Simultaneous production of biocrude oil and recovery of nutrients and metals from human feces via hydrothermal liquefaction

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Abstract

Hydrothermal liquefaction (HTL) is a thermochemical process specifically suitable for treating wet wastes. This study investigated its potential for the production of biocrude oil and the recovery of nutrients and metals from human feces via HTL. Specifically, the effects of temperature (260°C, 300°C, 340°C), retention time (10min, 30min, 50 min) and total solid (TS) content (5%, 15%, 25%) were studied. The maximum liquefied fraction was 87.89% and the highest biocrude yield reached 34.44% with a higher heating value of 40.29 MJ/kg. Experimental results showed that 54% of carbon in the human feces was migrated to the biocrude oil while 72% of nitrogen was released to the aqueous phase. In addition, most of heavy and alkaline-earth metal elements in the human feces, including Ca (89%), Mg (81%), Al (88%), Fe (72%) and Zn (94%) were distributed in the solid residue, whereas K (89%) and Na (73%) were mainly dissolved into the aqueous phase. This study demonstrated that the efficient degradation of human waste via HTL without any pretreatment and its potential for the valorization in biocrude oil as well as separated nutrients and metals.

Keywords

Human feces; Hydrothermal liquefaction; Biocrude oil; Metal distribution

1. Introduction

Wet human fecesis generated in a range of 116-200 g/person/d in China[1]. Currently, 1 billion people still use open defecation while another 2.5 billion people do not have improved sanitation facilities[2]. Human fecescontainsan arrayof pathogens,thatcan cause waterborne diseasesif being released into the environment without proper treatment[3, 4].

On the other hand, human fecescould beregarded as a renewable feedstockfor different purposes. Composting of human feceshas been an effective method for killingpathogenic bacteria and balancing the ratio between carbon and nitrogen[4].In addition, anaerobic digestion is frequently used to treat feces for biogas production[5]. However,both composting and anaerobic digestionrequire a long time to stabilize the feces[3, 5]. In comparison, pyrolysis is a much faster process, but it is under high temperatures ($>400^{\circ}\text{C}$) and requires an energy-intensive drying process of the wet waste[6].Hydrothermal liquefaction (HTL) allows for thedirect conversion of wet waste intobiocrude oil at temperatures of $200\text{-}350^{\circ}\text{C}$ and pressures of $5\text{-}20\text{ MPa}$, which has recently drawn increasing attention[7].It is important to point out that HTL also kills all the pathogens in the fecal feedstock due to the high temperature treatment. Characteristically,HTL is different from oil extraction and pyrolysis in two distinct aspects: (1) there is no need to dry the feedstock, making HTL especially suitable for wet biomass with atotal solid (TS) content of $10\text{-}25\%$ [8]; (2) not only lipids but also proteins and carbohydratescan participate in HTL conversion to produce biocrude oil[7, 9].Previous study showed that swine manure was successfully converted to biocrude oil, andthe highest oil yield was 24.2% with a higher heating value (HHV) of 36.05 MJ/kg [10]. HTL could also reduce negative environmental impacts associated with swine manure, because it completely deactivatedthe antibiotic resistant genes and destroyed the natural pathways of antibiotic resistant genes to the environment[11].

HTL of human feces could weaken its pollution to the environment as well as provide a value-added outlet for human feces.This study focusedon the HTL of human

feces for the production of biocrude oil as well as recovery of nutrients and metals. The objectives of this study were twofold: (1) to investigate the degradation of human feces and its potential for the production of biocrude oil via HTL; (2) to study the elemental distribution (including organic elements and metal elements) in HTL products: biocrude oil, aqueous phase, gases and solid residue.

2. Materials and Methods

2.1 Feedstock characterization

Fresh human feces was obtained from a latrine in a suburb of Beijing, China. It was homogenized through stirring for 20 min and then stored in a refrigerator at -20°C prior to use. The methods for proximate and biochemical analysis of the feedstock were performed as previously described [12]. The characteristics of the human feces in this study (Table 1) were similar to the literature [3].

