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Sustainable high-quality aviation oil recovery from organic solid wastes through microwave-assisted heating technology

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Abstract

Organic solid wastes are booming as society and industry rapidly develop, and it is necessary to reuse and recycle organic solid wastes to embrace a green and sustainable future. In this study, the mechanisms of microwave heating by comparing electrical heating were illustrated, the oil recovery performance during the microwave-assisted pyrolysis process of organic solid wastes was detailed, and the blueprint for sustainable high-quality aviation oil recovery from organic solid waste through using microwave-assisted heating technology was drafted. Microwave heating technology has the advantages of less reaction time, more rapid product formation, and lower reaction activation energy compared with electrical heating technology. The oil yields of the biomasses are below 50 wt. %, much lower than plastics (99, 78, 40, 98, and 79 wt. %). The oil components of organic solid wastes are hydrocarbons and oxygenated derivatives hydrocarbons, and the carbon numbers are mainly from C7 to C16. The highest recovered energy efficiency is 97% with the highest total energy efficiency of 63% when the microwave power is 650 W and the pyrolysis temperature is 460 ^{o}C for the polystyrene by using SiC. The unitary cost and unitary energy economic cost of the sustainable high-quality aviation oil recovery from organic solid wastes were 3.2 × 10^4 CNY/t and 779 CNY/GJ, respectively. The microwave-assisted pyrolysis has a good production on the oil yield and quality, and embraces good economic benefits and industrialization prospects. The aviation oil recovery blueprint can be drafted as: the organic solid wastes are recycled by the treatment plant, decomposed in the microwave pyrolysis factory, processed with some additives in the aviation fuel factory, and finally used in airplanes and filling stations.

***Keywords**: High-quality aviation oil; organic solid waste; microwave-assisted heating technology; electrical heating technology*

Nomenclature

CRF	Capital recovery factor
C_{ED}	Cost of energy dissipation (CNY)
C_{oven}	Microwave oven price (CNY)
EC_{fuel}	Unitary energy economic cost of fuel (CNY/GJ)
EC_{oil}	Unitary energy economic cost of the oil (CNY/GJ)
EC_{waste}	Unitary energy economic cost of the organic solid waste (CNY/GJ)
f_{EC}	Energy economic factor
$\mathrm{HHV}_{\mathrm{oil}}$	Higher heating value of the oil (GJ/kg)
$\mathrm{HHV}_{\mathrm{waste}}$	Higher heating value of the organic solid waste (GJ/kg)
i	Interest rate
L	Microwave oven lifespan
m_{oil}	Mass or weight of the oil (kg)
m_{waste}	Mass or weight of the organic solid waste (kg)
N	Number of annual batches
q_{oil}	Specific energy of the oil (CNY/GJ)
q_{waste}	Specific energy of the organic solid waste (CNY/GJ)

Q	Energy value of the microwave power consumption (GJ/kg)
$Q_{\mathrm{electricity}}$	Energy value of the electricity (GJ/kg)
Q_{ED}	Energy value of the dissipation (GJ/kg)
Q_{oil}	Energy value of the oil (GJ/kg)
Q_{waste}	Energy value of the organic solid waste (GJ/kg)
r_{EC}	Relative cost difference
UC_{oil}	Unitary cost of the oil (CNY/t)
UC_{waste}	Unitary cost of the organic solid waste (CNY/t)
φ	Maintenance factor
η_{r}	Recovered energy efficiency
η_{t}	Total energy efficiency

1. Introduction

Organic solid waste is mainly defined as biodegradable abandoned materials or by-products from humans, plants, or animals [1]. It mainly includes agricultural waste (rice husk, wheat straw, corn cob, bean nut, etc.), forest waste (branch, leave, weed, etc.), domestic waste (food scraps, paper, plastic products, etc.), industrial waste (waste from food processing plants, waste cloth from textile mills, etc.). Organic solid waste contains nutrient substances like lipids, carbohydrates, proteins, and minerals, and these nutrient substances ensure the organic solid waste can be biodegradable or recyclable as bio-based products such as bio-fertilizer, bio-oil, bio-gas, and bio-plastics [2-4].

The global generation of organic solid waste is difficult to estimate, and municipal solid waste production can reflect the organic solid waste to some extent. The annual generations of municipal solid waste are 1.3, 2.2, and 3.4 million tons in 2015, 2025, and 2050, respectively [5], and organic solid waste is more than 70% of the municipal solid waste including food waste, paper, textile, garden waste, and plastic [6]. Plastic waste is typical organic solid waste, and it increased from 353 million tons to 467 million tons during 2019 ~ 2030 (Figure 1). The plastic waste was recycled, incinerated, landfilled, and mismanaged in the amounts of 33, 67, 174, and 79 million tons in 2019. Nearly half of the plastic waste is landfilled, 19% of the plastic waste is incinerated, and recycled plastic slowly increased from 9% to 12% when the time changed from 2019 to 2030 [7].

