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Design, Fabrication and Performance Evaluation of an Inter-Row Cultivator for Sugarcane Fields

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Abstract: The aims of this research were to design and fabricate an inter-row cultivator for mounting on a medium-sized tractor (25.3 or 37.3 kW) for sugarcane fields, and to assess the performance of the cultivator when harvesting is conducted either by hand or with a sugarcane harvester. Moreover, this study was also designed to assess the performance of the cultivator in mixing sugarcane residues in the field. The inter-row cultivator has a working width of 80 cm, a rotor shaft speed of 500 rpm, and a total weight of 518 kg. The cultivator comprises 18 European C-type blades attached to three disk holder flanges arranged in a spiral formation. Two notch-cutting discs were mounted on the front to cut and press the sugarcane leaves before they were chopped and mixed by the inter-row cultivator. The working performance test was conducted for different thicknesses of trash blankets while using the inter-row cultivator mounted on 25.3 kW- and 37.3 kW-size tractors. The effective field capacity for trash incorporation of the inter-row cultivator was 0.30 ha·h^{-1} when trash was left through harvesting by hand. On the other hand, effective field capacity was 0.31 ha·h^{-1} when a sugarcane harvester was used. Moreover, the field efficiency exceeded 90% in all tested fields, with greater soil inversion. The results also showed that the fuel consumption of both tractors was higher when harvesting by hand compared with harvesting using a harvester.

Keywords: inter-row cultivator; sugarcane leaves; residue burning; field capacity

1. Introduction

Sugarcane is a perennial grass species that is native to the warm temperate regions of Asia. In Thailand, the sugarcane crop has a large impact on the Thai economy. In 2016, Thailand was the world's fourth largest sugar exporter after Brazil, India, and China [1]. Sugarcane is one of the primary agricultural sources of sugar. After harvesting, the sugarcane stalks are shredded, and the sugarcane juice is extracted. Raw sugar is produced from the juice, and is later refined into white sugar [2,3].

The Thailand Office of Agricultural Economics reported that over 103 million tons of sugarcane was produced in 2015 [4]. Sugarcane is grown in central, northern, and northeastern Thailand. The northeastern region has the largest growing production area. The main cultivation areas are in the Kanchanaburi, Suphanburi, Udonthani, Chaiyaphum, Nakhonratchasima, Khonkaen, and Nakornsawan provinces [4]. In 2015, the northeastern region produced 41.5 million tons of the 103 million tons of sugarcane produced in Thailand, while the northern and central regions generated 29.6 and 31.8 million tons, respectively.

The annual sugarcane plantation area of Thailand is 0.48 million ha. An area of 1 ha produces approximately 11 tons of sugarcane leaves and residues per year (Figure 1). This is reflected by the 11 ton·ha^{-1} of waste leaves burned each year that are not returned to the soil [5]. Burnt cane is easy to handle. Sugarcane milling should be performed as soon as possible to maximize sugar recovery. Green cane harvesting is not considered ideal, because it results in a large amount of sugarcane residue. Farmers usually burn the residues to avoid impacting (clogging) the implement used for the cultivation of the next ratoon cane. Most of the farmers prefer not to burn residues, as they can contribute a large amount of organic matter to the soil [6]. Burning sugarcane destroys soil organic matter, and thus frequent sugarcane farming results in decreased soil organic matter, poor soil physical properties, and low water infiltration and retention. Poor soil affects plant nutrients, particularly nitrogen, and returning leaves and other residues can reduce nitrogen fertilizer use. However, some farmers continue to burn residues before preparing the land [5]. Burning sugarcane debris, especially leaves and stems, produces carbon dioxide gas, which is one of the major greenhouse gases (GHGs) that is released to the environment [7,8].

Figure 1. Sugarcane leaves and residues after harvesting.

There are two prototypes of inter-row cultivators used in sugarcane fields in Thailand. The first prototype, designed by Chainarong [6], is a rotary tiller attached to a 21-kW tractor with a tilling width of 80 cm, and is used for mixing sugarcane residues. The rotary tiller with 18 European L-shaped blades is powered by the power take-off (PTO) shaft of the tractor. The performance of the rotary tiller was evaluated in a sugarcane field with a clay loam soil at a moisture content of 17.2% on a dry basis (db). The experimental field measured 45 × 50 m, and consisted of a crop that was ratooned two weeks earlier. A large amount of sugarcane residue was observed, which remained following the harvest of the earlier sugarcane crop. Tests were conducted with the tractor's forward speed at 1.0, 1.5 and 2 km·h^{-1}. It was found that mixing up to 95% of the residue was possible with this rotavator. The forward speed of the tractor did not affect the performance of the rotary tiller. During the field performance of the rotary tiller, it was observed that the average field capacity was 0.18 ha·h^{-1}, and the field efficiency was 78%. The lower field capacity in terms of working hours may be due to the limitations in the specified speeds used in the study.

