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Gathering Performance of Combine Harvester in the Case of Tef Crop Harvesting in Ethiopia

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ABSTRACT

The gathering performance of the combine harvester is affected by crop factor and machine setting parameters. The crop factor like the physico-mechanical behavior, has a profound effect on the performance of the combine harvester. Likewise, the machine setting parameters, *i.e.,* forward speeds, reel rotation speeds and cutter-bar settings, affect combine harvester performance. Over the years, different research was conducted to show the relationships and the effects of crop factor and machine setting parameters on the performance of combine harvesters. Following that, recommendations and further modifications have been performed on existing combine harvester units in different countries to improve combine harvester's efficiencies and adapt them to local crop conditions. However, when it comes to the Tef crop; a staple crop over 70 million Ethiopians depend on the initiatives to adapt existing combine harvesters to address the crop which are negligible owing to the nature of the crop and the very limited research works conducted on the theme so far. As a result of that, Tef farmers of Ethiopia continued to harvest the crop manually using rudimentary tools which entail a large sum of human labor and devotion of time. In this paper, the effects of crop factor and machine setting parameters on harvester's performance and the initiatives to improve existing combine harvesters are accounted indetail through a thorough review of published literature conducted in different countries. The reason why Tef farmers of Ethiopia do not employ existing combine harvesters is also documented along with the way forward to adapt such an important agricultural machine.

Keywords : Physico-mechanical behavior of crops, Combine harvesters machine settings, Header loss, Tef harvesting

ETHIOPIA is heavily dependent on agriculture as a predominant source of employment, income and food security for the vast majority of its population. The agriculture sector plays a central role in the life and livelihood of most Ethiopians (Benyam *et al.*, 2021). The agricultural sector of Ethiopia has a major share in country's GDP, creating employment opportunity and external earnings of 34.1, 79 and 79 per cent, respectively and also is the major source of raw materials and wealth for investment in international market (Diriba, 2020 and Kolhe *et al.*, 2024). Cereals have been the most produced crops in Ethiopia. According to the CSA (2018-19) main rainy season 'Meher' post-harvest crop production survey, about 71.6 per cent of the total area was covered by crops and more than 69.5 per cent of crop output was generated from cereals. In 2020-21, the area coverage of cereals increased to 81 per cent of the allotted 14.65 million ha of land for crop production out of which Tef crop took up about 29 per cent (CSA, 2021). Ethiopia is the largest Tef producer in the world accounting 24 per cent of the grain area followed by maize at 17 per cent and sorghum at 15 per cent (Table 1). Amhara and Oromia are the two major regions and collectively, those two regions that accounts for 85.5 per cent of the Tef area and 87.8 per cent of the Tef production (CSA, 2019).

TABLE 1

Production of cereal crops and Tef in Ethiopia

Crop	Area (ha)	Yield (ton/ha)
Grain crops	12,574,107 (100%)	-
Maize	2,135,571 (17%)	3.675
Sorghum	1,881,970 (15%)	2.525
Tef	3,017,914 (24%)	1.664

The demand for Tef in the country is continuously increasing day by day due to an increase in population. Table 2 shows the amount of cropped land area, production and yield of Tef across various cropping seasons. The increase in area, production, and yield consumed more labor and effort, which became a challenge for Tef growing farmer community and raised the need for mechanized Tef harvesting in the country.

Many findings associate the low productivity of the crop with low availability and use of modern inputs (seed and fertilizer) and the traditional method of production of the crop. However, most of the pertinent issues of Tef productivity are now being solved through integrated efforts of concerned governmental sectors and research institutes except the issue related to crop harvesting. Tef harvesting in Ethiopia is very time-consuming and resource-intensive work as the operation is done manually using sickles (Tadesse *et al.,* 2016). This harvesting method requires 8-12 human labour per day to harvest a 2000-2500 m^2 area of growing land and had there been mechanized harvesters, the number of days for labor per ha may have reduced by 70-80 per cent (Abraham, 2015). However, combine harvesters suitable for the Tef crop are not yet available and the existing harvesters have high lodging losses. This is mainly related to the nature of the crop (crop factor) and the way the gathering reel units of existing combine harvesters (machine factor).

The performance of a combine harvester is affected by crop factors (crop physical and mechanical properties), machine setting parameters and its design. This important agricultural machine's performance cannot be improved without in-depth knowledge of these relevant aspects. For this, it is imperative to review different literature which has been conducted on such themes. The purpose of this paper is, thus, to reveal the effect of crop and machine factors on the gathering performance of combine harvester.

