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Technical Feasibility to Utilize Wasted Empty Fruit Bunch from Small Scale Farms for Simultaneous Production of Biochar and Electricity

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ABSTRACT

Biochar production by pyrolysis stove and utilization of the excess heat to generate electricity, simultaneously, could improve the performance of the whole system, and give a significant solution to both energy and environment problem. This is especially if implemented as a standalone facility and applied in a remote area. The purpose of this study is to evaluate technical feasibility and strategy in using pyrolysis stoves to produce biochar and generate electricity by ORC, simultaneously. This study incorporates a variety of data obtained previously, consisting of pyrolysis stove design, performance test for biochar production and use of heat energy, simultaneously. Simulative study was conducted to evaluate pyrolysis stove-ORC integration. The results showed that biochar produced using the pyrolysis stove has characteristics that are very supportive for use as a soil enhancer. Excess heat from the pyrolysis stove during the production of biochar can be used to fuel the ORC system to generate electricity. The optimum biochar yield and thermal efficiency of the ORC were found to be optimum at the stove's airflow rate of 0.034-0.035 kg/s. Accordingly, a combination of biochar production and electricity generation using the ORC system is considered to be technologically feasible to meet the sustainability requirement.

Keywords: power generation, pyrolysis stove, thermal energy.

INTRODUCTION

Biomass is one of the renewable energy sources with high availability throughout the year (>85%) in Indonesia (Soerawidjaja 2010). About 21.76% of Indonesian's household, located mainly in rural area, still use biomass as feed stock for cooking (BPS 2017). More than half of Indonesia's population living in rural areas, and mostly have no access to modern energy and electricity. Therefore, biomass is a cost-effective solution for providing energy services in rural and remote areas. Biomass resources in the rural sector come from certain agricultural crop residues and forests, including palm oil waste (Palmer 2011). Both countries,

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Indonesia and Malaysia, produce around 85-90% of the total world palm oil production (Rahayu *et al.* 2020). Solid residue of palm oil industry consists of 5.5-8% palm shells, 20-23% empty fruit bunch (EFB), and 15% palm fiber from fresh fruit bunches, by volume (Abnisa *et al.* 2013; Kong *et al.* 2014; Azri *et al.* 2017). Shells and fiber are normally used to fuel boiler, while EFB is frequently used as fertilizer and the rest is burned in vain.

Environmental benefit of biomass utilization can be further enhanced by its simultaneous conversion to energy and biochar. Biochar is a porous and carbonaceous material produced by the pyrolysis process of biomass (Zhang *et al.* 2017). The carbon content of biochar is almost non-degradable by microbial processes compared to agricultural wastes (Liu *et al.* 2013). The benefit of biochar has attracted growing attention since it can be used to amend agricultural land, while sequestrating the carbon (Khan *et al.* 2008; Woolf *et al.* 2010; Lee *et al.* 2013; Hagemann *et al.* 2017).

Biochar can be produced by using a pyrolysis stove and combust the produced syngas to provide heat after the auto-thermal process. During the process, there will be thermal energy excess, which can be used to generate electricity. Organic rankine cycle (ORC), which uses organic fluid instead of water as a working fluid, is considered suitable to convert the waste heat to mechanical energy and then electric power. In comparison to water, organic fluids are advantageous when the temperature is low and power plant capacity is small (Drescher & Bru 2007).The purpose of this study is to evaluate technical feasibility and strategy in using pyrolysis stoves to produce biochar and generate electricity by ORC, simultaneously.

MATERIALS AND METHODS

This study combines various data obtained previously, which consists of pyrolysis stove design and performance test for simultaneous biochar production and thermal energy use (Pangala *et al.* 2016; Setiawan *et al.* 2018; Swastika *et al.* 2020). Those data then were used to analyze the technical feasibility of the simultaneous production of biochar and electricity generation using the excess heat from the pyrolysis stove. The integration of the pyrolysis stove with the ORC was conducted in a simulative study.

