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An Ecological Toilet System Incorporated with a Hydrothermal Liquefaction Process

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Abstract: The harmless disposal and resource utilization of human feces is important to the sanitation process. Hydrothermal liquefaction (HTL) can convert toilet feces into bio-crude oil and reduce waste. In this study, an integrated eco-toilet system was developed by combining vacuum micro-flush toilets with a continuous hydrothermal liquefaction reactor. The system operated stably for over 10 h. This system can serve 300 households and save 2759 m^3 of water per year compared to traditional flush toilets. The energy recovery from the feces was 2.87 times the energy consumed for the HTL process. The HTL bio-crude oil yield was 28 wt%, and the higher heat value (HHV) of the bio-crude was 36.1 MJ/kg. The biochemical compounds of the bio-crude oil consisted of acid ester, hydrocarbons, phenols, and a nitrogenous heterocyclic compound. The carbon in the human feces was mainly transferred to the bio-crude oil, while nitrogen was mainly transferred to the aqueous phase product. The post-HTL aqueous stream could be treated and used as fertilizer. This system achieves energy self-sufficiency, along with water and energy savings. This integrated eco-toilet effectively converts feces into bio-crude to realize waste reduction and resource utilization of human feces.

Keywords: hydrothermal liquefaction; human waste; micro-flush toilet; integrated eco-toilet; waste reduction; energy recovery

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1. Introduction

In China, the amount of wet human feces produced ranges from 116–200 g/day per person [1]. Currently, 2 billion people worldwide do not have access to safe and hygienic toilets, and 680 million people are still defecating in the open [2]. Human feces contain a variety of pathogens, which may cause serious intestinal infections and parasitic diseases, such as malaria [3,4]. Untreated waste released directly into the open environment poses serious public health risks, such as the contamination of groundwater [5]. Improving sanitation can increase the likelihood of achieving some of the Millennium Development Goals and Sustainable Development Goals (improve sanitation for all and end defecation in the open) [6]. Ecological sanitation systems, closely linked with toilets, are an alternative approach to achieving sustainable sanitation [7,8]. The toilet revolution aims to achieve cost-effectiveness, resource recovery, and waste reuse through eco-sanitation practices [9].

The two most important points in an ecological sanitation system are the treatment of human feces and the type of toilet. Fecal waste can be managed using feedstock, composting, anaerobic digestion, as well as thermochemical and biocatalytic methods. Biocatalytic methods can produce high-value products [10]. For instance, Arindam et al. used mesoporous polymers containing Ru/triphenylphosphine in a microwave reactor with formic acid to convert biomass into highly productive reduced sugars, xylitol (yielding ~95%), and sorbitol (yielding ~65%) [11]. At present, treatment of human feces is primarily performed by composting and anaerobic digestion. Composting human feces kills part of the