Literature Review

Grain harvesting is the act of collecting grains from the field and separating them from the rest of the crop material with minimum grain loss while maintaining the highest grain quality (Ajit *et al.*, 2012). Harvesting time is a critical factor dictating the losses during the harvesting operations. Grain loss occurs before or during the harvesting operations if it is not performed at an adequate crop maturity and moisture content. Too early harvesting of crops

TABLE 2

Cultivated area, production and yield of Tef in Ethiopia (CSA reports, 2019-2021)

Production year	Area Covered		Production		Yield q/ha
	ha	Distribution (%)	q	Distribution (%)	
2017-18	3,023,283.50	23.85	52834,011.56	17.26	17.48
2018-19	3,076,595.02	24.17	54,034,790.51	17.12	17.56
2019-20	3,101,177.38	24.11	57,357,101.87	17.11	18.50
2020-21	2,928,206.26	22.56	55,099,615.14	16.12	18.82

at high moisture content increases the drying cost, making it susceptible to mould growth and insect infestation, resulting in a high amount of broken seeds. Whereas, too late harvesting operation leads to high shattering losses, exposure to bird and rodent attacks and losses due to natural calamities (rain, hailstorms, etc.). In addition to the moisture content of the crop at the physiological maturity stage, the availability of harvested grain processing and storage options is also a critical factor in deciding the harvesting time of crops. Thus, optimization of the moisture content of the crop and the availability of grain processing facility options need to be dealt critically before harvesting physiologically matured crops to minimize grain losses and the associated costs as well (Metz, 2006). Harvesting operations are done either with machines (combine harvesters or windrows) or manually using sickles. The choice of the method and equipment however depends on the type of crop, planting method and climatic conditions (Srivastava *et al*., 1993). A modern grain combine performs many functional processes (Fig. 1). These are gathering and cutting (or in the case of windrows, picking up), threshing, separation and cleaning.

The header is one of the major components of a combine by which crop gathering and cutting are done. Research studies reveal that the efficiency of gathering operation of a header of a combine is greatly influenced by crop type and its physico-mechanical properties (Chinsuwan *et al.*, 2002), the combiner forward speed, reel design and speed (Quick, 1999; Mohammed & Abdoun, 1978 and Chinsuwan *et al.*, 2004), cutter-bar type and speed (Hummeland, 1979), reel interaction with the crop and reel position (Kutzbach & Quick, 1999). Crop factors *i.e.,* physical condition and associated mechanical behavior have a profound influence on the gathering and processing efficiencies of combine harvester (Yore *et al.*, 2002). As information on crop factors is crucial for early design and further improvements of components of the combine (Chinsuwan *et al.*, 1997), many researchers have researched the physical and mechanical behaviors of crops. Shaw *et al.* (2007) and Yiljep *et al.* (2005) proved that the physical conditions of crops (moisture content, stem diameter and thickness, stalk height, panicle length and weight, crop density, posture and crop variety) affect the mechanical properties of crops (tensile strength, shear module, bending strength, flexural rigidity and modulus of elasticity) (Tefari and Kolhe, 2021). Shahbazi and Nazari (2012) studied the bending and shearing properties of safflower stalk and found that the average bending stress value varied from 21.98 to 59.19 MPa. They also reported that Young's modulus in bending also decreased as the moisture content and diameter of stalks increased and the shear stress and the shear energy increased with increasing moisture content and diameter of the crop