Pyrolysis Stove Experimentation

The design of the biochar-producing pyrolysis stove is shown in Figure 1. The stove consists of two main chambers, namely the combustion chamber and the pyrolysis chamber. The combustion chamber is used to produce initial heat for the pyrolysis process in the pyrolysis chamber before reaching the auto-thermal process. The pyrolysis chamber consists of four compartments that can be used alternatively or in a consecutive way if the stove to be operated continuously.

The performance of the stove was evaluated in terms of thermal efficiency using the boiling test method, and the quality of the produced biochar. The thermal efficiency of the stove is defined as the ratio of heat transfer into the water being boiled with the stove and heat input to the stove, which is the standard boiling water test method, as shown in Eq.1.

$$\eta_{wt} = \frac{\left(m_w C_{p,w} \Delta T\right) + \left(m_w L_w\right)}{m_b LHV} x100\% \qquad [1]$$

Here, m_w is the initial mass of water (kg), $C_{p,w}$ is the specific heat capacity of water (4.18 kJ/kgK), ΔT is the temperature difference from initial to boiling point (K),

m_e is mass of evaporated steam (kg), L_w is the heat of evaporation of water (2257.2 kJ/kg), m_b is mass of consumed biomass (kg).

Quality of the produced biochar was evaluated in terms of several parameters, namely pH which was measured by using a digital pH meter, porosity using iodine absorption and Scanning Electromagnetic (SEM) Zeiss-EVO 50, and surface area using the methylene blue absorption indicator. Biomass is being used for the study was oil palm empty fruit bunch obtain from small scale farms, pre-treated to have an average moisture content of 4.8% w/w.

Pyrolysis Stove and ORC Integration

Simulative study on the integration of pyrolysis stove and ORC was based on the model as illustrated in Figure 2. The heat required to drive the ORC is provided by excess heat from the pyrolysis stove when producing biochar. The stove's excess heat is used to heat up and maintain a constant temperature of the oil bath before transferred to the ORC. The selection of working fluid to be used in the ORC was based on its theoretical performance at the temperature and heat obtainable from the stove, by using Engineering Equation Solver.

The performance of the ORC was analyzed using T-s diagram as shown in Figure 2 and 3. The energy balance in heat exchanger thermal oil is calculated by Eq. 2.

$$Q_{oil} = \eta_{HE} Q_{th} = \left(\dot{m}_{oil} C_{p,\mathrm{oil}} \Delta T\right) \quad [2]$$

Energy balance in the evaporator is expressed by Eq. 3.

$$Q_e = \eta_{HE} Q_{oil} = \dot{m}_f \left(h_3 - h_2\right) \quad [3]$$

The work consumption in the pump is given by Eq. 4.

$$w_p = \frac{\dot{m}_f \left(h_{2s} - h_1\right)}{\eta_p} \quad [4]$$

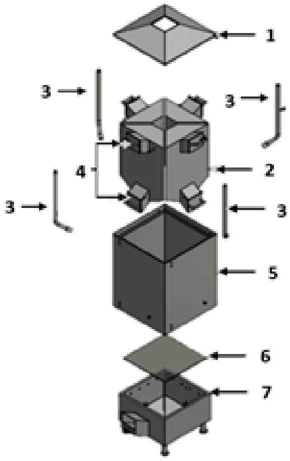

Figure 1 Pyrolysis stove parts (Swastika 2020).

The Turbine power is described by Eq. 5.

$$w_t = \dot{m}_f \left(h_3 - h_{4s}\right) \eta_t \quad [5]$$

The net output work (electricity) of the cycle is expressed by Eq. 6.

$$w_{net} = \left(w_t - w_p\right) \eta_e \quad [6]$$

Energy balance in the condenser can be expressed as in Eq. 7.

$$\eta_{HE} \left(m_w C_{p,w} \Delta T\right) = \dot{m}_f \left(h_4 - h_1\right) \quad [7]$$

Then, the cycle efficiency can be expressed by Eq. 8.

$$\eta_{th} = \frac{\left(w_t - w_p\right)}{Q_{th}} \quad [8]$$

The pinch point temperature difference in evaporator and condenser is given in Eq. 9 and Eq. 10.

