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The Renewability Indicator and Cumulative Degree of Perfection for Gamboeng Tea; Part.2, Exergy Calculation of Tea Factory

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Abstract

Renewability Indicator (RI) and Cumulative Degree of Perfection (CDP) were used to observe sustainability of Gamboeng Tea. The assessment then compared with black tea process in Black Sea Region in Turkey from the previous study. Calculation of exergy for Gamboeng fresh tea leaf had already described in Part.1. Since the main process for both production was drying, then tropical humid climate in Gamboeng is the main challenge to increase efficiency, and thus, renewability. This second part described the significant improvement of renewability had applied in Gamboeng by using wood pellet in rotary pannier. Further recommended improvement were by installing better humidity detector and connected to the process control so the process can adapt the ambient change which the relative humidity can be varied from 65% and up to 92%.

1. INTRODUCTION

Several methodologies have been studied and reported in previous reports for assessing the sustainability of various processes and/or products and then improving them. Some of them are life cycle assessment (LCA), material throughput analysis or mass flow analysis (MFA), cradle-to-cradle design (C2C), energy analysis (EA), and pinch analysis [1-5].

The most famous object to be observed by the food industry is energy in order to evaluate process performance and efficiency. According to laws of thermodynamics along with energy transformation from one form to another, some of its initial quality become irreversibly lost, that make the energy become a new degraded quality energy form [6]. Energy quality concept was described by Van Gool as the possibility of energy exchange between a donating and an accepting stream [7]. Cornelissen then defined the possibility as the "maximum work potential of a material or of a form of energy in relation to its environment,". The possibility of energy exchange was also called as exergy or available work. The term exergy was originally introduced by Rant [8,9].

According to consensus among many researchers from different scientific fields, a method called exergy analysis (ExA) was develops. ExA then defined as an objective methodology for assessing the efficiency, and furthermore the sustainability, of processes and systems. ExA was preferred because it's root is the first and the second law of thermodynamics. ExA considering both the quantity and the quality of material and energy streams simultaneously without having to categorized them into some subjective weighing factors [6, 10- 18]. The advantages edge of ExA compared to other assessment methods had discussed in several previous reports. [18,19]. ExA general definitions, basic principles, and its differences between energy and exergy had already been discussed [20,21].

Publications of ExA sustainability assessment in food process-related was mostly on drying technologies (66%), food chains with wider boundaries at the second place (10%) and

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followed by heating for pasteurization processes (6%) [22]. Conducting ExA for analyzing drying performance firstly introduced in Indonesia was for analyzing application of solar thermal storage [23]. Tea as the most consumed drink after water [24,25] had drying as the main process. In this present study, Gamboeng green tea will be evaluated by using Exergy analysis (ExA) and the results will be presented as Cumulative Degree of Perfection (CDP) and the renewability indicator (RI). Cumulative degree of perfection (CDP) is defined as the ratio of the exergy of the products to the sum of the exergies of the input materials and non-renewable fuels [26]. This renewability assessment has two approaches. First, calculation input/output ratio of a specific renewable resource based on benefit analysis or the second, investigate the sustainability of a concerned system by identifying the renewable resources component from its total historical resources [27]. CDP Calculation for Gamboeng tea plantation was conducted in part.1. In this part, CDP for tea factory was elaborated, and analyzed its sensitivity toward Gamboeng climate.

2. METHODOLOGY

For comparative purposes of the analytical results, the functional unit for Gamboeng green tea and Black Sea tea was chosen as one ton of products. Information about transportation requirement for Gamboeng tea were collected by direct observation and measurement from tea plantation and tea factory belong to Research Institute for Tea and Cinchona in Desa Mekarsari Kecamatan Pasir jambu Kabupaten Bandung. The tea factory was operated in batch for 14 – 20 hour per batch operated by 46 employees.

The amount of energy used by equipment for each green tea production steps were also obtained from interviewed with the tea factory manager. Calculations of energy utilization for the heating, ventilation and air conditioning (HVAC) units are according to theoretical approach by using Gamboeng environmental climatology data as basic of the calculation. The ambient air condition as basic for calculation were the average measured value from 15 September 2018 to 15 October 2018 which were 65% relative humidity and 30.5 ^oC of air ambient temperature. The climate data was collected from Automatic Weather Station (AWS) that placed in Gamboeng. Moisture content of tea leaf along the process was determined based the weight loss at 103 ^oC referring to SNI 3945:2016. The data was collected between 8th of October to 12th of October 2018 and the mean value was used in the calculation. LPG consumption for calculation was obtained from the monthly record of the factory manager.