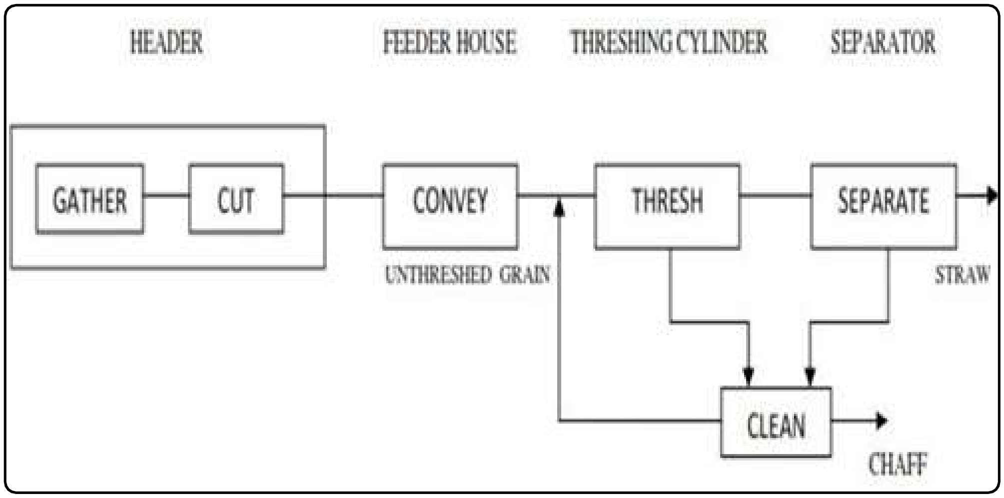


Fig. 1 : A process diagram of a combined harvester

stem. 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 of the stem with a moisture content of 37.16 per cent. Bending stress, Young's modulus, shearing stress and shearing energy were determined for Alfalfa (*Medicago sativa* L.) stem by Nazari *et al.* (2008) through the experiments conducted at a moisture content of 10, 20, 40, and 80 per cent wet basis. The results showed that the bending stress and the Young's modulus decreased as the moisture content and the diameter of the stalk increased, respectively. Tavakoli *et al. (*2010) and Yashwant *et al.* (2024) compared the mechanical properties of rice straw Hashemi and Alikazemi varieties. Moisture content taken for Hashemi was 71.6 per cent w.b. and for Alikazemi was 70.8 per cent w.b. at which the experiment was conducted. Shear strength was found to be 13.08 MPa for Hashemi and 8.56 MP for Alikazemi. Chandio *et. al*. (2013) worked on three different wheat varieties at different moisture content levels with three knife-cutting bevel angles at three shearing speeds of the pendulum. At 25 and 30 per cent moisture contents the shear strengths were less but at 35 per cent moisture contents shear strengths were greater. Shear strength was found to be increased with shearing speed and decreased with the decrease in bevel angle and moisture content. Tavakoli *et al.* (2009) in their research work to determine the effects of moisture content (at four levels) and internode position (three positions) on some physical and mechanical properties of wheat straw showed that the values of the physical properties and the shear energy increased with increasing moisture content and the diameter of the nodes. Geta (2020) reported that there were significant differences in the physico-mechanical properties of four varieties of Tef crops and suggested that further similar work should be done for other varieties of the crop. Machine parameters and settings have also a profound effect on the gathering performances and field efficiencies of combine harvester (Srivastava *et al.*, 1993). Martin *et al.* (2018) presented an overview of the combine harvester setting for barley and wheat crops. The custom setting differs from the one recommended by the manufacturer mainly in the gap between the basket, rotor and bottom sieve opening (20 and 29%, respectively) for barley reframe the sentence. The difference in custom setting for wheat is significantly greater than for barley, the gap between basket and rotor was increased by 146 per cent and the openings of upper and lower sieves were significantly changed by 42 and 72 per cent, respectively as shown in Table 3. During testing, lower losses were observed in the custom setting for both crops as shown in Table 4.

Omar *et al.* (2021) evaluated a combine harvester (CLAAS Crop Tiger 30) to see the effect of its forward and reel speeds on wheat gain losses in Gezira State, Sudan. The experiment was conducted in a split-plot design with three forward speeds (4, 5 and 6 km/h) in the main plots and three reel speeds (25, 35 and 45 rpm) in the sub-plots. The dependent parameters were total header loss, processing loss and total machine losses. According

Table 3

Overview of the combine harvester settings for different crops (Martin *et al.*, 2018)

Crop Setting	Spring barley			Winter wheat		
	Recommended	Custom	Difference (%)	Recommended	Custom	Difference (%)
Rotor speed, min^{-1}	750	770	+2.66	900	900	0.00
Cleaning fan speed, mm^{-1}	20	24	+20.00	15	37	+146.60
Opening of upper sieve mm	900	900	0.00	980	1050	+7.14
Opening of upper sieve mm	16	17	+6.25	14	20	+42.58
	17	12	-29.14	9	16	+77.70

TABLE 4

Average harvest losses of spring barley and winter wheat depending on combine harvester settings and overall grain yield

Spring barley			Winter wheat		
Avg. yield (tha^{-1})	Avg. losses at recommended setting (%)	Avg. losses at custom setting (%)	Avg. yield (tha^{-1})	Avg. losses at recommended setting (%)	Avg. losses at custom setting (%)
4.284	0.52	0.41	4.759	0.58	0.49
5.581	0.61	0.55	5.829	0.69	0.55
6.188	0.71	0.59	6.531	0.75	.63
6.898	0.80	0.61	7.807	0.88	0.70
7.543	0.95	0.68	8.039	0.97	0.75