$$T_{pe} = T_5 - T_2 \quad [9]$$

$$T_{pc} = T_4 - T_7 \quad [10]$$

Here, Q_{oil} is heat from thermal oil (kJ/s), η_{HE} is heat exchanger effectiveness (%), $\dot{m}_{oil}$ is the mass flow rate of thermal oil (kg/s), $C_{p,oil}$ is oil heat capacity (kJ/kgK), Q_{th} is heat from pyrolysis stove (kJ/s), $\dot{m}_f$ is the mass flow rate of the working fluids (kg/s), h_i is enthalpy at state i, η_p is isentropic efficiency of a pump (%), η_t is

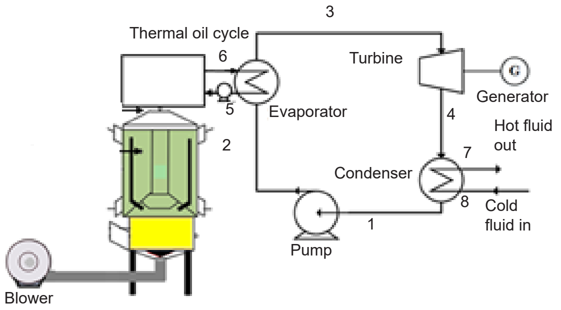

Figure 2 Power generation based on pyrolysis stove scheme (modified from Swastika 2020).

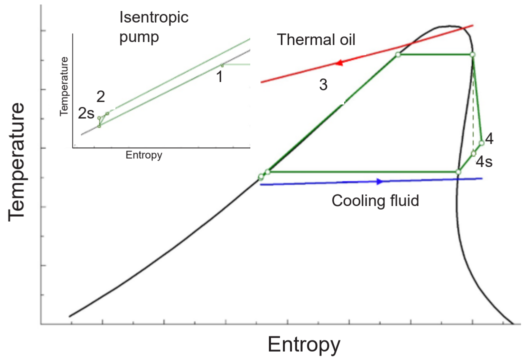

Figure 3 T-S diagram of the ORC (Setiawan *et al.* 2018).

isentropic efficiency of the turbine (%), $\dot{m}_w$ is the mass flow rate of cooling fluid (kg/s), $C_{p,w}$ is cooling fluid heat capacity, T_i is the temperature at state i (°C), state i: 1, 2, 3, 4, 5, 6, 7, 8.

RESULTS AND DISCUSSION

Biochar Quality

In this study, four kg of EFB produces biochar ranging from 1.053-1.164 kg using a pyrolysis stove. The airflow rate to the stove give a positive effect on the biochar yield (Table 1). Pyrolysis that taken place in this research was categorized as slow pyrolysis, which was indicated by the heating rate in the stove (0.145–0.246 °C/s). Slow pyrolysis produces biochar more than bio-oil and gas (Basu 2013). Debdoubi *et al.* (2006) explained that the biochar proportion produced by the pyrolysis process depends on the heating rate and residence time. The airflow rate affects the pyrolysis temperature, as shown in Figure 4. At the greatest air flow rate (0.038 kg/s) the pyrolysis temperature was the lowest and the biochar yield was the highest. On the other hand, at the lowest air flow rates (0.033 kg/s), the pyrolysis temperature was high and the biochar yield was the lowest. (Basu 2013) stated that at low pyrolysis temperatures more char is produced while high pyrolysis temperatures will reduce char yield. This is supposed to be related to the decomposition of lignocellulose, in which the composition of lignin is the dominant contributor to biochar yield. Lignin decomposes at a temperature range of 250-500 °C, while cellulose and hemicellulose decompose in a temperature range of 275-350 °C and 150-350 °C, respectively (Gupta *et al.* 2016). At the airflow rate of 0.033 kg/s, where the pyrolysis temperature was 336.2 °C, it might be lignin was only partially decomposed.

