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Energy and Exergy Analysis of Palm Tree Pruning Residues Gasification

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ABSTRACT
Gasification is the process of obtaining syngas containing combustible gases such as H_2, CO and small amounts of CH_4 from biomass by performing partial combustion with a limited oxygen supply or with the help of suitable oxidants such as CO_2 and water vapor. The efficiency of the gasification process is the most important parameter that determines the success of the system. In this study, the performance of the system in the gasification of palm pruning residues was evaluated by energy and exergy analysis methods. The gasification process was carried out at 7.6 Nm^3/h and 10.2 Nm^3/h air flow rates in the laboratory type fixed bed downdraft gasification unit manufactured in the Biosystems Engineering Department. The lower heating value of the syngas obtained as a result of gasification was found to be 4.09 MJ/Nm^3 at 7.6 Nm^3/h air flow rate and 3.76 MJ/Nm^3 at 10.2 Nm^3/h air flow rate. It has been observed that the lower heating value of the syngas is lower at high air flow rate. Energy efficiencies of the gasification system at 7.6 and 10.2 Nm^3/h air flow rate were calculated as 47.6% and 52.8%, and exergy efficiencies were calculated as 43.7% and 48.1%, respectively. Exergy efficiencies were found to be lower than energy efficiencies in both air flow rates. However, as the air flow rate increased, the energy and exergy efficiencies also increased. The results obtained are similar to the results of previous studies on gasification of biomass.

Keywords: Biomass, Syngas, Heating value, Irreversibility, Partial combustion, LHV

1. Introduction

Biofuels which are obtained from biomass have considerable potential as a clean and renewable energy source, which can be converted into secondary energies such as, generate electricity, heat and power. However, the most important challenge in biomass-based energy conversion systems is to develop efficient conversion technologies (Ptasinski et al. 2007). Energy conversion technologies of biomass are gathered under basic topics such as thermochemical, biochemical and extraction. Main thermochemical conversion methods are direct combustion, gasification and pyrolysis. The gasification process is also one of the thermochemical conversion methods of biomass, and the syngas which contains such as H_2, CO, CH_4, and CO_2 gases obtained as a result of the process can be used to obtain electrical energy, heat energy, and enriched hydrogen to fuel cells (Hao et al. 2003). In gasification process, air is generally used as gasification agent due to its low cost. When the air is used in the gasification process of the biomass, the low heating value (LHV) of obtained syngas is about 4-7 MJ Nm^{-3} depending on the raw material. 12-28 MJ Nm^{-3} of LHV can be obtained with using pure O_2, but the cost of syngas production increases due to cost of O_2 production (Laurence & Ashenafi 2012; Manatura et al. 2017).

Energy and exergy analysis are conducted to estimate the efficiency of the system in all energy conversion systems. Efficiency estimation, known as energy efficiency based on the first law of thermodynamics, is the standard measure of an energy producing system. Exergy is the maximum amount of work a system can do reversibly until it becomes dead state under ideal conditions (Thermodynamic equilibrium). Efficiency evaluation with exergy analysis is more meaningful than energy analysis since it is a measure of the approach to ideal conditions (Zhang et al. 2013). This thermodynamic analysis technique estimates the efficiency of the process and determines its energy quality and availability. Exergy analysis, on the other hand, is used to discover new ways to increase energy efficiency. This estimate is made in terms of the second law of thermodynamics and irreversibility. In recent years, exergy analysis has been used to evaluate the performance analysis of different systems and to improve their efficiency (Cohce et al. 2011; Saidur et al. 2012). Many exergy and energy researches have been conducted on biomass gasification.