Organic solid waste is usually incinerated or landfilled, whereas these two disposal ways are both harmful to the environment [8]. If these huge amounts of organic solid wastes are burned in the open air or incinerated in a furnace, a great amount of emissions and pollution (NO_x, SO_x, CO_2, etc.) will be released into the environment, deteriorating the environment and ecology we people and animals live in [9]. Meanwhile, landfilling needs plenty of land, and it significantly pollutes the soil, air, and water [10]. Therefore, it is crucial to consider environmentally friendly converting techniques by using organic solid waste to obtain valuable resources.

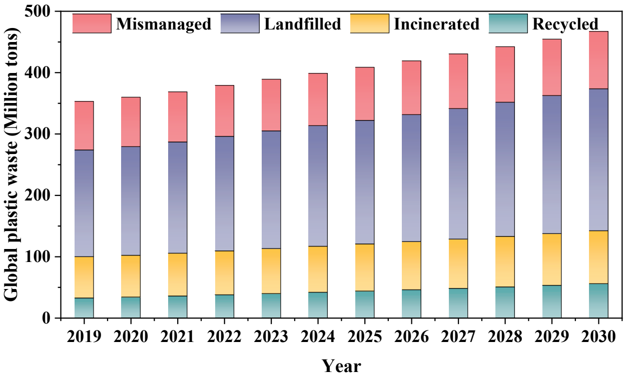


Figure 1 Plastic waste annual generation and disposal conditions [7].

An environmentally friendly treatment method for organic solid wastes is to convert them into valuable energy sources such as syngas, oil, and char. As compared with raw organic waste, the produced products (biorefineries or bio-based products) generally have high values and qualities [11]. Furthermore, bio-based products can minimize the CO_2 emission in the atmosphere [12]. There are many bioconversion techniques such as landfilling, composting, anaerobic digestion, and pyrolysis [12, 13]. The landfilling technology emits greenhouse gases and may pollute the soil, being forbidden in some countries [13]. The composting technology produces bio-fertilizer, bio-methane, and bio-pesticide with the advantages of non-chemical, low-cost, and soil protection, whereas this technology needs large land space, regular monitoring, and a long operation period. Also, this technology generates an obnoxious odor and may carry heavy metal [14, 15]. The anaerobic digestion technology can produce bio-gas and bio-fertilizer (digestion) via simple, less-emission, cheap, and easy operation, however, this technology also has a long operation period and requires accurate temperature. Moreover, this technology needs pretreatment and has a low-processing capacity [16, 17]. The pyrolysis technology is one of the most important thermochemical conversion routes to convert organic solid waste into high-value gas, oil, or char to resolve environmental concerns and protect energy safety [18, 19]. Microwave-assisted pyrolysis technology has the advantages of less reaction time, more rapid product formation, and lower reaction activation energy compared with conventional pyrolysis [12, 20].

The microwave-assisted heating technique is a promising technology among all kinds of pyrolysis technologies due to its advantages of less reaction time, more rapid product formation, and lower reaction activation energy. Yue et al. [21] studied the microwave-assisted pyrolysis corn straw to produce hydrogen enhanced by the catalyst and absorbent. Sun et al. [22] indicated that the bimetallic catalysts have a good performance in the pine wood pyrolysis process assisted by the microwave to produce oil and gas. Mahfud et al. [23] optimized the microwave-assisted pyrolysis oil generation process from the microalgae through response surface methodology. Oh et al. [24] estimated the microwave-assisted pyrolysis performance for sewage sludge, food waste, and livestock manure. Mohamed et al. [25] studied the switchgrass pyrolysis process for producing oil and char assisted by the microwave and catalytic. Other studies also analyzed the microwave-assisted pyrolysis performance of oil palm shell waste [26], empty fruit bunch [27], walnut shell [28], and rice husk [29].

The results from our previous studies indicated that some organic solid wastes can be converted into high-quality clean aviation oil, and the oil yield can be as high as 99 wt. % [30]. These supply a very good way to effectively reuse and recycle organic solid waste, reduce pollution emissions, and develop a circular economy. However, the processing processes and results were significantly varied by many factors, i.e., feedstock screened, furnaces used, conditions set, etc. Up to now, the heating fundamentals were still not well illustrated, and the conditions were still not well summarized.

In this study, coal, biomass, and plastic were selected to analyze the oil recovery performance through microwave-assisted pyrolysis technology due to the wide variety of organic solid waste. Based on the literature review, the economic analysis for the microwave-assisted pyrolysis process of organic solid waste was lacking, especially using plastics. The unitary cost, unitary energy economic cost, relative cost difference, and energy economic factor were applied as the economic parameters to assess the economic performance, based on the oil yield, oil component, and energy analysis.