Table 1 Biochar yield from pyrolysis stove

Air flowrate (kg/s)	EFB weight (kg)	Biochar weight (kg)	Biochar yield (%)
0.033	4	1.053	26.33
0.035	4	1.113	27.83
0.038	4	1.164	29.10

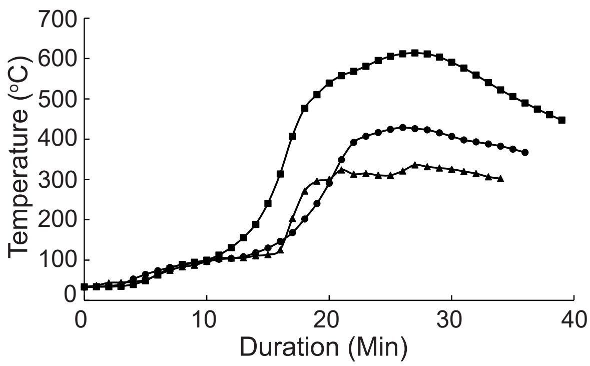

Figure 4 The temperature profile in the pyrolysis chamber. Air flowrate: 0.033 kg/s (▪), 0.035 kg/s (•), 0.038 kg/s (▴).

Table 2 Biochar characteristic

Characteristic	Value	Unit
pH	10.29	-
Iodine absorption	229.10	mg/g
Surface area	216.90	m²/g

The pH of biochar produced by the pyrolysis stove is 10.29 (Table 2). Lehmann (2007) reported that the pH of biochar produced ranged from 4 to 12 depending on raw material and temperature. Since the pH of biochar produced in this experiment is larger than 7, it is qualified as an ameliorant to increase soil pH, if applied as soil enhancers in acidic soils. Iodine absorption value can be used to determine the biochar's surface porosity. The higher absorption of iodine means the larger the pore on the biochar's surface. The average biochar iodine absorption test of biochar produced by the pyrolysis stoves was 229.1 mg/g, which was considered to be fairly small. Qualitative analysis of the pore using SEM is presented in Figure 5. The range of biochar's pore diameters was found to be 20.0–74.6 μm. The pore size is suitable as a habitat for colonizing, growing, and breeding of soil microorganisms. Soil microorganisms such as bacterial cells and fungal spores have diameter ranges 0.3-80 μm (Swift *et al.* 1979).

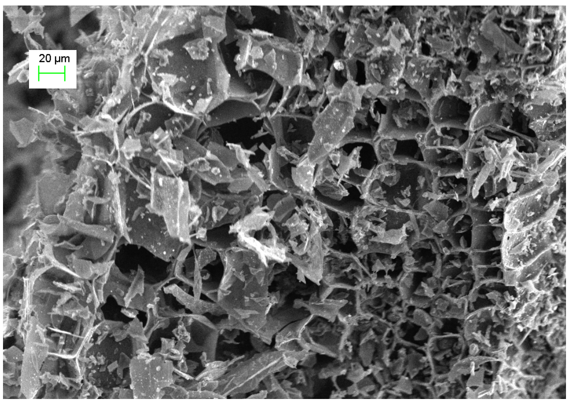

Figure 5 Biochar's pore structure as obtained by SEM, 500x magnification (Pangala *et al* 2016).

Power Generation

Based on the water boiling test, the stove had a thermal efficiency of 14.72% and had excess heat of 20.61 kW which is normally released as waste heat. To be efficiently used as a heat source of the ORC, the temperature of the excess heat has to be constant. Accordingly, an oil batch is required to become a temperature buffer before delivered to the evaporator of the ORC using a heat exchanger. In this case, consecutive use of the stove's compartment is necessary. Figure 6 shows the flame temperature and the oil's inlet temperature to be used for simulating the ORC's performance.

Even though the temperature is relatively high, the amount of available heat is small, so that ORC is considered more appropriate to be applied for electricity genenartion. Another parameter that is necessary for optimizing the ORC performance is the organic working fluid. The working fluid has to be suitable with the available heat and its temperature. The relatively high flame temperature takes only a few organic working fluids appropriate for the system since it is limited by its critical pressure and temperature. Working fluids generally used for high-temperature applications is hydrocarbon group with 5-6 carbon numbers (Turco *et al.* 2011; Carcasci *et al.* 2014). Thus, five different dry working fluids have been simulated, namely toluene, n-decane, n-dodecane, benzene, and oxylene. The operating conditions used in the simulation are presented in Table 3.