Exergy and energy analyzes have been made in the gasification of municipal wastes in fluidized bed gasifier. It is stated that the maximum energy and exergy efficiency is achieved at 0.4 of ER and 650 °C temperature (Tang et al. 2016). Pre-drying the biomass in the gasification process increases energy and exergy efficiency (Karamarkovic & Karamarkovic 2010). In the gasification process performed with high temperature steam, energy and exergy analyzes were carried out at different steam/biomass (S/B) ratios. It was stated that as the S/B ratio increases, exergy and chemical energy efficiency are negatively affected, while high preheating process positively affects the efficiency (Wu et al. 2014). Coconut shell, coir pith, bamboo and eucalyptus are gasified with steam. The highest exergy efficiency was achieved in the gasification process of coir pith with 79.2%. The exergy efficiencies of coconut shell, bamboo and eucalyptus were 77.5%, 74.4% and 68.3%, respectively (Sreejith et al. 2013). In the research conducted to compare exergy analysis in the gasification process of different biofuels, materials of different vegetable origin, vegetable oils and fertilizer were used. It is stated that exergy efficiency of solid biomass is lower than coal in the gasification process, and exergy efficiency increases when using obtained syngas in the drying process of the feedstock (Ptasinski et al. 2007). The type of biomass, the moisture content and the temperature of the gasification agent significantly affect exergy efficiency, the composition and heating value of the syngas. The performance of the gasification process improves as the moisture content of the biomass decreases and the temperature of the gasification agent increases. Exergy efficiency and working temperature are also significantly affected by the moisture content of the biomass. These values decrease as the humidity increases. Therefore, before the gasification process, the biomass containing excess moisture must be dried and brought to an acceptable humidity level (Wang et al. 2013). Because of its rich hydrogen production, the gasification process with steam generally has higher exergy efficiency than partial oxidation (Zhang et al. 2012). As the gasification temperature increases, the exergy efficiency increases, while the increase in the particle size of the material decreases the exergy efficiency. The steam/biomass ratio and flow rate initially increase exergy efficiency but later decrease it (Zhang et al. 2019). Chern et al. (1989) gasified wood chips at different air temperatures (25 °C, 293 °C and 348 °C) in their study. Researchers stated that as the air temperature increases, the exergy efficiency increases. Exergy efficiency of wood chips gasification at the highest air temperature was 65%. Moisture is an important problem in the gasification of sugar beet bagasse. In order to realize the gasification process, the moisture content in the bagasse must be below 30%. In addition, the preheating process increases exergy efficiency (Pellegrini & de Oliveira 2007). Hosseini et al. (2012) also stated that exergy efficiency in the gasification process of sawdust is significantly affected by the moisture content of the biomass.

It is stated that there are approximately 700 000 palm trees in cities located in the Mediterranean region of Turkey (Hazir & Buyukozturk 2013). In a study conducted to determine the physical and thermal properties of palm pruning residues in the province of Antalya, located in the Mediterranean region, it was stated that an average of 50 kg of pruning residue per year was obtained from a palm tree (Yilmaz et al. 2021). As it can be understood from these studies, 35 000 tons of palm pruning residue is generated every year in the Mediterranean region. The energy value of these residues is around 582 400 GJ/year. As can be seen, although palm pruning residues have a significant energy potential in the region, there is not enough research on their conversion to energy. In this research, it is aimed to determine the possibilities of evaluating this energy potential by gasification method. For this purpose, the pellets obtained from palm pruning residues were gasified in a micro-scale gasification unit at two different air feeding rates, and energy and exergy analyzes were carried out.

2. Material and Methods

2.1. The gasifier system

Experimental set up of the gasifier system includes gasifier reactor, cyclone, gas cooling unit, and vacuum pump and flare unit (Figure 1). Flare is a syngas burning unit. In addition, there are measurement and control components, gas chromatography device and its components in the system. The gasifier reactor is fixed-bed and downdraft type and has 170 mm in diameter, 750 mm in height and is made of high temperature resistant 5 mm thick stainless steel. Temperature sensors are installed in the reactor inlet and outlet. In addition, there are K-type thermocouples at 5 different points in the reactor. Air and syngas flow rates were measured by orifice flow meters. Experimental data was collected and monitored by PLC control system. The vacuum pump is located in the gas outlet line and also provides the suction of syngas. The pump operates with three-phase current and has a rated power of 0.37 KW and a maximum flow rate of 30 m^3/h. During the gasification process, the temperature of core region in the gasifier was kept about at 800 °C.

Figure 1- The gasification system units

2.2. Feedstock

In this research, pruning residues of palm trees were used in the gasification process. The pruning residue pellets were supplied from a company that produces pellets in Antalya.

Some physical properties and ultimate analysis results of pellets have been given in Table 1.