The second inter-row cultivator prototype was designed by Sngiamphongse [9]. They developed an inter-row cultivator that can be mounted on a tractor (Figure 2). This implement is offset at the rear of the tractor and is attached by three-point hitches. The working width is 90 cm. The PTO of the tractor is transmitted via a 67.14-kW gearbox, drive shaft, and driving chain system to the rotor shaft, which has a speed of 500 rpm. The rotor shaft has four flanges; each flange is fitted with six European C-shaped blades in a spiral arrangement. Test results from Khon Kaen Province at a soil moisture content of 7.88% (db) indicated that using European C-shaped blades with thicknesses of 8 mm and 6 mm resulted in an average fuel consumption of 25.67 L·ha^{-1}. The capacity of this arrangement was 0.3 ha·h^{-1} with 89.64% field efficiency. Sugarcane leaves covered 96% of the soil surface. However, an inter-row cultivator attached to a 63.4-kW tractor is rather expensive, and has high fuel consumption [9].

Before the rainy season, a limited amount of time is available for land preparation, cane planting, and the cultivation of ratoon cane. Within one to two weeks after harvesting, sugarcane residues need to be chopped and mixed into the soil. Performing this activity using a small tractor (21 kW) will take more time, but a larger tractor (63.4 kW) will be expensive. With this in mind, the objectives of this research were to develop an inter-row cultivator to be mounted on a medium-sized tractor (25.3 or 37.3 kW) for sugarcane fields after harvesting by hand, and to assess its use for mixing sugarcane residues in the field after harvesting using a sugarcane harvester.

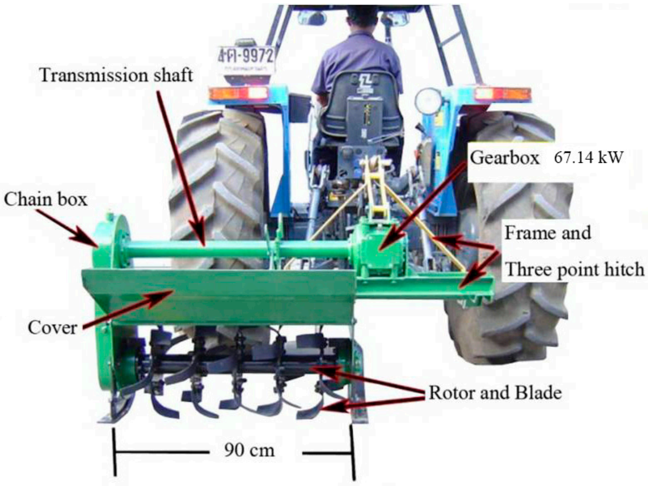

Figure 2. Prototype inter-row cultivator for mounting on a 63.4-kW tractor.

2. Materials and Methods

The inter-row cultivator was designed for cultivation and to mix sugarcane residues into the soil; consequently, this will mitigate the need for sugarcane burning. Design and fabrication components of the inter-row cultivator are discussed in the following sections. Furthermore, the evaluation of the inter-row cultivator in the field is also reported.

2.1. Design of the Inter-Row Cultivator

Medium-sized tractors (25.3 and 37.3 kW) have been widely utilized in various activities in the field by many Thai farmers due to their economic advantages. Thus, development of an inter-row cultivator for mounting onto these types of tractors would be very profitable, especially for sugarcane farmers.

The inter-row cultivator consists of six main units (Figure 3) as follows:

(1) PTO shaft: The speed of the PTO shaft of each tractor that was suitable for the inter-row cultivator was approximately 540 rpm.

(2) Gearbox: The gearbox (41.03 kW) was suitable for the requirements of the rotavator (speed ratio 1:1) and for attachment to 25.3- and 37.3-kW tractors. The gear box was used as the transmission system of this machine. It relayed the power of the tractor via the PTO shaft to the chain box to move the rotor blade.

(3) Rotor: The inter-row cultivator was designed with a consistent working width of 80 cm. Inter-row cultivators are mostly available with a working width of 80–90 cm, which is suitable for tractors with a 25-kW or higher power rating [9,10]. The blades attached to each flange were arranged

in a spiral form, which allows only one blade to make contact with the ground at the time of rotation. This enables the inter-row cultivator to consume less fuel. The rotor shaft had three flanges, each of which was fitted with six European C-shaped blades spaced 20 degrees apart in a spiral arrangement.

(4) Chain box: The chain box consisted of 13 upper sprockets and 14 lower sprockets, all driven by a chain.