pathogenic bacteria and balances the carbon–nitrogen ratio [4]. Anaerobic digestion is a common method for producing biogas from fecal matter [12]. However, both composting and anaerobic digestion necessitate a lengthy stabilization period for the feces [3,12]. Pyrolysis is faster than other processes; however, it requires high temperatures (>400 °C) and an energy-intensive drying process for wet waste [13]. Hydrothermal liquefaction is a thermochemical conversion technology that uses water as a solvent to transform biomass into small liquid organic molecules at specific temperature (200–350 °C) and pressure (5–20 MPa) via depolymerization, cleavage, and decarboxylation. The resulting unstable small molecules then re-polymerize to form liquid products, which can be further processed into bio-crude oil after separation [14–16]. During the hydrothermal process, the high-temperature decomposition of biomass components (such as macromolecules of lipids, proteins, and carbohydrates) occurs, leading to the formation of some small molecular monomers, such as fatty acids, amino acids, and monosaccharides. These monomers can further form bio-crude oil, solid residues, aqueous products, and gases through dehydration, decarboxylation, deamination, Maillard reaction, cyclization, or polymerization reactions [17,18]. Compared to oil extraction and pyrolysis, HTL has two unique features: (1) HTL is ideal for wet biomass due to the fact that it does not require the feedstock to be dried [19]; and (2) all components of biomass can be utilized for the production of bio-crude oil through HTL conversion [14,20]. One study discovered that bio-crude oil could be produced from human feces, with a maximum yield of 34.44% and a higher heating value (HHV) of 40.29 MJ/kg [21]. However, Yang et al. found that the elemental carbon content in bio-crude oil showed a trend of decreasing and then increasing with the increase in reaction temperature, with the highest calorific value of 36.59 MJ/kg at 350 °C [22]. Another study found that the yield of bio-crude could reach 53.16%, and the liquefaction conversion could reach up to 89.61% with the addition of an Ni-Tm/TiO2 catalyst [23]. However, these studies on hydrothermal technology for human feces treatment mainly focused on batch reactors to explore the reaction parameters of oil yield and bio-crude oil quality. Continuous hydrothermal treatment (HTL) has become a significant focus of research in recent years. Notably, the Pacific Northwest National Laboratories (PNNL) has designed a continuous reactor that can process various types of biomasses, including algae, macroalgal feedstock, and wastewater sludge [24,25]. The performance of the HTL reactor developed by Iowa State University was evaluated based on bio-crude yields obtained during steady-state operation [26]. Aalborg University has developed a continuous, pilot-scale HTL system capable of converting lignocellulosic wood chips into bio-crude oil at a rate of 20 kg/h [27]. Additionally, the university has independently developed a continuous HTL system to convert algal biomass into bio-crude oil, which has demonstrated successful, stable, and continuous operation in terms of product yield, nutrient recovery, energy recovery, and bio-crude oil properties [28]. This research reflected a growing interest in the sustainable production of bio-crude oil using continuous HTL systems, demonstrating the potential for cost-effective and scalable biofuel production. In the past, the most used toilet was the dry toilet, causing odor and the dispersal of bacteria [29]; with the development of the economy and technology, the flush toilet has become a common method, but the flush sanitation system requires a large amount of water [30]. To save water, a vacuum type micro-water flushing toilet needs to be researched and developed.

In this work, a vacuum micro-water flushing toilet, coupled with hydrothermal liquefaction technology, was integrated to form an ecological toilet system, which can not only reduce the risk of infectious diseases and improve the environment, but which can also produce energy. The research had three goals: (1) development of a mobile integrated ecological toilet system, (2) verification of the long-term stable operation of the system, and (3) analysis of the carbon and nitrogen balance of the system, including water utilization.

2. Materials and Methods

2.1. Feedstock Characterization

Human feces were collected from micro-flush toilets in a Beijing suburb. Human feces were collected daily and stored in storage tanks. The accumulated feces were converted into products such as bio-crude oil via the continuous hydrothermal treatment unit at the back of the toilet. The feedstock's proximate and ultimate analyses were conducted, as previously outlined [31]. The characteristics of the human feces in this study are listed in Table 1, and are compared with the literature data [3]. Each test was performed in triplicate.

Table 1. Proximate analysis, biochemical composition, and organic elemental analysis of human feces.

Parameters	This Research	Literature [3]
Proximate analysis (%, dw)		
Total solid	15.89 ± 0.05	19.6 ± 3.8
Ash (dw)	12.50 ± 0.3	17.0 ± 1.3
Biochemical analysis (%, dw)		
Cellulose	21.62 ± 0.45	/
Hemicellulose	3.68 ± 0.12	/
Lignin	5.26 ± 0.26	/
Protein	35.48 ± 0.62	/
Lipid	13.15 ± 0.21	/
Organic element analysis (%, dw)		
C	48.34 ± 0.24	42.4 ± 1.3
H	6.59 ± 0.02	6.9 ± 0.9
N	5.17 ± 0.05	5.9 ± 1.0
O *	39.89 ± 0.15	43.1 ± 3.1
HHV (MJ/kg)	22.18 ± 0.08	18.1 ± 2.2

* calculated by the difference; dw: based on dry weight.

The Dulong formula was used to determine the HHV of human feces and bio-crude oil [32]:

$$\text{HHV (MJ/kg)} = 0.3383\ \text{C} + 1.422\ (\text{H} - \text{O}/16)$$

where C, H, and O were the weight percentages of carbon, hydrogen, and oxygen in the feedstock and bio-crude oil, respectively.

2.2. System Design and Operation

The integrated eco-toilet system consisted of a front-end toilet module and a back-end continuous hydrothermal liquefaction module (Figure 1): the front toilet module adopted a vacuum type micro-water flushing toilet, which included an air flusher, a vacuum collection tank, a lifting pump, and a toilet control device. This eco-toilet module is specifically designed for schools. Human feces were directly pumped into the vacuum collection tank at a negative pressure of 0.55~0.60 MPa by a lifting pump. High-concentration feces and urine were processed in the continuous hydrothermal treatment module at the back of the toilet. The continuous hydrothermal treatment module was described in the previous study performed by this research group [28], with modifications to adapt to human feces and the scale of the toilet.

