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Full length article

Design and field testing of a sugarcane cutter

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ABSTRACT

Sugar is an important strategic commodity for all countries of the world. Sugar after wheat is of strategic importance in Egypt. It was, therefore, necessary to pay full attention to sugary crops, especially sugar cane, to increase productivity and to bridge the gap between production and consumption by increasing the productivity of sugarcane. The main problem of sugar cane plantation is the harvesting process. The sugarcane harvesting season lasts for 5 months in Egypt, starting in Dec. and ending in May. A tractor-operated sugarcane harvester was designed, manufactured, and tested, and the machine parts was designed by using "SolidWorks" software, and this program helps to find out the typical dimensions of various components of machine with great accuracy in small time. The machine was manufacturing and constructed by using the low-cost material available in local market. Results of the tests showed that the effective field capacity ranged from 1.16 to 1.3 Fed/h and increased with an increase in row spacing and forward speed. In the high crop density fields, the cutter head efficiency averaged 100 %. It, however, increased with a decrease in cutting height and, increased with an increase in row spacing and number of knives. The throughput capacity increased from 42.9 to 79.02 t/h as the row spacing increased from 71 to 88.75 cm and the maximum total operating costs are 120 EGP/h (98.5 and 92.3 EGP/Fed) depending on the power requirements.

1. Introduction

Since about 4 decades the sugar cane production is fully mechanized, the design and commercial manufacturing of mechanical sugar cane harvesters have taken first place in Hawaii, Australia, Southern USA, and Japan. Countries which have large areas of sugar cane such as Brazil, India, Cuba, South Africa, and China may have large agricultural sectors that economically apply full mechanization, medium sectors that apply semi-mechanization and small size farms that still harvest sugar cane manually. Except for Egypt, no successful sugar cane harvester has been developed so far. Several trails have been done to locally demonstrate imported sugar cane harvesters. The demonstrated machines were not accepted by the local farmers because of poor performance represented in poor cost-saving, poor labor-saving and poor timesaving. Therefore, no advantages of the demonstrated sugarcane harvesters' performance attract the farmers to use them. Other trails to develop and test local designs of sugar cane cutter harvesters through graduate students' research programs have not been succeeded. (Abdel-mawla, 2014). The manually cutting is a very labor-intensive, the workers usually become fatigued after a few hours, and they need frequent pauses for rest. (Rohit and Sharad, 2015). Due to the high levels of sun exposure, Precautions need to be taken to limit or protect the workers because it can result in various types of skin cancer conditions (Siddaling and Ravaikiran, 2015). Due to wages increasing and the unavailability of labor to cut sugar cane by hand, the South African Industry considered various options for mechanical sugar cane harvesting (Debeer, 1974).

The objectives of this study are to:

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1. Study some physical properties of sugarcane.
2. Design and construction of a prototype sugarcane harvester.
3. Test and evaluate the performance of the machine in the field.
4. Make an economical evaluation of the machine.

2. Materials and methods

To achieve the objectives proposed for the current study, an experimental sugar cane harvester was designed and manufactured at a local workshop in El-Minya governorate - El-Minya, Egypt, 2017. This experimental unit was designed to cut two rows of sugar cane and windrow them in one row below the tractor. The experimental unit was designed to be compatible with a wide range of row spacing, row height, and tractor types.

2.1. Description of the experimental sugar cane harvester

The entire experimental sugar cane harvester was subjected to standard design methodology. The sugar cane harvester consists of four main parts: machine frame, cutter head, transmission system, and power supply and hydraulic system, as shown in Figures from 1 to 6.

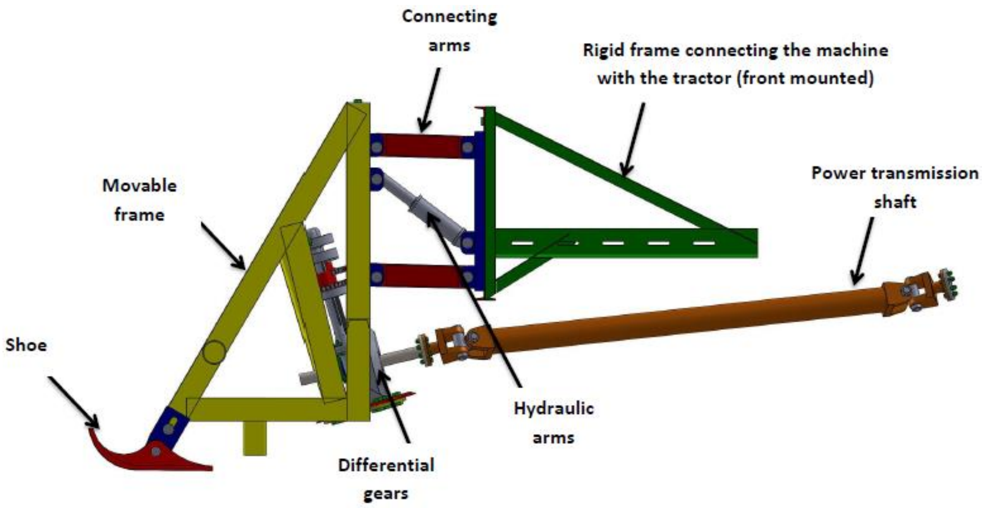

Figure 1. Side view of the proposed machine designed by SolidWorks program.