Simulation on the performance of using selected organic working fluid in ORC has been done at previous work (Setiawan *et al.* 2018). The results of the simulation on net electrical power that could be generated from the stove's excess heat, using the selected organic working fluids are shown in Table 4. O-xylene offers the highest net

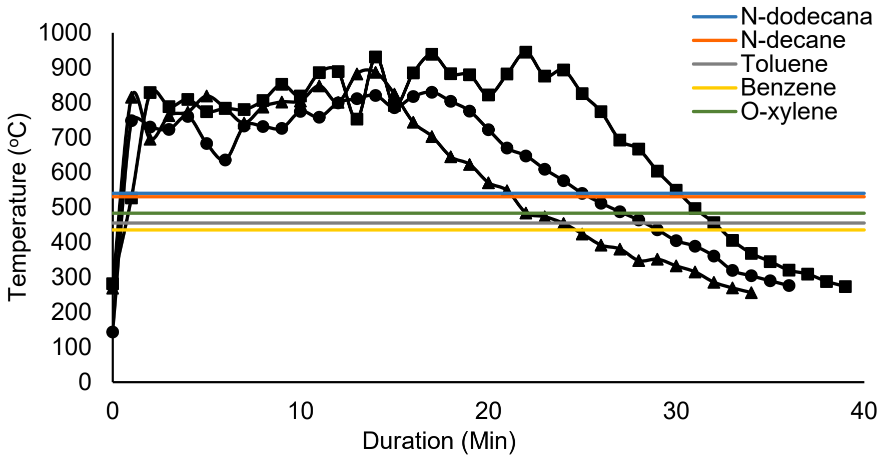

Figure 6 Temperature profile of the stove's excess heat and recommended inlet temperature of the thermal oil. Air flowrate: 0.033 kg/s (▪), 0.035 kg/s (•), 0.038 kg/s (▴).

Table 3 Operating conditions for power generation

Parameters	Value
Environmental pressure [kPa]	101.3
Environmental temperature [°C]	25
Working fluid mass flow rate [kg/s]	0.012
Thermal oil mass flow rate [kg/s]	0.020
Temperature inlet expander [°C]	285
Condenser temperature [°C]	30
Pinch point evaporator [K]	6
Pinch point condenser [K]	6
Cooling water mass flow rate [kg/s]	5
Subcool [°C]	5
Isentropic efficiency of the pump [%]	70
Isentropic efficiency of expander [%]	70
Generator efficiency [%]	90
Evaporator and condenser effectiveness [%]	80

Table 4 Simulation result of electric generation by ORC

Working fluid	Critical temperature (°C)	Critical pressure (bar)	Net power (watt)
N-dodecana	318.6	41.26	2248
N-decane	344.6	21.03	2188
Toluene	385.0	18.17	2230
Benzene	288.9	48.94	2033
O-xylene	357.1	37.38	2388

power compared to the other four working fluids, under the same working conditions. However, it is also necessary to pay attention to the saturation pressure in determining the working fluid for ORC. This is related to the level of security of ORC components, such as leakage rates. The saturation pressure of O-xylene is 14.91 bar at temperature 285 °C.

This simulation results suggested that the pump must be able to increase the condenser pressure up to the evaporator saturation pressure. Compared to N-dodecane, the O-xylene saturation pressure is much higher. Also, O-xylene has never been used as an ORC's work fluid. Many previous works showed that toluene is a good choice for recovering high-temperature heat, but the ORC performance decrease when the exhaust gas temperature is low (Chacartegui *et al.* 2009; Munoz *et al.* 2012; Clemente *et al.* 2013). On the other hand, based on the simulation results, toluene has a very high saturation pressure of 27 bar. Considering safety and pump power requirements, it is therefore not recommended the use of toluene as a working fluid. In general, ORC is not recommended to work above its working fluid's critical point, even though the pyrolysis stove can provide the required temperature. Based on the critical temperature, Benzene is not recommended to be used as a working fluid for ORC if fuelled by pyrolysis stove's excess heat.