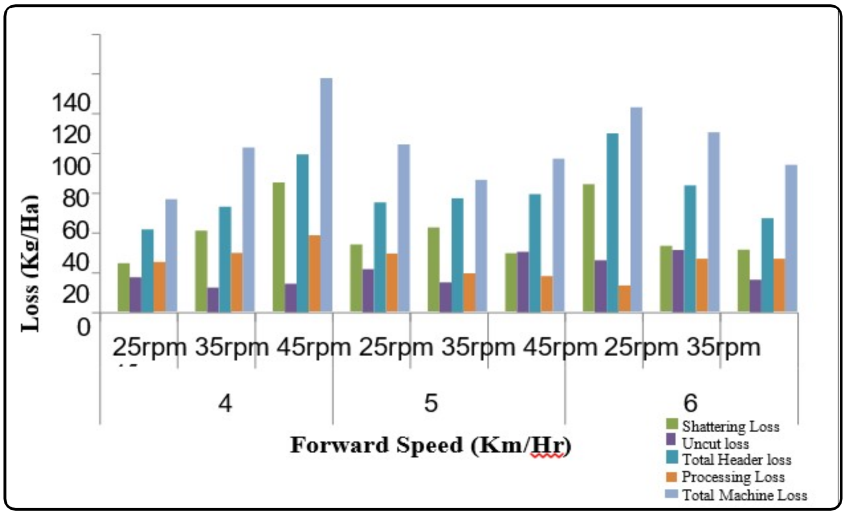


Fig. 2 : Effect of combine forward and reel speed on all losses

to the test result, the lowest (41.75 kg/ha) and the highest (90.10 kg/ha) total header losses were recorded from forward speeds of 4 km/h and 6 km/h at reel speed of 25 rpm in both cases, respectively. On processing losses, a forward speed of 6 km/h with a reel speed of 25 rpm recorded the lowest loss (13.2 kg/ha) while a forward speed of 4 km/h with a reel speed of 45 rpm was found to provide the highest loss (38.2 kg/ha). The lowest (56.74 kg/ha) and highest (118.02 kg/ha) total losses were recorded from a forward speed of 4 km/h at reel speeds of 25 rpm and 45 rpm, respectively (Fig. 2.).

Bawatharani *et al.* (2013) investigated the effect of reel index on header losses of two combine harvesters (Kubota DC-68G and Agroworld 4L-88) on long rice crop (Bg 94-1) in *Palugamam (*Sri Lanka) under a split-plot design with three replications. The main plots of the experiment were assigned to the forward speeds of the combiners i.e. 0.56 , 0.82 and 1.8 km/h for the Kubota harvester and 0.53 km/h, 0.76 km/h and 1.06 km/h for the Agroworld combine, and the sub-plots of were assigned to three levels of reel indexes (1.2, 1.7 and 2.5). The results revealed that reel index of 1.7 resulted insignificantly low header

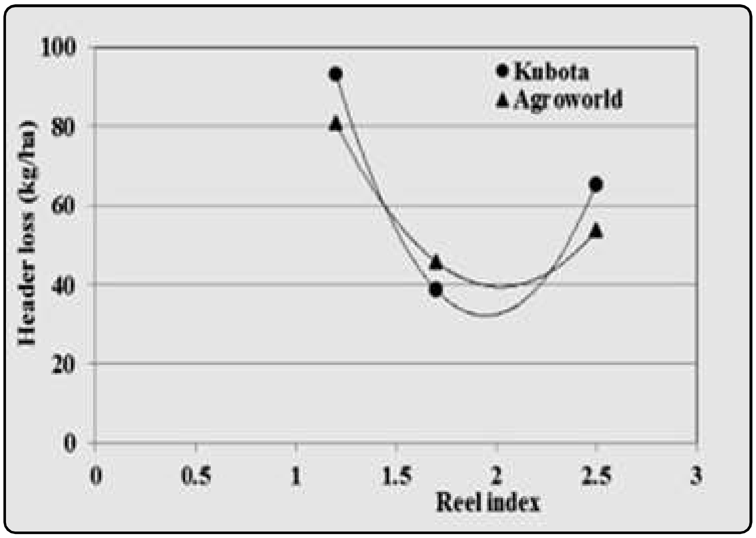


Fig. 3 : Header Losses at different reel index levels

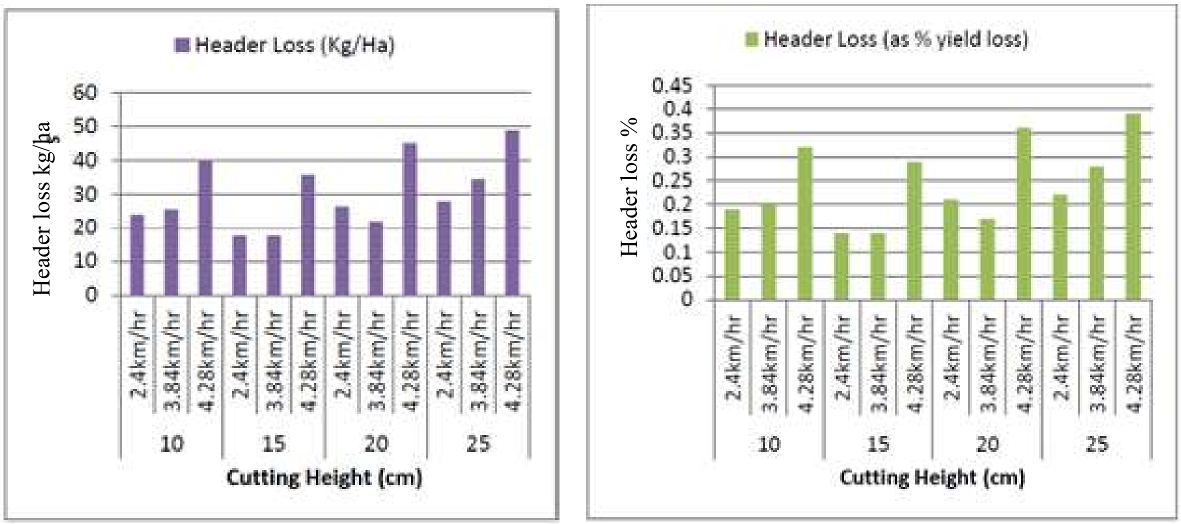
losses of 38.8 kg/ha and 45.8 kg/ha for Kubota and Agroworld harvesters, respectively. Whereas, reel indexes 1.2 had resulted in higher header losses in both combiner sowing to a greater header advancement and an increased tine bar velocity. The losses recorded for both combiners were also found to be high at a reel index of 2.5 due to lesser header advancement and an increased number of impacts of the reel on panicles of the crop (Fig. 3.).