The modification of the HTL system included the following aspects. The peristaltic pump in the previous feeding system was replaced by a screw pump, which can transport materials with high solid content, because the feces in the micro-water flushing toilet have high solid content and often include toilet paper. In addition, the unidirectional valve was installed between the feeding system and the reactor to avoid the back flow of high-pressure feedstock in the reactor. The monitoring system data acquisition system was not only upgraded to control the parameters of the HTL reactor, but also to record the number of toilet users, the amount of fecal materials, the pressure value of the lifting pump, and the solar panels outside the toilet system.

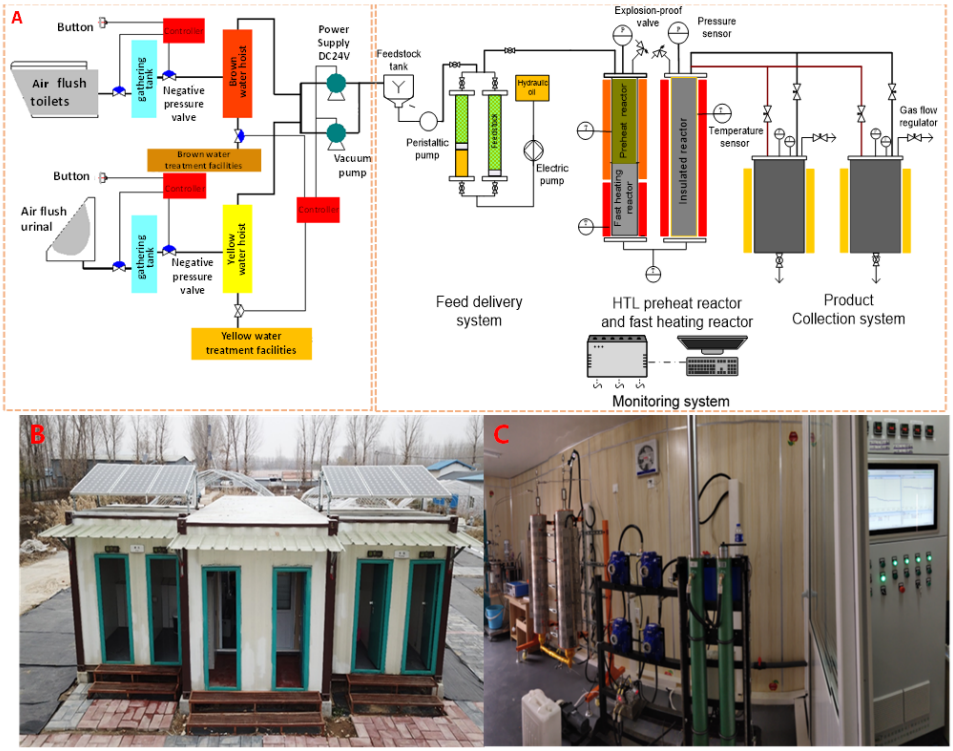

Figure 1. Schematic diagram of the integrated eco-toilet system: (**A**) design drawing; (**B**) front view of the eco-toilet module; (**C**) the HTL module at the back of the toilet.

The integrated eco-toilet system had several unique characteristics. The first is system integration, meaning that the front-end latrine must be a vacuum micro-flush latrine that can obtain a fecal concentration that meeting the concentration needs of the HTL treatment. Additionally, unlike a conventional flush toilets or pit toilets, the vacuum micro-flush latrine allows a relatively good mixing of the faces, thus provided uniformity and fluidity into the HTL reactor. Moreover, feces can be treated directly with the HTL reactor, eliminating the need for pipeline, collection, and transportation. It also reduces the spread of odors and the pathogen transmission. The second unique characteristic is the energy self-supply, meaning that solar panels were installed to convert solar energy into electricity for the whole system, allowing for the application of the system in remote rural areas. The third characteristic is water conservation, indicated by the fact that the vacuum micro flushing toilets used less water for flushing, the details of which are described later in Section 3.1.