Table 1- Some physical properties and ultimate analysis results of palm residue pellets

Physical properties	Values
Moisture (% db.)	5.95
Average pellet diameter (mm)	6
Average pellet length (mm)	35
pellet density (kg/m^3)	1000
Ultimate analysis results	
Ash Content (%)	6.30
Volatile substance content on the original basis (%)	69.33
Volatile matter content on a dry basis (%)	73.12
Fixed carbon content (%)	20.58
Carbon (%)	44.15
Hydrogen (%)	5.63
Nitrogen (%)	1,02
Oxygen (%)	42.09

The lower heating value of biomass was calculated by the following equation (Rupesh et al. 2020);

$$LHV_{Biomass} = 0.0041868(1 + 0.15[O]\left(7837.667[C] + 33888.889[H] - \frac{[O]}{8}\right) \quad (1)$$

Where; O, H, and C are the weight percentage of oxygen, hydrogen, and carbon elements in the biomass obtained from ultimate analysis.

2.3. Syngas and Air flow rate measurements

The electric motor operating the vacuum pump during gasification was operated at two different frequencies (25 Hz and 35 Hz). Syngas flow measurement with orifice type flow meter placed in the gas line before the gas sample outlet point was carried out in accordance with EN ISO 5167-2 standard.

After the syngas flow rate measurement, the air flow rate has been determined by the equation below (Dalmis et al. 2018);

$$AFR = \frac{GFR * N_{syngas}}{N_{air}} \quad (2)$$

2.3. Syngas analysis

The syngas sample with the help of a pipe from the main gas output line were taken and analyzed with Agilant 7890A GC model gas chromatography device. The device gives percentages by volume of gas components (H_2, CO, CH_4, CO_2 and N_2) contained in the syngas.

2.4. Energy and exergy analysis

The mass and energy flows used in the energy and exergy calculations in the gasification process are shown schematically in Figure 2.

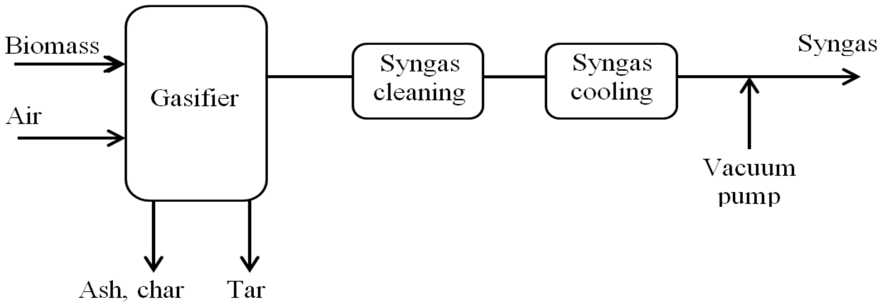

Figure 2- Schematic view of mass and energy flows in the gasification process

2.4.1. Energy analysis

Kinetic $(\dot{Q}_{ki})$ and potential $(\dot{Q}_{po})$ energy flows of syngas can be neglected. Thus, total energy flow can be shown as below (Manatura et al. 2017);

$$\dot{Q}_{syngas} = \dot{Q}_{ph} + \dot{Q}_{ch} \quad (3)$$

The physical (sensitive) energy of syngas is calculated as below;

$$\dot{Q}_{ph} = \dot{m}_{syngas}\, \Delta h = \dot{m}_{syngas} \int_{T_0}^{T} C_p dT \quad (4)$$

The chemical energy flow of syngas is calculated as below;

$$\dot{Q}_{ch,syngas} = \dot{m}_{syngas}\, LHV_{syngas} \quad (5)$$

The chemical energy flow of biomass, tar and syngas can be calculated by equations given below;

$$\dot{Q}_{ch,biomass} = \dot{m}_{biomass}\, LHV_{biomass} \quad (6)$$

$$\dot{Q}_{ch,tar} = \dot{m}_{tar}\, LHV_{tar} \quad (7)$$

The LHV of syngas is calculated by equations given below (Wang et al. 2013);

$$LHV_{syngas} = 12.622x_{CO} + 35.814x_{CH_4} + 10.788x_{H_2} \quad (8)$$

The energy efficiency of the gasification can be calculated by the following equation;

$$\eta_{En} = \frac{\dot{Q}_{syngas}}{\dot{Q}_{biomass}+\dot{Q}_{electricity}} \quad (9)$$

2.4.2. Exergy analysis

Exergy analyzes of the gasification of palm pruning pellets were performed by the method applied by Tang et al. (2016), Wang et al. (2013) and Zhang et al. (2010).