(5) Blades: European C-shaped blades (Manufacturer: Cumar, Valencia, Spain) were selected because of their thickness (8 mm), and the lack of a hooking problem caused by plant residues [9]. Such blades are commonly used in Thailand due to their reasonable efficiency and price. The size of each blade was 140 mm × 198 mm × 8 mm. The shape of the blades is shown in Figure 4.

(6) Notch-cutting discs: There were two notch-cutting discs (Manufacturer: Siam implement, Phitsanulok, Thailand) with a 40-cm diameter in front of the inter-row cultivator. The discs were used for cutting and pressing the sugarcane leaves into smaller sizes before being chopped and mixed by the inter-row cultivator. The working angle of the cutting discs is parallel to the axis of tractor advancement. Clearly, the notch-cutting discs separated the cultivated field from the non-cultivated field, and reduced the possibility of blocking as a result of long leaves.

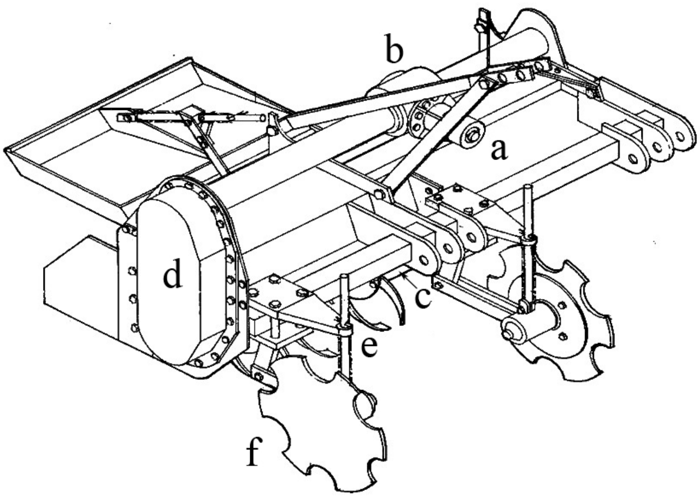

Figure 3. Prototype of the developed inter-row cultivator: (**a**) power take-off (PTO) shaft; (**b**) gear box; (**c**) rotor; (**d**) chain box; (**e**) blade; and (**f**) notch-cutting disc.

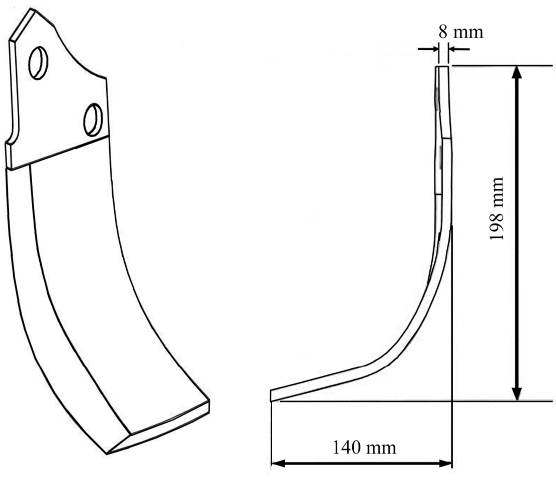

Figure 4. European C-shaped blade.

2.2. Field Evaluation

A field test was conducted in a sugarcane field in Bo Phloi, Kanchanaburi Province (14°19′30.61″N, 99°30′52.81″E), Thailand. The size of each field was 6.4 m × 147 m The layout of the field tests is shown in Figure 5. The field test plot consisted of five rows of sugarcane plants. During the field test, the tractor completed one pass for chopping and mixing. The chopping and mixing by the inter-row cultivator were assessed after harvesting by hand, and after harvesting using a sugarcane harvester. The tests using the inter-row cultivator were repeated five times using a 25.3- and 37.3-kW tractor with different thicknesses of the trash blanket. The following field performance were evaluated: the length of the sugarcane leaves before and after using the cultivator, soil inversion, field capacity, field efficiency, and fuel consumption. The machinery data for each test were evaluated following the Regional Network for Agriculture Machinery (RNAM) test codes [11]. Statistical analysis of the inter-row cultivator before and after the use of the machinery was conducted using *t*-tests. In each process, five replications were performed.

The performance test and the practical field test were conducted as follows:

(a) The length of the sugarcane leaves was measured before and after the cultivator pass based on sample collection from a 1 m × 1 m area, and the length of the sugarcane leaves was measured before and after the cultivator pass (Figure 5).

(b) The weight of the residue left on the soil surface per area (kg·ha^{-1}) was measured based on the leaves and the sugarcane residue in the 1 m × 1 m sampling area (Figure 5), which was then converted to total area (ha).