Therefore, work produced by the ORC system has to be optimized within the allowed temperature, which is below the working fluid's critical point. Simulation on the effect of the expander's temperature on the net power generated by the ORC is shown in Figure 7. It shows that the higher the inlet temperature of the expanders, the higher electric power could be generated. N-dodecane is able to work at higher temperature conditions than the other four working fluids, but at the same temperature condition, the inlet power output is still lower than O-xylene. Raising the expander's inlet temperature from 190 °C to 310 °C would increase the net power by 55.27% for O-xylene, and 56.32% for N-dodecane.

Pinch point temperature difference of evaporator and condenser is a very important parameter in the ORC system (Li *et al.* 2013; Guo *et al.* 2014; Yu *et al.* 2015). As shown in Figure 7, the temperature that can be provided by the stove still higher than the recommended inlet temperature of the oil batch. Therefore, increasing the evaporator's temperature still possible to minimize irreversibility. In this study, a simulation was conducted to find out how much the heat supply that can be absorbed by the ORC working fluid with a set pinch point of 6 K. The relationship between the temperature that must be supplied by oil with the temperature of the evaporator setting point is presented in Figure 8. It shows that all of the organic fluid temperatures at expander inlet increased with higher thermal oil inlet temperature. At the expander's inlet temperature of 250 °C, the required evaporator's inlet temperature is 501.8, 495.0, 438.2, 425.5, and 457.9 °C for N-dodecane, N-decane, Toluene, Benzene, and O-xylene, respectively. The higher the heat absorbed does not correlate with the electrical power output. In this case, O-xylene gives the highest power of 2133 Watt with lower oil temperature (43.9 °C), compared to N-dodecane. This is due to the latent and sensible heat of those working fluid. Setiawan *et al* (2018) reported that the latent heat of evaporation is directly proportional to exergy efficiency. Therefore, the use of waste heat from pyrolysis stoves is considered very suitable for organic working fluids with the high latent heat of evaporation.

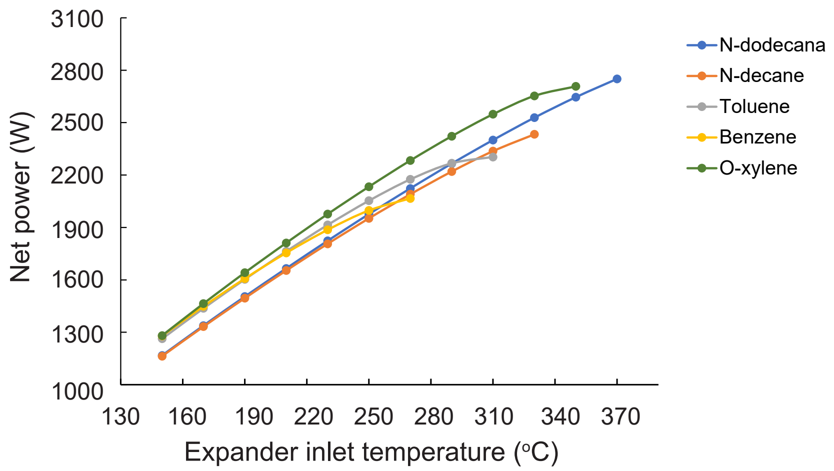

Figure 7 The effect of expander inlet temperature on net power.

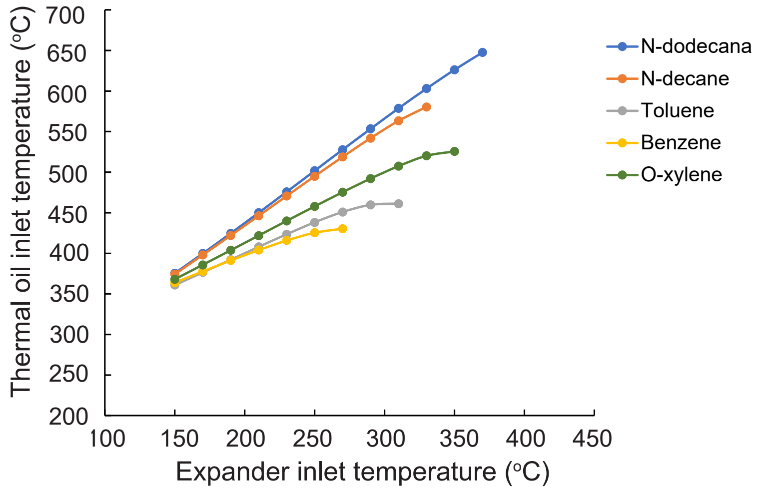

Figure 8 Required inlet temperature of the oil batch as affected by the expander inlet temperature.