Table 1

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

Parameters	This study	Literature [3]
<i>Proximate analysis (%)</i>		
TS	14.89±0.03	19.6 ± 3.8
Ash (based on dry biomass)	11.49±0.24	17.0 ± 1.3
<i>Biochemical analysis (%)</i>		
Protein	34.68 ±0.63	-
Lipid	14.01 ±0.41	-
Cellulose	22.42 ±0.53	-
Hemicellulose	2.48 ±0.06	-
Lignin	5.66± 0.26	-
Non-fibrous carbohydrate*	9.26 ±0.39	-
<i>Organic element analysis (%)</i>		
C	47.77±0.19	42.4 ± 1.3
H	7.19±0.03	6.9 ± 0.9
N	6.13±0.12	5.9 ± 1.0
O*	33.83±0.31	43.1 ± 3.1
HHV(MJ/kg)	20.38±0.09	18.1 ± 2.2

* O (%) = 100 - C(%) - H(%) - N(%) - Al(%) - Ca(%) - Mg(%) - Zn(%) - Fe(%) - K(%) - Na(%)

The HHVs of human feces and biocrude oil were calculated according to the Dulong formula [13]:

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

Where C, H and O were the weight percentages of carbon, hydrogen and oxygen in the feedstock and biocrude oil, respectively.

Total nitrogen (TN) of the aqueous phase was calculated by Eq. 1:

$$\text{TN (g/L)} = \frac{N_{\text{feedstock}} - N_{\text{biocrude oil}} - N_{\text{solid residue}}}{V_{\text{aqueous phase}}} \text{ (Eq. 1)}$$

Where $N_{\text{feedstock}}$, $N_{\text{biocrude oil}}$ and $N_{\text{solid residue}}$ were the mass of nitrogen in the human feces, biocrude oil and solid residue, respectively. $V_{\text{aqueous phase}}$ was the volume of the aqueous phase. It was assumed that there was a negligible amount of nitrogen formed in the gaseous products [14].

2.2 Experimental procedure

An orthogonal experimental design was applied to investigate the effects of the HTL operational parameters, including temperature (260°C, 300°C, 340°C), retention time (10 min, 30 min and 50 min) and TS (5%, 15% and 25%) on the production of biocrude oil from human feces. The experiments were performed in a 100 mL stainless steel batch reactor (Model 4598, Parr Instrument Company, USA) with a heating furnace and a stirrer. The maximum operating temperature and pressure of the reactor are 500°C and 35 MPa, respectively. The heating rate was 8-10°C/min. The separation of the products was carried out as previously described [15].

2.3 Analytical methods

Organic elemental components (i.e., Carbon, Hydrogen and Nitrogen) of the feedstock and biocrude oil were determined using an elemental analyzer (CE-440 Elemental Analyzer, Exeter Analytical, Inc. USA). Fourier transform infrared tests were carried out using FT-IR spectroscopy (Nicolet 6700, Thermo Fisher Scientific,

USA). ^1H nuclear magnetic resonance (NMR) was performed using a JNM-ECA600 (JEOL Ltd. Japan) spectrometer to determine the functional groups in the biocrude oil. Acetone was used as the solvent. The ^1H spectra of biocrude oil were acquired at 600 MHz with a 90 degree pulse angle.

Total carbon (TC), total organic carbon (TOC), total phosphorous (TP) and pH values were determined as previously described [16]. Chemical oxygen demand (COD) of the aqueous phase was measured using a water quality analyzer (DR 2800, HACH, USA).

Metal elements (i.e., Al, Ca, Mg, Zn, Fe, K and Na) were measured through an inductively coupled plasma optical emission spectrometer (ICP-OES, iCAP6300, ThermoFisher, USA). Gaseous products were analyzed using a gas chromatograph (SP-6890, Rainbow Chemical Instrument Co., LTD, China) with a capillary column (TDX-01, inner diameter: 0.25 mm) and nitrogen as the carrier gas at 50 ml/min. The measured gases were CO_2 , H_2 and CH_4 .

The liquefied fraction was determined based on dry feedstock using Eq. 2 and the yields of the biocrude oil, solid residue, gases and aqueous phase were calculated using the methods as in a previous study [17].

$$\text{Liquefied fraction (\%)} = 100 - \frac{\text{Mass of solid residue}}{\text{Mass of dry feedstock}} \times 100 \quad (\text{Eq. 2})$$

3. Results and discussion

3.1 Production of biocrude oil from human feces

Liquefied fraction was an important parameter for evaluating the performance of HTL, the maximum liquefied fraction was 87.89% (**Fig. 1**), obtained at 340°C, a 30 min retention time and a 5% TS. It meant that nearly all the organic components in the human feces were liquefied and degraded because the rest is the ash content of 11.49% in human feces, illustrating the high performance of HTL on the treatment of human feces. In addition, the biocrude yields varied from 25.09% to 34.44%, where the highest biocrude yield (34.44%) was obtained at 340°C, at a 10 min retention time and

a 25% TS. In comparison, the highest HHV (40.65MJ/kg) of the biocrude oil was achieved at 340°C, at a 30 min retention time and a 5% TS, suggesting that the condition for the highest oil HHV was not consistent with that for the highest biocrude yield. The products under these two conditions were chosen for further elemental analysis.