Figure 2. Power transmission shaft connection between machine and tractor.

Figure 3. A. Height control Mechanism, B. Width control Mechanism, C. Transmission power for both cutting disks.

Figure 4. Front view of the sugar can harvester showing the pusher.

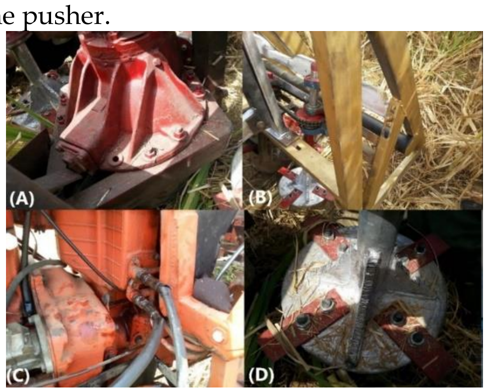

Figure 5. A. Gear box, B. Cutting system, C. Hydraulic system, D. Cutting disk.

Figure 6. Front mounted sugarcane harvester.

2.2. Performance Tests and Evaluation of proposed sugar cane harvesting unit

The prototype sugar cane harvester was tested in the Research Center and Agriculture Research – El-Minia - Egypt. Tests were carried out to evaluate the machine performance in terms of effective field capacity, field efficiency, material capacity, cutter head efficiency, fuel consumption, and power requirements.

Experiment design

Field tests were conducted to evaluate the performance of the harvesting unit by studying the following variables:

1. Forward speed 3, 3.5, 4.5 and 5 km/h.
2. Row spacing 71.0, 78.89 and 88.75 cm (Stalk diameter 2.63, 3 and 3.76 cm, respectively).
3. Cutting height at ground level, 2 and 4 cm.
4. The number of knives 2 and 4.
5. Knives velocity at constant speed ratio with the forward speed = 20:1.

2.2.1. Effective field capacity

The effective field capacity (Fed/h) of the machine was calculated according to the following formula:

$$Fc = \frac{Ap}{Tk}$$

where:

AP = area of the field portion, Fed.

T_k = time consumed to complete the harvesting area of the sugar cane crop, h.

2.2.2. Field efficiency

Field efficiency of the machine was calculated according to the following formula:

$$Fe = \frac{4.2 \times Fc}{S \times W}$$

where:

S = speed of operations, km/h.

W = operational width of the machine, m.

2.2.3. Throughput capacity

The throughput capacity (t/h) of the machine defined as the mass of material handled by the machine per hour was calculated according to the following formula:

$$Mc = Fc \times Y$$

where:

Fc = effective field capacity, Fed/h.

Y = sugarcane yield, t/Fed.

Mc = material capacity, t/h.

2.2.4. Cutter head efficiency

The cutter head efficiency was determined by selecting one hundred sugarcane stems from the field and harvesting them using the machine. The harvested stalks were then separated into those that were completely cut at the base, those that were uprooted and those that were not cut. The cutter head efficiency was calculated according to the following formula:

$$Bce = \frac{Nc}{Nt} \times 100$$

where:

Nc = number of stems completely cut.

Nt = total number of sugar cane stems (completely cut at base + uprooted + not cut).

2.2.5. Fuel consumption

A volume of fuel consumed (cm^3) was measured during each test run at cutting load. Consumption time for each test was measured and volumetric fuel consumption rate was calculated for each load as follows:

$$FC = (V * 3600) / (t * 1000)$$

where:

FC = volumetric fuel consumption, l/h

V = volume of consumed fuel, cm3

t = time of running the test, s.

2.2.6. *Power requirements*

The power requirements for harvesting sugarcane stalks were calculated according to the following formula:

$$P = FC * CV * \eta th / 3600$$

where:

P = power requirements, kW. (Brake power)

F_C = fuel consumption, kg/h. [(fuel consumption in L/h) x (ρ in kg/L)]

η_{th} = thermal efficiency (30 %).

CV = calorific value of kilogram fuel, kJ/kg [CV= 44800 kJ/kg for diesel fuel]

ϱ = density of fuel, kg/L [ϱ = 0.82 kg/l for diesel fuel]

2.3. *Cost estimation of owning and operating the proposed machine*

Formulas developed by the American Society of Agricultural and Biological Engineers (ASABE) are used to calculate costs. All costs are based on buying a new proposed prototype of the sugar cane harvester, owning the machine for 5 years and using it 1200 hours per year.

3. Results and discussions

The main factors affecting the performance of the proposed prototype harvesting sugar cane unit are field capacity, throughput capacity, power requirements, cutter head efficiency and total operating costs of the machine.

The controlled conditions of the criteria were: machine forward speed, row spacing, sugar cane stalk diameter, cutting height and number of knives. All experiments were carried out under field conditions to measure the effect of the controlled factors on the performance of this prototype harvesting unit.

3.1. *Physical properties of sugar cane stalks*

Physical properties of sugar cane stalks that affect mechanical harvesting were measured from the average of random sampling group of the test field in Center of Experiments and Agricultural Research, Faculty of Agriculture, El-Minia University, and sugar cane farms that all grow sugar cane variety C9.