The main objective of this study was to address the sustainability of high-quality aviation oil recovery from organic solid waste by using microwave-assisted heating technology. The specific objectives were to (a) illustrate the mechanisms of microwave heating by comparing electrical heating, (b) to detail and assess the oil recovery performance during the microwave-assisted pyrolysis process of organic solid wastes, and (c) to draft a blueprint for sustainable high-quality aviation oil recovery from organic solid waste through using microwave-assisted heating technology.

2. Electrical heating and microwave heating

2.1 Equipment

Figure 2 shows the typical furnaces used for electrical heating and microwave heating. Figure 2 (a) is a picture of a typical electrical furnace which is mainly named a Muffle furnace. The furnace is composed of a furnace body, electrical resistance, furnace door, flue, and control system. The core part is the electrical resistance located around the inner wall of the furnace. When the furnace is turned on, current flows through the electrical resistance, making the electrical resistance become hotter and even red. The furnace body is usually made of refractory material that can withstand high temperatures, while the shell is made of steel plate or other metal material to protect the internal structure of the furnace body. The furnace door is used to open and close the furnace body to allow materials to enter and exit. A flue is used to discharge smoke and exhaust gases. The control system is mainly used to control the temperature, pressure, and gas flow parameters in the furnace to ensure that the furnace can run normally and achieve the required heating effect. The furnace applications are wide, including water quality analysis, environmental analysis, and other fields of sample treatment, hot processing, industrial workpiece treatment, cement, building materials industry of small workpiece hot processing or treatment.

Figure 2 (b) is a picture of a typical microwave heating furnace. The microwave heating furnace usually includes a magnetron, waveguide, high-voltage transformer, and cooling fan. Magnetrons are the most common microwave generators and they are made of vacuum tubes, applied to consistently produce microwave irradiation in the wave band [31]. A waveguide serves as a hollow metallic conduit utilized for guiding microwaves. It facilitates the transmission of microwave signals through the mechanism of continuous reflections from the inner walls of the cylindrical tube. The high-voltage transformer is used to generate high voltage to meet the effective operation of the magnetron [32]. The cooling fan is applied to reduce the system temperature to avoid the condition of overheating. The microwave heating furnace has more advantages than the electrical heating method, such as (a) non-contact heating, (b) homogeneous temperature distribution, (c) rapid heating rate, and (d) volumetric heating pattern. Therefore, microwave heating furnaces have been applied in the food, construction, chemistry industries, and so on.

2.2 Heating mechanism

For the materials put in the furnaces, the heating mechanisms would be significantly difference. Figure 3 shows the heating mechanisms of electrical heating and microwave heating. Figure 3 (a) presents the electrical heating mechanism. The electrical heating pattern delivers the heat from the outside of the object target by conduction, convection, and even radiation. The electrical heating pattern easily causes the skin effect, and the water on the external surface of the object target rapidly evaporates, demonstrating that the conventional heating pattern is efficient for surface heating, non-uniform for object heating, and wasteful for the energy utilization because of the high thermal gradient and heat conduction or convection [34].

(a) Electrical furnace (b) Microwave furnace

Figure 2 Typical furnaces for electrical heating and microwave heating.

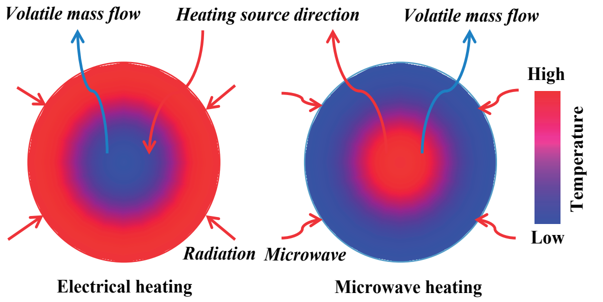


Figure 3 Heating mechanisms of electrical and microwave [33].

Figure 3 (b) shows the microwave heating mechanism. The microwave was first applied to dielectric heating in the 1970s as a novel heating technology, and microwave heating technology has the advantages of less reaction time, more rapid product formation, and lower reaction activation energy compared with electrical heating technology [35]. The microwave heating pattern produces heat in the inside of the object target by fractions of the polar particles or molecules. Microwave heating is uniform volumetric heating due to the polar particles or molecule's fraction heat generated from the core to the outside of the object target [36].

