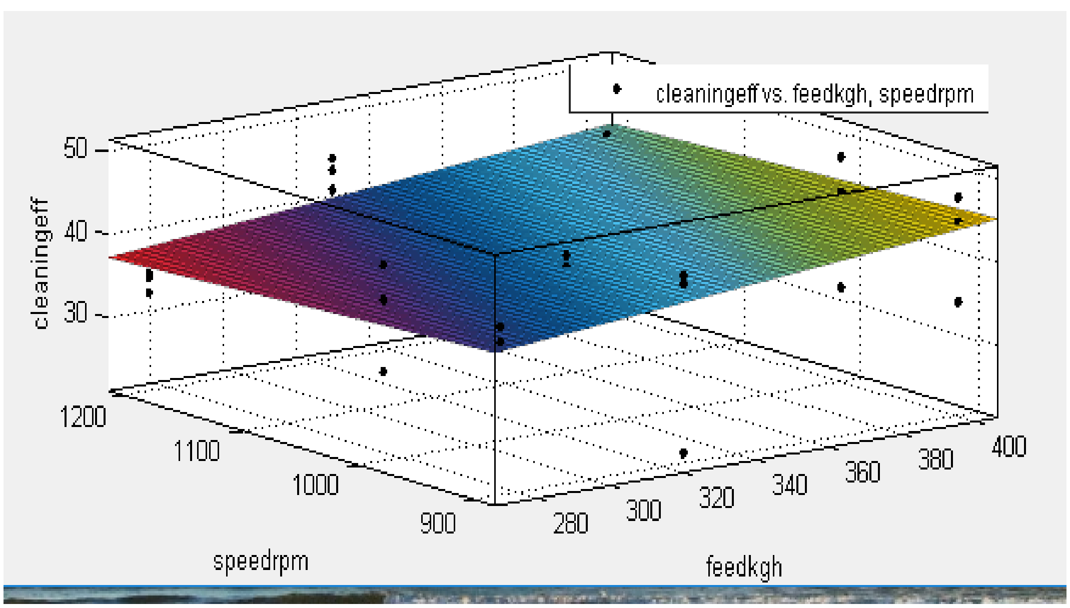


Figure 4. 47. The Computational model validation of cleaning efficiency (%) with feed rate **(**Kg.hr-1) and drum speed (RPM) for new threshing unit

For purpose of optimization the research implies the optimization model with an intrinsic part of a simulation model with the mathematical optimization method. The mathematical model for the capacity indicated with the formula equation 3.10 and the result of the best fit in computational model are optimized under the 2nd order of polynomial functions.

The threshing capacity is modeled with an input variable of feed rate(x) and speed of the drum(y) (RPM) with the equation 4.3.

$$f(x,y) = a + b*x + c*y + d*x*y + e*y\hat{}2 \qquad (4.3)$$

The cleaning efficiency is modeled with an input variable of feed rate(x) and speed of the drum(y) (RPM) with the equation 4. 4.

$$f(x,y) = a + b*x + c*y \qquad (4.4)$$

Where *x* is normalized by mean 333.3 and std 52.35 and where y is normalized by mean 1033 and std 127.1. Coefficients (with 95% confidence bounds):

Where:

f(x,y)-the capacity, $Kg.hr^{-1}$and cleaning efficiency in %

x-feed rate in $Kg.hr^{-1}$

y-speed of the drum in rpm

a,b,c,d,e- are the coefficients

The mathematical model for the separation efficiency indicated with the formula equation 5. 16 and the result of the computational model are optimized under the linear polynomial functions.

The separation efficiency is modeled with an input variable of feed rate(x) and speed of the drum (y) (RPM) with the equation 7.5.

$$f(x,y) = a + b*x + c*y \qquad (4.5)$$

Where *x* is normalized by mean 333.3 and std 52.3 and where y is normalized by mean 1033 and std 127.1. Coefficients (with 95% confidence bounds):

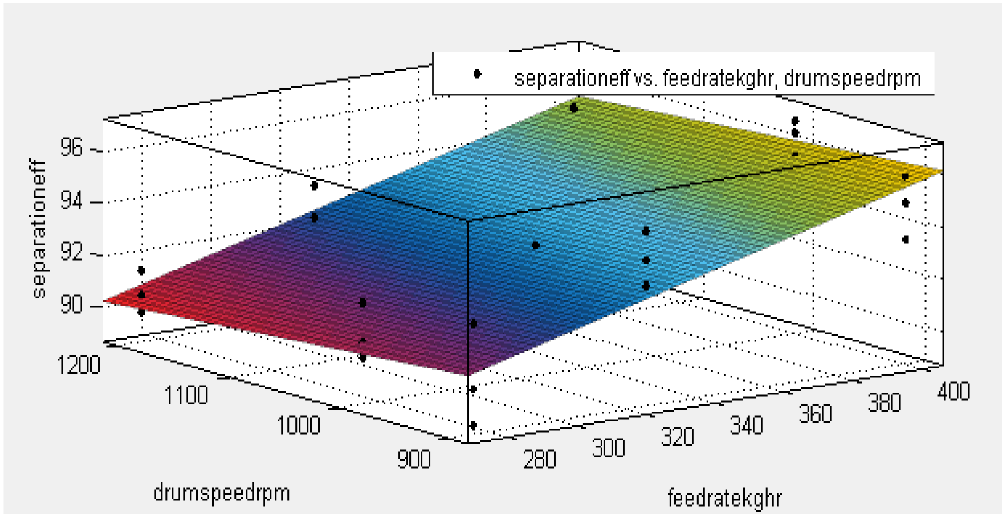


Figure 4.48. The Computational model validation of separation efficiency (%) with feed rate (Kg.hr^{-1}) and drum speed (RPM) for new threshing unit.

Table 4. 47. Model optimization in different in put variables (feed rate and rpm) and mean output variables (capacity, cleaning efficiency and separation efficiency) of new threshing unit

Outputs	Coefficients							function
	a	b	c	d	E	R^2	Ad. R^2	
Capacity Kg.hr^{-1}	46.59 (43.87 -49.32)	6.552 (5.132 -7.973)	0.191 (-1.497 -1.879)	5.023 (3.376-6.471)	2.057(0 .0074-4.939)	0.88	0.85	Polynomial
Cleaning efficiency (%)	41.19 (39.99-42.39)	2.079 (0.8568 -3.302)	-0.922 (-2.144 -0.301)	-	-	0.77	0.75	Linear
Separation Efficiency (%)	93.13 (92.63-93.63)	1.838 (1.331 - 2.346)	-0.407 (-0.914 - 0.1003)	-	-	0.69	0.67	Linear

4.4.2.2.The prediction and measured parameters for optimization of capacity model evaluation

The values of these evaluation parameters between the predicted and measured values indicates a better model because it shows that there exist but a little deviation between the predicted and measured values. The advancement of computer technology coupled with the availability of simulation and optimization packages have made it possible to develop a fundamental theory for prediction purposes (Dauda, 2015), which include the threshing and separation process of the threshing units. Figure 4.49., shows the graph of predicted versus measured values of capacity of the threshing unit. A statistically significantly high coefficient of determination (R^2) of 0.963 was obtained with the regression equation of.