(c) Soil inversion (SI) was quantitatively expressed as the ratio of the weight of the residue remaining on the soil surface after the cultivator pass relative to that before the cultivator pass (Equation (1)).

$$\mathrm{SI} = \frac{(Wp - We)}{Wp} \times 100 \tag{1}$$

where W_p is the residue weight per unit area before the cultivator pass, and W_e is the residue weight per unit area after the cultivator pass.

(d) Effective field efficiency (EFC), theoretical field capacity (TFC), and field efficiency (FE) are shown in Equations (2), (3), and (4), respectively.

$$\mathrm{EFC} = We \times Ve \times T_p \tag{2}$$

$$\mathrm{TFC} = W_t \times V_t\left(T_p + T_l\right) \tag{3}$$

$$\mathrm{FE} = \frac{\mathrm{EFC}}{\mathrm{TFC}} \times 100 \tag{4}$$

where W_e is the effective working width, V_e is the effective operation speed, T_p is the productive time (h) (time for operating the machine in the testing area), W_t is the theoretical working width, V_t is the theoretical operation speed, and T_l is non-productive time (h) (time lost for turning, loading and adjustment, excluding refuelling and machine trouble).

(e) Operating speed: Two poles spaced 20 m apart were placed approximately in the middle of the test run. On the opposite side, another two poles were placed in a similar position, also 20 m apart. The four poles formed the corners of a rectangle that was parallel to at least one long side of the test plot to measure the operating speed of the tractor.

(f) The working width was defined as the distance between the middle of the sugarcane row to the middle of the next sugarcane row (Figure 5).

(g) Fuel consumption: The tank was filled to capacity before and after the test. The amount of fuel required after the test was considered as the fuel consumed during the test.

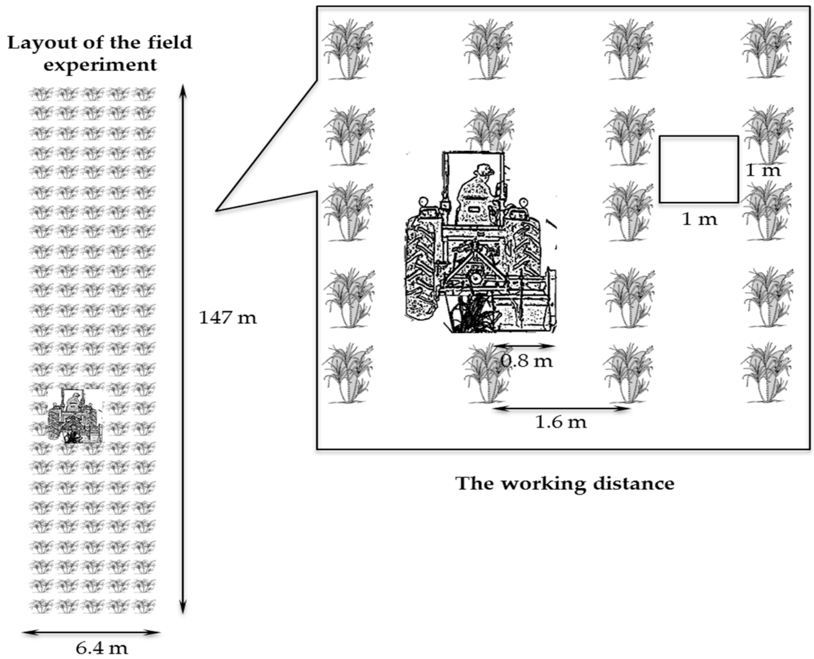

Figure 5. The layout of the field experiment and the working distance.

2.3. Economic Analysis of the Machinery

An economic analysis was performed to determine the break-even point [12]. The net incomes from the tractor and inter-row cultivator were also calculated individually. The details of the calculation are given below.

2.3.1. Tractor and Inter-Row Cultivator Cost

The cost was divided into two groups: fixed costs, which include annual depreciation, interest, taxes, and shelter charge; and variable costs, which include fuel, oil, lubricants, maintenance, repairs, and labor costs. In this case, the shelter charge was not included in calculating the cost.

2.3.2. Fixed Cost

Fixed cost was calculated on the basis of the following methods/assumptions [12]. For depreciation, the straight line depreciation method was used. The salvage value was assumed to be 10 percent of the initial price, and the total life was considered to be seven years [12]. The annual interest was calculated at a rate of 10%, which is commonly used for agricultural purposes. The equations for calculating depreciation and annual interest are presented below:

$$D = \frac{(P - S)}{L} \tag{5}$$

$$I = \frac{(P + S) \times 0.1}{2} \tag{6}$$

where D is the annual depreciation, P is the purchase price, S is the salvage value, L is the life of the machinery, and I is the annual interest cost.