2.3. HTL Temperature and Pressure Responses

The experiments in this study were carried out at 300 °C with a solid content of 15 wt%. In order to provide sufficient pressure to keep the water in the liquid phase, the back pressure regulator was set at 9.0 MPa, higher than the saturated vapor pressure of water at 300 °C (8.6 MPa). The total operation time of each test lasted at least 14 h, including a 2–3 h preheating time, a 10 h steady state time, and a 2–3 h washing and cooling time. The preheater and HTL reactor had the same volume of 1.08 L for each tubular reactor (including the volume of the connecting tubes). The retention time in the preheater and the HTL reactor was 30 min each. At the initial stage of the test, 95% of the total volume of the preheater, the HTL reactor, and the tubes were filled with distilled water. Once the inside temperature of the HTL reactor reached 300 °C, an alternating hydraulic feed pump was used to transport human feces into the reactor at a rate of 36 mL/min. The temperature in the reactor fluctuated up to 20–30 °C around the set temperature.

The product yield over time was irregular due to the variation in the reaction rate associated with the temperature fluctuation [33]. Under a steady state, the rate of changes of

system temperature, pressure, bio-crude oil yields, and bio-crude properties were less than 10%. The feed and discharge of the system were maintained by back pressure regulators and the hydraulic feed system. The detected steady time of human feces was 10 h. The mixed phases of the products were cooled and collected in a tank. The gases were collected through the gas outlet via an airbag, while the liquid phase was collected through an exit.

The bio-crude oil was gravitationally separated, with a settling time between 0.5 and 1.5 h [34]. The products in the collection tank were collected for 1 h, every two hours, and further analyzed during the steady state period, (Figure 2). The final step was the washing and cooling, during which the heater was turned off and the reactor was purged with distilled water for 2–3 h until the product liquid at the collection tank outlet appeared clear, with a temperature below 70 °C. Three sets of tests were carried out in sequence. Additionally, after each test, the back pressure regulators were cleaned with acetone. The products collected during the first, second, and third hour of the steady-state cycle are labeled 1, 2, and 3, respectively. The yield and properties of bio-crude oil obtained from human feces were better in the previous literatures [21].

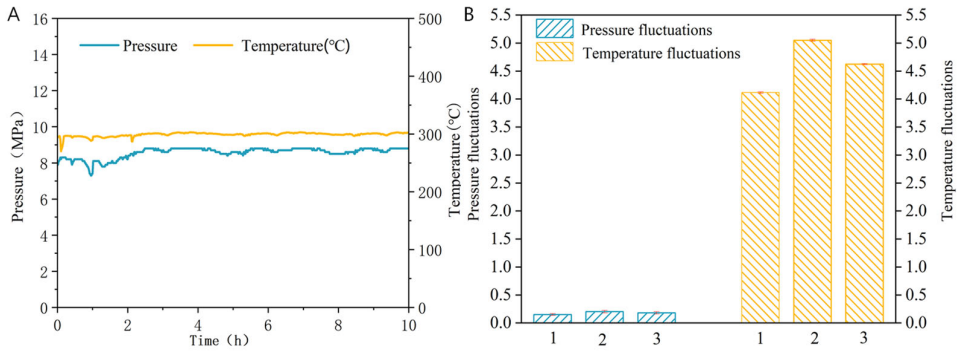

Figure 2. Engineering conditions: (**A**) temperature and pressure operating conditions diagram; (**B**) temperature and pressure fluctuation diagram.

The entire continuous hydrothermal treatment reaction was carried out for 16 h, and the system operated stably for 10 h, minus the time for heating, cooling, and cleaning (Figure 2A). From the figure, we can see that the temperature and pressure decreased at the beginning of the steady-state phase because the material flow was adjusted to a higher rate. This increased flow rate of the feedstock caused the temperature to decrease, and thus decreased the pressure in the HTL reactor. The pressure and temperature fluctuations were similar (Figure 2B), with relative standard deviations of 3% and 0.9%, respectively, which met the requirements for experimental error. The results of the engineering conditions showed that the performance of the integrated HTL reactor was in a stable state.

2.4. Products Separation and Analysis

The calculations of products yield were calculated according to Equation (1):

$$\text{Bio-crude oil yield (daf, \%)} = \frac{M_{\text{bio-crude oil}}}{M_{\text{feedstock}}} \times 100\% \quad (1)$$

where Mbio-crude oil and Mfeedstock are the mass of the bio-crude oil and the feedstocks, based on the dry ash free mass, respectively.

The human feces, bio-crude oil, and solid residue were subjected to elemental analysis (C, H, N content) using an elemental analyzer (Vario MICRO Cube, Elementar Analysensysteme GmbH, Germany). The components in the bio-crude oil were detected by GC–MS (Shimadzu QP2010, Kyoto, Japan), according to the methods used in a previous study [35].