Fig. 1. Mass balance of HTL products of human feces. Each experiment had at least 3 duplicates and the mean value was presented.

The biochemical composition of the feedstock has a great effect on the biocrude yield [12, 18]. The conversion rate of carbohydrates to biocrude oil was 0.001/min, in comparison to 0.28/min for proteins and 0.33/min for lipids at 350°C during the HTL of algae [19]. The high contents of proteins and lipids (total 48.69%) in the human feces in this study led to a relatively high biocrude yield. In addition, the analysis of the significance (**Fig.S1**) indicated that the TS content and reaction temperature were important factors for the production of biocrude oil while the retention time was an

167 insignificant parameter. The results were similar to a previous study which used algal
168 biomass from Dianchi Lake as the feedstock[20].

169 **Table 2**

170 Characterization of HTL products from human feces.

The conditions of HTL	Biocrude oil					Solid residue				Aqueous phase						Gases		
	C	H	N	O*	HHV	C	H	N	Ash [#]	TC	TOC	TN	TP	COD	pH	CO ₂	CH ₄	H ₂
	(%)	(%)	(%)	(%)	(MJ/kg)	(%)	(%)	(%)	(%)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)		(%)	(%)	(%)
260°C/10min/5%	75.31	10.49	2.98	11.23	38.39	34.96	4.22	2.12	64.19±0.23	9.76±0.41	9.29	2.69	0.09	36.52	7.09±0.06	93.34	6.63	0.04
260°C/30min/15%	74.42	10.18	4.25	11.16	37.67	38.33	4.09	2.65	50.17±0.14	35.20±1.14	33.63	7.76	0.19	96.49	7.125±0.04	92.90	7.03	0.07
260°C/50min/25%	74.04	9.85	4.43	11.68	36.98	37.95	4.57	4.23	53.84±0.27	49.47±0.60	47.38	13.48	0.15	132.97	8.05±0.34	90.47	9.51	0.02
300°C/10min/15%	75.64	10.06	4.66	9.64	38.18	31.63	3.87	2.42	46.40±0.25	28.83±1.21	26.58	7.67	0.11	80.45	7.645±0.12	93.49	6.48	0.03
300°C/30min/25%	77.25	10.63	4.50	7.63	39.89	32.93	4.10	2.83	51.29±0.14	51.61±0.08	49.25	14.84	0.15	92.62	8.645±0.49	92.59	7.37	0.03
300°C/50min/5%	77.03	10.21	3.39	9.38	38.91	27.50	3.23	1.47	41.47±1.04	11.04±0.04	9.80	2.74	0.07	32.43	7.49±0.06	94.00	5.93	0.07
340°C/10min/25%	75.97	11.34	4.07	8.62	40.29	32.75	3.88	2.18	44.52±0.30	41.69±0.20	28.70	14.84	0.10	82.55	7.545±0.07	88.15	11.78	0.06
340°C/30min/5%	77.54	11.1	3.66	7.70	40.65	24.68	2.76	0.81	37.74±0.26	10.83±0.57	9.59	2.78	0.09	27.64	7.69±0.05	91.66	8.23	0.10
340°C/50min/15%	76.09	10.07	4.56	9.28	38.41	28.75	3.08	1.69	38.29±1.13	27.38±0.32	24.65	8.05	0.12	76.05	8.455±0.09	84.17	15.77	0.06

171 *O (%)=100-C (%) -H (%) -N (%) (Results showed there were few metal elements in the biocrude oil). [#]Ash of the solid residue was measured based on dry mass

Besides biocrude oil, the yields of the solid residue, aqueous phase and gaseous products were within the ranges of 12.11-21.33%, 36.70-49.03% and 8.31-15.46%, respectively. The ash content of the human feces was 11.49% and part of the inorganic elements in the ash were distributed to the solid residue after HTL[20], while most of the nutrients and part of the organics in the feedstock were released to the aqueous phase[21, 22]. The contents of CO₂ and CH₄ occupied 84.17-94.01% and 5.93-15.77% in the gas phase, respectively. The decarboxylation of the fatty acids resulted in the formation of alkanes and CO₂, leading to the fact that CO₂ was the predominant gaseous product at relatively low temperatures (<350°C) in the HTL process[23-25]. This large amount of CO₂ could be utilized as a carbon source for algae cultivation[14].

