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**Towards sustainable sugar industry in Thailand: Cost and benefit analysis**Russamee Junkraweekoon<sup>1</sup>, Suphaphat Kwonpongsagoon<sup>1,2\*</sup> and Kanokwan Kingphadung<sup>3</sup><sup>1</sup>Department of Sanitary Engineering, Faculty of Public Health, Mahidol University, Bangkok, Thailand<sup>2</sup>Center of Excellence on Environmental Health and Toxicology (EHT), OPS, MHESI, Thailand<sup>3</sup>Department of Food Technology, Faculty of Engineering and Industrial Technology, Silpakorn University, Thailand\*Corresponding author: [suphaphat.kwo@mahidol.ac.th](mailto:suphaphat.kwo@mahidol.ac.th)Received 3 August 2023  
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**Abstract**

This study analyzes the financial costs and benefits associated with various agricultural practices, industrial processes, products, byproducts and waste management, starting from sugarcane plantations to the end users of products and byproducts of sugar processing. The field survey and data collection were conducted using face-to-face interviews during the 2020/21 crop year. The findings indicate that the total variable sugar production cost of the entire industry is 864 USD per ton of raw sugar crystal, with 77% coming from sugarcane production and 23% from the sugar production process. The highest cost of sugarcane production was in the weed control process, accounting for 38%, followed by fertilizer application, planting, sugarcane transported to the mill, harvesting, and others (land preparation, insecticide control and crop maintenance) at 24, 14, 11, 8 and 5%, respectively. The findings of Benefit-Cost Ratio, Net Present Value, and Internal Rate of Return analysis indicate that for the process of cane production and the entire sugar industry, the benefit category I, by using three main byproducts: 1) selling molasses for other uses or production; 2) selling filter cake as fertilizer, and 3) using bagasse as fuel to generate electricity, is the most economically feasible. Although all profits are returned only to the sugar factory, using these byproducts and wastes can bring enormous environmental benefits. Moving towards a sustainable sugar industry in Thailand, a need exists to improve sugarcane production by reducing production costs, e.g., reducing inputs such as chemicals, fertilizer and fuels, and increasing sugarcane productivity.

**Keywords:** Sustainable, Industry, Sugarcane, Sugar, Waste management, Cost, Benefit, Benefit-cost ratio (BCR)

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**1. Introduction**

Thailand produces sugar from sugarcane for domestic consumption and export. Domestic demand for industries and consumers is around 2.5 million tons yearly. Concerning exports, Thailand is the world's third largest sugar exporter after Brazil and India, with approximately 3.6 million tons in 2021 [1]. The sugar industry is reported to contribute more than 6 billion USD to the country's economy annually [2], making the sugar industry crucial to the Thai economy. The entire sugar industry system can be divided in two main production systems: sugarcane cultivation and sugar production. This means that sugarcane is the main raw material upstream of the supply chain. Sugarcane is also an important economic crop for Thailand's agricultural sector, in addition to rice, cassava and rubber.

In Thailand, sugarcane plantations account for about 46% of the country's total arable land [3]. The sugarcane cultivation in Thailand has increased yearly to meet the demand for food and fuel (ethanol) as end-user products. Over the past ten years, from 2013 to 2022, the sugarcane planted area has increased by about 15.6%, while sugarcane production has increased by only 0.43% [4,5]. Sugarcane cultivation in Thailand has a cropping calendar and cultural practices based on agro-ecological conditions and the allocation of water from irrigation. However, most sugarcane

fields are outside these irrigated areas, relying mostly on rainwater for cultivation [4]. In Thailand, sugarcane is a long-duration crop, with maturity for harvesting in 10 to 12 months. In preparing the soil for sugarcane planting, each time can be harvested up to three times over a three-year period. The main areas of sugarcane cultivation are located in the country's northern, central, northeastern and eastern regions. According to the Office of the Cane and Sugar Board (OCSB), in 2021/2022, the total sugarcane plantation area is approximately 1.76 Mha, producing 105.94 Mton of sugarcane which is equivalent to about 60 tons of cane per hectare (ha) [4].

For the sugar production industry, the conventional sugar manufacturing process in Thailand uses carbonation to produce crystalized sugar which is the main product of the sugar industry. Three byproducts are molasses, bagasse and filter cake. Altogether, 58 sugar mills operate in Thailand [6] with a trend to increase slightly in the future. More than 90% of sugar exports are sold to Asian countries such as Indonesia, Cambodia, Vietnam, South Korea and Taiwan [1,7].