2.3.3. Variable Cost

This was calculated individually on the basis of total annual use and the prevailing rates for labor, repair and maintenance (R&M), fuel, oil, and lubricants. The repair and maintenance cost are uncertain and considered % $R\&M$ unit times purchase price (P)/100 h gives numerical value that are easy to use for estimating.

$$M = \frac{\%R\&M \times P}{100} \quad (7)$$

where M is the cost associated with repair and maintenance of machine. In this case, it was considered $R\&M/100$ h is 5.0 as an tillage equipment operated by PTO [12].

2.3.4. Net Income

In each case, the total net income from all sources was calculated. The net income of an individual sample farm was subsequently determined.

3. Results and Discussion

A field test was conducted in a sugarcane field in Bo Phloi, Kanchanaburi Province, Thailand. The soil consisted of 30% sand, 32% silt, and 38% clay (i.e., a clay loam), and supported a ratoon crop. Before the test run, the field was found to contain a very large amount of widely spread sugarcane residues. Figure 6 shows the sugarcane residues after harvesting by hand. Figure 7 shows the sugarcane residues after harvesting using a sugarcane harvester. The working inter-row cultivator is shown in Figure 8. After the test run, the sugarcane residues were mixed into the soil using the inter-row cultivator (Figure 9).

Figure 6. Sugarcane field after harvesting by hand.

Figure 7. Sugarcane field after harvesting using the sugarcane harvester.

Figure 8. Inter-row cultivator operating in the field.

Figure 9. Sugarcane residues after being mixed into the soil by the inter-row cultivator.

3.1. Inter-Row Cultivator Attached to the 25.3-kW Tractor

The specifications of the 25.3-kW tractor are listed in Table 1. The results of the field test are listed in Table 2. The initial length of the sugarcane leaves collected after harvesting by hand was, on average, 9.62% longer than that after harvesting using the sugarcane harvester. The weight of the residue left per unit area on the soil surface was not significantly different among the fields. The forward speed of the machinery, the theoretical field capacity, and the effective field capacity in all field tests were not significantly different. The field efficiency of the machinery after harvesting using the sugarcane harvester was 3.23% higher than that after harvesting by hand, and 5.64% less fuel was consumed. The length of the sugarcane leaves after harvesting by hand was 40.80% longer compared with the sugarcane harvester. Soil inversion was greater (2.08%) after harvesting using the sugarcane harvester compared with harvesting by hand.

Table 1. Specifications of the tractors.

Description	Tractor 25.3 kW	Tractor 37.3 kW
Engine capacity (CC)	1647	2434
Bore × Stroke (mm)	87 × 92.4	87 × 102.4
Horsepower/rpm	34.7/2700	50/2700
Gear combination (km·h^{-1})	1.8–22.2	2.5–29.7
Forward speed	8 speed	8 speed
PTO speed	540	540
3-point hitch	Category I	Category I/II
Front wheel size	8–16	8.3–24
Rear wheel size	12.2–24	14.9–28
Wheel base (mm)	1610	2000
Weight (kg)	1115	1800

PTO: power take-off.

Table 2. The performance test and the practical field test of an inter-row cultivator attached to a 25.3-kW tractor.

Description	Trash Left Through		*t*-Test
	Harvesting by Hand	Harvesting Using the Sugarcane Harvester	
Field Test Condition			
Thickness of the trash blanket (cm)	10	10	
A length before cultivation (cm)	132.0	119.3	−5.939 **
Weight of the residue left on the soil surface per area (kg·ha^{-1})	6500	6600	0.615 ^{ns}
Results after Using the Inter-Row Cultivator			
Forward speed (m·s^{-1})	0.57	0.57	–
Theoretical field capacity (ha·h^{-1})	0.33	0.33	–
Effective field capacity (ha·h^{-1})	0.30	0.31	1.236 ^{ns}
Field efficiency (%)	90.91	93.94	4.044 **
Fuel consumption (L·ha^{-1})	19.50	18.40	3.627 **
A length after cultivation (cm)	32.60	19.30	20.822 **
Weight of the residue left on the soil surface per area (kg·ha^{-1})	494.7	372.9	−3.247 *
Soil inversion (%)	92.39	94.35	0.587 *

*, ** Significant at the 5% and 1% levels, respectively; ^{ns} Not significant.

3.2. Inter-Row Cultivator Attached to the 37.3-kW Tractor

The specifications of the 37.30-kW tractor are listed in Table 1. The results of the field test are listed in Table 3. The initial length of the sugarcane leaves collected after harvesting by hand was, on average, 5.62% longer than that after harvesting using the sugarcane harvester. The weight of the residue left on the soil surface per unit area was not significantly different among the fields. The forward speed of the machinery, the theoretical field capacity, and the effective field capacity in all field tests were not significantly different. The field efficiency of the machinery after harvesting using the sugarcane harvester was 3.23% higher than that after harvesting by hand, and fuel consumption was 5.86% lower. The length of the sugarcane leaves after harvesting by hand was 44.04% longer compared with the sugarcane harvester. Soil inversion was greater (1.71%) after harvesting using the sugarcane harvester than after harvesting by hand.