2.3 Heating performance

The heating performance comparison between electrical heating and microwave heating is presented in Figure 4. The heating material was wheat straw with a weight of 10 g and a size of 4 mm, and the absorbing material was SiC with a weight of 30 g and a size of 2-3 mm. The material was heated by two powers of 686 W and 984 W, and three different experimental groups were conducted: (a) the wheat straw by the electrical heating, named as Group I, (b) the wheat straw by the microwave heating, named as Group II, and (c) the wheat straw and SiC by the microwave heating, named as Group III. For Group I, the material temperature slowly increased in the first four minutes and then rapidly climbed with average heating rates of 33 ^{o}C/min for 686 W and 37 ^{o}C/min for 984 W. For Group II, the material temperature rapidly climbed in the first two minutes and then slowly increased with average heating rates of 16 ^{o}C/min for 686 W and 18 ^{o}C/min for 984 W. For Group III, the material temperature rapidly climbed with average heating rates of 82 ^{o}C/min for 686 W and 91 ^{o}C/min for 984 W. Microwave heating has a higher heating rate at the initial period than electrical heating, and the microwave heating assisted by the absorbing material (SiC) can have a 2.5 times heating rate compared with the electrical heating. This indicated that the microwave heating can effectively improve the heating rate compared with the electrical heating. The experimental reactant, apparatus, and procedure of the microwave-assisted pyrolysis process in references [43-46].

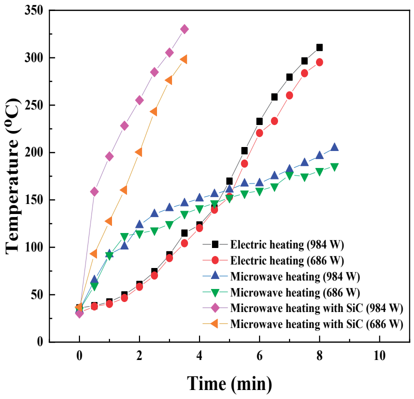


Figure 4 Heating performance comparison between the electrical heating and microwave heating.

2.4 Energy and economic criteria

Energy efficiency is an essential indicator to reflect the system's energy conservation or utilization state, and it also affects the performance, stability, and sustainable development of the system. The energy and economic flows can be found in reference [46]. For the sustainable high-quality aviation oil recovery process from the organic solid wastes through microwave-assisted heating technology, the recovered and total energy efficiencies can be calculated by following equations [46].

$$\eta_r = \frac{Q_{\text{oil}}}{Q_{\text{waste}}} \times 100\% \tag{1}$$

$$\eta_t = \frac{Q_{\text{oil}}}{Q_{\text{waste}} + Q_{\text{electricity}}} \times 100\% \tag{2}$$

$$Q_{\text{oil}} = m_{\text{oil}} \times \text{HHV}_{\text{oil}} \tag{3}$$

$$Q_{\text{waste}} = m_{\text{waste}} \times \text{HHV}_{\text{waste}} \tag{4}$$

$$Q_{\text{electricity}} = Q \times 3600 \times 10^{-6} \tag{5}$$

where η_r and η_t indicate recovered and total energy efficiencies, Q, Q_{oil}, Q_{waste}, and $Q_{\text{electricity}}$ are energy values of the microwave power consumption, oil, organic solid waste, and electricity (GJ/kg), m_{oil} and m_{waste} denote masses or weights of the oil and organic solid waste (kg), HHV_{oil} and $\text{HHV}_{\text{waste}}$ mean the higher heating values of the oil and organic solid waste (GJ/kg), respectively.

The economic analysis during the aviation oil production process can be conducted by following equations [46].

$$EC_{\text{oil}} = \frac{UC_{\text{oil}}}{q_{\text{oil}}} \tag{6}$$

$$EC_{\text{waste}} = \frac{UC_{\text{waste}}}{q_{\text{waste}}} \tag{7}$$

where EC_{oil} and EC_{waste} denote unitary energy economic costs of the oil and organic solid waste (CNY/GJ), UC_{oil} and UC_{waste} are unitary costs of the oil and organic solid waste (CNY/t), q_{oil} and q_{waste} means specific energies of the oil and organic solid waste (CNY/GJ), respectively.

$$C_{\text{oil}} = EC_{\text{oil}} \times Q_{\text{oil}} \tag{8}$$

$$C_{\text{waste}} = EC_{\text{waste}} \times Q_{\text{waste}} \tag{9}$$

where C_{oil} and C_{waste} mean costs of the oil and organic solid waste (CNY), respectively.

$$C_{\text{M}} = \frac{C_{\text{oven}} \times CRF \times \varphi}{N} \tag{10}$$

$$CRF = \frac{i \times (1+i)^L}{(1+i)^L - 1} \tag{11}$$

where C_{oven} is the microwave oven price (CNY), CRF denotes the capital recovery factor, φ indicates the maintenance factor, N means the number of annual batches, i is the interest rate, L indicates the microwave oven lifespan.