Mass, energy and exergy balance equations were used to analyze each process to determine the CEnC and CExC. The equation that used are:

Mass balance:

$$\sum(m)_{in} - \sum(m)_{out} = 0 \quad (1)$$

Energy balance:

$$\sum(mh)_{in} - \sum(mh)_{out} = Q - W \quad (2)$$

Exergy balance:

$$\sum(mb)in - \sum(mb)out - = \sum_{k=0}^{n} Qk\,(1 - \frac{T0}{Tk}) \quad (3)$$

k is referring to the heat sources index and the flow availability of a stream (neglecting the contribution of potential and kinetic energy) defined as

$$b = h - T_0 s - \sum x_i \mu^0{}_i. \quad (4)$$

Quantitative analytical results regarding chemical content in green tea was adopted from Harbowy and Balentine [28]. The results were used as representative of the observed stream for calculating physical properties. Epigallocatechingallate was used as cathechins representatives, theaflavin for theaflavis and gallic acid for the other polyphenols. Then the exergies for these organic group were regarding to Szargut et al. [26].

Energy for heating the air entering to the process step or the stream's exergy in the input and output were calculated as given in Eqs. (5), (6), and (7) using some coefficient from the psychometric charts.

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$$En = c_p.(T - T_0) \quad (5)$$

$$Ex = c.[(T - T_0) - T_0.(c. \ln(T/T_0))] \quad (6)$$

$$Ex = (h - h_0) - T_0.(s - s_0). \quad (7)$$

In case of specific equipment such as conveyor, fan, and motors, energy utilization were based on the factory manager detailed report. Energy and exergy utilization of each stream, including heat and work involved for green tea and black tea production process were computed based on the process flow diagrams presented in Figure 1 and 2.

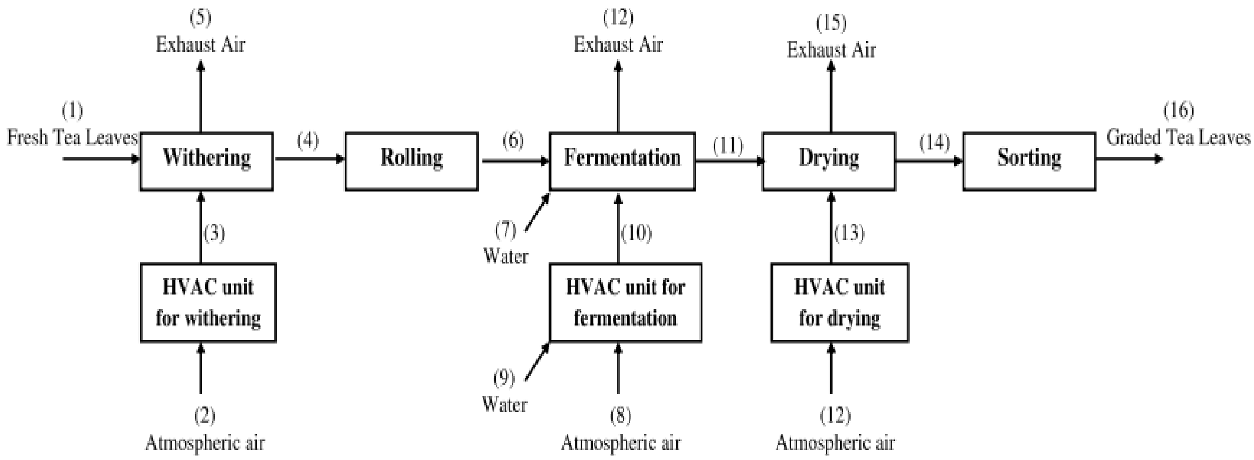

Fig.1. Flow diagram for black tea production process in Black Sea Turkey [27]