3.3. Inter-Row Cultivator Attached to the 25.3-kW Tractor at Different Thicknesses of the Trash Blanket

The results of the field test are listed in Table 4. The initial length of the sugarcane leaves was not significantly different among the fields. The weight of the residue left on the soil surface collected per unit area was 11.11% higher when the trash blanket thickness was 18 cm than when it was 10 cm. The forward speed of the machinery and the theoretical field capacity were not significantly different, whereas the effective field capacity differed by 3.23%. When the trash blanket thickness was 10 cm, the field efficiency of the machinery was 3.23% higher and the fuel consumption was 14.68% lower compared with a trash blanket thickness of 18 cm. When the trash blanket thickness was 18 cm, the length of the sugarcane leaves after harvesting was 39.68% longer than when the trash blanket thickness was 10 cm. The residue weight and soil inversion were not significantly different among the fields.

Table 3. The performance test and the practical field test of an inter-row cultivator attached to the 37.3-kW tractor.

Description	Trash Left Through		*t*-Test
	Harvesting by Hand	Harvesting Using the Sugarcane Harvester	
Field Test Condition			
Thickness of the trash blanket, cm	18	18	
Leaf length before cultivation (cm)	119.2	112.5	2.43 *
Weight of the residue left on the soil surface per area (kg·ha^{-1})	6780	6871	−0.610 ^{ns}
Results after Using the Inter-Row Cultivator			
Forward speed (m·s^{-1})	0.57	0.58	1 ^{ns}
Theoretical field capacity (ha·h^{-1})	0.33	0.33	-
Effective field capacity (ha·h^{-1})	0.30	0.31	1.12 ^{ns}
Field efficiency (%)	90.91	93.94	4.047 **
Fuel consumption (L·ha^{-1})	20.31	19.12	3.65 **
Leaf length after cultivation (cm)	27.7	15.50	19.87 **
Weight of the residue left on the soil surface per area (kg·ha^{-1})	352.95	244.86	5.24 **
Soil inversion (%)	94.79	96.44	−1.25 *

*, ** Significant at the 5% and 1% levels, respectively; ^{ns} Not significant.

Table 4. The performance test and the practical field test of an inter-row cultivator attached to the 25.3-kW tractor at different thicknesses of the trash blanket.

Description	Trash Thickness Level		*t*-Test
	Thickness of Trash Blanket (10 cm)	Thickness of Trash Blanket (18 cm)	
Field Test Condition			
Leaf length before cultivation (cm)	114.2	116.8	2.047 ^{ns}
Weight of the residue left on the soil surface per area (kg·ha^{-1})	5760	6480	10.126 **
Results after Using the Inter-Row Cultivator			
Forward speed (m·s^{-1})	0.56	0.56	-
Theory field capacity (ha·h^{-1})	0.32	0.32	-
Effective field capacity (ha·h^{-1})	0.31	0.30	1.213 **
Field efficiency (%)	96.88	93.75	−4.784 **
Fuel consumption (L·ha^{-1})	16.62	19.48	4.792 **
Leaf length after cultivation (cm)	19.17	31.78	29.748 **
Weight of the residue left on the soil surface per area (kg·ha^{-1})	374.40	482.60	18.17 ^{ns}
Soil inversion (%)	93.50	92.55	2.17 ^{ns}

*, ** Significant at the 5% and 1% levels, respectively; ^{ns} Not significant.

3.4. Inter-Row Cultivator Attached to the 37.3-kW Tractor at Different Thicknesses of the Trash Blanket

The results of the field test are listed in Table 5. The initial length of the sugarcane leaves was not significantly different among the fields. When the trash blanket thickness was 18 cm, the weight of residue left on the soil surface collected per unit area was 14.85% higher than when it was only 10 cm thick. The forward speed of the machinery and the theoretical field capacity were not significantly different, whereas the effective field capacity differed by 6.25%. When the trash blanket thickness was 10 cm, the field efficiency of the machinery was 6.25% higher, and the fuel consumption was 10.51% lower compared with a trash blanket thickness of 18 cm. The length of the sugarcane leaves was 57.42% longer when the trash blanket thickness was 18 cm, compared with a thickness of 10 cm. The residue weight left on the soil surface and soil inversion were not significantly different among the fields.

Table 5. The performance test and the practical field test of an inter-row cultivator attached to the 37.3-kW tractor at different thicknesses of the trash blanket.

