Hydrothermal treatment of paunch waste: A feasibility study

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1.0 EXECUTIVE SUMMARY

This project is focused on evaluating the feasibility of hydrothermal treatment of paunch waste. The project scope includes

- Experimental investigation of hydrothermal treatment of paunch waste and product characterization in a laboratory system
- Pot trials on hydrochar (i.e. residual solid material after hydrothermal treatment)
- Development of a process model in Aspen plus, and
- Techno-economic assessment.

The effect of critical parameters such as temperature, initial pressure and residence time were studied in a laboratory setup. Two paunch waste samples – before and after dewatering with solids content of 3% and 15%, respectively were studied in this work. It was found that temperature has a profound effect on the conversion rate. For example, for a paunch waste with 3% solids, the conversion was found to be almost doubled from around 40% to 80% with increasing temperature from 180°C to 240°C, respectively. Duration of treatment was found to have minor impact on the conversion and products distribution, while the effect of initial (nitrogen) system pressure appeared to be insignificant. Higher bio-oil yield (up to 45%) was obtained for 3% solids at the milder conditions of hydrothermal carbonization. This is mainly due to the soft texture of paunch waste, containing high volatile matter and carbohydrate, and low lignin and ash content. Biodiesel-like compounds were detected in the heavy bio-oil with a Higher Heating Value (HHV) of around 38 MJ/kg. The solid residue, here known as hydrochar, was found to have an enhanced HHV of ~24.5 MJ/kg and BET surface area of 68.1 m^2/g, indicating its suitability as a coal substitute or a porous medium in remediation or catalytic applications, respectively. Experiments with 15% solids demonstrated slightly lower conversion when compared with 3% solids suggesting that higher solids content would require either higher temperature or higher residence time.

Using the experimental data obtained from the laboratory work, a process model was also developed in Aspen plus V10. The main objective of the modelling work was to perform mass and energy balances and evaluate the feasibility of installing and operating hydrothermal treatment plant in an abattoir for processing paunch waste. A case study of multispecies red meat processing facility (slaughtering cattle and sheep) was performed in this work. The mass and energy balance data obtained from the process model were further used in the techno-economic assessment for estimating equipment size and cost. The cost of main equipment such as hydrothermal reactor, hot oil system, heat exchanger and product separators were determined employing quotations/cost equations available in the published reports of National Renewable Energy Laboratory (NREL). The economic viability was evaluated for three different cases as highlighted below.

- Hydrothermal treatment of paunch waste with 3% total solid at 240°C
- Hydrothermal treatment of paunch waste with 15% total solid at 240°C
- Hydrothermal treatment of paunch waste with 15% total solid at 380°C

The techno-economic assessment suggested that hydrothermal treatment of paunch waste with higher solids content (i.e. 15%) has a better Net Present Value (NPV). This may be due to the capital cost being the most critical parameter at smaller scale. It was found that, for all of the above three cases, the NPV did not look attractive with current average market value of crude bio-oil of $1.5/gallon unless the hydrochar sale price were assumed to be as high as $1500-2000/tonne. It is suggested that catalytic hydrothermal treatment with nano iron oxide catalyst may improve the commercial viability as it can (i) lower the operating temperature via catalytic effect, and (ii) produce high-quality magnetic hydrochar which can have higher sale price. More work is suggested on the catalytic hydrothermal treatment of paunch waste.

2.0 INTRODUCTION

Paunch waste is essentially a waste material collected from cattle stomach after slaughtering, thus appropriate handling of this biological waste is of great importance. The high organic content and lower ash content in paunch waste has prompted the meat processor companies to sponsor programs in applied research aiming to convert this resourceful waste stream into energy and valuable products. The management cost of wet paunch waste is greatly dependent on the procedure applied in the individual abattoir, its size, functionality and location, but averagely in a typical abattoir paunch waste management cost is found to be ~$18/tonne of wet waste.

Different research platforms have been investigated by the Australian Meat Processor Corporation (AMPC) to convert waste into energy which includes pyrolysis (Consulting, 2011b), hydrothermal carbonisation (Paz-Ferreiro, 2017), and even the possibility of employing paunch waste as a boiler fuel for co-combustion (Consulting, 2011a). This project extends the work carried out by Paz-Ferreiro (2017) on hydrothermal carbonisation. It is mainly focused on covering different modes of hydrothermal treatment such as carbonisation and liquefaction.