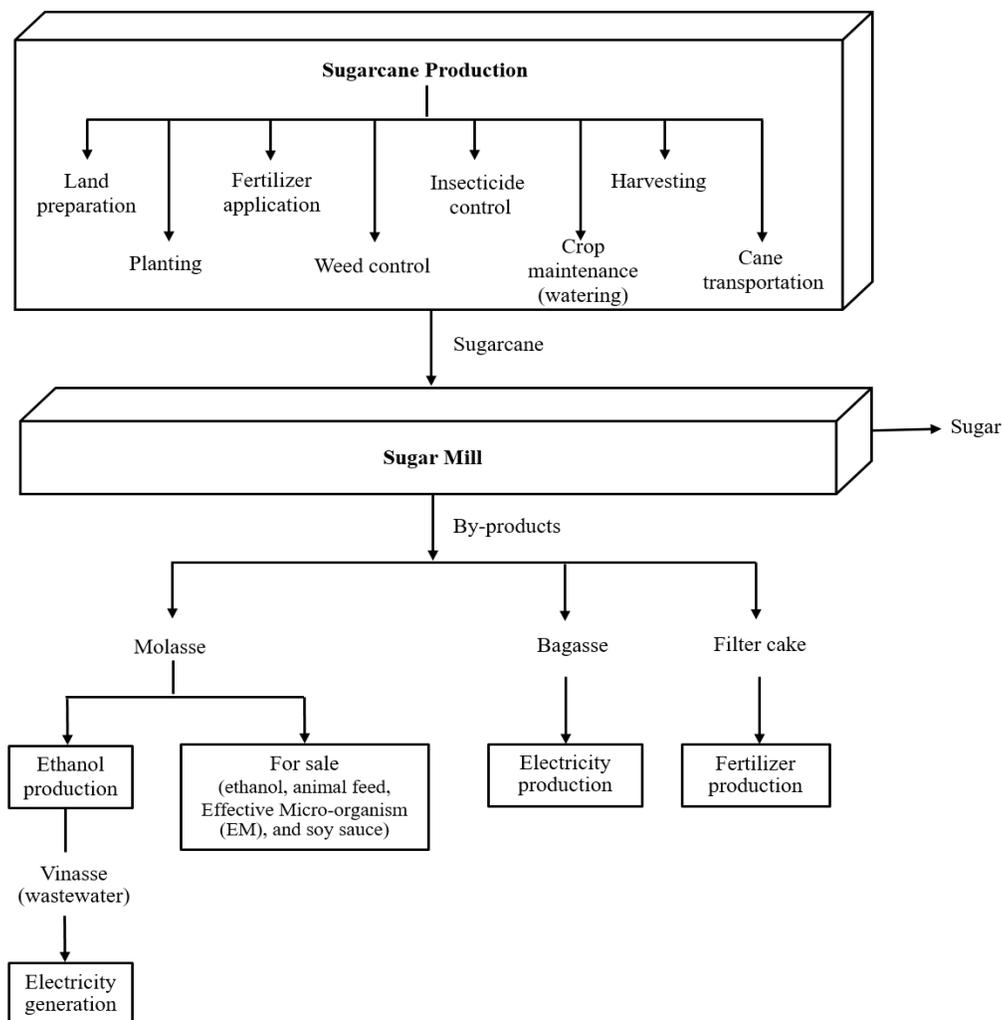
Moving towards a sustainable sugar industry depends on both sugarcane cultivation and sugar production, which should be carried out more environmentally friendly and sustainably for each phase and the entire system. The common factors of sugarcane production that are often considered are sugarcane yield, agricultural practices and sugarcane quality, e.g., sweetness. However, farmers' cultivation practices also affect their costs and profits in terms of materials and energy consumption, e.g., chemicals, fertilizers and fuel. In other words, the financial factors reflecting the cost and revenue dynamic are also key issues in sustainable sugarcane production. In the sugar industry, normally a clear profit is obtained from the sales of domestic and exported sugar products. With a massive volume of byproducts and wastes generated, sugar industries earn additional income from investing in related businesses that use some byproducts and excess materials from the sugar industry as raw materials such as ethanol, biomass power electricity generation, paper pulp, fertilizer, and particle board [8]. However, such additional revenues are rarely disclosed. In addition, according to Manivong and Bourgois [7], research on the economics of sugarcane farming in Thailand remains limited. Therefore, the opportunity to improve Thailand's sustainable sugar industry involves economic research that can reflect the financial cost and benefit of the whole industry, including sugarcane growing, sugar production and use of related byproducts. This would be helpful for designing financial risk modeling tools for profit or loss for the entire sugar industry in the future. The analysis in this study will be useful in interpreting the financial consequences of using byproducts and waste as substances to produce value-added products and the costs incurred by all processes of the sugar industry [9,10]. All of these can be revealed by designing profitability and cost-benefit analysis, calculating benefit-to-cost ratio (BCR), net present value (NPV), and internal rate of return (IRR). Moreover, conducting the entire cost-benefit analysis will help to gain a better understanding of the sugarcane grower's practices such as pesticide, fertilizer and energy use influencing the sustainable use of the materials in sugarcane production.

This study aimed to analyze and gain a more detailed understanding of the financial costs and benefits associated with various agricultural practices, industrial processes, products, byproducts and waste management, starting from sugarcane plantations to the end users of products and byproducts of sugar processing. However, this study does not consider the negative impacts of sugarcane cultivation, such as sugarcane burning, which contributes to PM 2.5 pollution. Overall, this study can provide economic indicators to stimulate stakeholders and encourage decision-makers to discuss and implement more sustainable policies for the overall sugar industry in Thailand with a focus on sugarcane farming activities and the use of byproducts and wastes from the sugar production industry.

## **2. Materials and methods**

### *2.1 Scope of Study and System Boundary*

Figure 1 shows the scope and system boundary of Thailand's sugar industry in this study. It starts from cane production in the agricultural stage to sugar factories at the industrial level. In the agricultural stage, several types of materials and energy are used in sugarcane fields through different activities such as tilling, applying pesticides and fertilizers and harvesting etc. At the industrial level, after the refining process, sugar (raw and refined) is the main product for export and both direct and indirect domestic consumption (or end-user industries such as beverages, food, confectionery, dairy products etc.). The three major byproducts or value-added products include molasses, bagasse and filter cake. Molasses is a raw material that can be used in the internal ethanol production process, or sold to other factories to produce ethanol, animal feed, effective micro-organisms (EM) and soy sauce. Wastewater, also known as "vinasse", which is discharged from the distillation tower of molasses ethanol production, can be used to generate electricity using a fermentation process with a modified covered lagoon digester. Bagasse or sugarcane fiber, which is the residue of sugarcane stalks after sugarcane juice is extracted, is used as a fuel for steam power plants to generate electricity while filter cake is sold directly for use as alternative fertilizer in various fields.



**Figure 1** Scope of Thailand's sugar industry in this study.

## 2.2 Study Area and Data Collection

The sugarcane plantation study area was selected as Suphanburi Province, one of the most productive sugarcane-growing areas in central Thailand. Most areas are plains with many rivers, canals and marshes. The average temperature and rainfall throughout the year are about 27.9°C, and 1,059.9 mm, respectively [11]. In addition, the target sugar mills selected for this study are in Suphanburi, and the neighboring province, Kanchanaburi, which is adjacent to the west and south of Suphanburi.

The field survey for gathering primary data was divided in two phases: the agricultural phase and the industrial phase. Data collection was conducted by interviewing respondents face-to-face with pre-arranged questionnaires during the 2020/21 crop year. The sample size of the interviewees consisted of 94 sugarcane growers and three managers and related staff of the three sugar mills. In the agricultural phase, the data collected covered sugarcane yields and resources (materials and energy) used such as the use and cost of chemicals, fertilizers, insecticides, herbicides, fuels and electricity used for various activities of sugarcane plantations including wages. For the industrial phase, the data collected included wages and the use and cost of materials, fuel and electricity used for sugar production. All value-added products obtained from related subprocesses (Figure 1), and their selling prices were also collected in this study.