Description	Trash Thickness Level		*t*-Test
	Thickness of the Trash Blanket (10 cm)	Thickness of the Trash Blanket (18 cm)	
Field Test Condition			
Leaf length before cultivation (cm)	114.5	118.0	2.152 ^{ns}
Weight of the residue left on the soil surface per area (kg·ha^{-1})	5620	6600	12.126 **
Results after Using the Inter-Row Cultivator			
Forward speed (m·s^{-1})	0.58	0.58	–
Theoretical field capacity (ha·h^{-1})	0.33	0.33	–
Effective field capacity (ha·h^{-1})	0.32	0.30	1.454 **
Field efficiency (%)	96.97	90.91	−5.409 **
Fuel consumption (L·ha^{-1})	17.79	19.88	2.778 **
Leaf length after cultivation (cm)	15.50	36.40	53.964 **
Weight of the residue left on the soil surface per area (kg·ha^{-1})	243.35	325.74	21.59 ^{ns}
Soil inversion (%)	95.67	95.06	1.82 ^{ns}

*, ** Significant at the 5% and 1% levels, respectively; ^{ns} Not significant.

From Tables 2–5, we determined the performance of the developed inter-row cultivator, which was satisfactory in terms of residue burial. Soil inversion was higher than 90% in all tested fields. This indicates the effectiveness of the cultivator in chopping and mixing the sugarcane residue into the soil. The initial length of the sugarcane leaves collected after harvesting by hand was longer than that collected after using the sugarcane harvester. The weight of the residue left on the soil surface per unit area and the forward speed of the machinery were not significantly different among the fields. The fuel consumption of the machinery after harvesting by hand was higher than that after harvesting using the sugarcane harvester. However, when considered in relation to the thickness of the trash blanket, the initial length of the sugarcane leaves, the forward speed of the machinery, the theoretical field capacity, and soil inversion were not significantly different. Moreover, the effective field capacity and field efficiency when the trash blanket had a lower thickness were higher than those measured under a thicker trash blanket. In addition, fuel consumption at the lower thickness of the trash blanket was lower than that at the higher thickness of the trash blanket.

3.5. Economic Analysis of the Machinery

From Equations (5)–(7), along with Table 6, we conducted a break-even analysis to quantify the benefits of purchasing a 25.3-kW tractor and an inter-row cultivator. It was determined that at least 48.15 ha would be needed to reach a break-even point (Figure 10). Moreover, for a 37.3-kW tractor and an inter-row cultivator, cultivation of at least 101.81 ha would be needed to reach the break-even point (Figure 10).

Eliminating sugarcane residues after harvest costs time and labor. Generally, farmers burn the residues, which causes environmental problems. To overcome this, an inter-row cultivator that incorporates residues into the soil was developed using European C-shaped blades. The inter-row cultivator was powered by a tractor PTO shaft. The performance of the developed inter-row cultivator was quantified in terms of residue burial. Field tests confirmed that the cultivator effectively chopped and mixed the residues into the soil.

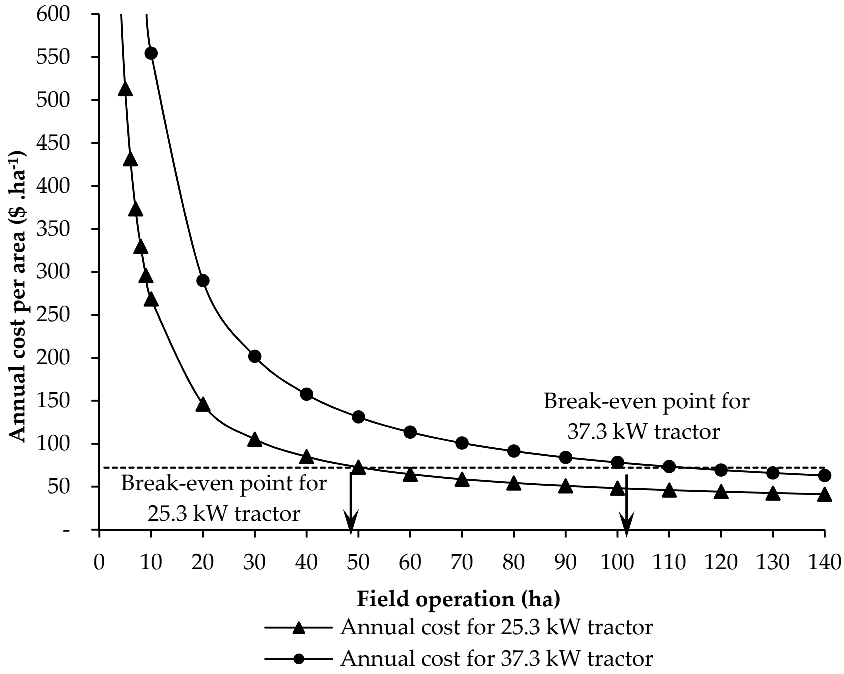

Figure 10. Break-even points of a tractor and an inter-row cultivator with tractors operating at 25.3 kW and 37.3 kW.