Ramadhan *et al*. (2013) conducted research on wheat crops in Babylon province (Iraq) to investigate the effect of three forward speeds (2.4 km/h, 3.34 km/h and 4.28 km/h) at three cutter-bar settings (10, 20, and 30 cm) of CLAAS combiner on the header and subsequent unit losses. The test result revealed that there were increased header losses as the forward speed increased from 2.4 km/h to 4.28 km/h. They also reported that a forward speed of 2.4 km/h at a 30 cm cutter-bar setting gave lower total harvester loss as compared to the other settings and there was a trend of increment in the total harvest loss as the forward speed increased.

Bawatharani *et al*. (2017) researched rice crops using a CLAAS C210 combine harvester equipped with a reel-type header at Anuradhapura (Sri Lanka) to investigate the header grain losses and quality of paddy grains for three levels of cutter-bar heights (10, 15, 20 and 25 cm) and forward speeds of 2.4, 3.84 and 4.28 km/h under RCBD design with split plot arrangement where the forwarded speed as the main plot factor and the cutting heights were considered as subplot factors. The result revealed that cutting heights of 10, 20 and 25 cm resulted in greater heading losses. The highest mean header loss, 37.04 kg/ha, was shown at 25 cm cutting height and the lowest, 23.71 kg/ha, was registered for 15 cm (Fig. 4.).

A forward speed of 4.28 km/h had shown statistically the highest significant loss, 42.41 kg/ha, whereas the lowest significant loss (23.96) was registered for a forward speed of 2.4 km/h. In terms of grain damage, the authors reported that cutting height hardly had a significant impact but forward speed had a strong negative relationship with grain damage (Fig. 5).

El-Nakib *et al.* (2003) used the Kubota combine as a mechanical harvester of rice crops for loss tracking under different conditions. They found that header, threshing, separating, and shoe losses increased with the increase of the forward speed and the decrease of grain moisture content. They also reported that optimum operating parameters for harvesting rice crops were a combined forward speed of 4.5 km/h and grain moisture content of 16.5 %.



a) b)