3.2 Element distribution in the HTL products

3.2.1 Analysis of organic elements in the products

Table 2 showed the organic elemental analysis of the HTL products. The carbon and hydrogen contents of the human feces were 47.77% and 7.19%, respectively. After HTL, the carbon content of the biocrude oil was over 74%, and the hydrogen content of the biocrude oil was 9.85-11.34%, whereas the oxygen content was reduced to 7.63-11.68%, much lower than that of human feces (38.91%). The highest HHV of the biocrude oil was 40.65 MJ/kg due to the high contents of carbon, hydrogen and low content of oxygen in the biocrude oil. The nitrogen content of the biocrude oil was 2.98-4.66%, higher than that of petroleum (<1%), indicating denitrogenation is needed to match the characteristics of petroleum.

Deoxygenation and denitrogenation are two important reactions during HTL in order to understand the formation of biocrude oil[20]. **Fig. 2** showed the relationships among molar ratios of H/C, N/C and O/C in the human feces and the HTL products via a three-dimensional Van Krevelen diagram. The molar ratios of H/C (1.79 and 1.72) in the biocrude oil were not significantly changed compared to those in the human feces (1.81). The slight decrease in molar ratio of H/C might result from the production of

gases containing hydrogen element, like H_2 and CH_4 via dehydration[20]. In comparison, the molar ratios of O/C and N/C in the biocrude oil were much lower than those in the human feces, indicating that the processes of deoxygenation and denitrogenation occurred during HTL[14, 20].

Fig. 2. Deoxygenation and denitrogenation during HTL of human feces via a three-dimensional Van Krevelen diagram. The HTL products (biocrude oil, solid residue, gases and aqueous phase) were obtained at two different conditions: 340°C, 10 min, 25% TS (in dark color); 340°C, 30 min, 5% TS (in light color).

FT-IR analysis was carried out to characterize the organic groups in the biocrude oil (**Fig. 3A**). The peaks at 2925 /cm and 2854/cm revealed the presence of aliphatic groups, such as $-CH_2$, $-CH_3$, together with the C-H deformation at 1458/cm and 1373 /cm, illustrating the existence of hydrocarbons[26, 27]. The peak at 1707 /cm was attributed to the $-C=O$ stretching vibration of ketones, esters aldehyde groups and acids[28]. Besides, 1H NMR analysis of the biocrude oil (**Fig. 3B**) confirmed the FT-IR results. The major peaks at 1.8-0.0 ppm in the spectrum indicated a high

percentage of aliphatic compounds in the biocrude oil while the peaks at 3.0-1.8 ppm were probably related to the oxygenated compounds and nitrogenous compounds in the biocrude oil [29, 30], and the peaks between 5 ppm and 6 ppm were mostly ascribed to the existence of alkenes. The analysis of biocrude oil through FT-IR and ^1H NMR showed an abundance of reactions occurred during HTL, and **Fig. 4** was drawn to elucidate the potential reaction pathways for the HTL of human feces [29, 31]. The hydrocarbons in the biocrude oil were produced through the decarboxylation of the fatty acids, which were from the hydrolysis of the lipids in the human feces [29]. The deoxygenation of biocrude oil was conducted through decarboxylation and dehydration. In particular, oxygen was removed in the form of CO_2 and H_2O [20, 30]. The ketones and aldehyde groups were mostly formed from polysaccharides through hydrolysis, dehydration and decomposition [30]. The nitrogenous compounds in the biocrude oil may consist of pyridine, pyrrolidine indole and quinolone, generated from amino acids and monosaccharides via Maillard and cyclization reactions [31].

On the other hand, the contents of carbon, hydrogen and nitrogen in the solid residue were reduced to 27.50-38.33%, 2.76-4.57% and 0.81-4.23%, respectively. Most ash remained in the solid residue (37.74-64.19%), which was a significant increase in comparison to the ash remaining in the solid residue of human feces (11.49%). In addition, the total contents of carbon, hydrogen and nitrogen in the solid residue were less than 50%, indicating a large amount of inorganic salts were present.