The total nitrogen (TN) content was measured using an ultraviolet spectrophotometer (UV-1800, Mapada Co., Shanghai, China) [36]. As previously mentioned, the values of total carbon (TC), total organic carbon (TOC), total phosphorous (TP), and pH were also

calculated [37]. The carbon and nitrogen distribution of the gaseous phase was calculated using the difference method. Each test is conducted in triplicate.

Energy recovery was calculated in Equation (2):

$$\text{Energy Recovery Rate} = \frac{\text{Energy}_{\text{output}}}{\text{Energy}_{\text{input}}} \times 100\% \quad (2)$$

In addition, for the verification of the stability of the continuous hydrothermal treatment module, standard deviation was used to verify the stability of the system during continuous operation. A previous study showed that a standard deviation of less than 10% indicates that the continuous reactor can operate stably [38]. Hence, the hydrothermal liquefaction reaction of human feces in the system is considered to be in a steady-state when the temperature and pressure fluctuation is less than 10%. When the systems reached its steady-state, the HTL products were collected and analyzed, and the stability of the system was further verified by analyzing the characteristics of the products collected for 1 h, every two hours. The products collected during the first, second, and third hours of the steady-state cycle are labeled 1, 2, and 3, respectively.

3. Results and Discussion

3.1. Performance of the Front-End Toilet

The performance of the front-end toilet was analyzed in terms of flushing effect, power consumption, and flushing volume. In order to measure the effect of flushing, set according to the solid content of the human feces, tests were conducted using simulated feces of different concentrations. From Table S1, we can see that: low-concentration simulated feces were sprayed on the side of the toilet due to excessive moisture, so residue remained during the rinsing process; medium-concentration simulated fecal flushing were normal and consistent with the expected results; and high-concentration simulated feces resulted in unclean flushing; due to high solid content, there were substances stuck to the wall of the toilet. The medium concentration of simulated feces (15%) was similar to that of real human feces, indicating that the parameters (e.g., flush volume, negative pressure value, and response time) set can meet the operational requirements. However, the corresponding parameters have been adjusted in an effort to meet all the situations that occur in the real world.

The power consumption of the toilet was calculated as 8×10^{-4} kWh/time. Assuming that each person goes to the toilet four times per day, the power consumption of each person was 3.2×10^{-3} kWh/d per person. After installation, the eco-toilet system was continuously monitored for two months (Figure 3). The results showed that the power consumption was 0.001 kWh when it was used for 120–130 people, which was the same as that when the toilet was used for 300 people, so the energy consumption of the eco-toilet was 2.4 times lower than that of the traditional toilet.

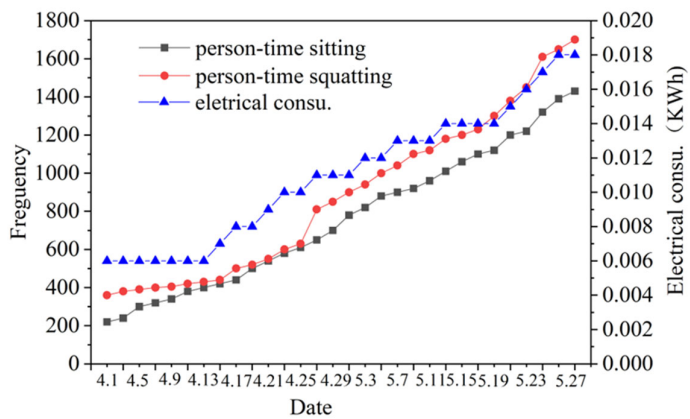

Figure 3. Power consumption of the eco-toilets.

The water consumption of the vacuum eco-toilet system was analyzed in this study. This air-flush system not only saved water, but also saved the cost of sewage drainage compared to traditional water flushing systems [39]. The traditional flushing system uses 5 L per flush, while the air-flush system uses 0.8 L water per flush. The eco-toilet was demonstrated in a village in the suburbs of Beijing, which includes 300 households for a total of 900 people. Each person uses the toilet twice a day on average [40,41]. The current local price of water is 0.17 USD/m^3, according to the operation of the whole system for one year; there was a 2759 m3 water use reduction, and the annual water savings was USD 479.86.