$$y = 1.0121x - 0.6374$$

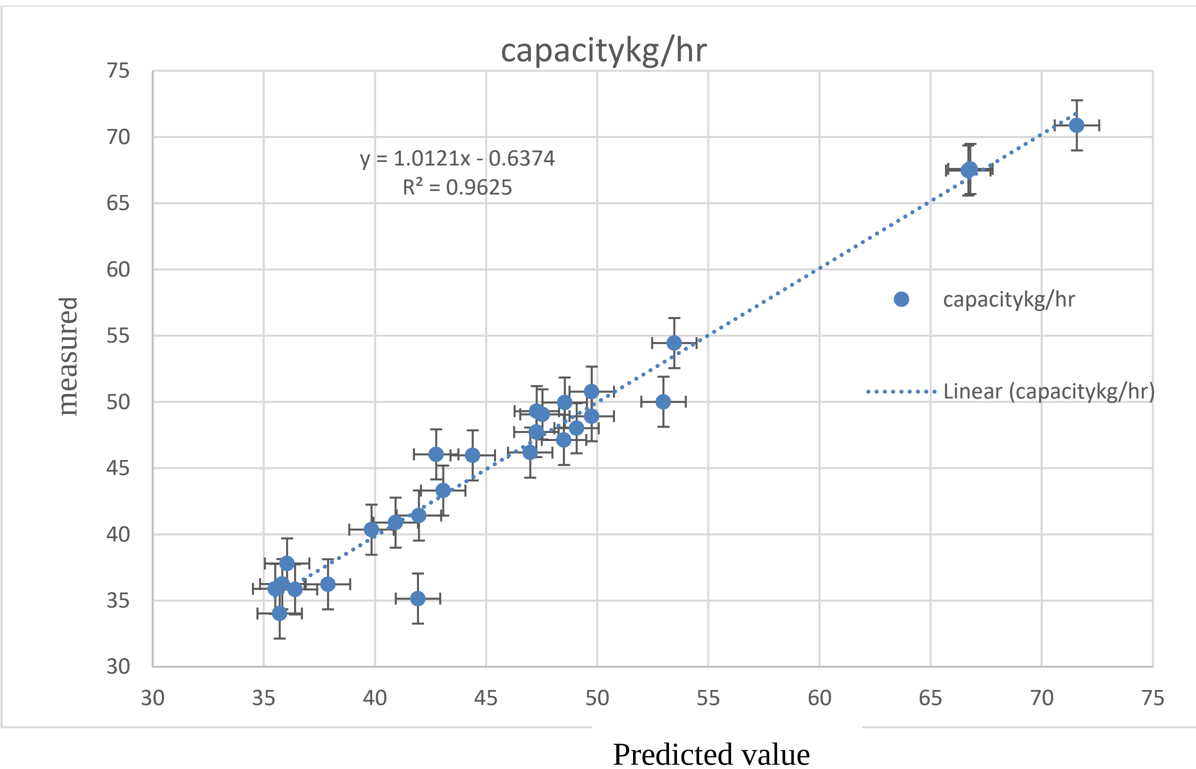


Figure 4. 49. The Computational model validation of capacity with feed rate ($Kg.hr^{-1}$) and drum speed (RPM) for new threshing unit

4.4.2.3. The prediction and measured parameters for optimization of cleaning efficiency model evaluation

The values of these evaluation parameters between the predicted and measured values indicate a better model because it shows that there exist a little deviation between the predicted and measured values. Figure 4.50. shows the graph of predicted versus measured values of cleaning efficiency. Statistically significant coefficient of determination (R^2) of 0.86 was obtained with the linear equation of.

$$y = 0.9216x + 1.033$$

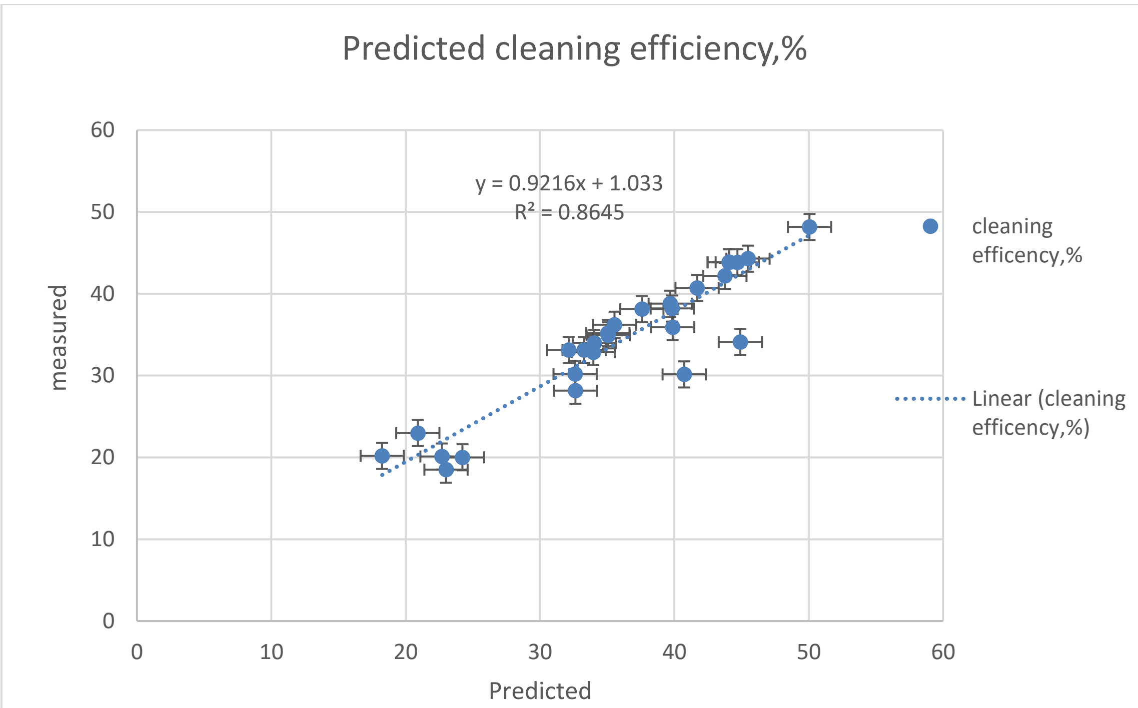


Figure 4.50. The Computational model validation of cleaning efficiency (%) with feed rate ($Kg.hr^{-1}$) and drum speed (RPM) for new threshing unit.

4.4.2.4. The prediction and measured parameters for optimization of separation efficiency model evaluation

The values of these evaluation parameters between the predicted and measured values indicate a better model because it shows that there exist a little deviation between the predicted and measured values. Figure 4.51. shows the graph of predicted versus measured values of separation efficiency.

A statistically significantly high coefficient of determination (R^2) of 0.905 was obtained with the regression equation of.

$$y = 0.8185x + 16.819$$

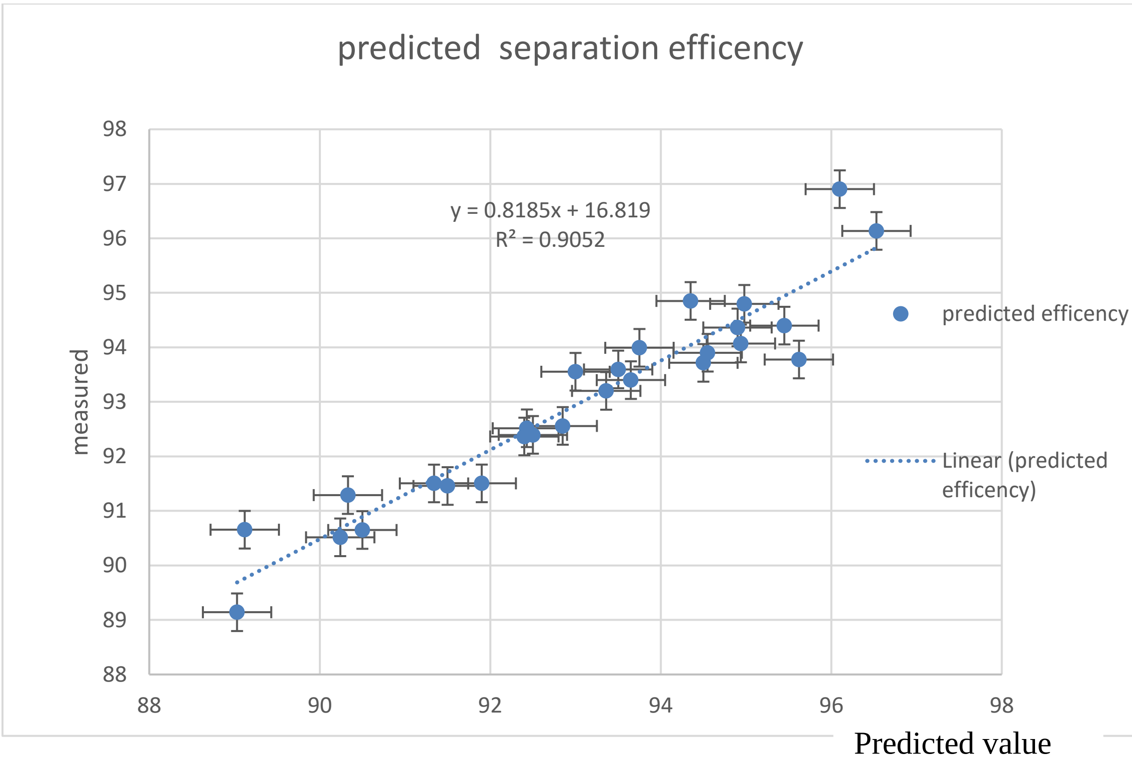


Figure 4. 51. The Computational model validation of separation efficiency (%) with feed rate (Kg.hr-1) and drum speed (RPM) for new threshing unit

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORKS

5.1. Conclusions

The use and advantage of threshing will continue to be used for threshing different crops and *tef* threshing will become a solution in decreasing the drudgery of *Tef* producers. The dissertation showed the improvement in design and manufacturing and also indicated the further challenges which need to be tackled in the area of threshing. The mechanical properties of *tef* stem used as input for designing the *tef* threshing unit and to determine the required threshing power. The use of *tef* threshing technology will improves the quality of *tef* crop.