### 2.3 Cost Analysis

The cost analysis of this study was calculated as described below.

#### a) Cost of sugarcane production

$$TC_{\text{Agri}} = C_{\text{AF}} + C_{\text{LP}} + C_{\text{P}} + C_{\text{FA}} + C_{\text{I}} + C_{\text{W}} + C_{\text{CM}} + C_{\text{H}} + C_{\text{T}} \quad (1)$$

where  $TC_{\text{Agri}}$  denotes the total sugarcane production cost,  $C_{\text{AF}}$  is fixed cost for land rental, and depreciation of agricultural equipment,  $C_{\text{LP}}$  is land preparation cost,  $C_{\text{P}}$  is planting cost,  $C_{\text{FA}}$  is fertilizer application cost,  $C_{\text{I}}$  is insecticide control cost,  $C_{\text{W}}$  is weed control cost,  $C_{\text{CM}}$  is crop maintenance cost,  $C_{\text{H}}$  is harvesting cost and  $C_{\text{T}}$  transportation cost.

#### b) Cost of sugar production and use of byproducts and waste

$$TC_{\text{Ind}} = C_{\text{IF}} + C_{\text{M}} + C_{\text{L}} + C_{\text{O}} \quad (2)$$

where  $TC_{\text{Ind}}$  denotes the total sugar production and use of byproducts and waste cost,  $C_{\text{IF}}$  is investment cost (land, construction, machine and equipment cost),  $C_{\text{M}}$  represents material cost,  $C_{\text{L}}$  represents labor cost and  $C_{\text{O}}$  represents overhead cost.

### 2.4 Benefit Analysis

The benefit analysis was first calculated based on the direct sales benefit of the main product from sugarcane production and sugar mills. Together with the value-added byproducts and wastes of the industrial phase, all various benefits (Figure 1) were grouped in three categories for analysis and comparison in this study.

Category I: Direct benefit from the sale of raw sugar and molasses, filter cake sold as fertilizer, and bagasse used as fuel to generate electricity.

Category II: Direct benefit from the sale of raw sugar, filter cake sold as fertilizer, bagasse used as fuel to generate electricity and molasses to produce ethanol.

Category III: Direct benefit from the sale of raw sugar, filter cake sold as fertilizer, bagasse used as fuel to generate electricity, molasses to produce ethanol and vinasse from molasses ethanol production to generate electricity.

This study presents a statistical analysis of all costs and selling prices as averages.

### 2.5 Profitability Analysis

Profitability is the ultimate goal of the farmer or industry to increase profitability using the minimum possible resources. The farmer or industry is profitable when its revenue has increased at a faster rate than that of its cost. Profitability index was calculated using the formula below [12, 13].

$$\text{Profitability index} = \frac{\text{Revenue}}{\text{Cost}} \quad (3)$$

### 2.6 Benefit-Cost Ratio (BCR), Net Present Value (NPV), and Internal Rate of Return (IRR)

The BCR is defined as the value of total benefits divided by the total costs. The BCR in this study is used to describe the profitability of sugar mills. If the ratio is greater than 1, the practice or approach is beneficial or is expected to deliver a positive net present value to the investor (refers to sugar mills in this study).

$$\text{BCR} = \frac{\sum_{t=0}^T \frac{B_t}{(1+r)^t}}{\sum_{t=0}^T \frac{C_t}{(1+r)^t}} \geq 1 \quad (4)$$

where BCR denotes benefit to cost ratio,  $B_t$  represents benefit (estimated by revenue minus costs) at year  $t$ ,  $C_t$  represents cost at year  $t$ ,  $T$  is project duration (40-year lifetime),  $r$  is discount rate 5.25% yearly (Minimum Loan Rate - MLR from a commercial bank of Thailand, 2020), and  $t$  is year  $t$ .

NPV is the difference between the present value of cash inflows and the present value of cash outflows and between the present value of cash outflows over a time period and is used to quantify the expected profitability of an investment. It has to be  $> 0$  to be profitable and was calculated using the formula below [14]:

$$NPV = \sum_{t=0}^T \frac{B_t - C_t}{(1+r)^t} \quad (5)$$

IRR is the discount rate making the net present value of all cash flows equal to zero when time-adjusted future cash flows equal the initial investment. IRR calculations rely on the same formula as NPV. IRR is used to estimate the profitability of potential investment. IRR was calculated using the formula below [14].

$$IRR = i: \sum_{t=0}^T \frac{B_t}{(1+r)^t} = \sum_{t=0}^T \frac{C_t}{(1+r)^t} \quad (6)$$

The unit of measurement for analysis in this study is expressed in US dollar (USD), using the exchange rate as of April 12, 2023 at 34.41 baht per 1 US dollar [15].

### 3. Results and discussion

#### 3.1 Cost Analysis

In this study, the total cost of sugar production in Thailand can be divided in two phases, namely, the sugarcane farming phase and the sugar production phase as described above. Tables 1 and 2 show the variable costs analyzed separately for the cane and sugar production phase. In cane production of Table 1, the variable cost of all activities is about 22 USD per ton of sugarcane yearly or accounting for 665 USD per ton of raw sugar crystal yearly (estimated based on one ton of raw sugar crystal obtained from 27.22 tons of sugarcane). For sugar production in Table 2, the variable cost is about 199 USD per ton of raw sugar crystal yearly. Thus, the total variable cost of the entire industry is approximately 864 USD per ton of raw sugar crystal with 77% from cane farming and 23% from the sugar production process. Clearly, to produce 1 ton of raw sugar in Thailand, the farming process requires approximately three times the variable costs compared with the industrial process. The fixed costs of cane and sugar production are described in Section 3.3 below.

During the sugarcane planting phase, the activities for sugarcane planting were analyzed as eight activities as listed below (Figure 1).