3.2. HTL Product Analysis and System Stability Verification

Figure 4 shows the HTL products: bio-crude oil and post-HTL aqueous material. The bio-crude oil and post-HTL aqueous material collected during the first, second, and third hour of the steady-state cycle are labeled 1, 2, and 3, respectively. The bio-crude oil yield is 28%, and the relative standard deviation for it and the aqueous phase collected in the same time interval is less than 4.8% and 4.7%, respectively. These results indicate that the whole system has been in a stable operation state. The bio-crude oil yield was slightly lower than that in the batch stirred tank reactor, as previously reported [21]. This was due to the difference in mass and heat transfer dynamics between the two reactors. In addition, the formation of a Pickering emulsion and the accumulation of bio-crude oil at the lower temperature region of the HTL reactor (e.g., corner and region of the back-pressure valve) reduce the bio-crude oil recovery, while the in-batch reactor Pickering emulsion was not a concern because of its high-speed stirring [42].

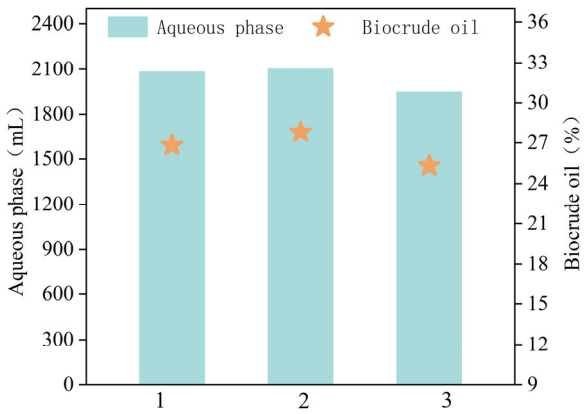

Figure 4. Contents of bio-crude oil and collected aqueous phase in each hour after the hydrothermal liquefaction reaction.

The ultimate analysis of HTL products collected at the same interval is shown in Table 2. The relative standard deviations of the C, H, and N contents of bio-crude oil were all less than 6%, indicating that the bio-crude oil collected in the same time interval had the same element content. The bio-crude oil produced in this study had similar elemental properties to that of bio-crude oil produced in a 100 mL batch reactor test at 300 °C [21]. The HHV of bio-crude oil is 35.87 MJ/kg and the relative standard deviation is less than 3%. Overall, the HHV of bio-crude oil collected at the same interval during was nearly the same, illustrating that the same potential combustion energy existed in all the bio-crude oil samples.

Table 2. Characterization of HTL products from human feces.

Bio-Crude Oil					Solid Residue			Aqueous Phase			
C (%)	H (%)	N (%)	O [a] (%)	HHV (MJ/kg)	C (%)	H (%)	N (%)	TC (g/L)	TOC (g/L)	TN (g/L)	pH
74.73	8.65	5.34	11.28	35.6	31.63	3.87	2.42	25.5 ± 0.21	24.34	6.89	7.69
75.36	8.69	4.72	11.23	35.9	31.93	4.10	2.83	23.65 ± 0.08	23.45	7.54	7.98
75.73	9.57	4.38	10.32	36.1	30.50	3.93	2.47	23.12 ± 0.04	22.65	7.67	8.21

[a] O (%) = 100-C (%)-H (%)-N (%) (Results showed there were few metal elements in the bio-crude oil).

The elements of solid residues and aqueous properties were also analyzed (Table 2). The relative standard deviations of these data are less than 10%, showing that the eco-toilet system operates stably during the data collection period. Furthermore, The C and N tests support the subsequent balance, and explore the flow of C and N in human feces for more efficient use.

Table S2 lists the compounds in the bio-crude oil derived from human feces. Only compounds detected by GC–MS, with a similarity index above 80%, were calculated. Compounds with more than one functional group were grouped into a class. Approximately 95% of the identified components in each bio-crude oil sample were classified using the above standard. These compounds were categorized into eight groups: hydrocarbons, acids (long chain saturated and unsaturated acid), esters, alcohols, ketones, amines, nitrogen-containing compounds (heterocyclic compounds and their derivatives), and others. The bio-crude oil collected during first, second, and third hour of the steady-state cycle are labeled 1, 2, and 3, respectively (Figure 5). The total peak area of various compounds in bio-crude oil derived from each one-hour collection was generally similar, Thus, the system can run steadily for a long time. The higher N-heterocyclic compound detected in the bio-crude oil is mainly due to the intensive dehydration/decarboxylation of amino acid hydrolyzed from protein [43].The GC–MS results for the bio-crude oil from the three runs were not exactly similar due to the limited detection accuracy. In other words, some high molecular weight compounds could not be detected via GC–MS [44,45].