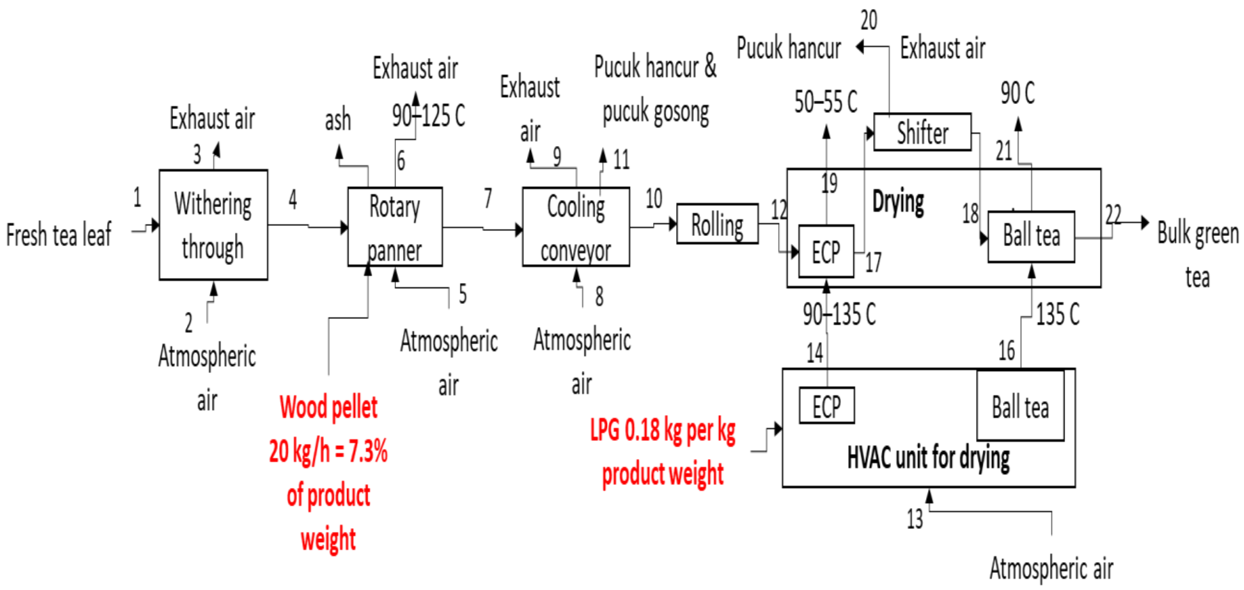

Fig.2. Flow diagram for green tea production process in Gamboeng Indonesia

The cumulative degree of perfection (CDP) is defined as the ratio of the exergy of the products to the sum of the exergies of the input materials and non-renewable fuels [26]. CDP was calculated by using equation 8.

$$CDP = \frac{(mb)product}{\sum(mCExC)raw\ materials + \sum(mCExC)fuels} \quad (8)$$

Renewability indicator was defined as:

$$Ir = \frac{(Wp - Wr)}{Wp} \quad (9)$$

Wp is the useful work obtained by the product, Wr is the restoration work. If the maximum work potential of the product is extracted via reversible process, then Wp equals to Xp [28].

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3. RESULTS AND DISCUSSION

3.1 Exergy calculation of Tea Factory

Even the main production unit is the same, which is drying, there was several main difference in producing black tea and green tea. In both process, fresh tea leaves entering the factory to the withering process. However, withering in black tea process is more essential since this step needs to ensure the moisture content are suitable for tea fermentation which is 58%-67%. Therefore, HVAC unit were required in black tea withering step [29]. In green tea process, withering just for pre-conditioning when the fresh leaves are too wet, in example when the process conducted in rainy season, so the moisture content slightly above 70%. Thus, total energy and exergy consumed in withering step of black tea process is above green tea process.

Large energy and exergy utilization in green tea process were actually happens in the next step which is panning which is not required in Black tea process. The objective of this step is actually to sterilize the tea leaves so the fermentation will not occur. Gamboeng tea plan using two-cylinder rotary pannier with capacity 1100kg of fresh tea leaves per hour. The machine was equipped with electric motor 4.69 kWh. The pannier was operated in 100 – 135 ^{o}C and using 20 kg of wood pellet per hour. The pannier product was at 90-100 ^{o}C and need to be cooled before it entering the rolling process. Exceeding heat exposure to some tea leaves in the pannier will caused the tea leave burnt out, loose its elasticity and crushed as fluff. This burnt out tea was called *pucuk gosong* or *pucuk hancur* and still have economic value. However, the price is much lower, thus need to be separated from the green tea main product to maintain quality. Sorting *pucuk gosong* from green tea main product was conducted during this cooling process. the cooling conveyor was equipped by electric motor with cooling fan above the conveyor. Total electricity that consumed in cooling conveyor was 4.02 kWh.