Only chemical exergy was considered for biomass. The exergy of biomass can be defined as;

$$\dot{E}x_{biomass} = \beta \dot{m}_{biomass} LHV_{biomass}$$

Chemical exergy $(\dot{E}x_{ch})$ and physical exergy $(\dot{E}x_{ph})$ are the sum of exergy $(\dot{E}x)$ of syngas;

$$\dot{E}x_{syngas} = \dot{E}x_{ch} + \dot{E}x_{ph} \qquad (11)$$

The chemical exergy of syngas can be determined by the composition analysis of syngas and the flow rate. Its value is obtained from the following equation;

$$\dot{E}x_{ch} = \dot{m}_{syngas}(\sum_i (y\ ex_{ch})_i + RT_0 \sum_i (y\ \ln y)_i) \qquad (12)$$

The standard chemical exergy of gases (ex_{ch}) can be obtained from any thermodynamics book. $\dot{m}_{syngas}$ is the syngas output rate from the gasifier.

The physical exergy of syngas is determined as:

$$\dot{E}x_{ph} = \dot{m}_{syngas}\ \sum_i \left(y\ ex_{ph}\right)_i \qquad (13)$$

For each gas components, the specific physical exergy in kJ kmol^{-1} is defined as:

$$ex_{ph} = (h - h_0) - T_o(s - s_0) \qquad (14)$$

The exergy efficiency of the gasification system can be calculated by the following equation;

$$\eta_{Ex} = \frac{\dot{E}x_{syngas}}{\dot{E}x_{biomass} + \dot{E}x_{electricity}} \qquad (15)$$

The irreversibility of the gasification system is calculated as below;

$$I_r = \dot{E}x_{input} - \dot{E}x_{output} \qquad (16)$$

3. Results and Discussion

The lower heating value (LHV) of pellets was calculated as 16640 kJ/kg by Equation 1. The air mass flow rate (AFR), syngas flow rate (GFR) and fuel consumption rate (FCR) obtained as a result of the gasification process performed by operating the electric motor connected to the vacuum pump at 25 Hz and 35 Hz frequencies are given in Table 2. These values express the performance of the gasification process. The specific gas production rates (SGPR) which are also given in Table 2 were calculated by using GFR and FCR values. Gunarathne et al. (2013) gasified the wood particles of rubber trees in a downstream gasifier and found the specific gas production rate between 2.84 Nm^3/kg-biomass and 2.91 Nm^3/kg-biomass. The specific gas production rate in the gasification of the grass pellet was found between 1.57 Nm^3/kg-biomass and 1.96 Nm^3/kg-biomass (Diken & Kayişoğlu, 2020). Specific gas production rates provided in the gasification of palm pruning wastes in this study were seen to be closer to the values obtained in the gasification of rubber tree wood particles. In the gasification process at both stages, the temperature of the core region varied between 700 °C and 800 °C.

Table 2- Performance parameters of palm pruning residues gasification

AFR (Nm^3/h)	*GFR (Nm^3/h)*	*FCR (kg/h)*	*SGPR (Nm^3/kg biomass)*
7.6	9.57	3.89	2.46
10.2	12.08	4.27	2.83

Gas components of syngas and heat values are given in Table 3. Therefore, the lower heating value of syngas at 7.6 Nm^3/h air flow rate were higher than 10.2 Nm^3/h air flow rate. The higher CH_4 rate in the syngas at this air flow rate was the most important factor that increased the lower heating value. Samadi et al. (2020) carried out a research in order to estimate the energy to be obtained in the gasification of biomass. Researchers stated that the specific heat values are high at small air flow rates, and the specific heat values decreases as the air flow rate increases.