Fig. 4 : Header loss due to cutting height at different forward speeds

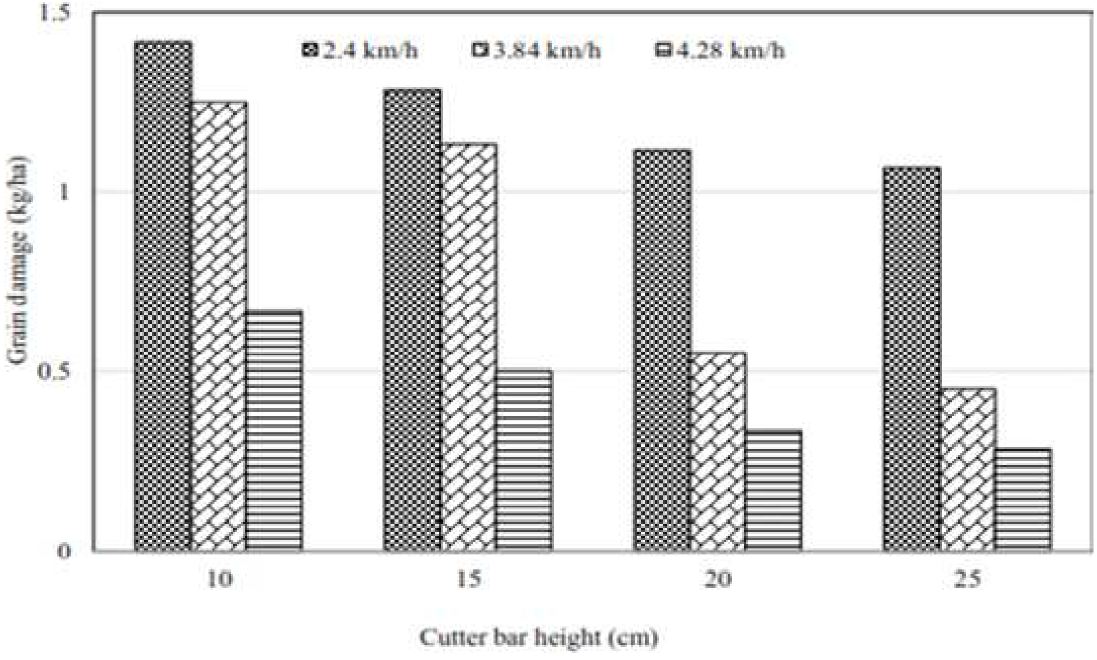


Fig. 5 : Effect of Cutter-bar height on grain damage

The comparative study conducted on different sizes of Yanmar combine concerning unit plot area by Badr (2005) indicated that increasing the forward speed from 1.0 to 4.0 km/h at a constant moisture content of 22 per cent, increased field capacity from 0.31 to 1.14 ha/h, while decreased field efficiency was from 89.3 to 82.7 per cent. El-Sharabasy (2006) indicated that increasing machine forward speed from 1.5 to 3.0 km/h increased effective field capacity from 0.277 to 0.452; 0.251 to 0.382; 0.208 to 0.349 and 0.181 to 0.296 fed /h different grain moisture contents of 21.45, 22.20, 23.12 and 24.60 per cent, respectively. The resulting assessment of the performance of the mechanized harvesting of grain crops indicates a very low degree of use of the potential of mechanization means. Victor *et al.* (2020),

TABLE 5

The calculated results of the coefficients to determine the performance of the processes of combine harvesting of grain crops

Coefficient name	Coefficient value
Planned performance (Sp), ha	1413.18
Coefficient of weather conditions (K_w)	0.58
Coefficient of Technical use (K_{TU})	0.83
Coefficient of technological adjustment (setting) (K_A)	0.86
Load Factor (K_L)	0.80
Coefficient of organizational downtime (K_o)	0.60
Actual performance (S_A), ha	480.57

elaborate on the contribution of various reasons for the decrease in the harvesting performance by the value of the indicators presented in Table 5.

Abdelmotaleb *et al.* (2009) reported that the increase of combine forward speed from 0.8 to 2.5 km/h leads to a decrease in the field efficiency from 84.96 to 62.35 per cent at a cutting height of 0.2 m without a control system. Fouad *et al.* (1990) studied a mechanism of self-propelled rice combine harvester and reported that raising travel speed from 0.8 to 2. km/h increased grain losses but decreased the field efficiency of the combine. Chaiyan Junsiri and Winit Chinsuwan (2009) developed prediction equations for losses of combine harvesters when harvesting. Thai Hom Malicerice, in their study, showed that grain moisture content (M), reel index (RI), cutter bar speed (V), the service life of cutter bar (Y), tine spacing (R), tine clearance over cutter bar (C), stem length (H), a product of M and Y (M×Y), a product of M and V (M×V), a product of RI and R (RI×R), a product of V and C (V×C), a product of V and H (VxH), V^2 and RI^2 were the major parameters affecting the losses. The prediction equations had $R^2 = 0.75$ and the average percentage header losses given by the estimation equation differed from the measurement by only 0.25.

Crop's interaction with the reel unit at the harvesting position is also a major factor influencing the gathering efficiency of a combine harvester (Srivastava *et. al.*, 1993 and Kolhe, 2009). In this connection, many researches were conducted to come up with equations useful to measure the deflection characteristics and the reaction forces of crops under the influence of reel engagement. Hirai *et al.* (2002a) developed a calculation method of flexural rigidity for materials with a heterogeneous cross-section using piano wire. An extended model that takes into account the effect of a crop ear was proposed and the relationships between the deflection and deflection force (horizontal force component) acting on a bunch of crops talks were analyzed understanding crop condition (Hirai *et al.*, 2002a). The effects of frictional force and the vertical force component were considered and horizontal and vertical reaction forces on the bunch of crop stalks were analyzed under a standing crop condition utilizing a differential equation describing deflection (Hirai *et al.*, 2002b). They reported that the equation was useful for investigating the deflection characteristics and also that the analytical accuracy of the reaction force would be increased by considering the effect of the initial shape of individual crop stalks. A redesign of tine kinematics and tine crop interaction was presented by Moses *et al.* (2012) with the view of increasing the pick-up performance of fixed tine combines for lodged and tangled crops. Such information/investigations are important especially at the design stage from the viewpoints of cost reduction, shortening of the development period and clarification of optimum machine operations according to crop conditions. Over the years, many research developments have been made on harvesting machines to account for local crops and conditions through various modifications. Prakash *et al.* (2015), designed a rice harvesting reaper binder with a field efficiency of 67 per cent and field capacity of 0.294 ha/h at a walking speed of 3.6 km/h. The labor requirement, fuel consumption, and the harvesting loss of the machine were 36 man-h/ha, 5.27 L/ha, and 1.44 per cent, respectively. Gupta *et al.* (2017) designed a pedal-driven, multi-crops cutter for small and large-scale farmers to reduce the harvesting time and labor force. Shalini P*etal* (2018), modified a tractor-driven heavy-weight reaper in to a self-propelled reaper which is less in weight and can be operated in both wet and dryland. Vilas *et al.* (2017), developed a multi-crop, mini harvester for small-scale farmers having less than 5 acres of land area. Chakaravarthi *et al.* (2016) designed a self-propelled, low-cost, cutter-bar mower to reduce the dependency on tractor mounted mover. Raut *et al.* (2013) designed a self-propelled, harvester useful for small scale farmers having land less than 2 acres. The harvester was found to have low operational cost and high field capacity as compared to the traditional methods. Narasimhulu *et al.* (2017), developed an engine-based reaper and evaluated its performance through different efficiencies, speeds and percentages of grain loss. They reported that the harvester could reduce labor costs by 67 per cent as compared with the traditional method.