The major advantages of hydrothermal treatment of paunch waste are highlighted as below.

1. The hydrothermal process does not require drying of paunch waste which otherwise in any thermal treatment would be an essential step.
2. Energy requirement in hydrothermal processing could be lower than pyrolysis mainly for bio-oil production.
3. The hydrothermal process has the lowest emission profile when compared with other thermal processes.
4. More than 60% reduction in the volume of paunch waste can be achieved along with complete eradication of all pathogenic agents in hydrothermal processing. This is expected to reduce overall paunch waste management cost.
5. The hydrothermal processing can produce crude bio-oil (i.e. fuel) that can be used at abattoir in their boilers with minimal cleaning or can be sold to refineries for further

upgrading and use. In any case, it can generate significant cost benefits in terms of additional revenues or cost savings.

6. The hydrothermal process is flexible and can utilize other waste streams as well as waste heat available at abattoir to lower down the overall capital and energy requirement of the site.

The potential issues with hydrothermal treatment of paunch waste are highlighted as below.

1. There are low number of commercial scale plants/technology providers available in Australia and across the globe.
2. Capital cost for hydrothermal reactor can be extremely high due to the requirement of pressure vessel configuration.
3. The bio-oil produced from hydrothermal treatment of paunch waste would require further upgrading/cleaning for it to be used in boiler at abattoir site or blending with diesel or gasoline offsite.
4. Unless functionalized, it is challenging to generate high revenue from the hydrochar (i.e. residual solid material) produced as a by-product from the hydrothermal treatment process.

In general, co-production of bio-oil and functionalized hydrochar from hydrothermal treatment of paunch waste is assumed to present an economically beneficial alternative to other available paunch waste management methods. This study evaluates this idea via conducting a laboratory work and preliminary techno-economic analysis.

3.0 PROJECT OBJECTIVES

Laboratory scale investigation

Conducted experiments of paunch waste conversion in a laboratory scale reactor with an emphasis on understanding the effect of process parameters such as temperature, residence time and initial system pressure.

Product characterisation

Characterised gas, liquid and solid products obtained from the hydrothermal treatment of paunch waste.

Pot trials

This task was completed in the previous project report. Report can be obtained from below link.

https://pdfs.semanticscholar.org/bb0d/c04b65997d750e2e5cc390c406d76a2f9bce.pdf

Due to COVID-19 restrictions, pot trials were not repeated in this project.

Process modelling

Constructed a process flowsheet and developed a comprehensive mass and energy balance codes based on thermo-chemical equilibrium calculations.

Techno-economic assessment

Performed preliminary techno-economic assessment to evaluate the feasibility of the process and suggested solutions forward.

4.0 METHODOLOGY

4.1 Experimental

The dewatered paunch waste was collected from Brooklyn Plant - JBS Australia, pretreated at PC2 facility of RMIT University and stored in the fridge at 4℃ for the experimental work. The origin and composition of paunch waste are depicted in Fig. 1. Total solid of 3% and 15% were chosen to resemble the samples before and after fan press, respectively.

Runs below 300℃ operating temperature for 3% solids in paunch waste were performed at RMIT University. The hydrothermal treatment of wet paunch waste at RMIT University was carried out in a bench-scale 600 mL Parr reactor setup with 50 to 75% working volume, as displayed in Fig. 2. Before every real test, a pressure test was performed to ensure there is no leakage in the system. During the pressure test, the vessel was pressurized to 50 bar with nitrogen gas and kept for 5 min. It was ensured that no pressure drops during the holding time. After pressure test, both gas inlet and vent valves were opened and the system was flushed repeatedly to remove all oxygen from the reactor. Initial nitrogen pressure of around 10 bar was maintained in the vessel to keep the water in its liquid state during the process. The reactor was set with temperature and time, and after adjusting stirrer speed to 500 rpm, the operation was started. In this study, the effect of temperature (160 to 240℃), processing time (5 to 150 min) and initial nitrogen pressure (10 to 30 bar) on the products distribution and properties was investigated.