Table 3-Rate of gas components and heat values of syngas

AFR(Nm^3/h)	*Gas components in syngas(%)*					*Heating value(MJ/Nm^3)*	
	H_2	*CO*	*CH_4*	*CO_2*	*N_2*	*LHV*	*HHV*
7.6	13.79	13.21	2.62	15.49	54.88	4.09	4.47
10.2	12.77	13.29	1.97	12.95	59.03	3.76	4.08

Dalmis et al. (2018) found the lower heat value of the syngas between 3.61 MJ/Nm^3 and 4.59 MJ/Nm^3 in the study where they gasified rice straw pellets. (Diken & Kayişoğlu, 2020) stated that the lower heat value of syngas obtained from gasification of grass pellets changes between 3.83 MJ/Nm^3 and 3.92 MJ/Nm^3. The lower heat value in the gasification of wood sawdust pellet was around 5.7 MJ/Nm^3 (Simone et al. 2012). Pellegrini and Oliveira (2007) found the lower heat value between 4.7 MJ/Nm^3 and 5.1 MJ/Nm^3 in the gasification of sugar cane with steam + air. Rao et al. (2004) determined the upper thermal values of the synthesis gases obtained by gasification of different biomass. Researchers found that these values are 5.6 MJ/Nm^3 in urban waste, 5.0 MJ/Nm^3 in wood sawdust, 4.82 MJ/Nm^3 in soybean pellets, 4.95 MJ/Nm^3 in corn cobs, 4.76 MJ/Nm^3 in pea stems and 4.80 MJ/Nm^3 in peanut shells. In this study, where the palm pruning wastes were gasified, heat values of obtained syngas were seen to be close to the values obtained in the gasification processes previously made using different biomass.

Energy and exergy balances at 7.6 Nm^3/h and 10.2 Nm^3/h air flow rate are given in Table 4 and 5. Energy and exergy efficiencies at 7.6 Nm^3/h were 50.1% and 43.2%, respectively. These values were 52.6% and 45.1% at 10.2 Nm^3/h. Energy efficiencies were higher than exergy efficiencies at both air flow rates. In addition, irreversibility value was higher than lost energy at both stages. In many previous studies, it is seen that the energy efficiency in the gasification of biomass is higher than the exergy efficiency (Cohce et al. 2011; Wu et al. 2014).

Table 4- Energy and exergy balances at 7.6 Nm^3/h air flow rate

Energy input	***(kW)***	***Exergy input***	***(kW)***
Biomass	17.98	Biomass	20.46
Electricity	0.37	Electricity	0.37
TOTAL	**18.35**	**TOTAL**	**20.83**
Energy output		**Exergy output**	
Chemical energy	8.56	Chemical exergy	8.49
Physical energy	0.12	Physical exergy	0.0021
Tar	0.51	Tar	0.51
Lost energy	9.16	Irreversibility	11.83
Energy efficiency (%)	**50.1**	**Exergy efficiency (%)**	**43.2**

Table 5- Energy and exergy balances at 10.2 Nm^3/h air flow rate

Energy input	***(kW)***	***Exergy input***	***(kW)***
Biomass	19.73	Biomass	22.46
Electricity	0.37	Electricity	0.37
TOTAL	**20.10**	**TOTAL**	**22.83**
Energy output		**Exergy output**	
Chemical energy	9.92	Chemical exergy	9.78
Physical energy	0.15	Physical exergy	0.0026
Tar	0.51	Tar	0.51
Lost energy	9.52	Irreversibility	12.53
Energy efficiency (%)	**52.6**	**Exergy efficiency (%)**	**45.1**

Beno et al. (2020) stated that the maximum thermal efficiency and exergy at the gasification of paddy husks are obtained at ER = 0.20 and decreases rapidly above this value. Researchers reported that thermal efficiency is 78% and exergy value is around 70%. In a study where poplar sawdust was gasified, it was stated that the average exergy efficiency was 48% and this value was close to coal gasification (Iribarren et al. 2014). Coconut shell and charcoal were gasified by mixing in certain proportions. When the coconut shell was gasified alone, the exergy efficiency was around 36%. Exergy efficiency in the mixture of 70% coconut shell and 30% charcoal exceeded 50% (Monir et al. 2018). Gu et al. (2019) used air, oxygen-enriched air and pure oxygen as gasifying agents to gasify the paddy stalk. The researchers found exergy yields in gasification as 55%, 58% and 63% respectively. Zhang et al. (2018) conducted exergy analyzes in conventional and partial gasification of biomass and found it to be 65.6% and 68.0%, respectively. The highest thermal energy and exergy efficiencies in the gasification processes performed with preheated air and steam at different temperatures were found as 81.5% and 76.2%, respectively, at the 1.83 steam/biomass ratio (Wu et al.2014). The maximum gasification exergy efficiency of pine with 10% moisture content is 73.73%, which is 1.45% and 2.67% higher than that of pine with 20% and 30% moisture content. The maximum gasification exergy efficiency of sawdust with 10% moisture content is 65.12% which is 1.14% and 1.96% higher than that of sawdust with 20% and 30% moisture (Wang et al. 2013). As can be seen, the energy and exergy efficiency in the gasification of biomass can be in a very different range depending on the composition of the biomass, its moisture content and the properties of the gasification agent. It is possible to say that the energy and exergy efficiency values obtained in this study are within acceptable limits.

