Fabrication and evaluation of mounted harvesting machine for sugarcane

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Abstract

Sugarcane is one of the important sugar crops in the world that depends on it in many industries, so we have fabricated and evaluated a machine for harvesting sugarcane to saves time, labors and costs necessary for harvesting, which is reflected in production and reduces costs. This harvester was designed for mounted on a small tractor and the single-row machine harvesting meets the functional requirements of the physical properties of the sugarcane. The performance of the harvester machine was evaluated on one shapes of cutter disc, three forward speeds and three cutter disc speeds. The results demonstrated that the average forward speed of 5 km/h, the average cutter disc speed 2000 rpm produced the lowest sugarcane losses while producing the highest power requirements and operating cost than other studied forward speeds and cutter disc speeds. It turns out that the fabricated mechanical harvester machine did not do major harm to the sugarcane and less than 6.38 % losses. Operating a sugarcane harvesting machine at optimal conditions saves time, labors and costs compared to common methods of manual harvesting.

1. Introduction

Sugarcane is one of the important sugar crops in the world that depends on it in many industries. Harvesting sugarcane by hand is one of the most common methods in many countries of the world, so we have fabricated and evaluated a machine for harvesting sugarcane to saves time, labors and costs necessary for harvesting, which is reflected in production and reduces costs. As the world production of sugarcane is 1 949.31 million metric tons (Statista, 2019), the cultivated area in Egypt of sugarcane about 136915 hectares and product 15242687 tons (FAO, 2018).

Usually, the sugarcane crop remains in the filed from 4 to 5 consecutive years, can be harvested several times from the original planting and the increase in yield and production depends on good service of the crop and fertilization. Different kinds of stalks demonstrate different mechanical properties in cutting processes, even for the same kind of stalks, the mechanical properties are different due to different crop maturity, moisture content and planting location. Manual work was the basic manner of sugarcane production.

Mechanization of sugarcane production is the inevitable choice to reduce production costs, improve labor productivity, and reduce the intense demands for farmers' labor. The quality of cultivation, especially in rows spaced 1-1.2 meters apart, is usually not reaching the required standards (Lai, 2003).

Wang et al. (2004) used the 4GZ-9 type sugarcane harvester as the test prototype to conduct both theoretical studies and field experiments. They optimized the parameters for the base-cutter, and the ratio of broken rootstock in ratoon sugarcane declined to 2.11%. Liu et al. (2004) carried out experiments to test the mechanical characteristics and failure of sugarcane stalks at bending load. The results showed that the sugarcane stalks mainly displayed four kinds of damage at bending load: neutral layer cracking, transverse cracking, bottom longitudinal cracking, and irregular cracking. These results are significant for research on the sugarcane cutting process, and blade design. Zheng et al. (2010) studied the matching problem between the forward speed of the sugarcane harvester and base-cutter rotating speed.

Yang et al. (2007) described the effects of the influencing parameters on the broken biennial root rate. The optimization of the broken rate at the condition of the minimum frequency and amplitude, as well as two soil bases, was performed. The results show that the frequency and amplitude have a remarkable influence on the broken biennial root rate. At the optimal condition, the broken rate is less than 11%. Qu et al. (2013) described that typical case is that mechanized production requires wider row spacing (wider than 1.2 m), while the traditional row spacing in China is about 0.8–0.9 m. Song and Ou (2004) stated that the influence of sugarcane size, and the dynamic response of the hydraulic system. As well as the influence on the number of broken roots caused by vibration, speed ratio, blade numbers, and inclination angle of the base-cutter (Lin et al., 2008; Lv et al., 2008).

Wang and Mo (2011) analyzed the economic efficiency of the small sugarcane harvesting system and found that it was feasible to use the small, chopped sugarcane harvesting system in present circumstances in China. Zhang et al. (2010) compared the cost of activities in sugarcane production using machines and human labor. The results showed that the mechanized system costs 14.19% less than the manual system. Among all the activities, harvesting costs more than any other operation in the mechanized system, while planting potentially saved more than any other activity. And they suggested that planting and harvesting were two operations that needed early mechanization.