Run for 380 ºC operating temperature, 15% solids in paunch waste and zero residence time was performed at University of Alberta. The bench-scale reactor used at University of Alberta is a 250 ml Parr reactor able to operate under supercritical water conditions. Similar methodology as described in the above paragraph for 3% solids was also followed in the experimental work conducted at University of Alberta.

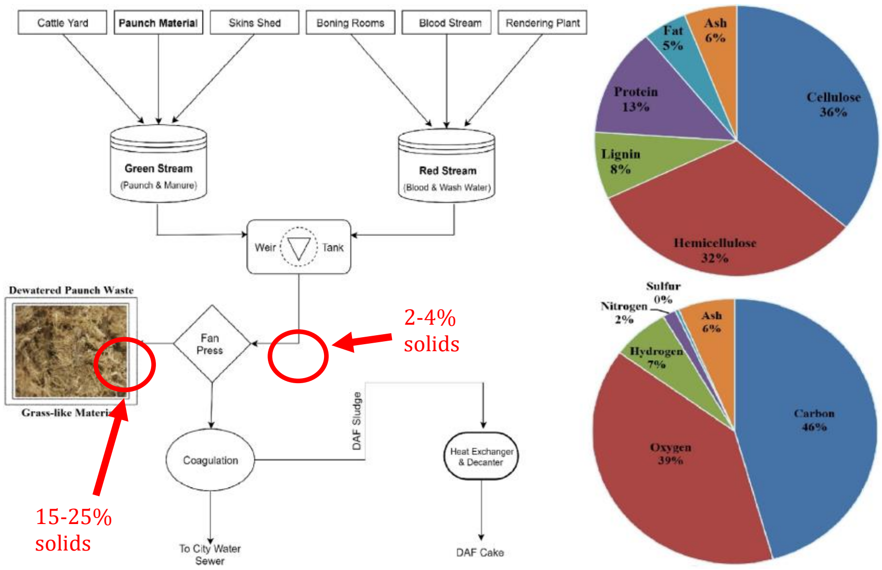

Fig. 1 The origin (left-hand side) and composition (right-hand side) of paunch waste.

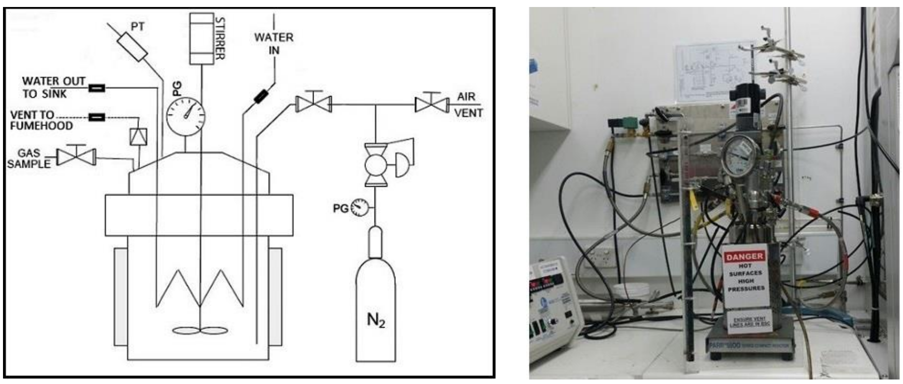

Fig. 2 Hydrothermal treatment setup used for processing paunch waste.

After each run, products were separated through a series of processes such as vacuum filtration, liquid-liquid extraction using DCM solvent, washing the hydrochar with ethanol, rotary evaporation and drying. Hydrochar was characterized using CHNS, XRF, FTIR, BET and SEM to assess its potential applicability as a coal substitute or porous media. Bio-oil samples were analyzed with GC/MS method. Gas phase was detected via FTIR.

4.2 Process modelling and techno-economic assessment

Figure 3 demonstrates the overall process simulation designed for hydrothermal treatment of paunch waste. The wet paunch waste is pressurized and heated to the desired operating conditions and sent to hydrothermal reactor (multi-tubular fixed bed reactor which allows reacting for the specified time). The products (gas, bio-oil, hydrochar and water in aqueous phase) are then cooled in a heat exchanger and separated through a series of equipment. Gas product is assumed to be not valorized in this work. Bio-oil (as the main product) is assumed to be sent to a bio-oil upgrading facility as its Higher Heating Value (HHV) is comparable to that of hydrocarbon fuel. Hydrochar is assumed to be sold for different possible applications such as soil conditioner or coal substitute. Ultimately, aqueous phase (considered to be fully sterilized given the processing conditions) which accounts for 10.7 % of products is assumed to be sent to wastewater treatment plant via existing sewer pipeline with no post treatment at this stage.