The unitary energy economic cost of fuel and the cost of energy dissipation can be calculated by Eq (12) and Eq (13):

$$EC_{\text{fuel}} = \frac{EC_{\text{waste}} \times Q_{\text{waste}} + EC_{\text{electricity}} \times Q_{\text{electricity}}}{Q_{\text{waste}} + Q_{\text{electricity}}} \tag{12}$$

$$C_{\text{ED}} = EC_{\text{fuel}} \times Q_{\text{ED}} \tag{13}$$

$$Q_{\text{ED}} = Q_{\text{oil}} - Q_{\text{waste}} - Q_{\text{electricity}} \tag{14}$$

where EC_{fuel} means the unitary energy economic cost of fuel (CNY/GJ), C_{ED} indicates the cost of energy dissipation (CNY), Q_{ED} is the energy value of the dissipation (GJ/kg).

The energy economic factor (f_{EC}) and relative cost difference (r_{EC}) can be calculated as follows.

$$f_{\text{EC}} = \frac{C_{\text{M}}}{C_{\text{M}} + C_{\text{ED}}} \tag{15}$$

$$r_{\text{EC}} = \frac{EC_{\text{oil}} - EC_{\text{fuel}}}{EC_{\text{fuel}}} \tag{16}$$

3. Oil recovery from microwave-assisted pyrolysis of organic solid wastes

3.1 Oil yields

Table 1 presented oil yields of several organic solid wastes (coal, biomass, and plastic) at different microwave-assisted pyrolysis conditions. The feedstocks include Indian coal, Indonesian coal, brown coal, brown coal and corn stover mixture (1:1), corn stover, wheat straw, microalgae, aspen pellet, solar panel, polystyrene, polypropylene, and polycarbonate. The oil yield is in the range of 7 ~ 99 wt. % with different microwave heating powers, pyrolysis temperatures, heating times, material sizes, and absorbents. The pyrolysis types have (a) flash pyrolysis, (b) fast pyrolysis, and (c) slow pyrolysis based on different reaction conditions. The flash pyrolysis has a high microwave power, high pyrolysis temperature, and high heating rate, leading to a high gas yield. Fast pyrolysis adopts medium microwave power, medium pyrolysis temperature, and medium heating rate, causing a high oil yield. The slow pyrolysis adopts the low microwave power, low pyrolysis temperature, and low heating rate, obtaining a high solid yield [12]. The pyrolysis conditions in Table 1 are: the heating power of 480 ~ 1250 W, pyrolysis temperature of 350 ~ 800 °C, and most conditions belong to fast pyrolysis. The pyrolysis conditions are conducive to oil production.

Figure 5 presents the oil yields of several organic solid wastes (coal, biomass, and plastic) at different microwave-assisted pyrolysis conditions. The oil yields of the coal and biomass are below 50 wt. %, much lower than plastics (99, 78, 40, 98, and 79 wt. %). The oil yield of polycarbonate is far lower than other plastics because of the generation of wax. The oil yield of brown coal is the lowest (average of 7 wt. %), whereas the oil yield of polystyrene is the highest (99 wt. %).

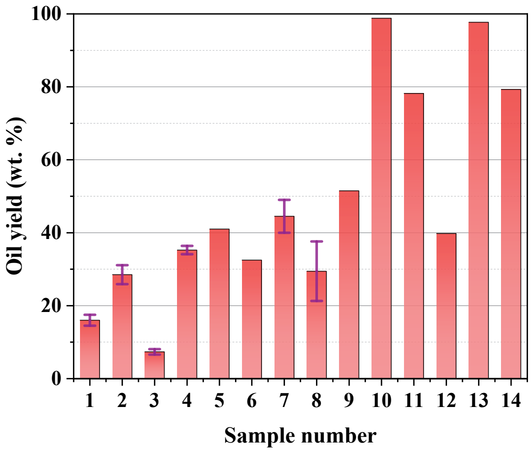


Figure 5 Oil yields of different organic solid wastes.

3.2 Oil components

The oil components are important to decide the physical and chemical properties of oil, and they can be applied to estimate the quality of aviation oil. Table 2 shows the main oil components of different organic solid wastes.