Bai et al. (2020) stated that the average power consumption was higher at the high feeding rate than at the low feeding rate during testing extractor of a sugarcane chopper harvester. Wang et al. (2019) showed that the energy consumption was proportional to the rotational speeds (RS) and cane stool diameters (SD), however, it had negative correlations with tilt angles (TA) and cane feeding rates (FR). In addition, it was concluded that RS, SD, and FR had a significant influence on the energy consumption in the process of sugarcane base cutting at 95% level, however, TA had no significant influence on it. Moreover, the influencing order of four above factors on base cutting energy was SD > FR > RS > TA (18.45 > 18.39 > 12.91 > 9.06), and the optimal factor-level combination was RS2, TA4, SD1, and FR3 (200 rpm disc rotational speed, 20° disc tilt angle, 60 mm stool diameter, and 1.0 m s^{-1} feeding rate). Understanding the relationship between energy consumption and the above four factors can provide valuable references for researchers to optimize the design of contra-rotating base cutter, which could increase energy efficiency and reduce the energy needed during harvesting sugarcanes.

Xie et al. (2020) studied the perpendicular cutting of sugarcane stalks at six different internodes and nodes on the stalk was tested using a single-point clamping method at three cutting speeds (3, 4, and 5 cm min^{-1}). At the 5 cm min^{-1} cutting speed, the maximum cutting forces at nodes and internodes upward along the stalk decreased progressively from 810 to 530 N and from 600 to 440 N, respectively. The maximum force of cutting was positively correlated to the cutting speed in the selfsame position.

Wu et al. (2019) designed and tested the cutting platform, that contains two discs with cutting blades, driven by two electric motors with variable-frequency. The results stated that the controller capped the overshoot under one percent in the speed step response and preserved the fluctuation of the speed variation of the two cutting discs at less than 2.5 rpm. Evaluating the cane quality of support-cutting against free-cutting indicated that support-cutting decreased the damage rate of stubble from 22.67% to as little as 6.67%. In addition, suggested that the time-frequency-controlled cutting platform was feasible for subsequent investigation for a better knowing of sugarcane support-cutting, such as the variation of energy-consuming or stubble damage rate with several rotating speed or several blade shape, that will provide statics constructive suggestions for the future base cutter design.

Gupta and Oduori (1992) designed and determined the operating characteristics of a revolving knife-type sugarcane base cutter that will minimize energy inputs. A blade peripheral velocity of 13.8 m s^{-1}, an oblique angle of 35 and a tilt angle of 27.8 were found to be appropriate. Gupta et al. (1996) developed a Self-propelled Single-axle walking-type sugarcane harvester powered by 6-kW (8-hp) gasoline engine was developed. It was designed for farmers from developing countries who cannot buy expensive sugarcane harvesters which used in their countries. This machine reduced the number of labors requirements for cutting and windrowing sugarcane stems. Infield tests, the average field capacity of the machine was found to be 0.13 ha/h with an average field efficiency of 71%.

Ma et al. (2016) investigate how cane stool density and stubble height affected sugarcane stubble damage in typical Hawaii sugarcane fields. Damage of stubble was classified based on the damage length: damaged lightly value (damage length < 51 mm), damaged moderately value (51 mm < damage length < 102 mm), and damaged severely value (damage length > 102 mm). The measured damage of stubble levels was then plotted against cane stool density and height of stubble to study the changes in damage of stubble with the changes in these parameters. The results showed that cane density of stool value range of 75 to 142 canes m^{-2} had a negative correlation (r2 = 0.87) and height of stubble value range of 0.12 to 0.59 m had a positive correlation (r2 = 0.79) with damage level of stubble. Specifically, when the height of stubble increased from an average of 0.12 to 0.59 m, the mean damage length increased from 15 to 85 mm. Meanwhile, the percentage of damaged stubble severely increased from 0–53%. Understanding the correlation that of damage grade stubble has with cane density of stool and stubble height should provide essential information to engineers to improve the design of sugarcane base cutting mechanisms towards optimizing base cutter height control, that have ability led to reduced harvest-induced damage of sugarcane stubble.