Both green tea and black tea process were using roller. Previous reports stated high energy utilization in roller, up to 720 MJ/ton product [29]. Baruah et al. stated that the consumed energy in roller was within 360– 720 MJ/t black tea [30]. The Asian Institute of Technology (2002) reported that the consumed energy specifically in the rolling step were 360– 1080 MJ/t of black tea [31]. Pelvan and Oziglen using the value slightly lower than the minimum value which is quite similar with what was used in the Gamboeng tea factory. Gamboeng tea factory using Open Top Roller which have 4 rollers that run by a single electric motor 10.05 kWh which connected to roller by gearbox. Total energy consumption was 307.1 MJ/t of green tea.

The rolled tea leaves were going to the continuous fermentation stage for black tea process. The tea leaves oxidation process was held by blowing air for 30 min over the tea leaves, while they were moving on the belt conveyor. This step is the main difference between black tea and green tea production process. fermentation was skipped from green tea process so the product was sent directly to drying unit.

In order to reduce the water content of fresh tea from 65% to 3%, Pelvan and Ozilgen using several assumptions in their calculation for drying process to obtain the value of utilized energy 5360 MJ/ton of black tea. Their report was lower than the ones reported by the Asian Institute of Technology [31] and de Silva [32], but higher than those of Baruah et al. [30]

The main assumption of their calculation was the air outlet from the dryer at the most attainable humidity and the least temperature, so almost all heat uptake capacity of inlet air was used. Utilized energy in Gamboeng green tea process were calculated based on real consumption of LPG by the factory which then further confirmed by the moisture content determination in each drying steps.

Gamboeng green tea production factory using three steps of drying in three different units. The ECP is the first drying unit which is a tray oven dryer with automatic spreader that generated by 6.7kWh electric motor. Around

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90 kg of tea leaves input were processed in ECP for 30 minutes at 50-55 ºC of tea leaves bed temperature with 90 – 135ºC of hot air temperature entering continuously to ECP during process. Direct determination of moisture content confirmed that ECP reducing the moisture content from 57.3% to 41%. The ball tea dryer was conducting the main drying duty by reducing moisture content from 41% to 5.08%.

Table 1. Enthalpy and entropy of the stream in Gamboeng green tea process for calculating exergy and exergy destruction, basis process 15 ton of fresh tea leaves per batch.

			dry air (%)	Water (%)	dry tea (%)	total mass flow (kg)	T	H (MJ)	S (MJ/K)	Ex (MJ)
withering	in	stream-1	0	70	30	15000	30.5	2,865	-	178
		stream-2	98.4	1.6	0	246381	30.5	17,334	54.6	771
		W-Fan 1.34 kWh								0.402
	out	stream -3	98.2	1.8	0	246789	30.5	18,270	57.5	774
		stream -4	0.0	69.2	31	14591	30.5	2,785	-	173
	exergy destruction (MJ)									2.4
rotary panner	in	stream -4	0	69	31	14591	30.5	2,785	-	173
		stream -5	98.4	1.6	0	268706	30.5	18,904	59.5	841
		Q wood pellet, 20kg/jam, 17 MJ/kg pellet								5,638
		W motor 4.69 kWh								224
	out	stream -6	97	3	0	272759	100	62,306	139,1	5,459
		stream -7	0	57	43	10539	64	4,447	-	309
	exergy destruction (MJ)									1,108
cooling conveyor	in	stream-7	0	57	43	10539	64	4,447	-	309
		stream-8	98.4	1.6	0	393000	30.5	27,649	87,1	1,230
		W motor + fan 4.02 kWh								192
	out	stream-9	98.2	1.8	0	393759	32	29,843	93,1	1,438
		stream-10	0%	55.0	45	9600	30.5	1,807	-	64
		stream-11	0%	55.0	45	400	30.5	75,275	-	2.6
	exergy destruction (MJ)									226
roller	in	stream-10	0	55	45	9600	30.5	1,807	-	64
		W motor 10.05 kWh								1,389
	out	stream-12	0	55	45	9600	30.5	1,807	-	64
	exergy destruction (MJ)									1,389
HVAC	in	stream-13	98.4	1.6	0	213887	30.5	5,048	47	669
		Q, 0.18 kg LPG/kg dry tea, 47.07 MJ/kg LPG						38,325		
	out	stream-14	98.4	1.6	0	120402	135	22,725	48.8	2,825
		stream-15	98.4	1.6	0	60367	175	14,130	27.3	1,886
		stream-16	98.4	1.6	0	33118	135	6,251	13.4	777
	exergy destruction (MJ)									33,507
ECP	in	stream-12	0	55	45	9600	30.5	1,807	-	64
		stream-14	98.4	1.6	0	20402	135	22,725	48.7	2,825
		W motor 6.7 kWh								1,286
	out	stream-17	0	41	59	7322	40	1,624	-	78.6
		stream-19	97	3	0	122680	135	15,048	47.4	670
	exergy destruction (MJ)									3,427
shifter	in	stream 17	0%	41	59	7322	135	1,624	-	78,6
		W motor 3.73 kWh								258
	out	stream 18	0	41	59	7,322	135	1,624	-	78,6
	exergy destruction (MJ)									258
Ball tea	in	stream-15	98.4	1.6	0.0	60367	175	14,130	27.3	1,886
		stream-17	0	41	59	7322	135	1,624	-	78.6
		W motor 4.02 kWh								2,635
	out	stream-18	0	5.08	94.92	4551	55	1,215	-	82