In light of this, the following conclusions were drawn from this research work:

- The mechanical properties like the modulus of elasticity, flexural rigidity and shear strength of *tef* stem were determined.
- This could help immensely in any type of further research focused in *tef* morphological and pre- harvest and post-harvest technology development.
- The output of the mechanical properties of *tef* stem generates threshing and cutting forces of *tef* stem.
- These forces are implemented as inputs for applying in empirical formulas for development of improved threshing units and other *tefs'* machineries (harvest and post-harvest technologies).
- Generally, the minimum and maximum value of mechanical properties of *tef* stem with different factors (moisture, diameter and thickness of the stem) shows 5 and 32 Mpa, 0.13 and 3.8 Gpa, 1.30 and 40 $kNmm^2$ for shear stress, modulus of elasticity and flexural rigidity respectively.
- The performance of *tef* threshing units at the existing size of the stationary threshers were evaluated in three response variables i.e. capacity, cleaning efficiency and separation efficiency with two independent variables, feed rate (400,325and 275$Kg.hr^{-1}$) and drum speed (1200,1000,900 rpm).
- The result revealed that the mean values were 45.61 and 42.30 $Kg.hr^{-1}$; 35.92% and 24.85% and 94.56 % and 86.33% for newly developed and SG-2000 threshing units.

- The maximum value obtained 70.88 and 52.11 $Kg.hr^{-1}$; 50.2% and 32.14% and 96.53% and 91.52% for newly developed (cylindrical shape concave) and SG-2000 (open concave) threshing units respectively.
- The result shows that there is an increment of mean values for newly developed over SG-2000 threshing units i.e. 7.8%, 44.54% and 9.5% and the maximum value obtained 36.4%, 56.19% and 15.4% in capacity, cleaning efficiency and separation efficiency respectively.
- The performance of newly developed axial threshing unit had better efficiency in all evaluation performance indices. Therefore, it is possible to utilize the technology for intending purpose.
- The model is intended as a useful design tool and the basis for the simulation of *tef* threshing unit working process. Some performance factors of threshing units such as clearance between concave and drum, length of the drum (concave) were not considered due to lack of test data in the modeling process.
- The simulation model describes the capacity, separation efficiency and cleaning efficiency with two variables feed rate and rpm of the drum. For optimization of three response variables the model shows a mean value 46.59 $kg.hr^{-1}$, 41.19% and 93.13% under regression coefficient(R^2) 0.88, 0.77 and 0.69 for capacity, cleaning efficiency and separation efficiency respectively.
- Mathematical functions of both models have been validated with experimental data obtained from the testing of *tef* threshing units.
- The predicted value over the measured value indicates under coefficient of regression *(R^2)* are 0.96, 0.86 and 0.91 for capacity, cleaning efficiency and separation efficiency respectively. This shows it is a very good agreement between theoretical and experimental data.

5.2.Recommendations

Even though, the efforts exerted to determine the mechanical properties of *tef* stem and to improve *tef* threshing mechanisms to full fill the demand of farmers during this research work, there remains much to be done in the future. The following points are suggested as future interventions:

- For Agricultural scientists: in order to tackle the problem of lodging, it is better to see the morphological structure of each variety of *tef* stem, which has better modulus of elasticity and diameter of the stem.
- *Tef* stem had better elasticity and shear strength than some cereals and needs more attention for designing harvesting and threshing machines.
- The length of t*ef* stem had effect in lodging and *tef* straw (is useful for animal feed), thus it is a must to compromise its length towards the stem morphology.
- For agricultural technology manufacturers and service providers: the newly developed threshing units shows its better output in capacity, cleaning and separation efficiency compare with the SG-2000 thresher.
- The threshing system could implement for all types of threshing units and after the result validation, it recommended for further extension and end users.
- The newly developed threshing unit could be one technology option for technology manufacturer and create job opportunity.
- The effective threshing zone was determined, based on the result it is recommended to minimize the length of both threshing units without affecting the existing features.
- The new threshing units (concave with different hole size and drum) could be for multi crop thresher, especially for threshing cereals.
- It is recommended to utilize for all types of threshers and it would help for increasing the performance of the threshers.
- For Universities, Agricultural Mechanization Research Institutions and Ministry of Agriculture: After the validation of the research out puts and feedback from end-users and manufacturer, it is possible to use the profile of the new threshing unit as a reference for developing a new threshing system for any type of threshers.

5.3. Future Works

To improve the performance of the newly developed threshing unit the following views and ideas are recommended for further investigations:

- The shear and tensile test result indicated on the maximum test moisture (between 30- 40 %) (w.b.) the shearing and tensile force decreased, that means there is an optimum level of moisture to keep the stem strong.

- There is a need to determine the optimum moisture content that may protect the lodging of *tef*.
- Since, the *tef* stem has better mechanical properties than some cereals it is recommended to apply for composite material and identify the fiber properties and its density.
- In order to obtain closer to 100% clean *tef*, improvement of the threshing units performance should be done by considering and incorporating sieves under the concave including by determining the exact shaking (sieve) motion and inclination angle.
- Further study should be done by optimizing the opening of the concave holes (for improving cleaning and separation efficiency).
- According to the test result, the active zone of threshing units were well identified, so there is a possibility to reduce the length of the drum and concave for both tested threshing units.
- In order to have full modeling and simulation results of the *tef* threshing units, the optimization parameters including the clearance and length of the threshing units should be determined. The optimization will enhance motivation and encouragement in improving the overall performance of the threshing unit.

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APPENDIXES

Appendix I. Model development data (measured and predicted) for cleaning efficiency, capacity and separation efficiency for new threshing unit

Measured cleaning Efficiency %	Predicted cleaning Efficiency %	Predicted Capacity $kg.hr^{-1}$	Measured Capacity $kg.hr^{-1}$	Predicted Separation efficiency, %	Measured Separation efficiency, %
39.69	38.7812	66.7919	67.59	94.799	94.98
23	18.5106	48.5071	47.13	91.2903	90.33
44.68	43.8522	66.6932	67.47	89.1417	89.03
32.13	33.1285	71.5867	70.88	92.3952	92.5
24.23	20.0134	49.7536	50.77	92.3655	92.4
44.08	43.8321	41.9367	35.15	92.5593	92.85
35.55	36.2154	53.4707	54.44	91.5051	91.9
44.08	43.8716	47.2823	49.3	90.6501	90.5
50.06	48.1639	49.7536	48.92	94.3655	94.9
41.69	40.7154	48.5375	49.95	92.516	92.43
34.04	33.981	52.9838	50.01	93.3993	93.65
37.58	38.1108	47.5375	49.06	90.516	90.24
40.73	30.1428	41.979	41.42	93.992	93.75
20.90	22.9826	35.5112	35.88	91.504	91.34
32.61	30.1946	42.7554	46.04	91.4573	91.5
33.28	33.1086	46.9838	46.17	94.3993	95.45
43.76	42.187	35.8326	36.24	93.2017	93.36
32.63	28.1542	39.8444	40.35	94.852	94.35
39.84	38.192	37.8869	36.23	93.716	94.5
22.7	20.109	36.4009	35.84	93.9018	94.55
35.07	34.9181	36.0482	37.8	94.0715	94.94
44.91	34.1092	35.7144	34.02	93.7773	95.62
39.87	35.9182	40.9351	40.88	96.1363	96.53
18.25	20.1872	44.4009	45.96	96.9018	96.1
35.05	35.1932	49.0698	48.01	90.6553	89.12
45.48	44.2873	47.2632	47.72	93.5952	93.5
33.96	32.8715	43.0698	43.3	93.553	93

Appendix II. Calculated data for separation and cleaning rate along the concave length of threshing units

X(concave length,m)	F1R1				F1R2				F1R3			
	Nts	sgs	ntcl.	sgcl.	nts	sgs	ntcl.	sgcl.	nts	sgs	ntcl.	sgcl.
0	0	0	0	0	0	0	0	0	0	0	0	0
0.1	14.46	45.86	5.67	9.7	15.17	50.97	4.35	13.71	11.42	38.99	4.88	9.18
0.2	50.89	68.58	14.27	4.8	49.3	71.58	9.75	5.55	44.35	63.4	12.08	5.75
0.3	73.53	81.22	8.75	2.67	73.09	81.58	6.79	2.69	69.38	77.19	10.71	3.38
0.4	83.98	86.17	4.09	1.05	84.55	84.05	3.28	0.67	81.93	84.16	5.37	1.64
0.5	88.48	87.82	1.78	0.35	89.29	85.46	1.35	0.38	87.35	86.64	2.32	0.58
0.6	90.14	88.56	0.67	0.16	92.9	85.86	1.03	0.12	90.95	87.41	1.54	0.18
0.7	91.04		0.35		93.93		0.29		92.07		0.48	

X (concave length,m)	F2R1				F2R2				F2R3			
	Nts	sgs	ntcl.	sgcl.	nts	sgs	ntcl.	sgcl.	nts	sgs	ntcl.	sgcl.
0	0	0	0	0	0	0	0	0	0	0	0	0
0.1	13.05	49.3	5.76	12.9	11.42	42.44	3.35	11.01	14.47	38	3.86	9.72
0.2	46.8	71	14.91	5.68	48.29	62.72	10.81	5.26	50.61	64.81	9.65	6.86
0.3	69.37	79.52	9.97	2.23	71.32	74.37	6.75	3.02	76.92	77.4	7.03	3.22
0.4	80.69	82	5	0.65	83.82	79.26	3.66	1.27	87.3	83.69	2.76	1.61
0.5	86.24	83.39	2.45	0.36	88.73	80.55	1.44	0.34	91.33	85.54	1.07	0.47
0.6	90.96	84.32	2.08	0.24	92.56	81.27	0.58	0.19	93.35	86.65	0.54	0.28
0.7	92.07		0.49		94.43		0.55		94.4		0.28	