Table 1 *Oil yields of different organic solid wastes at different conditions.*

No.	Feedstock	Oil yield (wt.%)	Conditions	Ref.
1	Indian coal	16±2	Heating powers of 480 W and 640 W, coal sizes of 0.3 mm and 2.8~3.5 mm, maximum pyrolysis temperature of 800 °C, graphite as the susceptor	[37]
2	Indonesian coal	29±3		
3	Brown coal	7~8	Pyrolysis temperature of 500~600 °C, heating time of 20 min, absorbent of SiC	[38]
4	Brown coal and corn stover mixture (1:1)	34~36		
5	Corn stover	41	Heating power of 700 W, heating time of 15 min, pyrolysis temperature of 600 °C, Na_2CO_3 as a catalyst	[39]
6	Wheat straw	33	Pyrolysis temperature of 600 °C	[40]
7	Microalgae	40~49	Heating power of 500~1250 W, pyrolysis temperature of 462~627 °C	[41]
8	Aspen pellet	21~38	Heating power of 700 W, pyrolysis temperature of 350 °C and 500 °C, molecular sieve-based zirconium oxide catalysts	[42]
9	Solar panel	52	Heating power of 600 W, pyrolysis temperature of 550 °C, panel sheet size 20×20 mm^2	[43]
10	Polystyrene	99	Heating power of 650 W, pyrolysis temperature of 460 °C, absorbent of SiC	[30]
11	Polypropylene	78		
12	Polycarbonate	40		
13	Polystyrene	98	Heating power of 650 W, pyrolysis temperature of 460 °C, iron-based absorbent	[44]
14	Polypropylene	79	Heating power of 600 W, pyrolysis temperature of 450 °C, absorbent of SiC	[45]

The oil components of different organic solid wastes are various. The oil components for the solar panel are: aliphatic hydrocarbons (44 area%) > aromatic hydrocarbons (16 area%) > oxygenated derivatives of hydrocarbons (31 area%). The hydrocarbons for the polystyrene mixed with SiC are: monocyclic aromatic hydrocarbons (54 area%) and polycyclic aromatic hydrocarbons (4 area%). The oil components for the polypropylene in [30] are mainly composed of cycloalkane (40 area%), and olefin (16 area%). The oil components for the polycarbonate are: monocyclic aromatic hydrocarbons (1 area%), polycyclic aromatic hydrocarbons (1 area%), and olefin (84 area%). The oil components for the same organic solid waste (for example, the polypropylene in [30] and [45]) are different, and the carbon number of oil components is also various because the experimental conditions of [30] and [45] are not exactly the same. This indicates that the oil components can be controlled by changing the experimental conditions. The oil components of organic solid wastes are hydrocarbons and oxygenated derivatives hydrocarbons.

The oil component yields based on the carbon number for various organic solid wastes are shown in Figure 6. The carbon numbers are mainly from C7 to C16, and only polycarbonate has the component C6 and solar panel has the component C19. For various organic solid wastes and various experimental conditions, the carbon distributions and yields are different. For example, the yield of polystyrene in [30] intensively appears in C8 (46 area%), whereas the yields of polystyrene in [44] focus on C8 (37 area%), C9 (12 area%), and C15 (9 area%). This is because the absorbents are different: (a) SiC is used as the absorbent in [30] and (b) Fe is adopted as the absorbent in [44]. This demonstrates that the absorbent has an important effect on the oil components.

Table 2 *Main oil components of different organic solid wastes.*

No.	Feedstock	Components (area%)	Carbon range	Ref.
1	Solar panel	Aliphatic hydrocarbons (44), aromatic hydrocarbons (16), and oxygenated derivatives of hydrocarbons (31)	C6 ~ C19	[43]
2	Polystyrene	Monocyclic aromatic hydrocarbons (54) and polycyclic aromatic hydrocarbons (4)	C7 ~ C15	[30]
3	Polypropylene	Cycloalkane (40) and olefin (16)	C9 ~ C14	[30]
4	Polycarbonate	Monocyclic aromatic hydrocarbons (1), polycyclic aromatic hydrocarbons (1), and olefin (84)	C6 ~ C16	[30]
5	Polystyrene	Monocyclic aromatic hydrocarbons (62), polycyclic aromatic hydrocarbons (21), and others (17)	C8 ~ C16	[44]
6	Polypropylene	Alkanes (7), alkenes (18), and cyclanes (53)	C8 ~ C14	[45]