- Stalk length, cm
- Stalk diameter, cm
- Stalk weight, kg

Table 1 show average values of physical properties of green sugar cane stalks. Length of unbranched stems ranged from 216 to 242 cm depends on row spacing. Sugar cane stalk diameters were ranged from 2.63 to 3.76 cm and weight of unbranched stems were also ranged from 1.175 to 1.763 kg. The samples collected from a uniform growing area of the sugar cane field.

Table 1

Average values of physical properties of sugarcane stalks*.

Cane stalk properties	Field (1)**	Field (2)***	Field (3)****
Average stalk length, cm	216	239	242
Average stalk diameter, cm	2.63	3.12	3.76
Average stalk weight, kg	1.175	1.468	1.763

* Sugar cane variety C9. ** Row spacing = 71 cm. *** Row spacing = 78.89 cm. **** Row spacing = 88.75 cm

3.2. *Field performance*

The performance of sugarcane cutter unit with three forward speeds, three distance (with stalk diameter 2.5, 3, 3.5 cm), three cutting height and two types of number knives were tested and evaluated according to the following aspects:

1. Effective field capacity.
2. Field efficiency.
3. Material capacity.
4. Cutter head efficiency.
5. Fuel consumption.
6. Power requirement.

Results of the experimental work could be summarized as follows:

3.2.1. *Effect of forward speed*

The proper forward speed required for harvesting sugar cane at the ground level is a very important factor. Four forward speeds were used as 3, 3.5, 4.5 and 5 km/h to determine the proper forward speed for harvesting sugar cane stalks from the ground level. The length of each test was 25 m and was repeated thrice. The proposed fixed parameters to carry out these experiments were: cutting heights = Ground level, 2, and 4 cm, row spacing = 70, 80, and 90 cm, stalk diameters = 2.5, 3, and 3.5 cm and No. of knives = 2, and 4.

Results indicated that the best appropriate forward speed required for harvesting sugar cane stalks are:

a) For stalk diameter 2.63 cm, row spacing 71 cm, cutting height 0 cm with both (2 and 4) knives. The proper forward speed of the harvester was approximately, 5 km/h. This forward speed gives maximum machine field capacity of (1.16 Fed/h), through put capacity (42.9 ton/h). Also, the average base cutter efficiency 100%, the cutting energy decreased up to (39.73 kW) and the total operating costs are 110.5 EGP/h (94.9 EGP/Fed).

b) For stalk diameters (3.12 and 3.76 cm), row spacing (78.89 and 88.75 cm), cutting height 0 cm with both (2 and 4) knives. The proper forward speed of the harvester was ranged from 4 to 4.5 km/h. This forward speed gives maximum machine field capacity of (1.18 and 1.30 Fed/h), through put capacity (57.45 and 79.02 ton/h). Also, the average base cutter efficiency 100%, the cutting energy decreased up to (42.78 and 46.88) kW and the total operating costs are (115.3 and 120 EGP/h) (98.5 and 92.3 EGP/Fed), respectively.

3.2.2. Effect of row distance

The distance between the rows is an important factor that plays a vital role, especially in estimating the field capacity of the machine in addition to the throughput capacity, as shown in Figures 7, 8 and 9. Row spacing is one of the most important factors that affect stalk diameters. At row spacing 71 cm, the average stalk diameter is 2.63 cm, while at row spacing 78.89 and 88.75 cm average stalk diameter was 3.12 and 3.76 cm, respectively, as shown in Figures 7, 8 and 9.

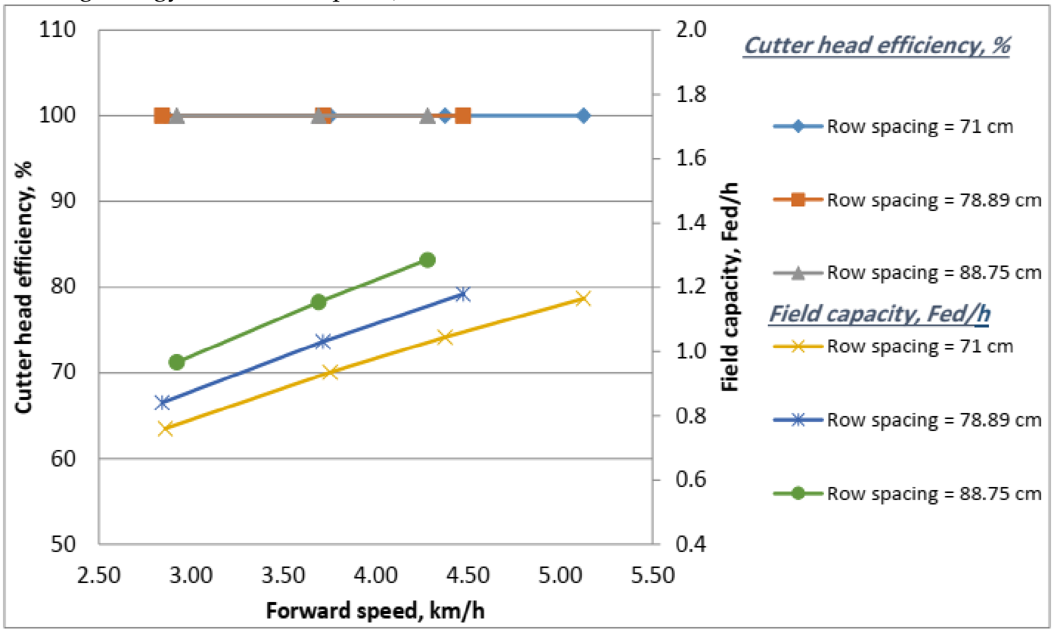

Figure 7. Effect of row spacing on field capacity and cutter head efficiency. (Cutting height = ground level and No. of knives = 4).