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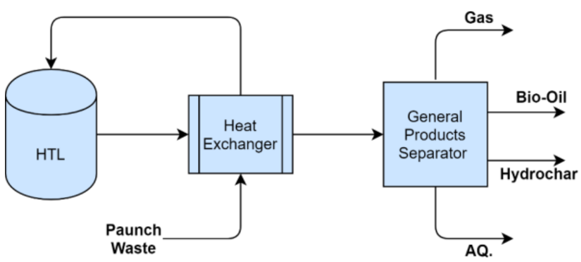

Fig. 3 Simplified process flow diagram of hydrothermal liquefaction (HTL), AQ = Aqueous.

For the current project, a case study of multispecies red meat processing facility (slaughtering both cattle and sheep) is considered. It is assumed that the facility produces 90 tonnes of paunch waste per day with 30 wt% solids. This equates to 27 dry tonnes of paunch waste per day. The average paunch waste management cost in this facility is assumed to be $18/tonne of wet-waste i.e. $60/tonne of dry paunch waste. When hydrothermal treatment option is considered, this cost is counted as the feedstock credit in economic analysis (because it is assumed that the facility currently pays this amount to have its paunch waste disposed/managed offsite). Proximate and ultimate analyses of the paunch waste is summarized in Table 1.

Table 1 The proximate and ultimate analyses of paunch waste.

Proximate Analysis		Ultimate Analysis	
Moisture, wt%	1.79	C, wt%	45.25
Volatile, wt%	78.27	H, wt%	6.52
Fixed Carbon, wt%	13.54	N, wt%	2.44
Ash, wt%	6.4	S, wt%	0.37
		O, wt%	39.02
		Ash, wt%	6.4
HHV = 19.3 MJ/kg			

The process design of paunch waste hydrotreatment simulated in Aspen plus software is provided in the Appendix 1. Mass and heat balances were carried out, and thus the net energy required for the plant and the products distribution were obtained. In order to utilize the less amount of energy, a heat exchanger was included in the model to pre-heat the feedstock using the energy of the products stream. The energy needed for the plant was supplied by burning natural gas in this model.

The general strategy employed for the techno-economic analysis is illustrated in Fig. 4. This explains that data obtained from experiments in the laboratory was used to develop a hypothetical process flow diagram. This allowed for implementing a more detailed Aspen plus simulation in which a rigorous process modelling was conducted. Material and energy balances were completed accurately, as these are the underlying factors in estimating the capital and operating cost of the plant under investigation. Finally, discounted cash flow analysis was carried out to execute a meticulous economic analysis with respect to the financial assumptions. The NPV was approximated to assess the viability of plant (Snowden-Swan et al., 2016, by Indirect, 2011).

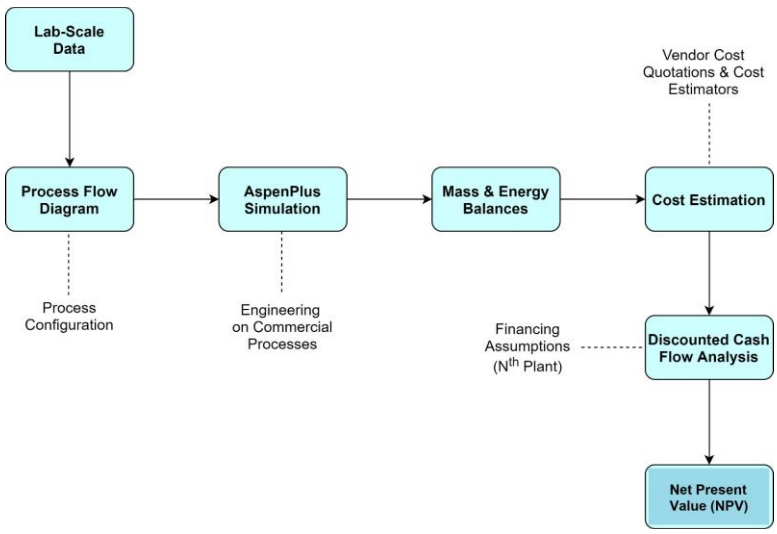

Fig. 4 Strategy to hydrothermal treatment of cattle paunch waste design and analysis.