Ma et al. (2015) stated that harvesting is one of the most expensive field operations in sugarcane production. Improving sugarcane harvesters in terms of percent of cane stalk recovery and field efficiency will be essential to reduce overall harvest costs and increase sugarcane productivity. Wang et al. (2019), demonstrated that the contra-rotating base cutter has a lower stubble damage rate than the traditional base cutter and can improve cutting quality. Additionally, the results indicated that the optimal parameters of the contra-rotating base cutter are a disc rotational speed of 550 rpm, a cane stalk feed rate of 0.5 m/s, five blades, and a disc tilt angle of 0°. With the establishment of these optimal parameters, the stubble damage rate of the contra-rotating base cutter was 15%, which was much lower than that of the traditional base cutter (25%).

OU et al. (2013) reported the machine type 4GZ-9 full stalk harvester, mounted on 11-14.7 kW small hand tractor, which was developed in 2002 by Guangxi Institute of Agricultural Machinery. The sugarcane stalks are laid down on the soil beside the machine following cutting. It can be used when the sugarcane is not seriously lodged. Its field capacity is 0.1 to 0.15 ha/h, and it is suitable to row spacing of ≥ 1.0 m.

Studies have shown that the harvesting rate will decrease by 33% and 14% when cane yield increases from 56 to 78 ton/ha, respectively, for single-row and two-row whole stalk harvesters. For a full stalk harvester, the cost per hour of a single-row machine was 35% less than that of the double row machine. However, cost per acre was 69% more expensive because the field capacity of a single row harvester was 61% less than a harvester with double row (Salassi and Champagne, 1996).

Serrated-edge blade has better cutting ability than a smooth-edge blade (Mello and Harris, 2003). For a serrated-edge blade, the ones with shorter pitch consume less energy (Mello and Harris, 2000).

The main problem of research is that there are no machines suitable for sugarcane cultivation in agricultural areas not cultivated using agricultural mechanization, as there was a difference between agricultural distances between the many farmers, manual harvesting has become very expensive, few workers and high expenses, this leads to higher costs of the sugar industry when it reaches the consumer, the cultivated areas are limited and need to have machines of suitable size with limited holdings. Therefore, this study aimed to fabrication and evaluation of the harvester machine mounted on small tractors to suit all cultivation distances for farmers, being easy to disassemble, install, adjust, maintain, and it works in limited agricultural holdings and works to reduce the costs of the kidney in the harvest process, which is due to reducing the costs of the sugar industry as a strategic product.

The specific objectives of this research were to fabricate a harvester machine for sugarcane, identify the optimum operating, engineering parameters of the fabricated harvester, decrease costs, labor and specific energy requirement.

2. Materials And Methods

The sugarcane harvester machine was assembled at a private workshop at El Ibrahimia, Al Sharkia Governorate, Egypt. The experiment was carried out on clay soil at a private farm in Santimay, El Dakahlia Governorate over the winter season of 2020 and for harvesting sugarcane.

2.1. Sugar cane plants

Sugar cane physical and mechanical properties (C9) are shown in Table 1.

Table 1
Physical and mechanical properties of sugarcane (C9).

Sugarcane characteristic	Average value
Stem height above the ground, mm	4500
Stem diameter, mm	30
Weight of one sugar cane, g	1860
Cut force of stem sugar cane, N	914

2.2. Tractor

Model super master AS 400 X made in China with a diesel engine has output PTO shaft maximum speed 1000 rpm and maximum power 29.43 kW.

2.3. Machine specification

Mounted machine for harvesting sugarcane was fabricated and evaluated and consists of four main parts mainframe, cutter unit, gearbox, power transmission, as shown in Fig. 1 & Fig. 2.