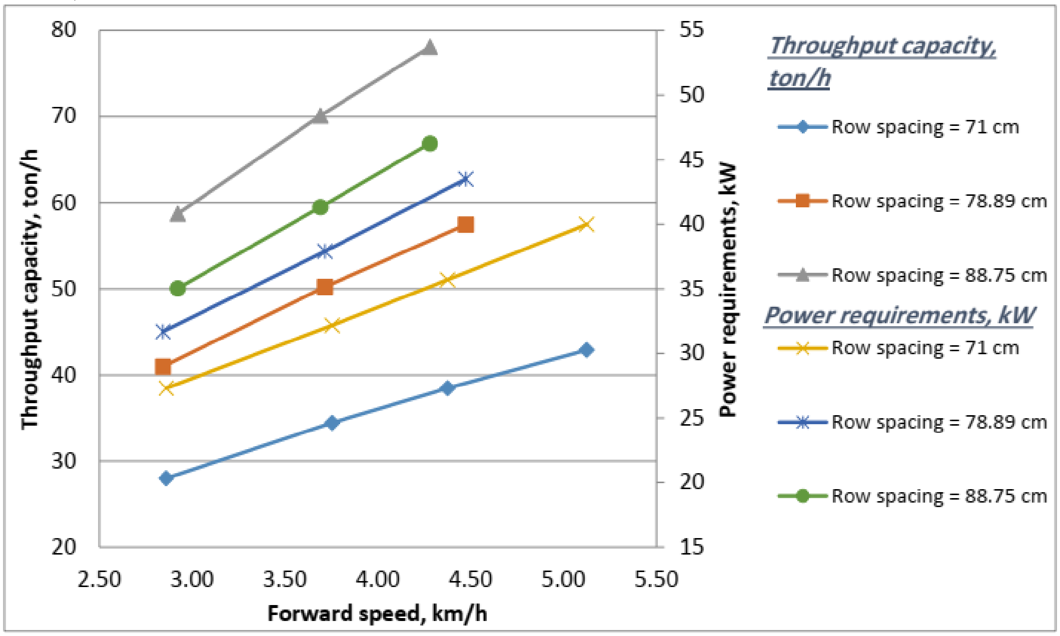

Figure 8. Effect of row spacing on throughput capacity and power requirements. (Cutting height = ground level and No. of knives = 4).

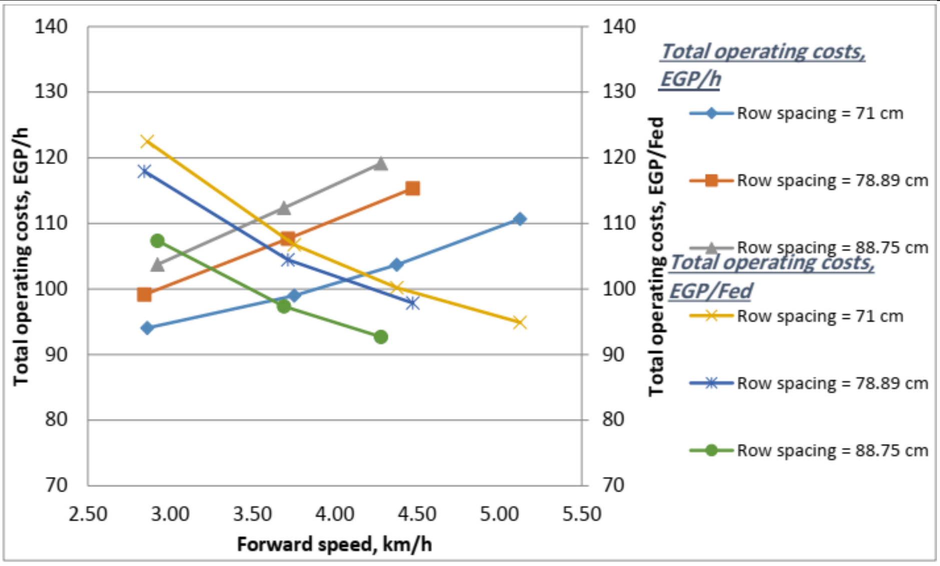

Figure 9. Effect of row spacing on total operating costs. (Cutting height = ground level and No. of knives = 4).

Figure 7 illustrate the effect of row spacing on cutter head efficiency and field capacity, Results shows that increasing the row spacing increasing the field capacity from (1.04 to 1.29 Fed/h) while the cutter head efficiency stile constant (100%). Figure 8 shows the effect of row spacing on throughput capacity and power requirements, Results shows that increasing the row spacing increasing the throughput capacity from (37.47 to 78.09 t/h) and the power requirements from (35.7 to 46.27 kW). Figure 9 shows that increasing the row spacing decreasing the total operating costs from (104.6 to 92.7 EGP/Fed).