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		stream-20	94	6	0	63138	135	13,398	35.2	1,161
									exergy destruction (MJ)	3,356

Ball tea was rotated by 4.02 kWh electric motor for 12 hours with drying cylinder capacity 200 – 300 °C. Hot air entering the dryer at the temperature 75 °C at the loading and unloading products and 175 °C in most operational time. The finishing drying step was called repeat dryer to ensure the product moisture content was below maximum limit, which is 5%, in the room temperature. The Gamboeng green tea moisture content is maintained in range 3-4.5%. Two repeat dryer with each capacity 65 kg were powered by 4.02 kWh electric motor with hot air inlet was 100 – 105 °C. Each drying unit equipped by their own HVAC but the LPG line for the HVAC heater was from a monitored main line, thus, total LPG consumption in real time can easily be determined.Gamboeng green tea was manually packaged by using gunnysacks with 40 kg capacity. Since the gunnysacks were reused, then energy and exergy for packaging was considered negligible to overall process. the summarizes of thermodynamic properties of the stream in Gamboeng green tea process were presented in Table 2.

3.2 Comparison of energy and exergy of green tea and black tea

Exergy destruction was the amount of exergy that not transferred or absorbed by exergy increase of the process output which usually came from unrecovered energy from fuel combustion and electricity involvement. Comparison of destruction exergy for each step of production for black tea and green tea was presented in Figure 3. Even in the exergy destruction that previously reported for Black Sea Tea, HVAC unit was separated for each step [27]. in this study all HVAC exergy destruction was sum up for comparison convenient.

In both case, Hot Ventilating and Air Conditioning unit was the main source of exergy destruction, or in other words, the hotspot of tea processing. Exergy destruction from HVAC in Black Sea Tea was calculated based on assumption approach that no heat was lost to the surroundings. The obtained value was close enough with the exergy destruction for Gamboeng green tea that calculated based on real LPG consumption. This is indicating that drying process that conducted in Gamboeng Tea factory is really close to the theoretical-no-heat-loss value.

3.3 Assessment based on Cumulative Degree of Perfection and Renewability Indicator

Cumulative Degree of Perfection (CDP) is the modified version of exergy efficiency that excluding renewable fuel utilization from calculation. The required data for calculating CDP was summarized in Table 2. It can be seen that CDP for Gamboeng tea was 0.814 and it was higher than Black Sea tea. Calculation of exergy efficiency for Gamboeng tea gave 0.751. significant increase was shown in CDP due to utilization wood pellet for about 11% of total utilized fuel.

Increasing of CDP by utilization of renewable fuel was also reported in previous research. The CDP for soybean was 0.92 as reported by Özilgen and Sorgüven. It can significantly increase by hypothetical reduction of ADO consumption or substituting ADO with biodiesel combined with good agricultural practices up to 1.6 for soybean oil production process. With similar calculation approach, CDP for olive oil will increase from 0.98 to 1.6 and for sunflower oil will be from 2.36 to 2.9 [33]