However, when it comes to the Tef crop, one of the major cereal crops in Ethiopia, the attempts to come up with a solution to harvest the crop using self-propelled machines are limited. *Tef*, being a local crop, hasn't captured the required attention of the global scientific community and the wider agricultural machinery industry so far though it is a widely cultivated, staple crop in Ethiopia (Kebebew *et al.*, 2013; Berhane *et al.*, 2011 and Fufa *et al.*, 2011). Tef (*Eragrostistef)* is a warm-season annual grass, characterized by a large crown, many tillers and a shallow diverse root system. It is an essential food grain in Ethiopia but used as a forage crop in other countries like Australia; South Africa and the United States (Fikadu *et al*., 2019 and Kaleb, 2018). It is resistant to extreme water conditions, as it can grow under both drought and waterlogged conditions (Minten *et al*., 2013 and Teklu & Tefera, 2005). Combined with its low vulnerability to pests and diseases, it is considered a low-risk crop (Minten *et al*., 2013 and Fufa *et al*., 2011). Nutritionally, Tef grain is considered to have an excellent amino acid composition, higher lysine levels, gluten-free and excellent iron content as compared to other cereal crops (ATA, 2013c and Berhane *et al*., 2011). Its importance is beyond being a principal food as it is connected to the socio-cultural heritage of the society (Siyum and Ummal, 2020). In terms of production, Tef has been produced largely throughout the country. In the main production season (*Meher*) of 2018-2019 for example, Tef was produced by 6.78 million farmers, resulting in a total production of over 5.03 million metric tons on 3.08 million hectares of land. This accounted for the largest share of cereals cultivated in Ethiopia (CSA, 2019 and Kolhe *et al.,* 2024). However, despite its being the primary crop and valued as a national heritage by many and produced in large areas, its productivity (1.756 ton ha^{-1}) is very low compared with the other cereal crops produced in the country (CSA, 2019). Many findings associate the low productivity of the crop with low availability and use of modern inputs (seed and fertilizer) and the traditional method of production of the crop. However, most of these pertinent issues of Tef productivity are now being solved through integrated efforts of concerned governmental sectors and research institutes except the issue related to harvesting the crop.

Harvesting of Tef crops is a very laborious and time-consuming activity that entails intensive investment and human forces although the grain loss associated with it is negligible (Tadesse *et al*., 2016). Tef harvesting in Ethiopia is done using sickles (Fig. 6). The operation requires a tremendous amount of time, human labor involvement and investment as well (Abraham, 2015). This is because of the lack of

Fig. 6 : Manual harvesting of Tef

an efficient mechanized harvester that can handle well the nature of the crop with minimum harvest loss. The Tef plant has a different structure of stem (as compared to other cereals) having different numbers of panicles containing different amounts of Tef seeds at each panicle. The crop is highly susceptible to lodging which is related to its morphological traits (Seyifu, 1997 and Gindo *et al.,* 2023) and partly to the high seeding rate farmers utilize for crop establishment (Tareke and Nigusse, 2008). Lodging is one of the causes for low productivity of the crop and the yield loss associated with it is estimated to be as high as 30 per cent (Seyifu, 1997).

The lodging nature of the crop is also one of the very factors that make harvesting Tef with combine harvesters challenging. Since the crop has a high and disarray lodging nature, even the existing combines with tine pickup reels couldn't successfully clear/ harvest the crop from the field. As a result of this, farmers are usually forced to harvest their Tef crops manually using sickles; which is a time and resource-intensive method. Even in areas where combine harvesting operations are well introduced, farmers employ the existing combines with pick-up reels just for threshing and cleaning activities through feeding the already manually harvested and gathered Tef crop onto the conveying platform of the machine since the loss associated with the header of the units is significant. Had there been efficient mechanized harvesters, the number of days spent on fields for harvesting the crop would have been reduced by 70-80 per cent (Abraham, 2015) and the resources and time allocated to such operations would have been used/redirected to other farming operations.