3.2.3. Effect of stalk diameter

The results showed that the stalk diameter was an important factor in the mechanical harvesting of sugar cane. It was found that at the stalk diameter 2.63 cm, the power requirements were 22.25 % less than stalk diameter 3.76 cm when the other factors stabilized, but it is necessary to work close to the soil surface in order to avoid bending the stalks before cutting.

3.2.4. Effect of cutting height

The cutting height is a very important factor, especially in estimating the power requirements and cutter head efficiency at different forward speed and row distance, as shown in Figures (10, 11 and 12). Three cutting heights were used as follow; cutting at ground level, 2.00 and 4.00 cm to determine the power requirements and base cutter efficiency of harvesting sugar cane stalks from the ground level. The length of each test was 25 m and was repeated thrice. The proposed fixed parameters to carry out these experiments were: forward speeds = 3, 3.5, 4.5 and 5 km/h, row spacing = 70, 80, and 90 cm, stalk diameters = 2.5, 3, and 3.5 cm and No. of knives = 2, and 4, as shown in Figures (10, 11 and 12).

Figure 10 clearly shows that cutter head efficiency decreased by 2% due to increasing the cutting height from (ground level to 4 cm) while the field capacity unchanged. Figure 11 illustrate the effect of cutting height on throughput capacity and power requirements, Results showed that the throughput capacity changed from (78.09 to 78.49 t/h) and the power requirements still constant. Figure 12 indicate that increasing the cutting height does not affect the total operating costs.

In general, it was found that the height of the cutting has a significant impact on the machine performance, especially in the base cutter efficiency where the cutting efficiency was 100% at the ground level and decrease by 9% at 4 cm. The cutting height also has another effect on the amount of loss during the harvesting process, where 1 cm leads to loss between 200 to 340 kg / cm per Feddan depending on the row spacing. On the other hand, it was found that the row spacing have not effect on both the field capacity and the total operating costs.

3.2.5. Effect of number of knives

Two groups of knives were used as 2 and 4 knives to determine the power requirements and base cutter efficiency of harvesting sugar cane stalks from the ground level, as shown in Figures 13, 14 and 15. The length of each test was 25 m and was repeated thrice. The proposed fixed parameters to carry out these experiments were: forward speeds = 3, 3.5, 4.5 and 5 km/h, cutting heights = 0, 2, and 4 cm, stalk diameters = 2.5, 3, and 3.5 cm and row spacing = 70, 80, and 90 cm.

Figure 13 clearly shows that the cutter head efficiency and the field capacity unchanged. Figure 14 illustrate the effect of No. of knives on throughput capacity and power requirements, Results showed that the throughput capacity and the power requirements still constant. Figure 15 indicate that increasing the No. of knives does not affect the total operating costs.

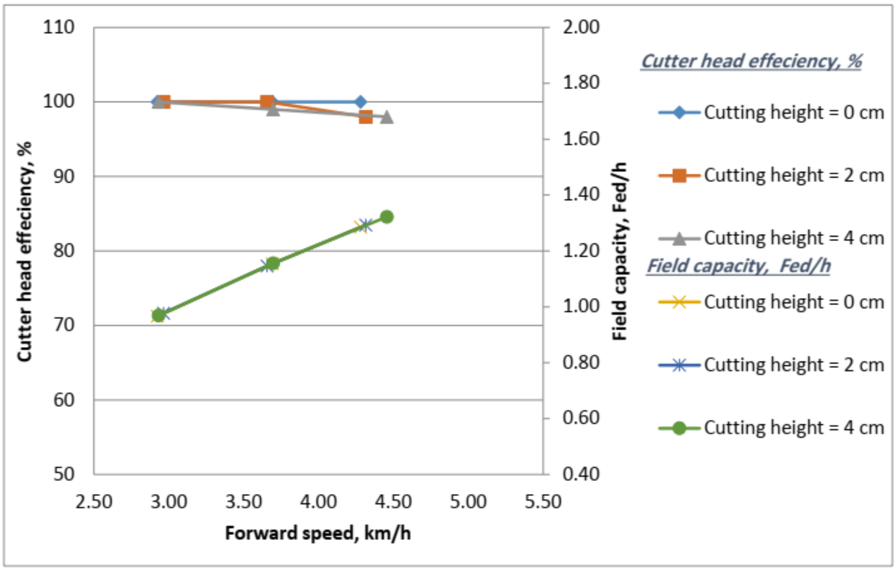

Figure 10. Effect of cutting height on field capacity and cutter head efficiency. (row spacing = 88.75 cm and No. of knives = 4)