- 1) Land preparation
- 2) Planting
- 3) Fertilizer application
- 4) Weed control
- 5) Insecticide control
- 6) Crop maintenance (watering)
- 7) Harvesting, and
- 8) Transport sugarcane to the mill

In Table 1, the results indicated that the highest cost was in the weed control process, accounting for 38%, followed by fertilizer application, planting, transporting sugarcane to the mill, harvesting, and the remaining activities (land preparation, insecticide control and crop maintenance) were at 24, 14, 11, 8 and 5%, respectively (Figure 2). Considering weed control activity, sugarcane farmers used a variety of 11 herbicides with high application rates, resulting in the highest cost of all other activities. All farmers used herbicides in their sugarcane fields, while only 6% of farmers used insecticides. Looking at fertilizer application activity, the high cost found in this study depends on both high application rates and their prices. Thailand's chemical fertilizer industry is in the downstream stage, which is almost entirely dependent on imports from abroad, divided in 1) imports of parent fertilizers and 2) imports of finished or semifinished chemical fertilizers [16]. This means that domestic fertilizer prices depend on chemical fertilizers in the world market, which are rising due to high energy prices, high transportation costs and the depreciation of the THB against the USD in recent years. As a result, the cost of importing fertilizer and selling price of fertilizer increased. Therefore, managing the use of herbicides and fertilizers for sugarcane farming in Thailand is essential for the sustainability of sugarcane production and the whole sugar industry. For sugarcane planting activity using labor and

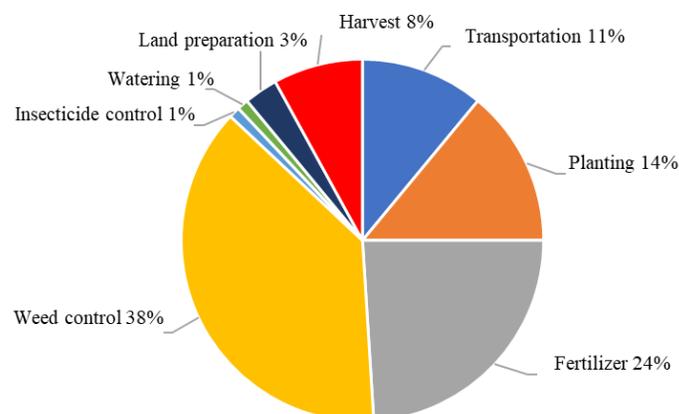
for transporting sugarcane to the mill, the main activities take place in the first year only, most of the cost comes from the high fuel cost, especially when using the farmer's own vehicles (Table 1). In the case of self-transportation, most farmers use 10-wheel trucks to transport sugarcane to the mill, which are smaller in size, involve less loading and consume more fuel per ton of cane transported compared with 18 or 20-wheel loader trucks from outsourcing.

**Table 1** Variable cost of sugarcane production activities in Thailand

Activity/Cost type	Cost		Unit cost (USD/ton sugarcane/yr)	Unit cost (USD/ton raw sugar crystal <sup>b</sup> /yr)
	1 <sup>st</sup> year planting <sup>a</sup> (USD/yr)	2 <sup>nd</sup> or 3 <sup>rd</sup> ratoon <sup>a</sup> (USD/yr)		
<b>1. Land preparation</b>	<b>860.63</b>	<b>502.86</b>	<b>0.71</b>	<b>21.97</b>
- Fuel cost	317.40	185.45	0.26	8.10
- Labor cost	543.23	317.41	0.45	13.87
<b>2. Planting</b>	<b>2,866.94</b>	<b>0.00</b>	<b>2.98</b>	<b>92.39</b>
- Manual (Labor)	2,398.24	0.00	2.49	77.29
- Tractor rental (including fuel)	468.70	0.00	0.49	15.10
<b>3. Fertilizer application</b>	<b>4,913.59</b>	<b>4,913.59</b>	<b>5.10</b>	<b>158.34</b>
- Fertilizer cost	4,517.47	4,517.47	4.69	145.58
- Fuel cost	253.28	253.28	0.26	8.16
- Labor cost	142.84	142.84	0.15	4.60
<b>4. Weed control</b>	<b>7,855.68</b>	<b>7,855.68</b>	<b>8.16</b>	<b>253.16</b>
- Chemical cost	7,785.24	7,785.24	8.09	250.89
- Fuel cost	8.89	8.89	0.01	0.29
- Labor cost	61.55	61.55	0.06	1.98
<b>5. Insecticide control</b>	-	<b>211.19</b>	<b>0.22</b>	<b>6.81</b>
- Chemical cost	-	146.40	0.15	4.72
- Fuel cost	-	7.65	0.01	0.25
- Labor cost	-	57.14	0.06	1.84
<b>6. Crop maintenance (watering)</b>	<b>118.41</b>	<b>118.41</b>	<b>0.12</b>	<b>3.82</b>
- Labor cost	71.42	71.42	0.07	2.30
- Fuel cost	26.59	26.59	0.03	0.86
- Electricity cost	20.40	20.40	0.02	0.66
<b>7. Harvesting</b>	<b>1,684.25</b>	<b>1,684.25</b>	<b>1.75</b>	<b>54.28</b>
7.1 Manual				
- Fuel cost (grab cane loader)	112.30	112.30	0.12	3.62
- Labor cost	1,506.54	1,506.54	1.56	48.55
7.2 Sugarcane harvester				
- Fuel cost	65.41	65.41	0.07	2.11
- labor cost	-	-	-	-
<b>8. Transportation</b>	<b>2,302.61</b>	<b>2,302.61</b>	<b>2.39</b>	<b>74.21</b>
8.1 Own vehicle				
- Fuel cost	915.62	915.62	0.95	29.51
- Labor cost	322.46	322.46	0.33	10.39
8.2 Outsource				
- Fuel cost	471.68	471.68	0.49	15.20
- Labor cost	592.85	592.85	0.62	19.11
<b>Total variable cost</b>	<b>20,602.11</b>	<b>17,588.59</b>	<b>21.43</b>	<b>664.98</b>

Note: <sup>a</sup> An average sugarcane cultivation area for one farmer is 10.24 hectares.

<sup>b</sup> One ton of raw sugar crystal is obtained from 27.22 ton of sugarcane grown on 0.33 hectares.