X concave length,m	F3R1				F3R2				F3R3			
	nts	sgs	ntcl	sgcl	nts	sgs	ntcl	sgcl	nts	sgs	ntcl	Sgcl
0	0	0	0	0	0	0	0	0	0	0	0	0
0.1	13.27	44.96	4.57	11.39	11.45	35.35	4.63	10	11.37	40.42	4.25	11.71
0.2	39.37	67.21	8.99	5.64	47.9	58.58	14.72	6.57	46.12	68.24	12.98	8.05
0.3	67.06	77.88	9.54	2.71	72.73	71.46	10.03	3.65	68.93	79.8	8.52	3.35
0.4	80.95	83.59	4.79	1.45	86.44	77.94	5.54	1.83	81.83	85.83	4.65	1.74
0.5	87.67	85.54	2.32	0.49	92.89	79.7	2.61	0.49	87.27	87.81	2.2	0.58
0.6	92.53	86.74	1.68	0.31	95.55	80.4	1.07	0.2	89.79	89.77	0.94	0.31
0.7	93.85		0.46		96.6		0.42		91.66		0.7	

*nt-newly developd threshing unit; *sg- SG-2000 threshing unit; s-separation rate, cl- cleaning rate

Appendix III. Different Figures

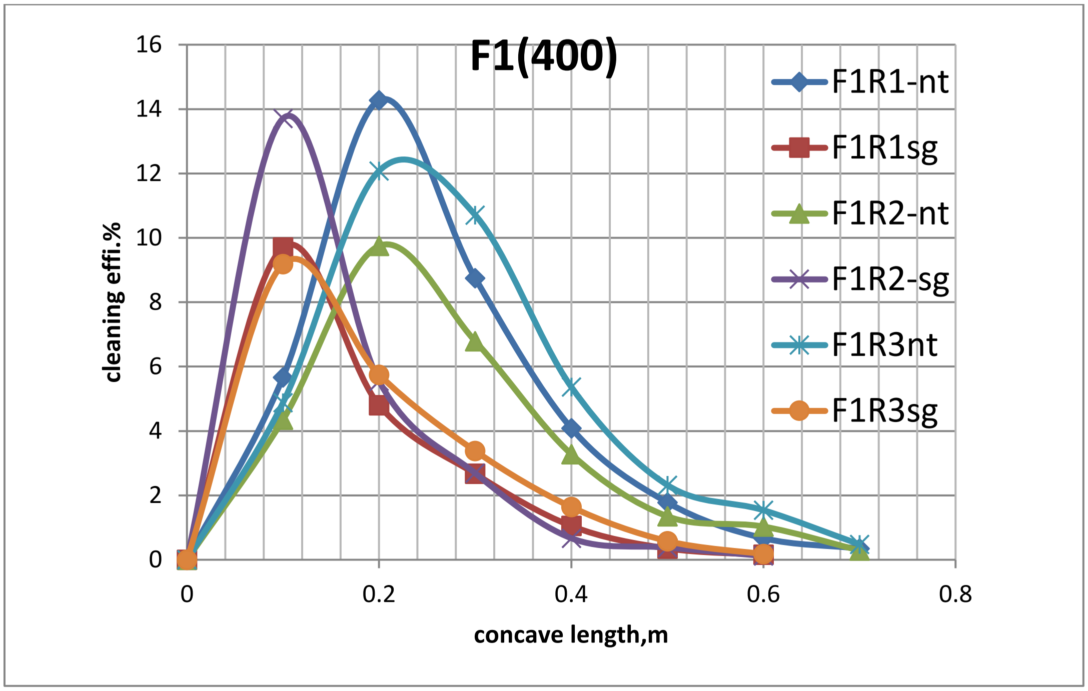

Figure 1.The effect of rpms on the cleaning distribution along concave length

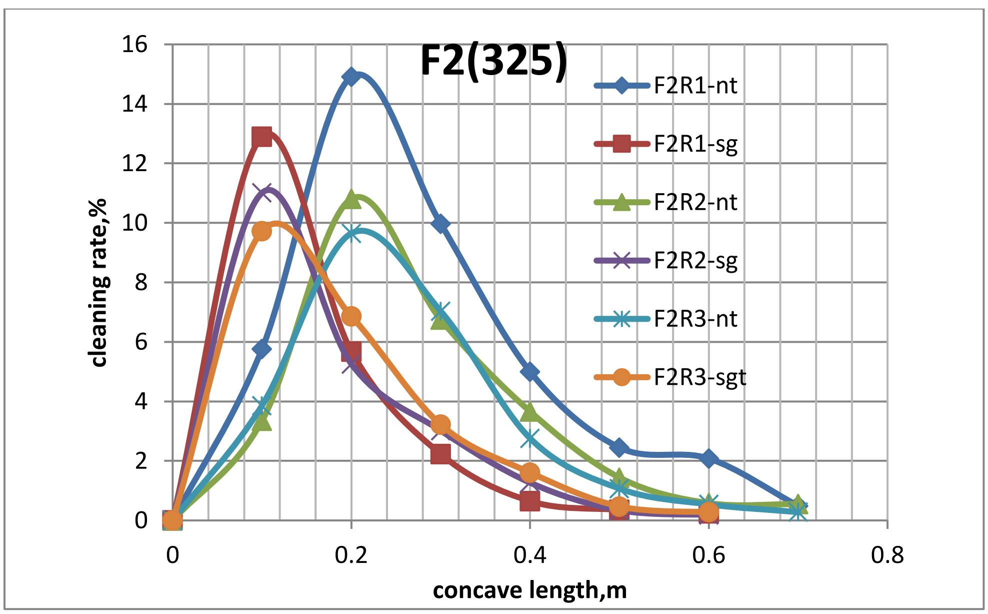

Figure 2.The effect of rpm on the cleaning distribution along concave length

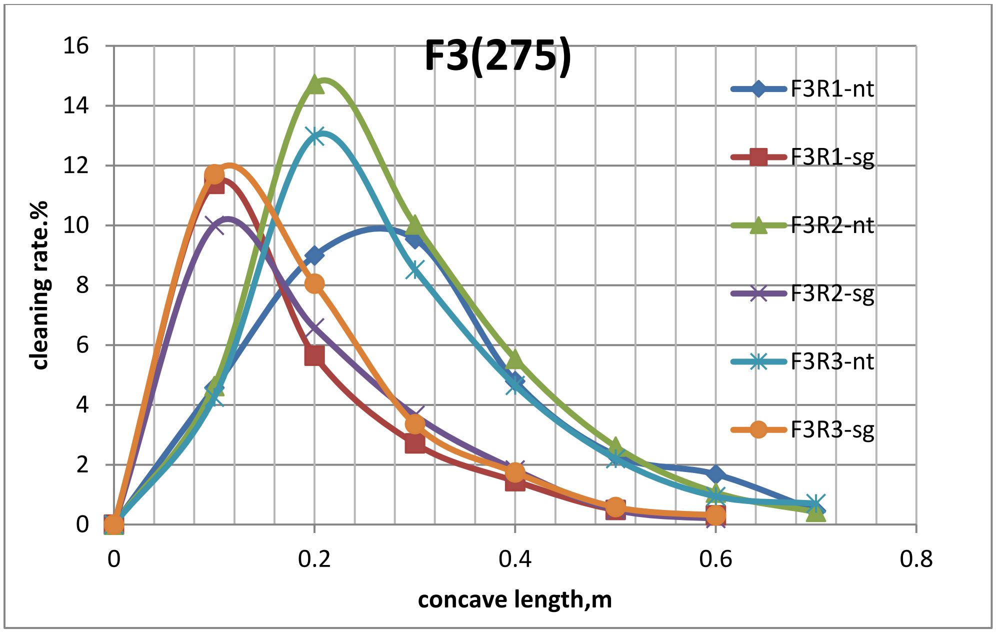

Figure 3. The effect of rpms on the cleaning distribution along concave length

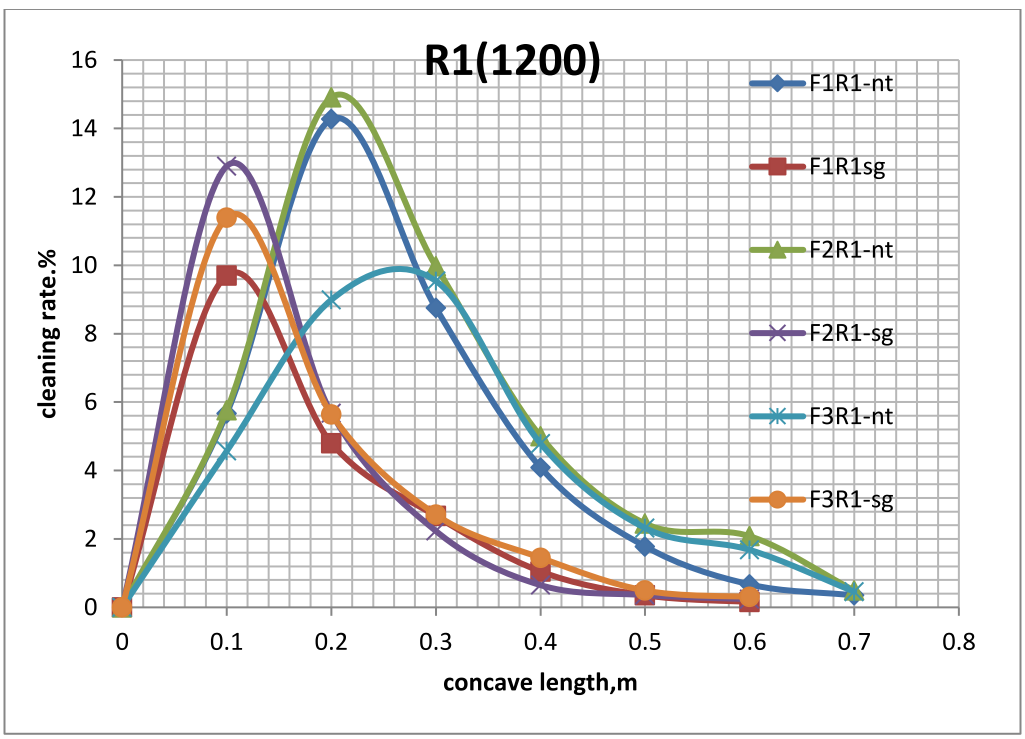

Figure 4. The effect of feedrate on the cleaning distribution along concave length

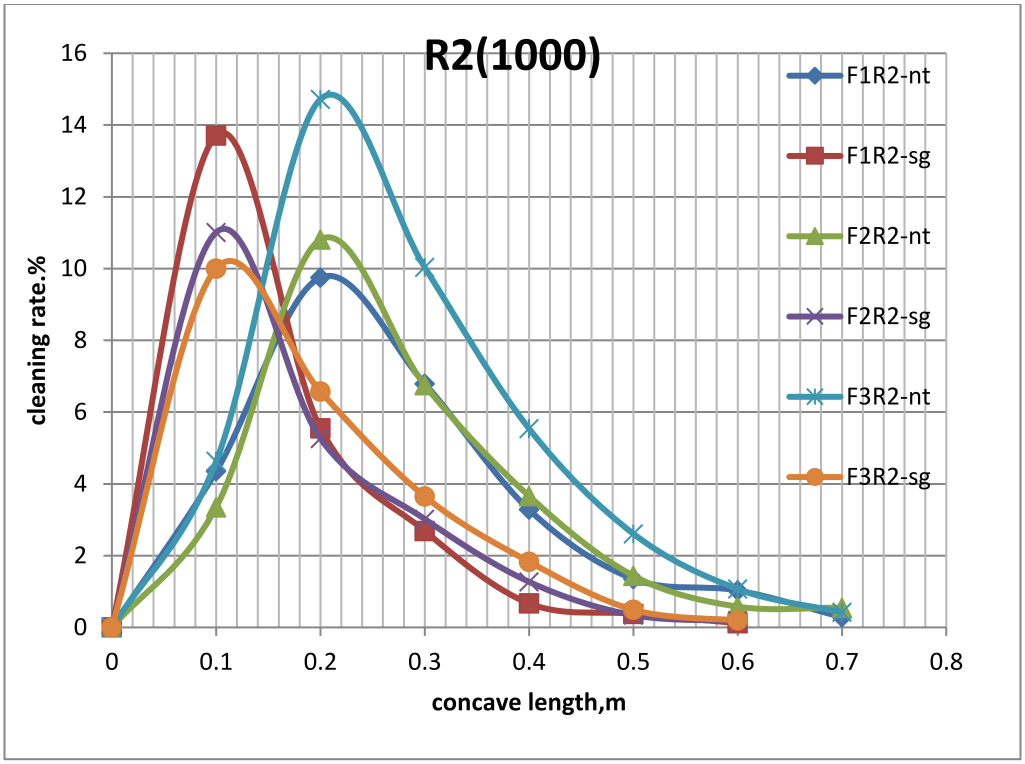

Figure 5. The effect of feedrate on the cleaning distribution along concave length

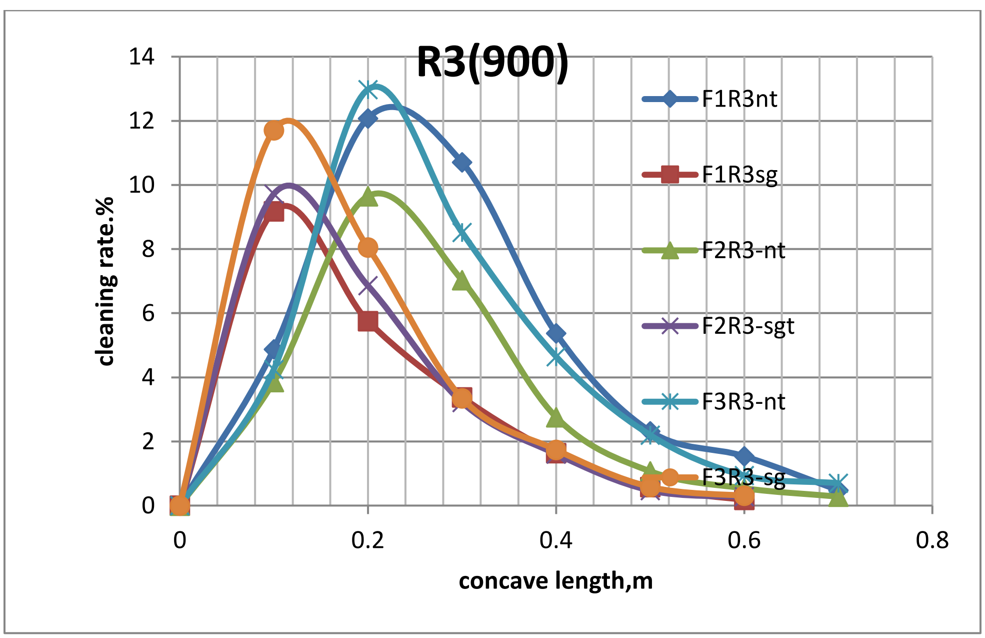

Figure 6.The effect of feedrate on the cleaning distribution along concave length