Based on its efficiency it can be explained that the higher the inlet temperature of the oil, the higher the ORC efficiency for all of the organic working fluids. O-xylene has the highest thermal efficiency, although its use is limited to oil inlet temperatures below 540 °C. At the oil inlet temperature of 430 °C, the highest efficiency is shown by Benzene type working fluids. The use of low thermal oil temperatures will have an impact on the low thermal oil flow rate. This will result in the selection of a thermal oil pump in terms of power consumption. Based on its thermal efficiency, the utilization of the pyrolysis stove's excess heat for ORC result in the selection of N-dodecane type as a working fluid. This is due to being able to work at high temperatures with high efficiency relatively. The effect of expander inlet temperature on thermal efficiency is shown in Figure 9.

The utilization of pyrolysis stove's excess heat for ORC produces two main products, namely biochar and electrical energy. However, there would be a tradeoff between both products' yield, which need to be optimized. Figure 10 shows

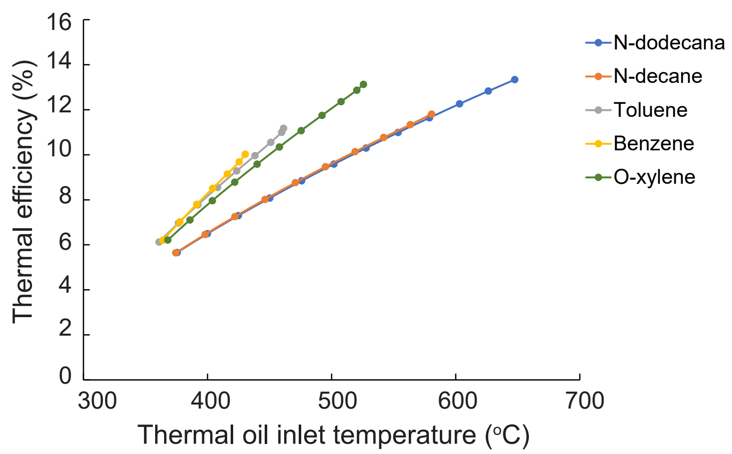

Figure 9 The effect of expander inlet temperature on thermal efficiency.

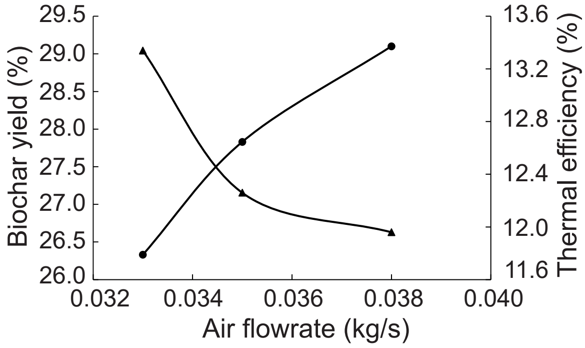

Figure 10 The optimum point of biochar production and thermal efficiency to air flowrate. Note: biochar yield (•), thermal efficiency (▲).

the biochar yield and thermal efficiency of ORC as affected by the airflow rate used in the pyrolysis stove. Here, N-dodecane was used as the working fluid of the ORC. It was found that the airflow rate has to be set at the range of 0.034-0.035 kg/s. Thereby, the production of biochar combined with the use of excess heat from the pyrolysis stove to generate electricity using the ORC system at the conditio as explained above is considered to meet the sustainability requirement.

CONCLUSION

Excess heat from the pyrolysis stove during the production of biochar can be used to fuel the ORC system to generate electricity. The optimum biochar yield and thermal efficiency of the ORC were found to be optimum at the stove's airflow rate of 0.034-0.035 kg/s. Accordingly, a combination of biochar production and electricity generation using the ORC system is considered to be technologically feasible to meet the sustainability requirement.

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