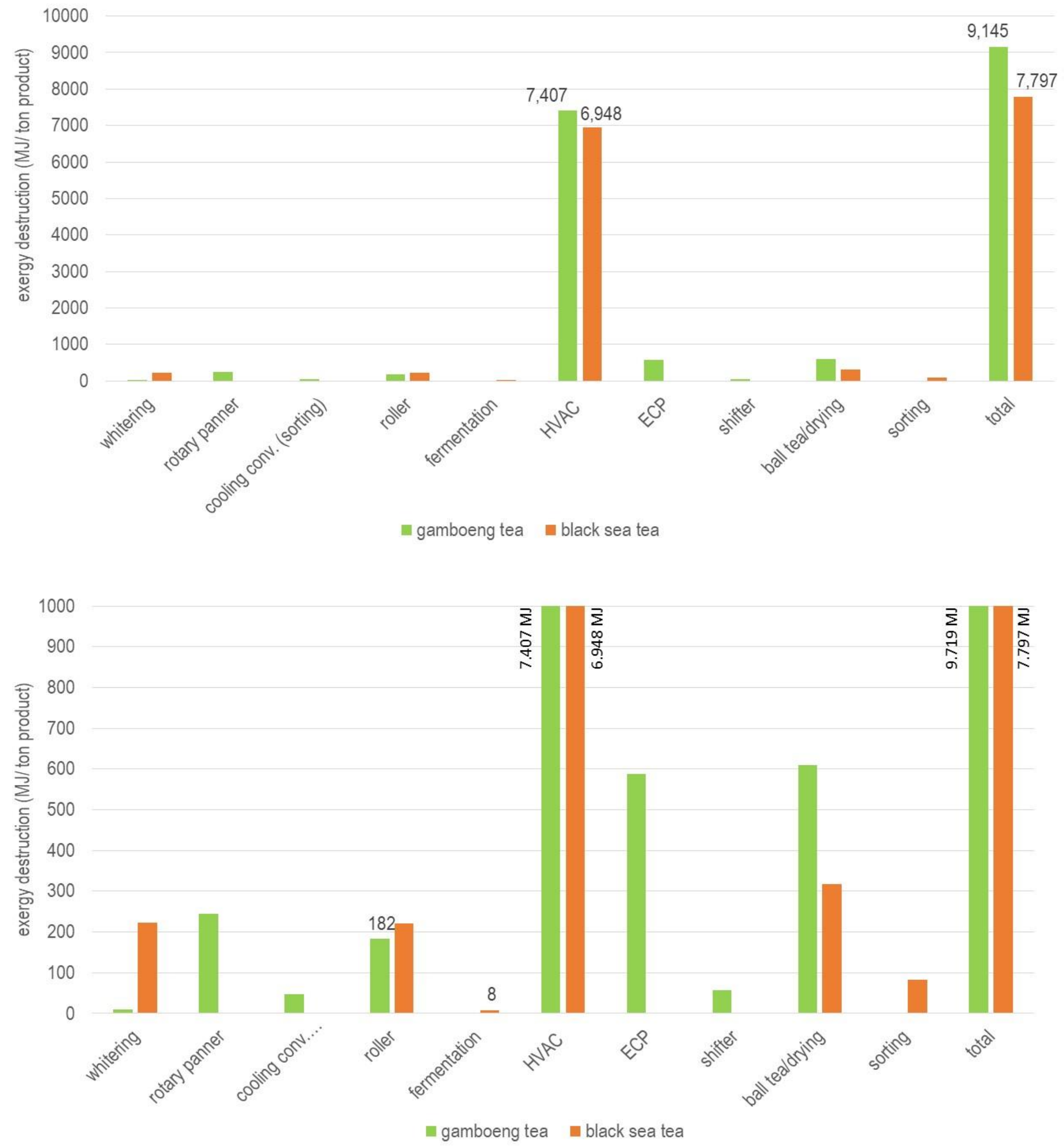

Fig. 3. Comparison of exergy destruction for Black Sea Tea and Gamboeng Tea. Up for real scale ordinate axis and bottom for truncated ordinate axis.