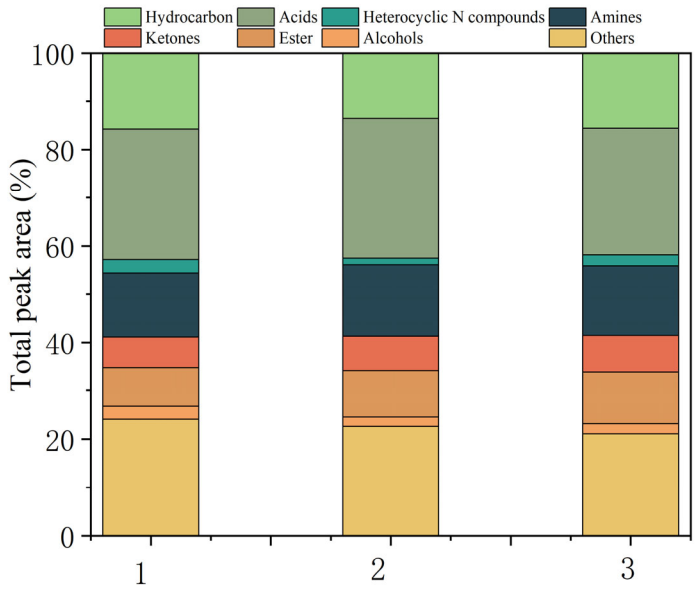

Figure 5. Organic compounds of the bio-crude oil detected through GC–MS.

3.3. TC and TN Balance

The TC and TN flows obtained from the integrated eco-toilet system are shown in Figure 6. For the coupled system, 53.8% of the carbon and 18.8% of the nitrogen in the human feces are distributed into the bio-crude oil. The content of nitrogen in the bio-crude oil is very high, indicating that further bio-crude oil upgrading is needed. However, 23.1%

of the carbon and 75% of the nitrogen in human feces were distributed into the aqueous phase, indicating that the aqueous phase is rich in nutrients and can be used for biological treatment, such as microalgae cultivation [46,47]. Since HTL only dramatically influenced the bio-crude oil and the aqueous phase, these two reaction products were investigated in detail. This analysis is essential as a design tool for any future process integration, as it could provide a good estimation for resource recovery based on the final product.

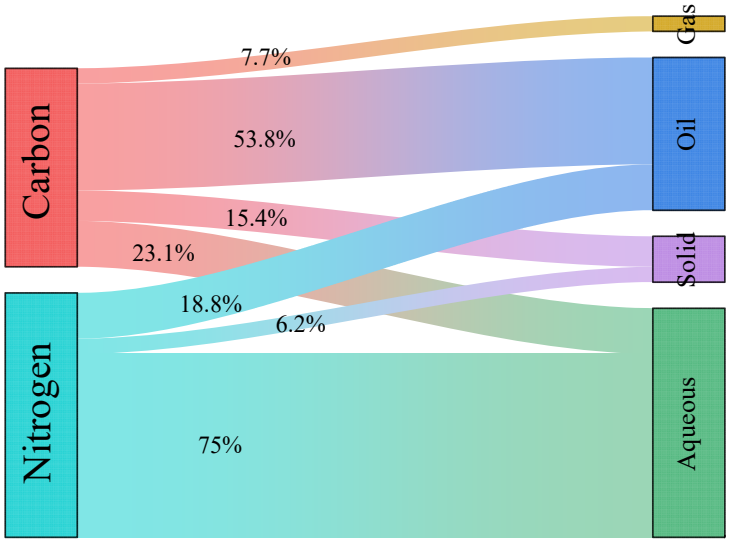

Figure 6. Sankey diagrams showing total carbon (TC) and total nitrogen (TN) flows for the integrated toilet and HTL system. The widths of the bands are proportional to the percentage of carbon and nitrogen.