The high concentrations of TC (9.76-51.61 g/L), TOC (9.29-49.25 g/L) and COD (27.64-132.97 g/L) revealed the distribution of organic matter in the aqueous phase. TOC/TC was close to 1, indicating little inorganic carbon was in the aqueous phase. The organic matter in the aqueous phase could be treated and converted to gas fuels (hydrogen and methane) [32]. Besides, the TN contents of the aqueous phase were 2.74-14.84 g/L and the pH values were 7.09-8.64, indicating that there might be an abundance of ammonia in the aqueous phase. Ammonia was formed during HTL of biomass, and pH had great effects on the equilibrium between free ammonia (NH_3)

245 and ammonium (NH_4). The equilibrium shifted towards ammonia when the pH
 246 increased [33].

247

248 **Fig. 3.**FT-IR (A) and ¹H NMR (B) spectrum of the biocrude oil (a: biocrude oil
 249 obtained at 340°C, 10min, 25% TS; b: biocrude oil obtained at 340°C, 30min, 5% TS).

Fig. 4. Potential reaction pathways for the conversion of human feces via HTL[29, 31] (a: hydrolysis; b: dehydration; c: decarboxylation; d: deamination; e: Maillard reaction; f: cyclization; g: polymerization; h: decomposition).

Apart from organic matter, most nitrogen and phosphorous in the original feedstock were channeled into aqueous phase during HTL[16, 22]. In particular, volatile fatty acids (acetic acid, lactic acid, etc.), and allyl alcohol were identified in the aqueous phase. Monosaccharide could also be produced in the aqueous phase through dehydration of cellulose and hemicellulose in the human feces, and the acids and alcohols were probably generated as a result of further degradation of the monosaccharides[16, 21, 34] (**Fig. 4**). These organic compounds contributed to the high concentration of COD in the aqueous phase. Denitrogenation in HTL occurred via deamination of amino acids from the hydrolysis of proteins[35], and nitrogen mostly accumulated in the aqueous phase, resulting in high N/C ratios of the aqueous phase. An abundance of cyclic amides and organic acids can be generated under hydrothermal conditions through deamination and cyclization involving alcohols,

ammonia and amino acids[21, 22] (**Fig. 4**).The amides were easy to dissolve in the water and led to the high nitrogen content of the aqueous phase.Heterocyclic compounds containing both nitrogen and oxygen elements (propanamide, pyrrolidine, acetamide, etc.)and organic acidsmade up a large percentage of the majorchemical compositions in the aqueous phase[36].Moreover, the phosphate groups could be introduced to proteins by conjugation with glucose-6-phosphate via the Maillard reaction, which could affect the concentration of phosphate in the aqueous phase[37].The reaction pathway of phosphorus-containing proteins during HTL is not clear and needs further study[36].Moreover, the aqueous phase could be recycled for algal cultivation because nutrients (nitrogen and phosphorus) in the aqueous phase were needed for algae growth[16].

Fig. 5.Element distribution in the products after HTL of human feces (a: products obtained at 340°C, 10 min, 25% TS; b: products obtained at 340°C, 30 min, 5% TS. It was assumed that there was no nitrogen in the gases [14], and hydrogen content in the aqueous phase and metal contents in the biocrude oil were calculated by difference).

283

284 **Fig.5** illustrates the results of the elemental distribution of carbon,
285 hydrogen, nitrogen and oxygen in the HTL products. Carbon of 54.71% in the
286 feedstock entered into the biocrude oil as obtained at 340°C, 10min, and 25% TS. This
287 agreed well with a 55.3% of carbon recovery obtained in a previous HTL study of
288 algae[14]. The total hydrogen recovery of the biocrude oil and aqueous phase was
289 over 96%, while only a trace amount of hydrogen was in the solid residue and gases.
290 Part of the hydrogen recovered was from the dissociation of water because water
291 could serve as a hydrogen source and supply hydrogen atoms that participated in
292 reactions during the HTL process[38]. Moreover, 26.64% of carbon and a majority
293 of nitrogen (>72%) in the human feces were distributed to the aqueous phase as
294 obtained at 340°C, 10min, and 25% TS. About half of the oxygen in the human
295 feces was released into the aqueous phase, resulting in only 6.18-8.77% of the
296 oxygen content in the biocrude oil. The gaseous phase contained approximately 20% of
297 the oxygen in the original human feces. Even though more than 70% nitrogen in the
298 original feedstock was distributed to the aqueous phase, there was still a fraction of
299 nitrogen (2.98-4.66%) migrated to the biocrude oil. Further upgrading of biocrude oil
300 is needed to reduce nitrogen for the purpose of transportation fuels.