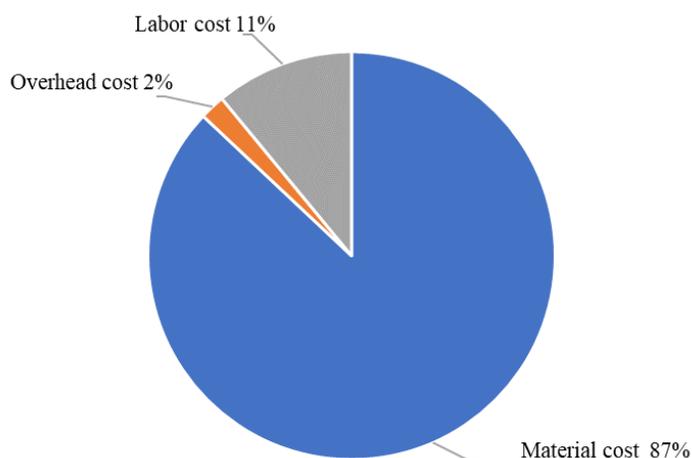
**Figure 2** Percentage of variable cost in sugarcane production.

Table 2 shows the variable cost of sugar production during the industrial phase. The total variable cost for producing 1 ton of raw sugar in Thailand at this phase is about 199 USD, which is about three times lower than the above reported during the agricultural production stage. The study found that material cost accounted for 87% of total industrial cost followed by labor cost and overhead cost at 11 and 2%, respectively (Figure 3).

**Table 2** Variable cost of sugar production in Thailand.

Cost type	Total cost (USD/yr)	Unit cost (USD/ton raw sugar crystal/yr) <sup>a</sup>
<b>1. Material cost</b>	<b>11,609,000.00</b>	<b>171.99</b>
- Quantity of sugarcane (ton/year)	470,000.00	-
- Sugarcane price (USD/ton)	24.70	-
<b>2. Labor cost</b>	<b>1,507,410.99</b>	<b>22.33</b>
<b>3. Overhead cost</b>	<b>301,912.66</b>	<b>4.47</b>
- Fuel cost for machinery and other equipment	63,956.75	0.95
- Vehicle fuel cost	2,013.54	0.03
- Electricity cost	102,833.75	1.52
- Chemicals cost	133,108.62	1.97
<b>Total variable cost</b>	<b>13,418,323.65</b>	<b>198.79</b>

Note: <sup>a</sup> Raw sugar crystal production in 2020 was 67,500 tons.



**Figure 3** Percentage of variable cost in sugar production.

### 3.2 Benefit Analysis

In the agricultural phase, the only direct benefit of sugarcane production is sugarcane sales, accounting for 24.7 USD per ton of sugarcane in this study (Table 2). Based on the variable cost of sugarcane production in Table 1 above, the average profit of sugarcane growers or the difference between sugar sales and variable cost is around 3.27 USD per ton of sugarcane.

For the sugar production process, the benefit of this phase comes from two kinds of products: 1) main products that can be sold or provide revenue directly – raw sugar crystal, and 2) byproducts and wastes providing revenue indirectly – molasses, bagasse, filter cake and vinasse. All benefits are divided in three categories for comparison as described above. In Table 4 below, the result shows that the revenue of benefit categories I, II and III is about 767.98, 844.86 and 845.63 USD per ton of raw sugar crystal, respectively. At this point, clearly, the more byproducts and wastes are used, the more benefits sugar millers will obtain. When considering revenue alone, category III clearly provides the greatest benefit for the sugar industry phase and the entire industry.

### 3.3 Profitability Index

In sugarcane production, the farmer's profitability index is about 1.15 when considering only the variable costs shown in Table 3, indicating less profitability; that is, the average farmer's income is only 15% higher than the cost of sugarcane cultivation. When fixed costs are considered together with variable costs, the farmer's profitability index

drops to 0.91, meaning that the farmer cannot make a profit when revenue decreases faster than costs. This estimated result is consistent with the farmer interviews in this study and the finding of Athipanyakul [17] that Thai sugarcane farmers face high average production costs and have lower incomes. The situation has resulted in some farmers switching from sugarcane cultivation to other crops such as cassava due to low sugarcane prices and droughts. This has a significant impact on the uncertainty of sugarcane supply. As a result, the overall amount of sugarcane sent to the factory may decrease, resulting in a decrease in sugar production and exports. It becomes evident that for the Thai sugarcane industry to be more competitive and sustainable, improving sugarcane production efficiency to reduce production costs such as reducing inputs (e.g. chemicals, fertilizer, and fuels) and increasing sugarcane productivity is necessary.

According to the three benefit categories in the sugar industry of this study, the profitability indexes, based on variables and total costs presented in Table 4, are all greater than 1, indicating that all benefit categories are profitable. Considering only variable costs, the results indicate that categories II and III provide the highest profit of 4.68 times. In other words, the sugar mills' income in categories II and III is 4.68 times higher than the variable cost of sugar production. When fixed costs are included, the profitability index decreases about three times.

**Table 3** Profitability index of Thai sugarcane farmers.

Item	Value <sup>a</sup> (USD/year)
Variable cost	18,070.75 <sup>b</sup>
Fixed cost	4,821.09
Total cost	22,891.84
Revenue	20,861.50
Profitability index based on variable cost	1.15
Profitability index based on total cost (fixed + variable cost)	0.91

**Note:** <sup>a</sup> Average sugarcane cultivation area for one farmer is 10.24 hectares. One hectare yields 82.48 tons of sugarcane.

<sup>b</sup> Calculated in proportion to the number of interview data for sugarcane planting in the 1<sup>st</sup> year, and 2<sup>nd</sup> or 3<sup>rd</sup> ratoon.