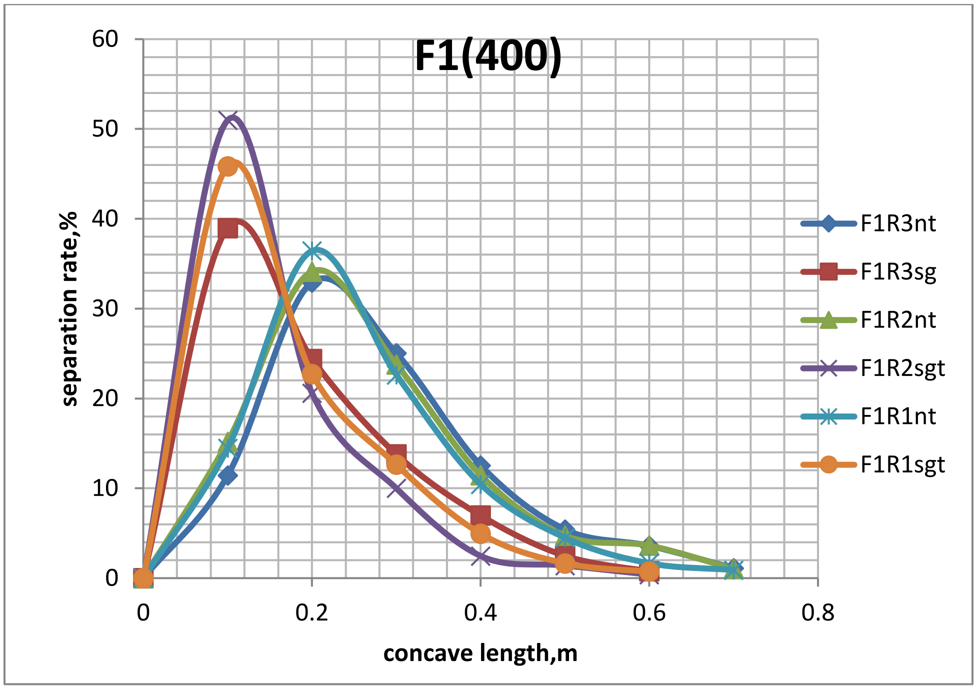

Figure 7. The effect of rpms on the separation distribution along concave length

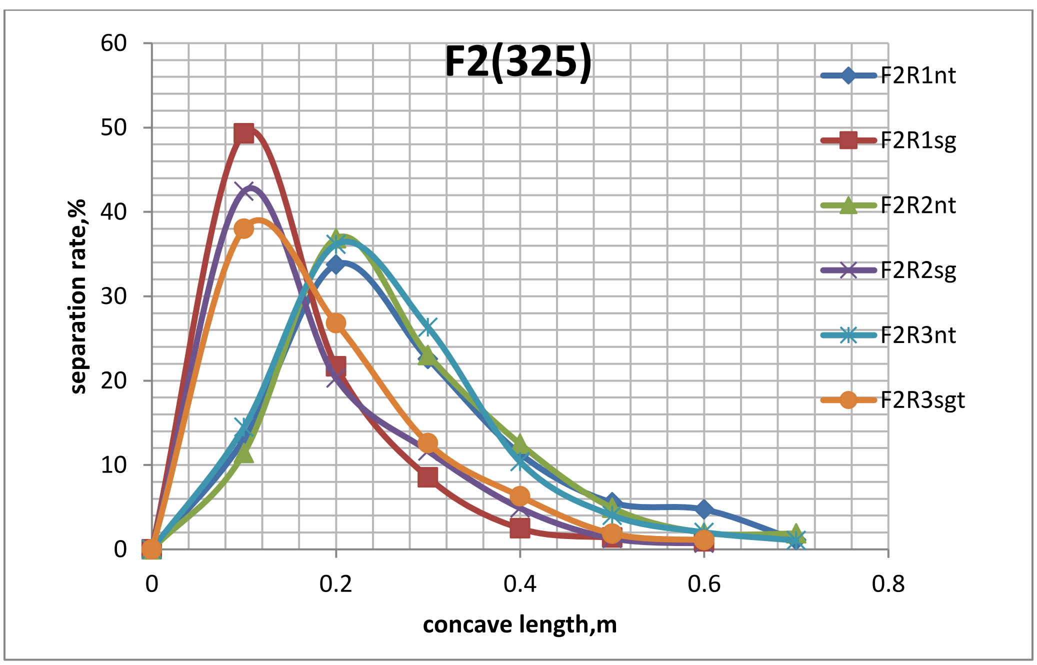

Figure 8.The effect of rpm on the separation distribution along concave length

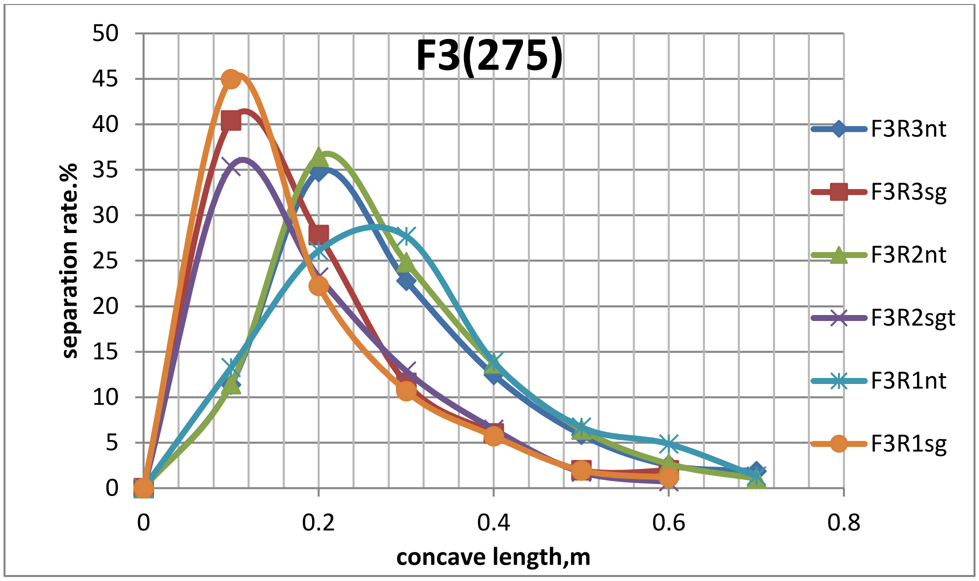

Figure 9.The effect of rpm on separation rate along concave length of threshing units

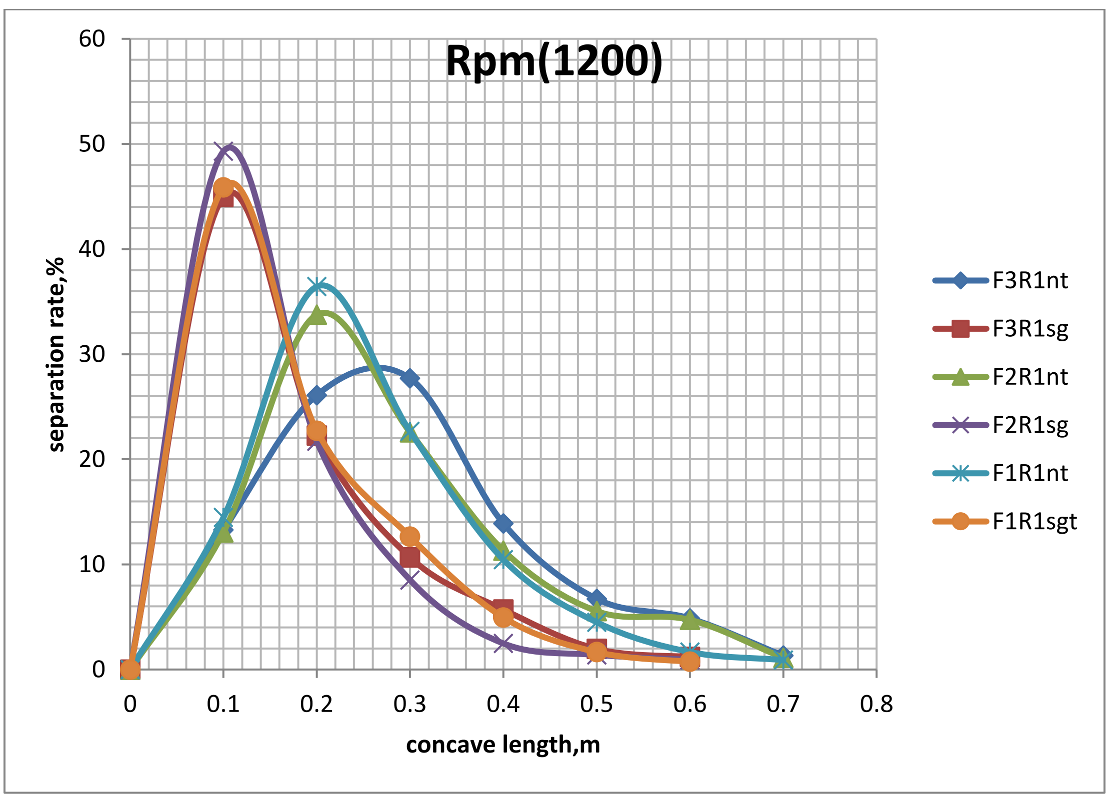

Figure 10. The effect of feeding rate on the separation distribution along the concave length

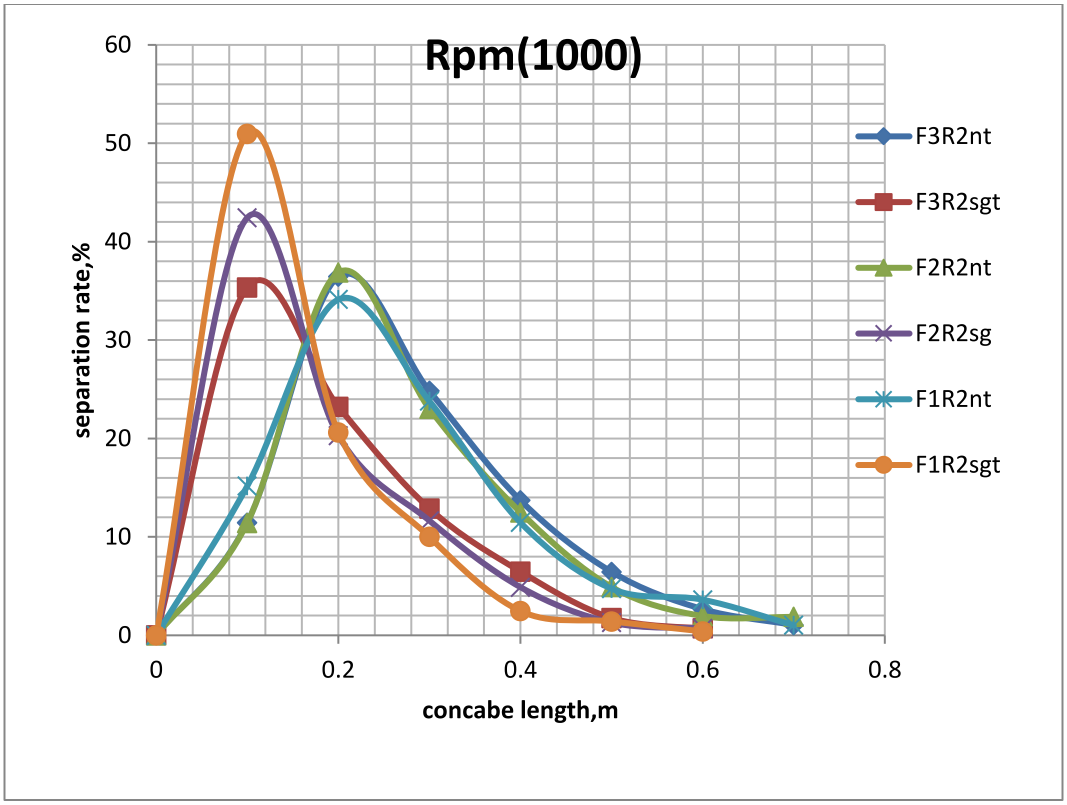

Figure 11.The effect of feedrate on the separation distribution along the concave length