4. Conclusions

In this study, palm pruning residues were gasified at two different air flow rates and the energy and exergy efficiencies of the gasification process were investigated. Energy efficiency was higher than exergy efficiency at both air flow rates. It was observed that the gas has a higher thermal value at a lower air flow rate. Despite the differences in the structure of the biomass, the thermal value, energy and exergy efficiency values obtained in this research have remained within the limits of the results obtained in the previous studies. Palm is grown as an oil plant in Far East Asian countries. In Turkey there are quite a lot, especially the palm populations in parks and gardens in the Mediterranean region. With the pruning of palm trees, thousands of tons of waste are generated each year. The evaluation of these wastes as an energy source through gasification will make important contributions to the economy and the environment.

This article is derived from the master thesis which prepared by Demirtas (2019), "Gasification of Palm Tree Pruning Waste (in Turkish) ".

Abbreviations and Symbols

AFR	Air flow rate (Nm^3/h)
C_p	The specific heat at constant pressure of the syngas (kJ kmol/K)
$\dot{E}x_{biomass}$	The exergy flow of the biomass (kW)
$\dot{E}x_{syngas}$	The exergy flow of the syngas (kW)
$\dot{E}x_{ch}$	The chemical exergy flow of the syngas (kW)
$\dot{E}x_{ph}$	The physical exergy flow of the syngas (kW)
ex_{ch}	The standard chemical exergy of gas components (kJ/kmol)
ex_{ph}	The specific physical exergy of gas components (kJ/kmol)
GFR	Syngas flow rate (Nm^3/h)
h, h_0	The specific enthalpy at the current and dead state of syngas components (kJ/kmol)
I_r	The irreversibility of the gasification system (kW)
$LHV_{Biomass}$	The low heating value of the biomass (kJ/kg)
LHV_{tar}	The low heating value of the tar (kJ/kg)
LHV_{syngas}	The low heating value of the syngas (kJ/Nm^3)
$\dot{m}_{Biomass}$	The mass flow rate of the biomass (kg/s)
$\dot{m}_{tar}$	The mass flow rate of the tar (kg/s)
$\dot{m}_{syngas}$	The mass flow rate of the syngas (kmol/s in Equation 3 and Equation 11, Nm^3/s in Equation 4)
N_{syngas}	Volumetric ratio of nitrogen in the syngas (%)
N_{air}	Volumetric ratio of nitrogen in the air (%)
$\dot{Q}_{syngas}$	The total energy flow of the syngas (kW)
$\dot{Q}_{ph}$	The physical energy flow of the syngas (kW)
$\dot{Q}_{ch,syngas}$	The chemical energy flow of the syngas (kW)
$\dot{Q}_{ch,biomass}$	The chemical energy flow of the biomass (kW)
$\dot{Q}_{ch,tar}$	The chemical energy flow of the tar (kW)
$\dot{Q}_{ch,syngas}$	The chemical energy flow of the syngas (kW)
$\dot{Q}_{electricity}$	The electrical input to gasification system (kW)
s, s_0	The specific entropy at the current and dead state of syngas components (kJ/kmol K)
T_0	The temperature at dead state (298.15 K)
T	The syngas outlet temperature (K)
y_i	The molar fraction of each gas composition (i) in the syngas.
$x_{CO}, x_{CH_4}, x_{H_2}$	Molar fractions of gas components in syngas, respectively
β	The quality coefficient of the biomass
Δh	The specific enthalpy change of the syngas (kJ/kmol)
η_{En}	The energy efficiency of the gasification system
η_{Ex}	The exergy efficiency of the gasification system

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