**Table 4** Profitability index of Thailand's sugar mill by three different benefit categories.

Item	Cost (USD/ton raw sugar crystal)	Revenue (USD/ton raw sugar crystal)		
		Cat. I	Cat. II	Cat. III
Production variable cost	198.79	-	-	-
Cost saving (use electricity generated from bagasse in sugar mill)	18.13	-	-	-
Total production variable cost	180.66			
Production fixed cost	290.61	-	-	-
Total cost	471.27			
Revenue from main product				
- Raw sugar	-	501.31	501.31	501.31
Revenue from byproducts and waste				
- Molasses (for sale)	-	59.29	-	-
- Filter cake (for sale)	-	190.64	190.64	190.64
- Electricity (generated from bagasse)	-	16.74	16.74	16.74
- Ethanol (produced from molasses)	-	-	136.17	136.17
- Electricity (generated from vinasse)	-	-	-	0.77
Total revenue		767.98	844.86	845.63
Profitability index based on variable cost		4.25	4.68	4.68
Profitability index based on total cost (fixed+variable cost)		1.63	1.79	1.79

According to the above study results, it can be empirically confirmed that the sugarcane plantation process has a high production cost with low profitability compared with the industrial process for producing raw sugar crystals. Farmers are unable to make a profit because their expenses are 9% higher than their incomes (Table 3), while the sugar industry can make a profit, with incomes higher than their expenses by 63 to 79% (Table 4). Moreover, existing sugarcane farming practices, such as overuse or high input applications, can also emit more greenhouse gas emissions into the atmosphere.

### 3.4 Benefit-Cost Ratio (BCR), Net Present Value (NPV) and Internal Rate of Return (IRR)

Table 5 summarizes the unit price, unit cost and unit profit of sugar, byproducts, and waste used to estimate net benefit, BCR, NPV and IRR. By analyzing the net cash flow for each benefit category, the NPV, IRR and BCR indicators can be calculated, as shown in Table 6. The results indicate that benefit category I is the most economically feasible. The IRR of benefit category I is 6.73%, which is higher than MLR at 5.25%. The NPV of benefit category I

is greater than zero and the BCR is greater than 1. Therefore, the benefit category I of the sugar industry by selling molasses for other uses or production (e.g., ethanol, animal feed and soy sauce), selling filter cake as fertilizer and using bagasse as fuel to generate electricity is expected to deliver a positive net value to the sugar industry.

**Table 5** Summary of unit price, unit cost, and unit profit of sugar crystal, byproducts and waste.

Items	Unit	Price	Cost	Profit
Sugar crystal	USD/ton	501.31	489.42	11.89
Molasses	USD/ton	87.18	72.65	14.53
Filter cake	USD/ton	232.49	190.57	41.92
Electricity from bagasse	USD/kWh	0.1162	0.0689	0.0474
Electricity from vinasse	USD/kWh	0.1162	0.1157	0.0006
Ethanol produced from molasses	USD/ton	0.7509	0.5251	0.2258

**Table 6** Cost and benefits of sugar production and utilization of byproducts and waste according to three different benefit categories.

Items	Annual value (USD/ year)	Value (million USD)		
		Cat. I	Cat. II	Cat. III
Cost of operating raw sugar crystal	33,035,884.92	-	-	-
Cost of operating molasses	3,334,786.40	-	-	-
Cost of operating filter cake	10,547,834.44	-	-	-
Cost of operating electricity (generated from bagasse)	6,118,083.71	-	-	-
Cost of operating ethanol (produced from molasse)	6,427.69	-	-	-
Cost of operating electricity (generated from vinasse)	51,185.30	-	-	-
Total operating cost		53.04	49.71	49.76
Total investment cost		110	141.97	147.78
Benefit (profit) from sugar crystal	802,388.84	-	-	-
Benefit (profit) from byproducts and waste				
- Molasses	666,957.28	-	-	-
- Filter cake	2,320,517.79	-	-	-
- Electricity (generated from bagasse)	4,207,795.97	-	-	-
- Ethanol (produced from molasses)	2,763.87	-	-	-
- Electricity (generated from vinasse)	257.21	-	-	-
Net benefit		8.00	7.33	7.33
BCR		1.21	0.86	0.82
NPV		22.66	-20.32	-26.13
IRR (%)		6.73	4.15	3.18

Based on the findings of this study, when analyzing the data for 2020, the sugar industry in benefit categories II and III has slightly better profits than benefit category I. Benefit categories II and III can generate 79% more revenue than expenses, while the benefit category I can generate 63% more revenue than expenses. However, when considering the investment, net cash flow, discount rate and project lifetime using NPV, BCR, and IRR indicators, benefit categories II and III are not economically feasible as they have low net benefits and require high investment. Therefore, the sugar industry should be encouraged to operate under the benefit category I by using three main byproducts: selling molasses for other uses or production (e.g. ethanol, animal feed, soy sauce), selling filter cake as fertilizer, and using bagasse as fuel to generate electricity.

However, although all profits from any benefit categories are returned only to the sugar factory, the use of these byproducts and wastes can bring enormous benefits to the environment by reducing waste disposal and contamination, reducing greenhouse gases (GHGs), reducing the use of fossil fuels (from ethanol production and its use), reducing energy consumption (from electricity generation) and reducing the use of chemical fertilizers (from using filter cake). Among these excess materials, in fact, vinasse, which is distillery wastewater from molasses ethanol production, is not yet widely used in the country. Currently, vinasse is used as fertilizer in the fields; but it has been reported that vinasse contains low levels of macronutrients and micronutrients [18]. On the other hand, several studies have revealed the potential of renewable energy to generate electric power from vinasse biogas [18-21]. Thailand itself can use this in the future, but it will require high investment as shown in this study in benefit category III above.

### 3.5 Sensitivity Analysis

A sensitivity analysis was performed to identify the key factors with respect to profitability, IRR, NPV and BCR. The analysis is useful in answering the question of which factor is the most sensitive, and to what extent this factor will quantitatively change, resulting in changes in profitability, IRR, NPV and BCR.

Material costs, labor costs, and overhead costs, i.e., fuel costs, tend to increase in the future. According to the Ministry of Labour, the minimum wage in the study area has increased by 7% annually [22]. Additionally, the price of fuel is likely to increase by 2% yearly [23]. Likewise, material cost tends to increase each year. In this sense, it means that the revenue tends to decrease or the production costs increase. Because all benefit categories occur at the stage of the industry, the following sensitivity analysis; therefore, focuses on the stage of sugar production.