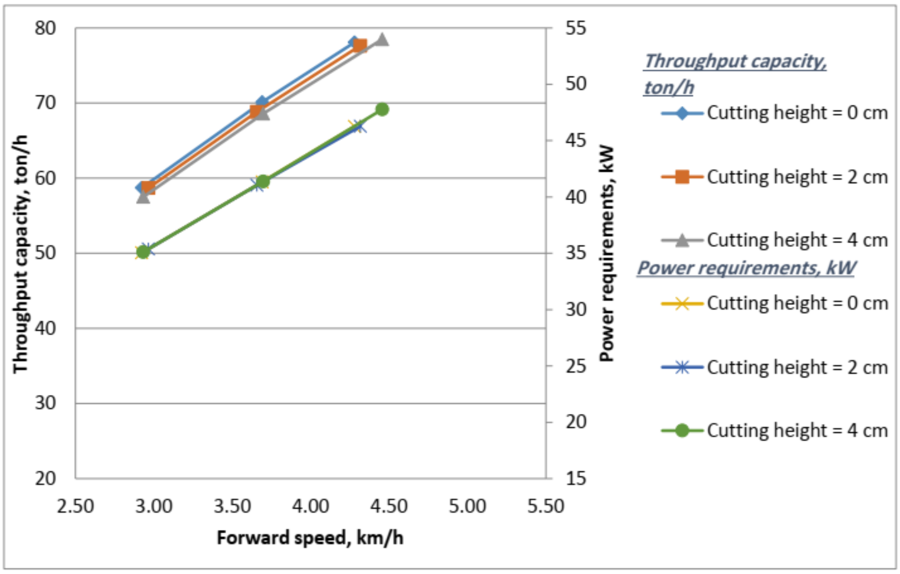

Figure 11. Effect of cutting height on throughput capacity and power requirements. (Row spacing = 88.75 cm and No. of knives = 4)

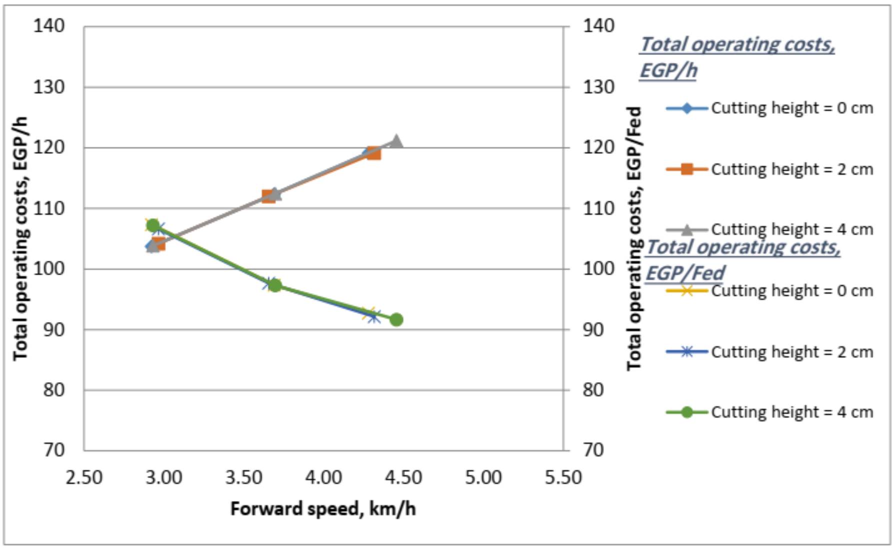

Figure 12. Effect of cutting height on total operating costs. (row spacing = 88.75 cm and No. of knives = 4).

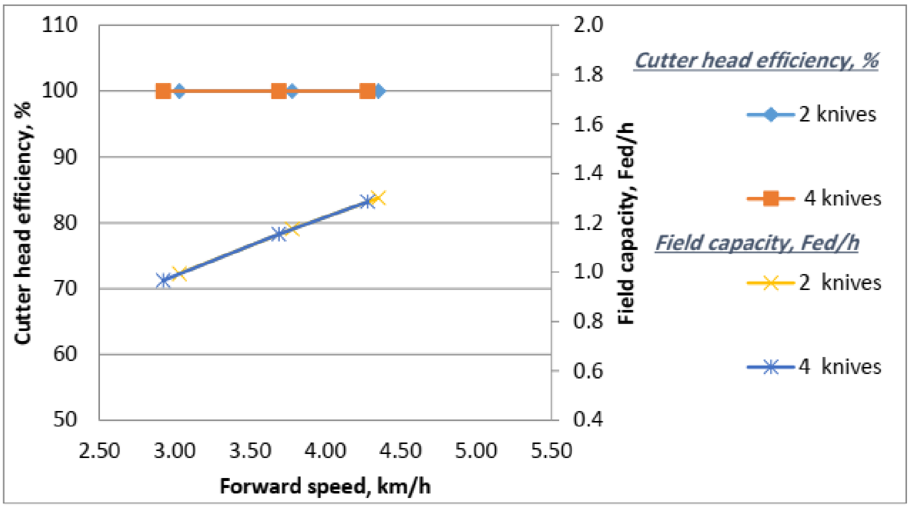

Figure 13. Effect of No. of knives on field capacity and cutter head efficiency. (Cutting height = ground level and row spacing = 88.75 cm)