Table 6. Economic analysis of a tractor and an inter-row cultivator.

Description	25.3-kW Tractor	37.3-kW Tractor	Inter-Row Cultivator
Fixed Costs			
Purchase price (P, $)	13,333.33	26,666.66	2166.66
Economic life (years)	7	7	7
Salvage (10% P, $)	1333.33	2666.66	216.66
Annual interest rate (%)	10	10	10
Variable Costs			
Fuel consumption ($L{\cdot}ha^{-1}$)	19.50	19.88	–
Price of oil ($\${\cdot}L^{-1}$)	0.83	0.83	–
Field capacity ($ha{\cdot}h^{1}$)	0.32	0.33	–
Fuel cost ($\${\cdot}h^{-1}$)	5.18	5.45	–
Lubricant ($\${\cdot}h^{-1}$)	0.47	0.59	–
Maintenance ($\${\cdot}h^{-1}$)	6.66	13.33	1.08
Labor ($\${\cdot}h^{-1}$)	0.83	0.83	–
Break-even point (ha)	48.15	101.81	–

4. Conclusions

An inter-row cultivator was designed to mitigate the practice of burning sugarcane leaves and increase the organic matter in sugarcane fields. The inter-row cultivator was fabricated with working width of 80 cm and a total weight of 518 kg. The PTO from the tractor was transmitted via a gear box, drive shaft, and driving chain system to the rotor shaft, which had a speed of 500 rpm. The performance of the developed inter-row cultivator was quantified in terms of chopping, mixing, and residue burial. The field test indicated that there was no difference in effective field capacities of the inter-row cultivators for trash incorporation, while the deposition of trash in the field was observed through harvesting of sugarcane by hand and a harvester. The forward speed was limited for 25.3 and 37.3 kW tractors. The fuel consumption of the 37.3-kW tractor was higher than that of the 25.3-kW tractor.

Moreover, when considering soil inversion, it was found that the inter-row cultivator could mix 90% of the residue into the soil. Satisfactory residue chopping and mixing into the soil were also observed.

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References

1. Illovo Sugar. International Sugar Statistics. Available online: https://www.illovosugarafrica.com/home (accessed on 20 August 2017).
2. Srisink, S. *Sugarcane Management*; The Plant Protection Research and Development office, The Department of Agriculture: Bangkok, Thailand, 2015.
3. Singh, G.; Pathak, B.K. A decision support system for mechanical harvesting and transportation of sugarcane in Thailand. *Comput. Electron. Agric.* **1994**, *11*, 173–182. [CrossRef]
4. Office of Agricultural Economics. *Agricultural Production. Sugarcane*; Office of Agricultural Economics, Agricultural Statistics, Ministry of Agriculture and Cooperatives: Bangkok, Thailand, 2015.
5. Boontrum, A.; Tangpremsri, T.; Prammanee, P.; Lairungreang, C. *A Use of an Inter-Row Cultivator to Solve a Problem of Sugarcane Leave Burning after Harvesting*; The Institute of Field Crop Research, The Department of Agriculture: Bangkok, Thailand, 1997.
6. Chainarong, T. Development of a Rotary Tiller for Mixing Sugarcane Residues. Master's Thesis, Asian Institute of Technology, Bangkok, Thailand, 2002.
7. Sangla, L.; Suppadit, T. The impacts of sugarcane leaf burning and solving methods. *Thai J. Environ. Manag. Nida Thail.* **2005**, *2*, 85–102.
8. Jenjariyakosoln, S.; Gheewala, H.S.; Sajjakulnukit, B.; Garivait, S. Energy and GHG emission reduction potential of power generation from sugarcane residues in Thailand. *Energy Sustain. Dev.* **2014**, *23*, 32–45. [CrossRef]
9. Sngiamphongse, S.; Senanarong, A.; Khaehanchanpong, Y.; Wannaronk, K. *A Research and Development of an Inter-Row Cultivator for Incorporating Sugarcane Leaves between Sugarcane Planting Plots*; Research Registration Number 09-01-42-0101; Agricultural Engineering Research Institute: Bangkok, Thailand, 2005.
10. Sngiamphongse, S. *Design and Development of Rotary Tiller for Small Four Wheel Tractor*; Agricultural Engineering Research Institute: Bangkok, Thailand, 2000.
11. Regional Network for Agricultural Machinery (RNAM). *Test Code & Procedures for Farm Machinery*, 2nd ed.; RNAM: Bangkok, Thailand, 1995.
12. Hunt, D. *Farm Power and Machinery Management*; Iowa State University: Ames, IA, USA, 1995.