Figure 4 presents the sensitivity analysis of benefit categories decrease, resulting in the change of profitability. The results of the analysis showed that when the revenue decreases, the profitability of the benefit categories I, II and III decreases accordingly. At the profitability of 1, the benefit category I decreased by 76.51%, while the benefit categories II and III decreased by 78.70% equally. This means that if the revenue reduce (or production cost increase) by more than 76.51 or 78.70% according to the benefit category, it would not be worth the investment.

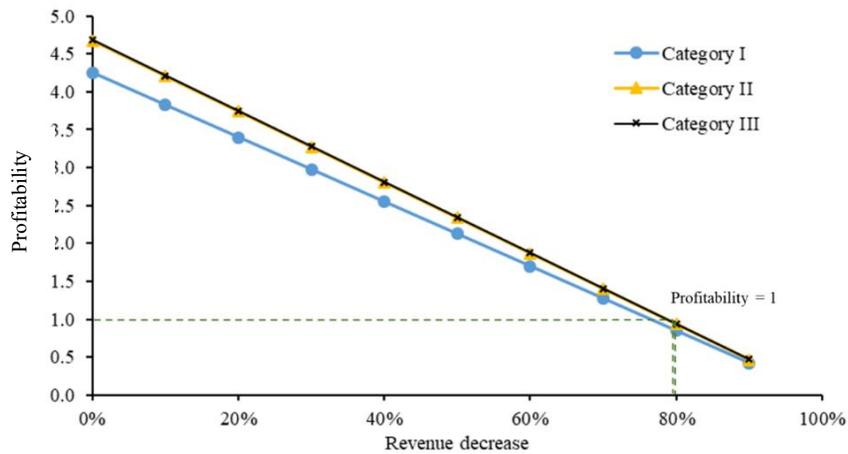


Figure 4 Sensitivity analysis of revenue decrease.

Figure 5 shows the sensitivity analysis of various cost increments, resulting in the change of profitability. Of all benefit categories, category I contributes the least profit. The results in Figure 5 indicate that material cost is the most sensitive and contributes the largest change in the profitability.

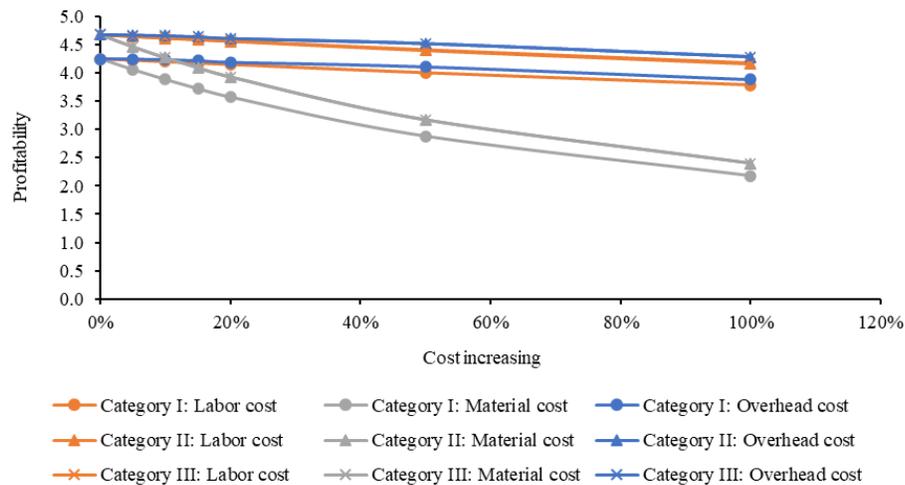
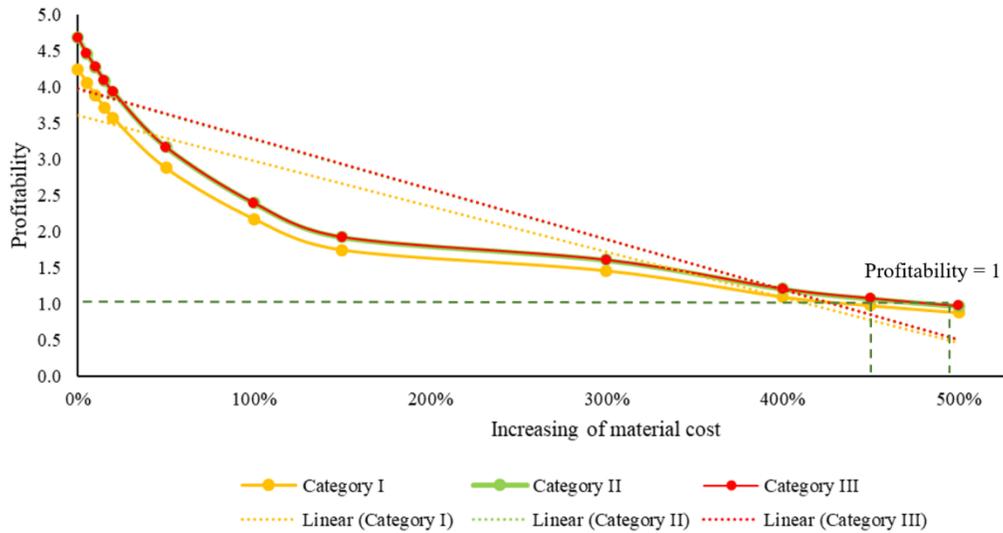


Figure 5 Sensitivity analysis of cost increase.

Figure 6 shows the sensitivity analysis of material cost increase, resulting in the change in the profitability. When labor and overhead costs were constant, at the profitability of 1, material cost for benefit category I increased by 441.67%, while the material cost for benefit categories II and III increased by 486.36% equally. In other words, this means that if the price of sugarcane (material cost) increases by more than 441.67 or 486.36% according to the benefit category, it would not be worth the investment.



**Figure 6** Sensitivity analysis of material cost increase.

Figure 7 shows the sensitivity analysis of sugar price, discount rate and project lifetime on the changes in IRR Figure 7(A), NPV Figure 7(B), and BCR Figure 7(C). The result shows that sugar price is the most sensitive to changes in IRR, NPV and BCR of all benefit categories (I, II and III).