3.4. Energy Analysis of System

The results of the energy analysis of the eco-toilet are shown Figure 7. Table S3 lists the energy input and energy output of the system. As shown in Figure 7, the energy input included the chemical energy of the human feces and the energy consumption of the HTL conversion process, accounting for 95.2% of the total. The energy output mainly included bio-crude oil, the solar energy installed in the system, and the energy of the gas and aqueous phases, as well as the energy lost as wasted heat. The energy loss associated with the gas and aqueous phases accounted for about 20% of the overall energy input in the conversion process from human feces. In the gas product, the content of CO_2 and CH_4 was about 90% and 10%, respectively. The decarboxylation of fatty acids leads to the formation of alkanes and carbon dioxide, resulting in carbon dioxide being the main gas product in the HTL process [48–50]. The CO_2 produced in the HTL process could be utilized as a carbon source for algae cultivation [51]. In addition, irreversible reaction (hydrolysis reactions and solar-thermal conversion) cause energy destruction, which is only a small section of the energy input. The energy of the heat exchanger accounts for 5.6% of the total energy, of which the recovery efficiency is 25%, which was described in the previous literature [52]. Overall, when the human feces were used as the energy source and the system was equipped with solar energy and heat exchangers, the energy recovery rate of the system reached a maximum of 287%, indicating the eco-toilet system could be a net energy producer and improve the environment.

Figure 7. Exergy distribution of the eco-toilet system.

3.5. Performance Comparison of the System

The eco-toilet system was compared with previous studies of similar integrated system [53–59] (Table 3). The table shows that no research has been conducted regarding energy balance. Most of the studies were focused on the conversion of toilet feces into organic fertilizer for the existing rural application. Due to the process characteristics of organic fertilizer, most of the toilets were dry toilets or flush-free toilets, from which it can be seen that the choice of toilet type was closely related to the choice of the subsequent feces resource utilization. The overall performance of the eco-toilet system in this study can not only save water and energy, but can also completely disinfect the pathogens; thus reduced the spread of diseases.

Table 3. Performance comparison of eco-toilet integration systems.

Toilet Type	Conversion Technology	Processing	Product	Energy	Flushing Method	Sanitation (Sterilization Rate)	Reference
Flush-free toilet	Aerobic composting	On-site	Organic fertilizers	/	Water-free flushing	Most	[53]
Pit Toilet	Composting	All-in-one	Organic fertilizers	/	No water	Part	[54]
Vacuum Toilet	Aerobic composting	On-site	Organic fertilizers	/	No water	Part	[55]
Flush Toilet	Septic tank	On-site	Organic fertilizers	/	4–5 L/time water	Part	[56]
Flush-free toilet	Composting	Off-site	Organic fertilizers	/	No water	No treatment	[57]
Vacuum Toilet	Composting	Off-site	Organic fertilizers	/	No water	No treatment	[57]
Foam Toilet	Composting	Off-site	Organic fertilizers	/	Foam and less water	No treatment	[57]
Flush-free toilet	Composting	Off-site	Organic fertilizers	/	Flushing with treated urine	Most	[57]
Flush-free toilet	Bacterial decomposition	On-site	CO2, water	/	Flushing with treated urine	Part	[57]
Flush Toilet	Anaerobic digestion	Off-site	Biogas	/	4–5 L/time water	Part	[57]
Pit Toilet	Composting	Off-site	Organic fertilizers	/	Organic fertilizers	Part	[57]
Vacuum Micro-flush Toilet	Hydrothermal liquefaction	All-in-one	Bio-Crude oil, aqueous phase, gas	287%	0.8 L/time water	Complete	This study

4. Conclusions

This study proved the feasibility of an ecological toilet system (vacuum micro-flush toilets coupled with hydrothermal liquefaction) to convert human feces into bio-crude oil, retaining nutrients in the post-HTL aqueous phase. The analysis of working conditions and product properties showed that the integrated system could operate stably for ten hours, thus demonstrating that the eco-toilet system could operate stably for a long period of time. The carbon content of the bio-crude oil was 54% that of human feces. The post-HTL aqueous phase contained 75% of the nitrogen and 23.1% of the carbon found in the feces.

The energy recovery of the system reached a maximum of 287%, when the feedstock was considered as a waste stream with zero-energy value. The use of eco-toilet systems in a village of 900 people could save 2759 m^3 of water per year and reduce costs by USD 479.86 annually. Adoption of this technology could lead to water savings on a national level, as well as cost savings for rural communities. The results from this study suggest that the eco-toilet system could be a promising approach to mitigate the rural sanitation problem, recover energy and nutrients from a waste stream, and improve the environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15086373/s1, Table S1: The data of suction performance; Table S2: Organic compounds in bio-crude oil from the continuous HTL of human feces; Table S3: Energy input and energy output of the system.

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