The mainframe of sugarcane harvesting machine constructed from iron angles L-shape with dimensions of (50×50×5 mm). Total dimensions of the mainframe were 1400 mm for length, 400 mm for width and 810 mm for height and weights were added on one side of the mainframe to save the balance of the system during the mounted with the tractor and while working in the field. The cutter unit consists of two main parts. The first part is the plate disc with a sharp-toothed edge. It is diameter 615 mm that made from sheet metal iron with 3 mm thickness. The second part is a steel shaft that made of steel bar metal with dimensions of 25 mm diameter and 320 mm length. The gearbox fixed on the frame machine, As the movement exits from the gearbox to another steel shaft fixed to the end of the cutter disc to change the transmission direction of the power source (PTO) and an increase in the ratio of (1:2).

The power transmission system transmitted from the PTO shaft transmitted the motion to the steel shaft fixed with two bearings on the frame machine. Then the movement is transmitted to another steel shaft using two pulleys and two belts and fixed on the frame machine. It was fixed previous steel shaft on one side by bearing and the other side was fixed to the gearbox (Fig. 3).

2.4. Experimental conditions

The performance of sugarcane harvesting machine was studied at three forward speeds 2, 3.5 and 5 km/h, four cutter disk speeds 1000, 1500 and 2000 rpm.

2.5. Instruments

A scale balance (OHAUS- USA) was used for massing the sugarcane samples. The maximum mass of the balance was 2610 g and accuracy were 0.1 g. The Digital force gauge was used to measure mechanical properties such as cutter force. FGN-5 model was made in Japan, measuring range ± 500 N, accuracy ± 0.2% at 23º C and Weight approx., 450 g.

Laser tachometer was used for measuring the rotating speed of pulleys, cutter disc and shafts. This tachometer is suitable to measure rotating speed from 0.05 to 19999 rpm with an accuracy of ± 0.05 %. Digital Vernier caliber with an accuracy of 0.01 mm was used to measure the diameter of sugar cane stem. The moisture content of the sugarcane stem was determined in compliance with the ASAE S358.22 standard.

2.6. Measurements

Actual field capacity was computed using the following equation:

$Afc = 1/T_{total}$ (1)

Where:

Afc is actual field capacity in (ha/h) and T_{total} is the total actual time in (h/ha).

Field efficiency was computed using the following equation:

$\eta = Afc/Tfc$ (2)

where:

η is field efficiency in (%); Afc is actual field capacity in (ha/h) and Tfc is theoretical field capacity in (ha/h).

The following equation was used to estimate power (P) as provided by (Hunt, 1983).

$P = (FC/c) \times (\eta th/100) \times HV$ (3)

Where:

P is the required power in (kW); FC is fuel consumption in (kg/h); ηth is the thermal efficiency in (%); HV is the fuel heating value in (kJ/kg); c is constant (3600).

The specific energy requirement was calculated as follows:

$Ser = P/ Afc$ (4)

Where:

Ser is specific energy requirement (kW h/ha); P is the required power in (kW); and Afc actual field capacity in (ha/h).

The equation as provided by (Hunt, 1983).

AC = (FC%) P/100 + (c A)/(S w e)[(R&M) P + L + O + F + T)] (5)

Where:

AC is the annual cost of the operating machine in ($/year); FC% is the annual fixed cost percentage; P is the purchase price of the machine in ($); c is a constant (10); A is the annual harvested area in (ha); S is the forward speed in (km/h); w is the effective width of action of the machine in (m); e is the field efficiency in (%); R and M are the repair and maintenance costs in ($/h); L is labor rate in ($/h); O is oil cost in ($/h); F is fuel cost in ($/h); and T is the cost of tractor use by machine in ($/h) and T = 0 if self-propelled.

Oc = Mc/ Afc (6)

Where:

Oc is operating cost in ($/ha); Mc is machine cost in ($/h); and Afc actual field capacity in (ha/h).

2.7. Energy requirements for the cutting action using the rotary disc cutter

Equations of motion (El Didamony and El Shal, 2020), as shown in Fig. 4.