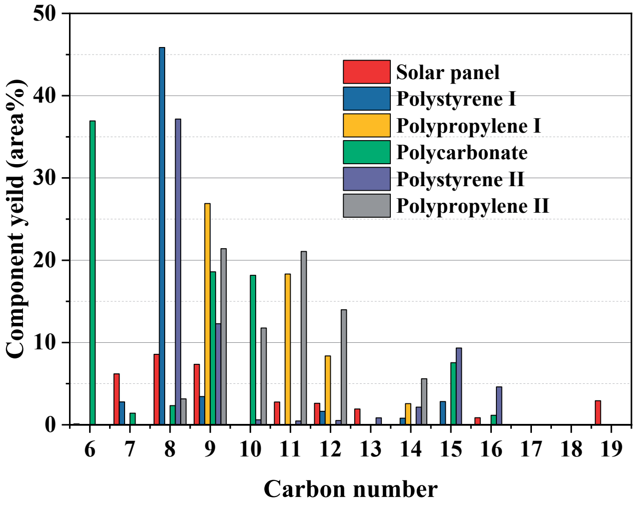
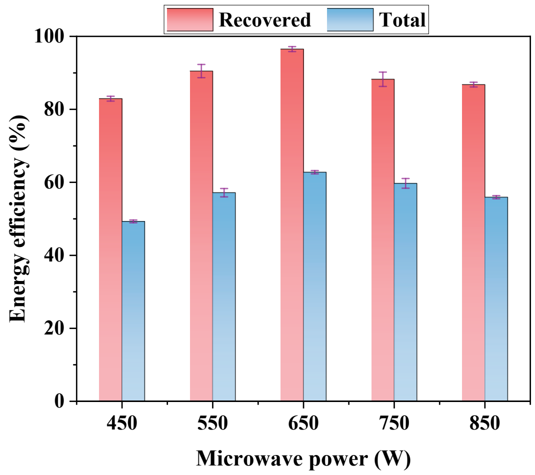


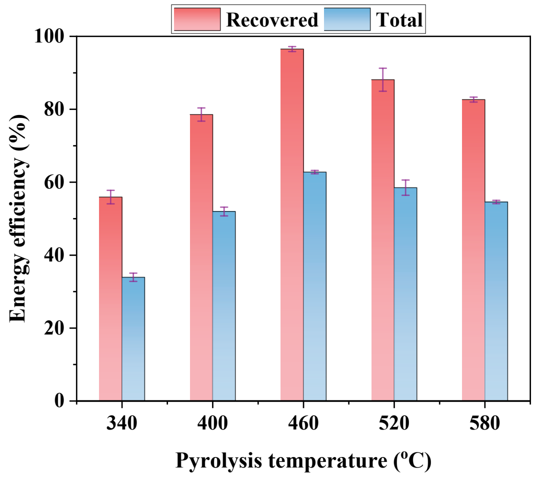
Figure 6 Yields at different carbon number for various organic solid wastes.

3.3 Energy analysis

The energy analysis for sustainable high-quality aviation oil recovery from organic solid wastes is still not widely studied. The recovered and total energy efficiencies from references [43] and [46] are discussed. The recovered and total energy efficiencies in [43] were in the ranges of 24% ~ 75% and 12% ~ 46%, respectively. The recovered and total energy efficiencies in [46] are presented at different conditions in Figure 7. The recovered and total energy efficiencies in [46] were in the ranges of 56% ~ 97% and 34% ~ 63%, respectively. The recovered and total energy efficiencies in [46] were much higher than the efficiencies in [43], indicating that plastics have a good energy conversion performance. Furthermore, plastics have a high oil yield and good components, therefore, plastics recycling to produce aviation oil is a potential technique to address the energy crisis and embrace a sustainable future.



(a) Energy efficiencies at different microwave powers.



(b) Energy efficiencies at different pyrolysis temperatures.

Figure 7 Recovered and total energy efficiencies at different conditions [46].

The best microwave power and pyrolysis temperature can be found in Figure 7. The recovered energy efficiency is the highest (97%) with the highest total energy efficiency of 63% when the microwave power is 650 W and the pyrolysis temperature is 460 ^{o}C. Also, the highest recovered energy efficiency of 75% and the highest total energy efficiency of 46% are obtained when the microwave power is 600 W and the pyrolysis temperature is 550 ^{o}C in [43]. This indicates that the reaction conditions control is significant to obtain good aviation oil.

3.4 Economic analysis

The optimal economic performance was achieved under the conditions of a microwave power of 650 W, a pyrolysis temperature of 460 ^{o}C, and a SiC loading of 2 t. The corresponding values for the key performance indicators were as follows: unitary cost of 3.2×10^4 CNY/t, unitary energy economic cost of 779 CNY/GJ, relative cost difference of 1.5, and an energy economic factor of 71% [46]. Figure 8 presents the unitary energy economic costs and relative cost differences at different microwave powers. The unitary costs of aviation oil (UC_{oil}) decreased from 3.9×10^4 CNY/t to 3.2×10^4 CNY/t when the microwave power increased from 450 W to 650 W, and then increased to 3.6×10^4 CNY/t as the microwave power climbed to 850 W. The relative cost difference (r_{EC}) changed in similar way, decreasing from 1.8 to 1.5 and then increasing to 1.8 with the microwave power increasing. Conversely, The energy economic factor (f_{EC}) increased from 61% to 71% and decreased to 67%.