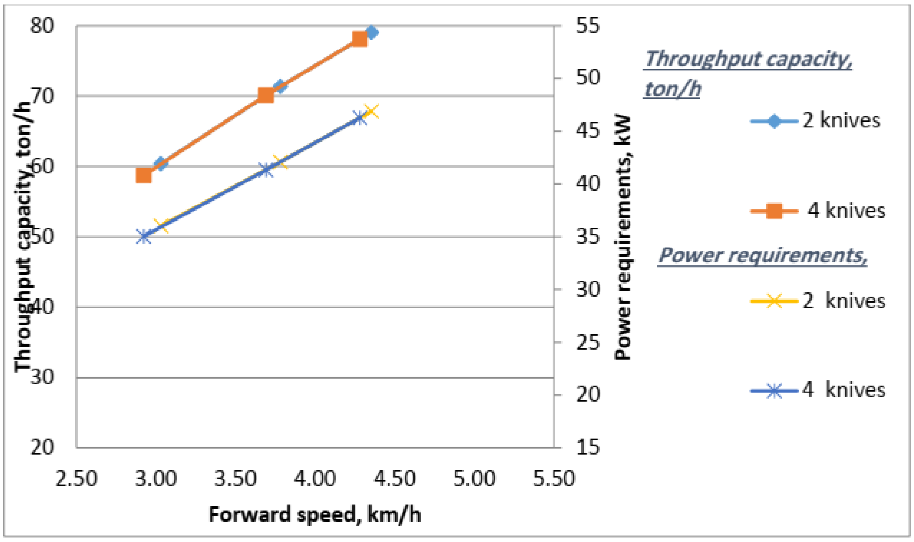

Figure 14. Effect of No. of knives on throughput capacity and power requirements. (Cutting height = ground level and row spacing = 88.75 cm).

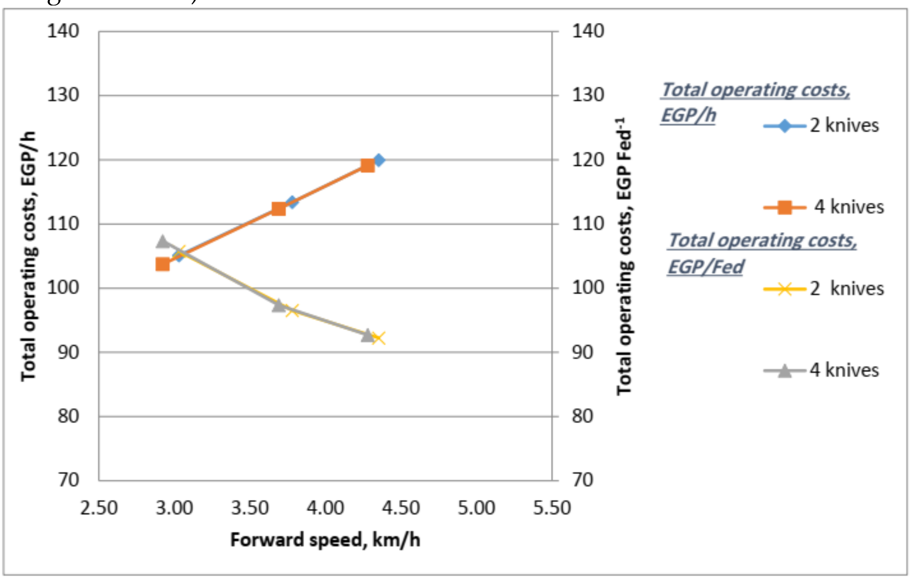

Figure 15. Effect of No. of knives on total operating costs. (Cutting height = ground level and row spacing = 88.75 cm)

In general, the number of knives had a direct effect on the base cutter efficiency and did not effect any of the other performance parameters where it was the best performance of the machine when the number of knives is 4 and decreased when using only two knives. The number of knives had another effect on the stability of the machine during the operation and we found that the working with four knives was smooth operation free of vibrations and noise.

3.3. Operating costs of the proposed unit

Although the first requirements of a machine is that it be able to perform its intended function satisfactorily, the management and economic aspects of the machine application are also of great importance. The farm machinery design is largely controlled by economic considerations. To work most effectively, it should have a thorough determining the factors affecting field capacities and the economic principles governing the costs of owning and operating field machines. Farm machinery costs could be divided into two categories: annual ownership costs, which occur regardless of machine use, and variable costs, which vary directly with the amount of machine use.

Machine costs could be estimated by making a few assumptions about machine life, annual use, fuel and oil prices and labor wage. The operating costs of the proposed sugar cane harvesting machine are listed in Table 2. It is clear also, that all costs components of the harvesting unit.

Table 2

Operating cost of the purposed sugar cane harvester.

Operating cost	Machine	Tractor
Fixed costs, EGP/h		
Depreciation	3.02	16.67
Interest on investment	1.51	16.67
Taxes, insurance and sheltering	0.3	3.33
Total fixed costs	4.83	36.67
Variables costs, EGP/h		
Repair and maintenance	3.02 + 16	16.67
Fuel	--	*
Lubricants	--	*
Labors (one man)	--	20
Total variable costs	19.02	36.67

*The fuel and lubricants costs per hour depend on power requirements.

The total operating cost was calculated at all treatments as shown in the previous figures and tables, and we found that the least total operating cost was (79.44 EGP/Fed) when the no. of knives were (2 and 4), the forward speed was (5.01) km/h, the row spacing was (88.75) cm, sugar cane stalks diameter was (3.76) cm and the cutting height was (4) cm.