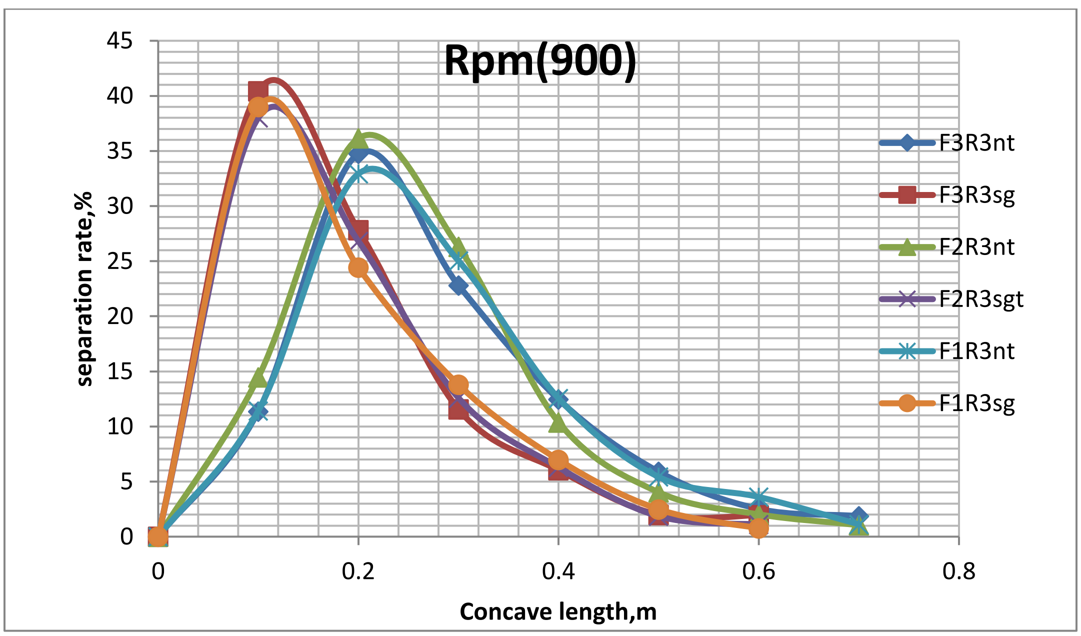

Figure 12.The effect of feedrate on the separation distribution along the concave length

Appendix IV. Test procedure

Procedure for Evaluation of *Tef* Threshing units (adopted from Smith *et al*., 1994)

1. Scope

This procedure is applicable for the evaluation of stationary motor powered *Tef* Thresher, The procedure gives definition of terms, general testing procedures and prescribes the items to be directly measured during evaluation and examine the performance, working capacity and suitability for the task.

2. Definitions of terminology

Moisture Content (M)

From the material which is to be threshed, 3samples are randomly taken approximately 0.5kg each and measured immediately with sensitive balance. The samples are placed in sealed plastic containers and taken to laboratory where the grains and straw are separated by hand. The straw and grains from each sample are kept paired. After weighing, the samples are oven dried at 105^{o}c for at least 15 hours and then reweighed. The moisture content on dry basis,:

$$M = \frac{\text{Weight of wet sample-weight of dry sample}}{\text{Weight of dry sample}} \times 100$$

Grain/Straw ratio(K)

After determining the weight of the dry samples from the above equation, the results of the paired samples are used to calculate the mean grain/straw ratio. The grain/straw ratio(K):

$$K = \frac{\text{weight of dry grain}}{\text{Weight of dry straw}}$$

Size of Grains and straw

From a representative sample of the test material the grains and straw size at least 3 each measured and then grain and straw separated by hand and the weight will be measured. From these measurements, the average diameter and length of straw is calculated.

Machine for Test

The manufacturer shall supply the machine complete and in working order with specifications concerning construction, adjustment details and expected performance for tef crop.

Prior to any test work, the technology specification shall be confirmed and details listed for inclusion in the test report.

a) Overall dimensions and weights
b) Power source and transmission system
c) Details of threshing unit
d) Details of concave
e) Type of sieve
f) Method of transport
g) Safety arrangement

Crop Conditions

Sufficient quantity of at least 2 varieties of *tef* shall be provided in order to carry out the complete test series /but for the first prototype one variety is enough/. Samples shall be taken from each batch in order that the following can be specified

a) Type/variety
b) Moisture content
c) Grain/straw ratio
d) Straw size(length and diameter)

When the expected throughput of the machine has been established, smaller quantities of the crop are pre weighed.

Measuring Equipments

Weighing

Balances the appropriate accuracy for weighing crop and grain samples /with sensitive balance / shall be provided. And the samples for each feed rate shall be measured as tied sample (bulk sample) , each sample weight is better to be 5-10kg.

The outputs in each test chambers (out lets) shall be measured as pure tef, chaff, straw and or material other than grain.

Preliminary Running

With the machine set up in accordance with the testing procedures and the threshing mechanism adjusted for the type of crop (Tef), runs are made at various input rates and speeds. These runs will enable feed rates to be established and allow operators and engineers to familiarize themselves with operation of the machine.

Performance Tests

Test runs of limited time duration will be carried out using 1 variety of crop 3 level of feeding rates for 3 level of thresher speed. During the test period, samples of threshed grain, straw and chaff shall be taken at their respective outlets (for Tef thresher the test stand has 7 compartments for collection of outputs as tef and chaff ,and 1 out let for straw).The time over which the sampling is done shall be recorded.

Any times for stoppages will be recorded, together with the total testing time. Observations on factors affecting the operation of the machine shall be recorded together with any adjustments and repairs. At the end of each test, the machine shall be operated idle for 2 to 3 minutes to clear residue from the outlets.

The following measurements shall be made.

Test record sheets are given in the appendix.

Parameters		Units	Symbol
1	Time of test runs	mins	T
2	Weight of threshed grain at all main outlet per unit time	kg	B
3	Weight of threshed grain at all other outlets per unit time	kg	C
4	Weight of unthreshed grain at all outlets per unit time	kg	D
5	Weight of damaged grains collected at all outlets per unit time	kg	E
6	Percentage of damaged grains in total input before threshing	kg	F
7	Weight of whole grains collected at chaff and straw outlets per unit time	kg	G
8	Weight of all grains(whole, damaged and un-threshed) at chaff and straw outlets per unit time	kg	H
9	Weight of unthreshed grain at all outlets per unit time	kg	J
10	Weight of whole grain at main grain outlet per unit time	kg	K
11	Weight of whole material at main outlet per unit time	kg	L

		units	symbol	Calculation
a	Total grain in put	kg	A	B+C+D
b	Percentage of unthreshed grain	%	N	J/A x 100
c	Threshing efficiency	%		100-N
d	Cleaning efficiency	%		K/L x 100
e	Increase in percentage of damaged grains	%		$\frac{[E \times 100]-F}{A}$
f	Percentage of blown grain	%		$\frac{G}{A} \times 100$
g	Percentage grain loss	%		$\frac{H}{A} \times 100$
h	Threshing recovery	%		$\frac{B}{A} \times 100$
i	Output capacity	Kg/h	W	$\frac{B}{T} \times 60$
j	Corrected output capacity to standard moisture content (SMC) and standard grain ratio(RS)	Kg/h	Wc	$\frac{W \times (100-MC)}{(100-SMC)} \times \frac{RS}{R}$

Durability Tests

The thresher should be operated for at least 20 hours under load with continuous runs of at least 5 hours. During these tests, particular attention should be made to adjustments, repairs ease of operation, clogging and maintenance of feed rate.

Experimental set up:

After data collection the analysis will be based on factor factorial with CRD. The dependent variables are cleaning efficiency in%, threshing efficiency in % and threshing capacity in $kg.h^{-1.}$

The independent variables are feed rate in kg/h and threshing drum speed in rpm.