301 **3.2.2 Analysis of metal elements in the products**

302 **Table 3** illustrated the analysis of metal elements in the products. The contents of Al,
303 Ca, Mg, Zn and Fe were 1.10 mg/g, 16.97 mg/g, 7.56 mg/g, 0.28 mg/g and 0.94 mg/g in
304 the human feces, respectively. In comparison, the contents of these metals in the solid
305 residue, as obtained at 340°C, 10min, and 25% TS, were 6.74 mg/g, 105.75 mg/g, 45.58
306 mg/g, 1.76 mg/g and 3.99 mg/g, respectively. These high metal contents led to the high
307 ash content in the solid residue. One interesting finding was that the contents of K and
308 Na in the solid residue were 3.48 mg/g and 3.89 mg/g, significantly lower than
309 those in human feces (15.77 mg/g and 7.46 mg/g). On the contrary, the
310 concentrations of K and Na in the aqueous phase were 3930 mg/L and 1731 mg/L,

respectively, while the concentrations of other metals such as Al, Ca, Mg, Zn and Fe in the aqueous phase were less than 90 mg/L. A previous study also found that K and Na were almost entirely extracted into the aqueous phase when using swine manure and chicken manure as feedstocks during hydrothermal processing [39]. These results imply the metal elements have selective routes for their distribution in the HTL products. Further investigations are needed to elucidate the effects of TS content, reaction temperature and retention time on the element distribution.

Table 3

Metal element analysis of human feces and HTL products.

	Conditions	Al	Ca	Mg	Zn	Fe	K	Na
Human feces(mg/g)	Dry feedstock	1.10	16.97	7.56	0.28	0.94	15.77	7.46
Aqueous phase(mg/L)	340°C/10min/25%	5.85	37.00	87.61	0.32	2.67	3930.00	1731.00
	340°C/30min/5%	1.07	11.99	71.89	ND	1.18	767.60	392.50
	340°C/10min/25%	8.82	138.50	55.91	2.41	6.12	3.48	3.89
Solid residue(mg/g)	340°C/30min/5%	6.74	105.75	45.58	1.76	3.99	7.87	9.57

ND: Not detected.

The distribution of metal elements showed that the majority of Ca (>89%), Mg (>81%), Al (>88%), Fe (>72%) and Zn (>94%) in the feedstock were migrated to the solid residue, while most of K (>89%) and Na (>73%) were released to the aqueous phase (Fig. 5). A small amount of metal elements were found in the biocrude oil, consistent with previous findings using algal biomass as the feedstock [20, 40]. These results can be explained by the chemical properties of metal elements and pH values of the aqueous phase. Due to the alkaline aqueous phase (Table 2), K and Na could dissolve in the solutions while heavy and alkaline-earth metal elements (Ca, Mg, Al, Fe and Zn) were easily precipitated in alkaline solution and transferred to the solid residue. Previous studies reported that carbonates or hydroxides of Na and K could be used as homogeneous catalysts to improve the performance of HTL [30, 40-43]. This study showed that K and Na were mostly dissolved in the aqueous phase, which might be reused for catalyzing HTL in further experiments. Furthermore, Ca and Mg are secondary nutrients while Fe and Zn are trace elements for the growth of the plants [40], so the metal elements in the solid residue might be utilized as biofertilizers.

Overall, the analysis of metal elements suggested that HTL might be developed as a potential approach for the recovery of metals in organic wastes in addition to energy recovery.

4. Conclusions

This study demonstrated the feasibility of degradation of human feces, production of biocrude oil, and separation of nutrients and metals via HTL. The maximum liquefied fraction was 87.89% and the highest biocrude yield was 34.44% with a HHV of 40.29 MJ/kg. Fifty-four percent of carbon in the human feces was migrated to the biocrude oil while 72% of nitrogen and 49% of oxygen were released to the aqueous phase. In addition, most Ca, Mg, Al, Fe and Zn in the feedstock were distributed to the solid residue, whereas K and Na mainly dissolved into the aqueous phase. Results from this study suggest that HTL could be developed as a promising tool for treatment and valorization of wet human wastes, and further supporting energy production as well as resource recovery (i.e., nutrients and metals) from biowastes.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest. All authors have read and have abided by the statement of ethical standards.

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