In case of investment in the benefit category I, it will be economically feasible when the factory invests 110 million USD (Table 6) to build the factory, purchase machinery and equipment with a minimum project life of 30 years, MLR lower than 6.25% per year, and sells sugar at a minimum price of 501.31 USD per ton (Table 5). For investment in benefit categories II and III, it will be economically feasible when the factory invests 141.97, and 147.78 million USD (Table 6), respectively, with MLR lower than 3.25% yearly, and sells sugar at a minimum price of 526.38 USD per ton, which is 5% higher than the initial price (Figure 7).

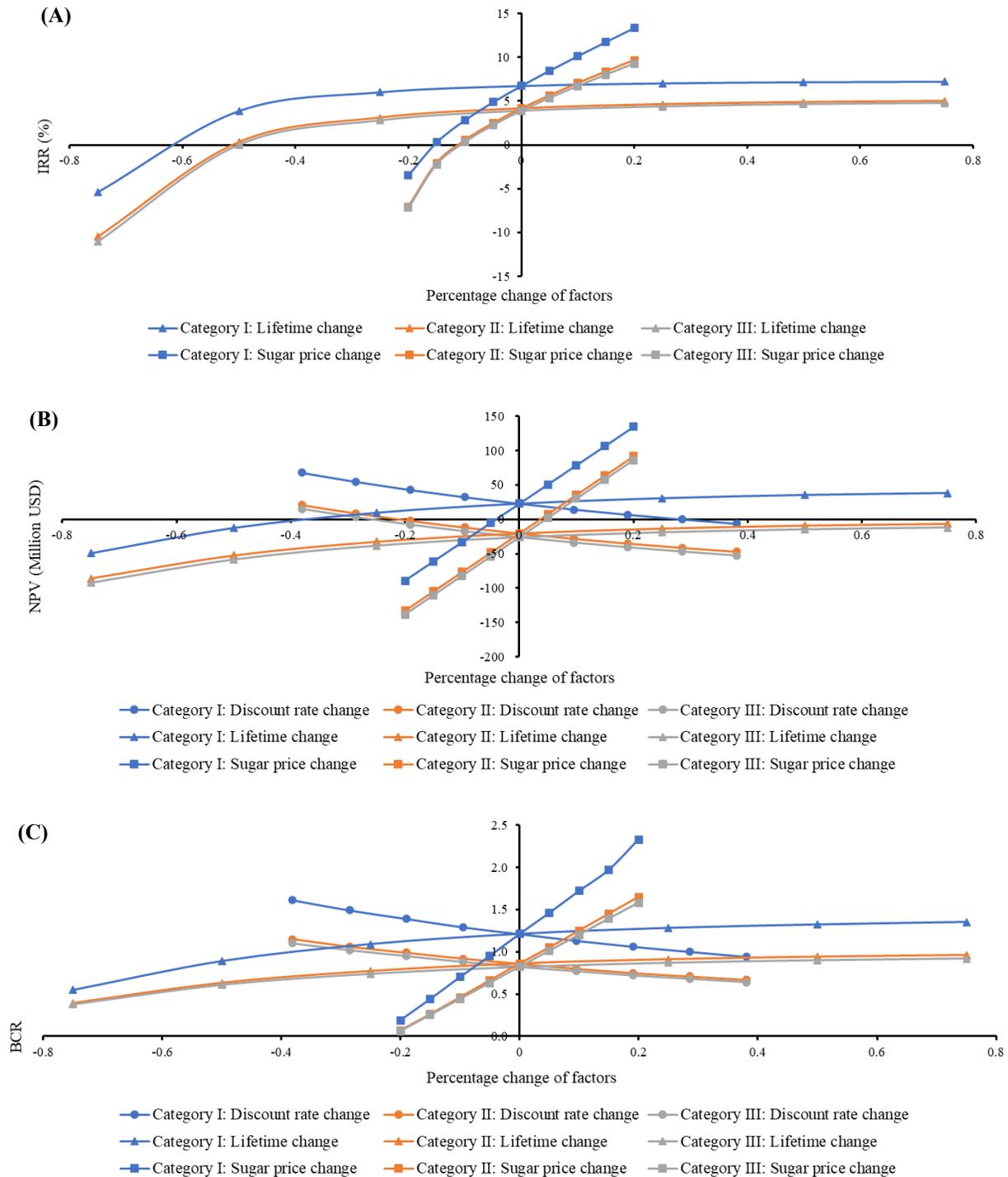


Figure 7 Sensitivity analysis of discount, lifetime and sugar price: (A) IRR, (B) NPV and (C) BCR.

#### 4. Conclusion

For the overall sugar industry in Thailand, the variable cost of sugar production is 864 US per ton of raw sugar crystal, with 77% coming from the cane production phase and 23% from the sugar production process. In sugarcane production, the only benefit for farmers comes directly from the sale of sugarcane, while the benefits of the sugar

industry can be derived from both the primary products (sugar), and the utilization of various byproducts and wastes (molasses, bagasse, filter cake and vinasse). Moving towards a sustainable sugar industry in Thailand, clearly in sugarcane cultivation, management of material inputs such as herbicides, fertilizers and fuel is essential for the sustainability of sugarcane production and the sugar industry as a whole. Based on the financial cost and benefit analysis related to the three different benefit groups of this study, it can be concluded that benefit category I, by using three main byproducts: 1) selling molasses for other uses or production (e.g. ethanol, animal feed, soy sauce); 2) selling filter cake as fertilizer, and 3) using bagasse as fuel to generate electricity, is the most economically feasible. According to the recent research on Industry 4.0 transformation of the Thai sugar industry [24], reducing the environmental impacts of the sugar industry by using byproducts and wastes generated is one of the potential drivers towards a sustainable industry; however, the obstacles are the high investments and uncertain benefits. The implication of this study can extend not only to the sugar industry but also to other agro-industries. With the insights gained from this study, a financial cost-benefit analysis can be conducted for comparing between sugarcane farmers (as well as the cultivation activities) and sugar mills in the sugar industry. The study also provides empirical financial results to guide sugar mills and the whole industry to realize the different benefits of using byproducts and wastes generated.

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