Method of data analysis will be in completely randomized design (CRD) and employed on the treatment factor replicated three times. The collected data will be subjected to analysis of variance (ANOVA). Significance of the mean difference will be tested by LSD and significance will be accepted at 1-5% level.

Report

Diagram/ photograph

A line drawing and a photograph showing the principal details of the construction and layout of the machine shall be provided.

Brief description

A brief description shall be provided of the power transmission system and the threshing mechanism

Specification

Make :AMMITDE

Model:NT-2017

Serial number:

Manufacturer name and address:Amhara Region, Bairdar

Overall dimensions

	For operation		for transport	
Length	1500	mm	1500	mm
Width	1400	mm	750	mm
Height	1320	mm	1320	mm
Weight	150	kg		

Power source

Type: Motor

Make: Italy

Model: ADN-14

Rated output : 12 kW

Rated speed: 3000 rev/min

Power Transmission system: Pulley

Feeding arrangements:

Type: Manual

Arrangement of mechanical feed : Manual feed

Length and width of feeding table: 700 x 900 mm/mm

Height of feeding table above ground: 1000 mm

Feed rate(s) average: 400 kg/h

Results of performance tests

Crop____ Tef
Variety ______________________________ Dz-Cr-387/RIL-355(Quncho)
Moisture content:_______________ %
Grain/straw ratio:__________________________
Size of grains:____________________________ mm/mm
Damage to grains:_______________________________ none %

1. Summary of test result data sheet (For each test)

Threshing drum speed or settings Rpm	1200			1000			900		
Replications	1	2	3	1	2	3	1	2	3
Total grain input, (kg)									
Threshing efficiency, (%)									
Cleaning efficiency, (%)									
Increase in percentage of damaged grains, (%)									
Percentage of blown grains, (%)									
Percentage of grain loss, (%)									
Threshing recovery, (%)									
Output capacity, (kg/h)									
Output capacity corrected to % moisture content and standard grain ratio, (kg/h)									
Power requirements,(kwh/ton)									
Labour requirements, (man h/ton)									

Crop feed rate, kg/h	400			325			275		
Replications	1	2	3	1	2	3	1	2	3
Total grain input,(kg)									
Threshing efficiency,(%)									
Cleaning efficiency,(%)									
Increase in percentage of damaged grains, (%)									
Percentage of blown grains, (%)									
Percentage of grain loss, (%)									
Threshing recovery, (%)									
Output capacity , (kg/h)									
Output capacity corrected to % moisture content and standard grain ratio, (kg/h)									
Power requirements, (kwh/ton)									
Labour requirements, (man h/ton)									

Repairs or adjustments during tests:

Comments and observations:

Technology variant for evaluation

I. SG model threshing unit (SGT)

II. Newly developed threshing unit (NT)

it	Variables	Variants			Remarks
1	Thresher	SGT	NMT		
2	Feed rate (kg/h)	400(F1) Fast	325(F2) Medium	275(F3) low	Feed rate approximation will depend by speed of operator
3	Drum speed (RPM)	1200(R1)	1100(R2)	900(R3)	

Treatments

Treatments (code)	Combination of treatments	Replications		
		1	2	3
1	Nt, F1R1			
2	Nt,F1R2			
3	Nt,F1R3			
4	Nt, F2R1			
5	Nt, F2R2			
6	Nt, F2R3			
7	Nt, F3R1			
8	Nt, F3R2			
9	Nt, F3R3			
10	SGt, F1R1			
11	SGt, F1R2			
12	SGt, F1R3			
13	SGt, F2R1			
14	SGt, F2R2			
15	SGt, F2R3			
16	SGt, F3R1			
17	SGt, F3R2			
18	SGt, F3R3			

Remark: Total number of test is the combinations of treatments time's replications and sample boxes

18 X3=**54 test** and a total of **54 x8=432** test samples shall collect.

Data sheets (as appendix)

1. Data sheets for crop samples

	Sample			average
	1	2	3	
Variety	Tef /quncho/	Tef /quncho/	Tef /quncho /	Tef /quncho/
Moisture content /w.b/ %	11.16	9.78	13.60	11.51
Grain/straw ratio	1:8.1	1:6.4	1:4.2	1:6.25
Length of the stem average , mm	430	590	520	513.33
Length of the panicle average, mm	250	320	510	360
Bulk density of the Tef, kg/m^3	46.81	51.80	54.06	50.89

2. Test data sheet for each samples

Test no	date	Starting Time, H min	Stopping Time H min	Duration of test h min	Drive Speed rpm	Feed Rate Kg/h	Number of samples (code)	Quantity of samples Kg

3. Data sheet for analysis of test samples(each samples)

Sample no (Code)	Feed rate Kg/h	Thresher Speed rpm	Total Mass of Sample kg	Sample from	Mass , kg			Total threshing time(min)
					Clean grain	chaff	straw	
				out let 1				
				Outlet2				
				Outlet3				
				Outlet4				
				Outlet5				
				Oulet6				
				Oulet7				
				Straw outlet				
				overflow				

4. Stoppages during test

Test number

Time			Reason for stoppages
From	To	Total	

5. General observations :

Appendix V: Cost estimation for *tef* threshing unit with test stands

Itno.	Description	Material	Size (LXW) (mm x mm)	Qty	Unit price		Total Price	
					birr	cen	birr	cen.
1	Concave cover	Sm thic.=1.5mm	475x 835	2	216	63	433	26
2	Concave cover plate	SM thick=1.5mm	500 x500	1	81	25	81	25
3	Crop collector right and left	Sm thick=1.5mm	500x835	2	135	69	271	38
4	Crop collector middle	Sm thick=1.5mm	497x420	8	100	05	800	40
5	Crop collector F&R	Sm thick=1.5mm	500x420	2	136	50	273	00
6	Drum bush	Mildsteel shaft dia=50mm	50x10	2	55	00	110	00
7	Drum cover	Sm, thick=1.5	360 x 360	2	84	24	168	48
8	Puelly	Aluminum shaft dia 300mm	70mm	1	210	00	210	48
9	First drum auger	Sheet thick 3mm	750x60	3	43	87	131	61
10	First drum	Sm thick 1.5mm	1131x250	1	191	50	191	50
12	Main shaft	Solid shaft dia 35mm	1100mm	1	460	00	460	00
13	Feeding table	Sm thick 1mm	1135x700	1	450	00	450	00
14	Feeding table reinforcements	Rods dia 6mm	1800mm	1	110	00	110	00
15	Third drum	Sm thick 1.5mm	1131x200	1	125	00	125	00
16	Outlet lower plate	Sm thick 1.5mm	168x250	2	54	00	108	00
17	Outlet side plate	Sm thick 1.5mm	168x200	2	47	38	94	76
17	Round concave cover	Sm thick2mm	475x475	2	62	25	124	50
18	Round concave	Perforated sheet thick=3mm	786x835	1	1500	00	1500	00
19	Round concave bar	Flat iron 3mm thick	786x25	3	125	00	375	00
20	Second drum peg	Flat bar thick 6mm	360x40	8	54	25	434	00
21	Second drum	Sm thick1.5mm	1131x360	1	135	00	135	00
22	Short angle iron frame	Angle iron	440x40x40x4	1	35	50	35	50
23	Square pipe lower support	Square pipe	500x40x40x3	1	42	20	42	20
24	Square pipe left support	Square pipe	705x40x40x3	1	60	00	60	00
25	Angle iron F&R	Angle iron	580x40x40x4	2	48	33	96	66
26	Main frame_(stand)	Square pipe	1000x40x40x4	4	92	35	369	40
27	Long square pipe	Square pipe	915x40x40x3	2	83	87	167	74
					Total		7359	12

Material Cost -7359.12 Birr

Labour cost –36 x 50=1800Birr

Machine cost- 10 x120=1200Birr

Subtotal = 7359.12 + 1800 +1200=**10359.12**

Manufacturing cost for threshing unit with test stand= **10359.12 Birr**

Material cost for *tef* threshing unit (drum assembly and Concave)=**4311.12Birr**

Diesel motor 14hp motor cost = **40000Birr**

Grand total cost =50359.12 Birr

Appendix VI: Published research article

1. **Characterization and evaluation of the mechanical and physical properties of *Tef* stem (*Eragrostistef* (Zucc.) Trotter).** by: Geta Kidanemaram, Daniel Tilahun and Adamu Zegeye. AgricEngInt: CIGR Journal Open access at http://www.cigrjournal.org Vol. 21, No. 1 April, 2019.
2. **The effect of threshing units' design on performance of tef[Eragrostistef (zucc.)Trotter] thresher**. by: Geta Kidanemaram, Daniel Tilahun and Adamu Zegeye. A NNALS of Faculty Engineering Hunedoara – International Journal of Engineering.Vol.17 no3, May 2019. ISSN-L 1584 – 2665.

Appendix VII. Manufacturing drawing for new threshing unit and test stand

Tef Threshing Unit's Test Stand