$\theta = \omega t$ (7)

$\omega = 2\pi N$ (8)

N = rpm (9)

$X = Vt + R \cos\theta$ (10)

$X = Vt + R \cos\omega t$ (11)

$\dot{X} = (dx/dt) = V + \omega R \sin\omega t$ (12)

$\ddot{X} = (d\dot{X}/dt) = -\omega^2 R \cos\omega t$ (13)

Where:

θ is angle; N is rotating speed; R is the disc radius; X is the instantaneous displacement; $\dot{X}$ is motion velocity; $\ddot{X}$ is the acceleration of motion; V is the forward speed of the sugarcane harvester; and ω is angular velocity = $2\pi N$; t = Time.

$Ke/rev = 0.5\ m\ \dot{X}^2$ (14)

Where:

Ke is kinetic energy; rev is the revolution of the cutter disc; and m is mass of the cutter disc = (W/g) weight of disc/acceleration of gravity.

P/rev = Ke ×0.745/t ×75 (15)

Where:

P is power (kW); rev is the revolution; Ke is kinetic energy (N M); and t is the time of one revolution = 60/N.

Cp = P/rev×Car (16)

Where:

Cp is cutting power (kW); P is power (kW); rev is the revolution; and Car is cross-section area revolution (cm^2).

3. Results And Discussion

3.1. Actual field capacity and field efficiency

Single row the field capacity of a sugarcane harvester is determined by the swath width. The cutting disc of sugarcane harvesters has been designed to cover one row of sugarcane single row at a time, which causes a substantial variation in swatch width. Forward speed was the principal parameter governing the actual field capacity and field efficiency of the fabricated sugarcane harvester machine (Fig. 5). It shows that, for the serrated edge cutter disc, increasing average forward speed from 2 to 5 km/h led to increased actual field capacity by 94.4 % with average values ranging from 0.161 to 0.313 ha/h, respectively. Vice versa, increasing forward speed the field efficiency decreased by 22.3% with average values ranging from 80.67 to 62.69 %, respectively.

3.2. Sugarcane losses

Forward speed and cutter disc speed are the principal parameters governing the sugarcane losses of the fabricated sugarcane harvester machine. The results in (Fig. 6) show that generally increasing the forward speed and serrated cutter disc speed from 2 to 5 km/h produced more sugarcane losses percentage. Increasing forward speed from 2 to 5 km/h and the serrated edge cutter disc speed of 1000, 1500, 2000 rpm, increased the average sugarcane losses values from 3.02 to 6.38 %, 2.15 to 5.76 % and 0.75 to 3.46 %, respectively.

This can be attributed to the low cutter speed such as 1000, 1500 rpm did not have ability cutting all sugarcane during the faster forward speed of tractor which is considered more effective for highest of cutter disc speed 2000 rpm. The data are consistent with the findings of El Didamony and El Shal (2020), who turns out that the harvester prototype by two serrated discs at ideal cutter disc tilt angle and cutter disc speed did not do major harm to the cabbage and less than 4% damage.

Linear Regression Model $y = 1.681x + 1.35$, $R^2 = 0.9997$

Square of the correlation declaration that there is a significant relation between sugarcane losses and forward speed at cutter disc speed 1000 rpm.

Linear Regression Model $y = 1.8015x + 0.1133$, $R^2 = 0.9506$

Square of the correlation declaration that there is a significant relation between sugarcane losses and forward speed at cutter disc speed 1500 rpm.

Linear Regression Model $y = 1.356x - 0.432$, $R^2 = 0.9508$

Square of the correlation declaration that there is a significant relation between sugarcane losses and forward speed at cutter disc speed 2000 rpm.

These statics emphasizes that there is a significant correlation between sugarcane losses and forward speed at different cutter disc speeds.

3.3. Power required and specific energy requirement

The results in (Fig. 7) show that for the serrated edge cutter disc rotational speed of 2000 rpm, by increasing the average forward speed from 2 to 5 km/h and the average serrated edge cutter disc speed of 1000, 1500, 2000 rpm, power requirement increased by 28.42, 39.59 and 34.39 %, respectively, while increasing the average forward speed from 2 to 5 km/h and the average serrated edge cutter disc speed of 1000, 1500, 2000 rpm, increased specific energy requirement by 33.89, 28.2 and 30.86 %, respectively (Fig. 8).