.**Table 2.** Summarized data for calculating Cumulative Degree of Perfection

	Gamboeng green tea	Black Sea tea
exergy product	8184*	3488**
exergy raw material	393,501.92	106,090
exergy renewable fuel	1,246,275.38	
exergy fossil fuels	8,472,239.83	6,947,662
exergy electricity	1,181,478.72	448,427
CDP (per ton base)	0.0008146	0.0004649
CDP (per kg base)	0.814	0.465

Note:
* the sum of stream 22 (green tea/ main product) and stream 11 (*pucuk gosong*/ side product) at 30 C
** exergy at 20 C

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Renewable indicator was originally created for assessing renewable fuel which then adapted to food industry [22]. Restoration work stated in equation (9) that used in renewable fuel assessment then replaced by irreversible exergy. In Black Sea tea, the exergy destruction from fermentation step was considered as irreversible exergy and for the Black Sea tea was the oxidation reaction that occur in pannier which cause *pucuk gosong*. Wp which stated as useful potential work was replaced by product exergy. Then the renewable indicator for Black Sea tea and Gamboeng tea was -1.35 and -36.52, respectively. Both values are negative, thus, both processes were considered as nonrenewable process. However, green tea was considered more nonrenewable compared to black tea. This is simply caused by the choice of product.

3.4 Cumulative degree of perfection dependency to the climate

Exergy efficiency of the drying process was believed to be highly sensitive to combination of air condition and tea production capacity [34]. The driving force for moisture to migrate from tea leaves onto the hot air is the difference between hot air moisture content to its saturated moisture content at the similar condition.

Since there is no moisture removal from hot air, then hot air moisture content is equal to the moisture content of ambient air. Relative humidity of ambient air was presented in Table.3. together with rainfall and air temperature. Adjustment of LPG consumption from main inlet was conducted manually, thus the advantage of ambient air humidity not fully explored. For example, consumption in September and August can potentially be reduced if extrapolated from data consumption of October.

Further recommended improvement were by installing better humidity detector and connected to the process control so the process can adapt the ambient change which the relative humidity can be varied from 65% and up to 92%. Reducing 0.01 kg LPG per kg of product means reducing 42.2 kg of LPG per batch which reduce cost Rp 477.000 per batch. Not only reducing cost, cooperation of wood pellet with ambient adapting control was a contribution from Gamboeng tea for achieving Sustainable Development Goal which is affordable and clean energy and also an applicable climate action

Table 3. LPG consumption of Gamboeng tea factory and Gamboeng climate data.

Month	Rainfall (mm)	RH (%)	Temp (ºC)	LPG consumption (kg LPG/kg product)	CDP
January	222.6	92	27.3	n.r	-
February	263.8	86	27.3	n.r	-
March	209.1	89	27.6	n.r	-
April	210.6	84	28	n.r	-
May	174.6	80	27.4	n.r	-
June	124.6	79	27.9	0.2	0.745
July	35	80	27.7	0.19	0.778
August	18.6	73	28.9	0.19	0.778
September	2.8	71	29.6	0.2	0.745
October	3.2	65	30.8	0.18	0.815
n.r. = record unavailable					

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4. CONCLUSION

In this work Cooperation of wood pellet with ambient-adapting controller was examined as a contribution from Research Center for Chemistry and Gamboeng tea for achieving affordable and clean energy and also an applicable climate action.

The exergy utilization of Gamboeng tea was 11, 293 MJ/ton of green tea product and the amount of exergy destruction was 9,718 MJ/ ton of green tea. It was really comparable with Black Sea tea that calculated the exergy in drying unit by using theoretical approach. This is indicating that drying process that conducted in Gamboeng Tea factory is really close to the theoretical-no-heat-loss value.

CDP for Gamboeng tea was 0.814 and it was higher than Black Sea tea which is 0.465. Calculation of exergy efficiency for Gamboeng tea gave 0.751. Significant increase was shown in CDP due to utilization wood pellet for about 11% of total utilized fuel. Then the renewable indicator for Black Sea tea and Gamboeng tea was -1.35 and -36.52, respectively. Both values are negative, thus, both processes were considered as nonrenewable process. however, green tea was considered more nonrenewable compared to black tea. This is simply caused by the choice of product.

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NOMENCLATURE

μ_i Chemical potential, kJ/kmol

b Flow availability of a stream

b^{ch} Sum of the chemical exergies

CDP Cumulative degree of perfection

CEnC Cumulative energy consumption

CExC Cumulative exergy consumption

EX Exergy (kJ)

Ex Exergy (kJ/kg)

H Enthalpy (kJ/kg)

h Enthalpy (kJ)

HVAC Heating, ventilation, and air conditioning

Ir Renewability indicator

k Index of heat sources

m Mass

Q Heat

s Entropy (kJ/K)

S Entropy (kJ/kg K)

T Temperature (◦C)

W Work

W_p Useful work obtained by the product

W_r Restoration work

xi Molar fraction

X_{loss} Exergy loss

X_p Exergy of the product

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