Also, we found that the largest total operating cost was (110.3 EGP/Fed) when the No. of knives were (2 and 4), the forward speed was (2.86) km/h, the row spacing was (71) cm, sugar cane stalks diameter was (2.63) cm and the cutting height was (0) cm.

Throughout the calculations of the machine operating costs the following assumptions were used

Initial cost of the machine and the new tractor were 18150 EGP and 200,000 EGP respectively.

- Interest rate used = 20%
- Repair and maintenance costs = Depreciation + knives costs.
- Tractor power = 90 hp (59.7 kW)
- Fuel price = 3.65 EGP/l
- Inflation rate = 35%
- Taxes, insurance and sheltering = 2% of purchase price
- Oil costs = 15% of the fuel costs.

3.4. Labor costs

Labor charges should be based upon prevailing wage rates. The labor cost per Feddan is inversely proportional to the field capacity of the machine. Selecting the optimum width or size of a machine minimizes the total cost per Feddan for performing the harvesting operation.

The proposed sugar cane harvesting unit needs only one skill operator for the tractor which costs (20 EGP/h), as shown in Table 2.

4. Conclusions

It was, therefore, necessary to pay full attention to sugary crops, especially sugar cane, to increase productivity and to bridge the gap between production and consumption by increasing the productivity of sugarcane. The main problem of sugar cane plantation is the harvesting process. The sugarcane harvesting season lasts for 5 months in Egypt, starting in December and ending in May.

It can be concluded that the best operating conditions for harvesting sugar cane stalks to obtain the maximum machine performance are:

1. At row spacing = 88.75 cm, stalk diameter = 3.76 cm and cutting height at ground level the proper machine forward speed = 4.5 km/h, knives rotational speed = 1104.9 rpm, power requirements = 46.88 kW and field capacity = 1.3 Fed/h

2. At row spacing = 78.89 cm, stalk diameter = 3.12 cm and cutting height at ground level the proper machine forward speed = 4.5 km/h, knives rotational speed = 1111.9 rpm, power requirements = 42.78 kW and field capacity = 1.16 Fed/h
3. At row spacing = 71 cm, stalk diameter = 2.63 cm and cutting height at ground level the proper machine forward speed = 5 km/h, knives rotational speed = 1100.3 rpm, power requirements = 39.73 kW and field capacity = 1.16 Fed/h.

The main recommendations of this study could be concluded as follows:

1. Using four knives gave maximum working stability while using two knives lead to machine instability.
2. The sharpening angle of knives should be at down position to reduce wear and protect it from rocks in the soil.
3. The forward speed mustn't exceed 4.5 km/h incase lodging conditions of stalks.
4. In case the stalk diameters are greater than 3 cm it is convenient to harvest at forward speed of 4.5 km/h to maintain the safety clutch in operation without slipping.

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تصميم واختبار آلة لتقطيع قصب السكر

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[٢] قسم الهندسة الزراعية والنظم الحيوية، كلية الزراعة، جامعة الإسكندرية، الشاطبي، الإسكندرية، مصر.

الملخص العربي

يعتبر السكر محصول استراتيجي مهم لجميع دول العالم. حيث يحتل المرتبة الثانية بعد القمح من حيث الأهمية الاستراتيجية في مصر. لذلك كان من الضروري إيلاء الاهتمام الكامل للمحاصيل السكرية وخاصة قصب السكر، لزيادة الإنتاجية وسد الفجوة بين الإنتاج والاستهلاك عن طريق زيادة إنتاجية قصب السكر. المشكلة الرئيسية في زراعة قصب السكر هي عملية الحصاد حيث يستمر موسم حصاد قصب السكر لمدة ٥ أشهر في مصر، يبدأ في ديسمبر وينتهي في مايو. كان الهدف الرئيسي من الدراسة هو تصميم وتصنيع آلة لحصاد قصب السكر تناسب الحيازات الزراعية واختبارها تحت الظروف المصرية. تم تصميم آلة لحصاد قصب السكر يتم تشغيلها بواسطة الجرار وتصنيعها واختبارها، كما تم تصميم أجزاء الآلة المختلفة باستخدام برنامج "SolidWorks"، تم تصنيع الماكينة وتجميعها باستخدام المواد منخفضة التكلفة المتوفرة في السوق المحلي.، أظهرت نتائج الاختبارات أن السعة الحقلية الفعلية تراوحت من ١,١٦ إلى ١,٣ فدان/ساعة، وازدادت بزيادة تباعد المسافة بين خطوط الزراعة والسرعة الأمامية. في الحقول ذات كثافة المحاصيل العالية، بلغ متوسط كفاءة القطع ١٠٠ %. وتتناسب كفاءة القطع عكسياً مع ارتفاع القطع وأيضًا وطردياً مع المسافة بين الخطوط وعدد السكاكين. زادت السعة الإنتاجية من ٤٢,٩ إلى ٧٩,٠٢ طن / ساعة مع زيادة تباعد الصفوف من ٧١ إلى ٨٨,٧٥ سم والحد الأقصى لتكاليف التشغيل الإجمالية ١٢٠ جنيهًا/ساعة (٩٨,٥ و ٩٢,٣ جنيهًا مصريًا /فدان) بناء علي القدرة اللازمة للقطع.