Linear Regression Model $y = 1.2244x + 7.4717$, $R^2 = 0.9882$

Square of the correlation declaration that there is a significant relation between power requirement and forward speed at cutter disc speed 1000 rpm.

Linear Regression Model $y = 2.0112\,x + 8.1083$, $R^2 = 0.9968$

Square of the correlation declaration that there is a significant relation between power requirement and forward speed at cutter disc speed 1500 rpm.

Linear Regression Model $y = 1.9516\,x + 9.7846$, $R^2 = 0.9061$

Square of the correlation declaration that there is a significant relation between power requirement and forward speed at cutter disc speed 2000 rpm.

These statics emphasizes that there is a significant correlation between power requirement and forward speed at different cutter disc speeds.

Linear Regression Model $y = -9.0586x + 61.328$, $R^2 = 0.9521$

Square of the correlation declaration that there is a significant relation between specific energy requirement and forward speed at cutter disc speed 1000 rpm.

Linear Regression Model $y = -8.9033x + 70.196$, $R^2 = 0.8844$

Square of the correlation declaration that there is a significant relation between specific energy requirement and forward speed at cutter disc speed 1500 rpm.

Linear Regression Model $y = -10.881x + 81.01$, $R^2 = 0.9961$

Square of the correlation declaration that there is a significant relation between specific energy requirement and forward speed at cutter disc speed 2000 rpm.

These statics emphasizes that there is a significant correlation between specific energy requirement and forward speed at different serrated cutter disc speeds.

It is accompanied with these effects are in line with the outcomes of El Shal and Awny (2019), stated that the lowest cutting energy was about 3.68 J at 0.5 cm branch diameter of a fig, 20° bevel angle and 10% MC for cutting by a serrated knife.

3.4. Operating cost

The results in (Fig. 9) indicate that, at the cutter disc speed 2000 rpm, the highest cost of 5.96 $/h at forwarding speed 5 km/h, while the lowest cost of 4.84 $/h at forwarding speed 2 km/h and at cutter disc speed 1000 rpm.

This can be attributed to the high influence of forwarding speed and cutter disc speed on increased operating cost. In manual harvesting, the cost per hectare costs about $143 to be harvested manually for 6 h, in addition to the need for a full day to harvest it, by about 6 workers.

Comparison between manual and machine harvesting for harvesting one hectare

is clearly (Fig. 10).

From results, as shown in (Fig. 11), indicated that manual cost for harvesting 1 hectare is very expensive, have a significant effect on price sugar and black honey. It is a high need to reduce cost, labor and time to reduce sugar cost production all over the world.

4. Conclusion

The fabricated machine harvester is recommending harvesting sugarcane by one serrated edge cutter disc and operating it on the average forward speed of 5 km/h and 2000 rpm cutter disc speed giving the highest actual field capacity of 0.313 ha/h, lowest sugarcane losses of 3.46%, the power required of 15.28 kW, the specific energy requirement of 48.76 kW h/ha., and operating cost of 5.96 $/h. We found that the sugar cane harvesting machine has economic importance as it works to save costs, energy and labors, which is reflected in reducing the costs of the sugar industry and reaching the consumer at lower prices. The research work in this paper can effectively improve the efficiency of the harvesting of sugarcane and the agricultural mechanization level.

Declarations

Author Contributions:

Conceptualization, A.M.E.S. and M.I.E.D.; methodology and investigation, A.M.E.S.and M.I.E.D.; writing-original draft preparation, A.M.E.S.and M.I.E.D.; primitive and final field experiments, A.M.E.S. and M.I.E.D.; writing-review and editing, A.M.E.S. and M.I.E.D. Both authors have read and agreed to the published version of the manuscript.

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Declaration of Competing Interest

The authors declare no conflicts of interests.

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