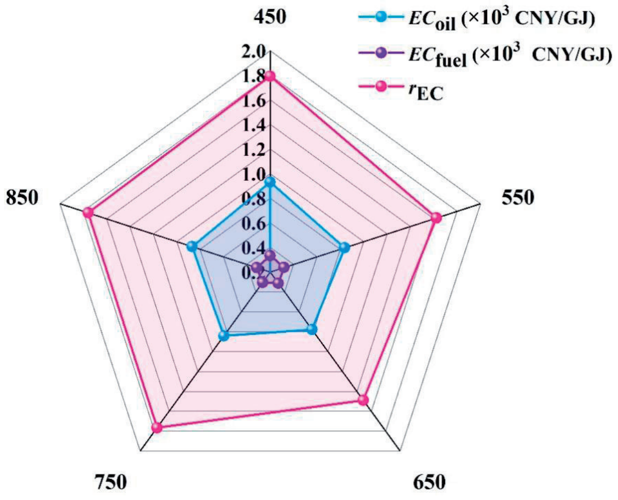


Figure 8 Unitary energy economic costs and relative cost differences at different microwave powers [46].

4. Aviation oil recovery blueprint

Sustainable high-quality aviation oil recovery from organic solid wastes through microwave-assisted heating technology can be produced by controlling the reaction conditions, such as microwave power, pyrolysis temperature, and absorbent. The unitary cost and unitary energy economic cost of the sustainable high-quality aviation oil recovery from organic solid wastes were 3.2×10^4 CNY/t and 779 CNY/GJ, respectively [46]. The energy and economic benefits contribute to the aviation oil recovery applications of organic solid wastes, and the industrial production of sustainable high-quality aviation oil can be expected. Therefore, the aviation oil recovery blueprint can be drafted as: the organic solid wastes are recycled by the treatment plant to be classified and pretreated, and then the organic solid wastes are decomposed in the microwave pyrolysis factory to produce the raw oil. The raw oil is processed with some additives in the aviation fuel factory, and finally, the hydrocarbon fuel can be used in airplanes and filling stations, as shown in Figure 9.

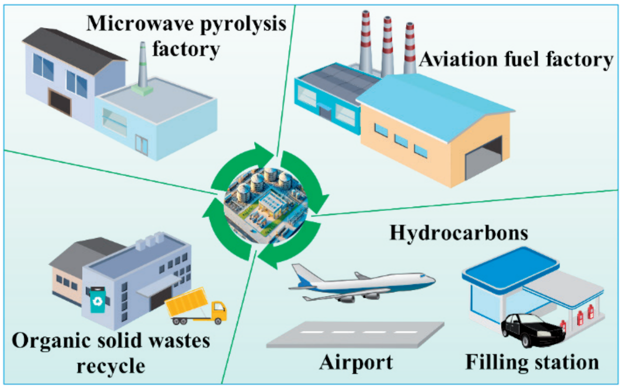


Figure 9 Aviation oil recovery blueprint.

5. Conclusions

In this study, the sustainability of high-quality aviation oil recovery from organic solid waste through using microwave-assisted heating technology is conducted. Some conclusions are obtained.

The microwave heating technology has more advantages than the electrical heating method, such as (a) non-contact heating, (b) homogeneous temperature distribution, (c) rapid heating rate, and (d) volumetric heating pattern. The microwave heating assisted by the absorbing material (SiC) can have a 2.5 times heating rate compared with the electrical heating.

The oil yield is in the range of 7 ~ 99 wt. % with different microwave heating powers, pyrolysis temperatures, heating times, material sizes, and absorbents. The oil yields of the biomasses are below 50 wt. %, much lower than plastics (99, 78, 40, 98, and 79 wt. %).

The oil components of organic solid wastes are hydrocarbons and oxygenated derivatives hydrocarbons, and the carbon numbers are mainly from C7 to C16. However, the carbon distributions and yields are different for various organic solid wastes and various experimental conditions.

The highest recovered energy efficiency is 97% with the highest total energy efficiency of 63% when the microwave power is 650 W and the pyrolysis temperature is 460 ^{o}C for the polystyrene by using SiC.

The aviation oil recovery blueprint can be drafted as: the organic solid wastes are recycled by the treatment plant to be classified and pretreated, and then the organic solid wastes are decomposed in the microwave pyrolysis factory to produce the raw oil. The raw oil is processed with some additives in the aviation fuel factory, and finally, the hydrocarbon fuel can be used in airplanes and filling stations.

Although microwave irradiation heating methods are more effective than conventional heating methods, its applications are still limited. One of the biggest challenges is that the energy conversion efficiency from electricity to microwave energy (50% ~ 65%) is considerably lower than the conventional electric heat conversion (90%) [47, 48]. Also, thermal damage emerges in the microwave heating process caused by abnormal temperature gradients induced by uneven material properties or non-uniform microwave irradiations [49]. Furthermore, most studies on microwave irradiation are conducted in laboratory settings and microwave leakage remains a serious concern due to its harmful effects on humans [50].

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