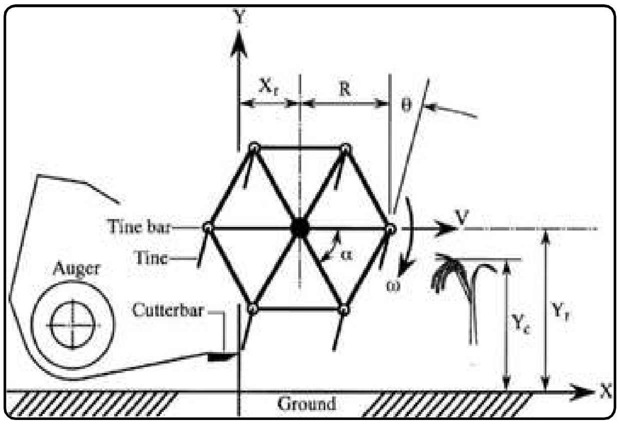


Fig. 7 : Tined combine harvester reel with a relevant parameter

This poor gathering performance of the existing combines may be associated with the way their pick-up reel units are designed and operated. The existing combine use tines with preset/fixed angles on the reel periphery that do not vary throughout the entire cycle of the reel rotation (Fig. 7). This may make the operation of the tines *i.e.* penetration and picking-up, feeding to the cutter-bar and releasing the already cut crop onto the gathering platform, inefficient during harvesting the already lodged crop as each of these three stages calls for a time orientation that is contradictory with the requirements of the other two stages (Moses *et al*., 2012).

According to Moses *et, al*. (2012), for lodged and tangled crops, the current practice of utilizing a preset tine rake angle may not be the most appropriate and this calls for an alternative reel design accommodating the different tine orientations angles at the harvesting zones of such crop (Fig. 8). However, in literature, very few studies observed on attempts to harvest tef by using a combine harvester, only limited research

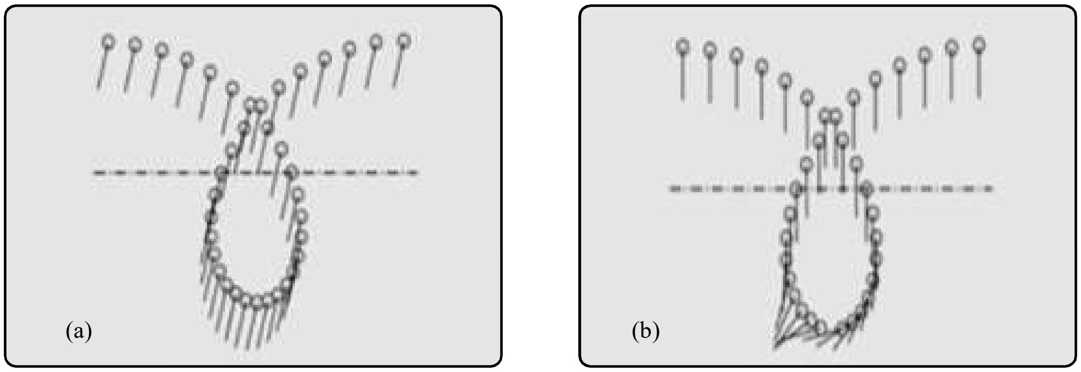


Fig. 8 : Tine kinematics; a) Conventional, b) Proposed (Moses *et al.,* 2012)

reported by Ephrem *et al.* (2014). In their research work using a crop mechanical model that was Hirai *et al.* (2003) developed for lodged and tangled wheat crops, they suggested that a reel unit having a fixed, preset tine angle but pitched 5^0C at its tip (penetrating side) would perform better for Tef crop harvesting. However, the efficiency of the suggested reel unit couldn't be measured as it was just theoretical research findings that were made based on the crop factor and kinematics of the tines. The absence of research and development works on the issue may relate to Tef being a local and 'orphan' crop (Kebebew *et al.*, 2013 and Asrat & Kolhe 2022). Thus, to have alternative solutions to Tef harvesting issues using combine harvesters, the following key points must be taken into consideration :

1) Well-coordinated and continuous efforts must be exerted by all stake holders to aware the wider scientific community about the crop and encourage in-depth research works to be conducted on the issue
2) The performance of the existing harvesters, which are developed for wheat or other crops that share more or less similar physico-mechanical characteristics, must be investigated thoroughly on lodging cultivars of Tef through different settings of the machines
3) The deflection characteristics of lodging varieties of Tef crop during their interaction with reel units of existing harvesters need to be studied under different machine settings to obtain optimal settings eventually accounting for the varieties' conditions
4) The physico-mechanical properties of various lodging cultivars of Tef crop must be studied along with their posture condition (shape factor) at harvesting time
5) The design of the existing harvesters reel system, in particular and the header units, in general, must also be reviewed again with Tef crop lodging condition. This should encompass further improvement works on such units to obtain alternative solutions

Tef harvesting is laborious and time-consuming, though, the physico mechanical properties of Tef crops are similar to other cereal crops. The researchers in different countries amended combine harvester utility and efficiencies to adapt it to local **c**rop conditions by refining the reel mechanism and machine setting parameters. More focus needed on the reel unit having a fixed, preset tine angle that may perform better for the crop harvesting.

A combine harvester may be very useful for Tef crops by refining existing gathering performance for Tef crops due to their grain header design and the high lodging nature of the crop. That may be significant for increasing the production and harvesting efficiency of the Tef crop in Ethiopia.

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