Project financing assumptions were made based on the Nth-Plant Economics. The US Department of Energy's Bioenergy Technologies Office (BETO) unified the assumptions applicable for bio-energy production which in known as Nth-Plant (Dutta et al., 2011). Table 2 summarizes the general assumptions, showing the inclusion of return rate, plant life, income tax, debt conditions, depreciation timetable, construction and start-up times. Interestingly, this techno-economic strategy was able to predict the available biofuels price with a reasonable accuracy (namely soy biodiesel: market price is $2.15/gal, while the model predicted it to be $2.55/gal) (by Indirect, 2011).

Table 2 List of Nth-plant assumptions used in this study (by Indirect, 2011, Dutta et al., 2011).

Assumption Description	Assumed Value
Internal rate of return	10%
Plant financing debt/equity	60% / 40% of total capital investment
Plant life	30 years
Income tax rate	35%
Interest rate for debt financing	8.0% annually
Term for debt financing	10 years
Working capital cost	5 % of Fixed Capital Investment (Excluding land cost)

Depreciation schedule	7-years MACRS schedule
Construction period	3 years (8% 1^{st} yr, 60% 2^{nd} yr, 32% 3^{rd} yr)
Plant salvage value	No value
Start-up time	6 months
Revenue and cost during start-up	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal
On-stream factor	90% (330 operating days per year)

4.2.1 Capital Investment

In order to estimate the capital cost, two main factors have to be taken into account for calculation which are the quote cost year and the capacity of equipment. Vendor cost quotation or estimator cost major equipment might be for several years before, therefore these capital costs must be updated to the targeted year. After estimating the scaled uninstalled cost in the targeted year (2020) it should be multiplied by an installation factor to determine the installed cost. Installation factor usually depends on the type of equipment being installed, however it is within the range from 1.5 to 2.5 (Jones et al., 2014). The hydrothermal liquefaction (HTL) system comprises static mixer, feed pump, heat integration, HTL reactor and K/O drums. The phase separation unit includes solids filter, and oil/water separator.

Sum of installed costs for all pieces of equipment and the cost for balance of plant (known as the additional components required to deliver energy) is defined as Total Installed Cost (TIC). Every plant must pay some direct and indirect costs when being established. Total Direct Cost (TDC) includes TIC, costs for building (1% of TIC), site development (9% of TIC) as well as additional piping (4.5% of TIC). Indirect costs are also imposed to the plant from explicit ways including prorated expenses (10% of TDC), home office and construction fees (20 % of TDC), field Expenses (10 % of TDC), project contingency (10% of TDC), start-up and Permits (5% of TDC). Fixed Capital Investment (FCI) is the sum of total direct and indirect costs. Working capital is assumed to be 5% of FCI, as mentioned in the Nth-plant assumptions. Land is expected to be provided by the red meat processing facility at no cost. Ultimately, if we sum FCI and working capital (+land), it gives the Total Capital investment (TCI).

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4.2.2 Operating cost

Apart from the capital investment, operating costs also plays a role in process economics analysis. Table 3 presents the detailed operating values considered in the current study. As shown, operating cost is generally divided into two main categories: Fixed and variable operating costs.

Table 3 Detailed calculation of operating cost.

Fixed Operating Cost	
Title	Number
Plant Manager	1
Maintenance	2
Shift Operators	3
Overhead and Maintenance	90% of Labour
Maintenance Capital	3% of FCI
Insurance and Taxes	0.7% of FCI
Variable Operating Cost	
Title	Value
Paunch waste credit	$60/tonne of dry paunch waste
Hydrochar credit*	$1000/tonne of dry hydrochar
Natural Gas (supply energy) (2020c)	$6/GJ (Vic-Industry 2020)
Utilities (e.g. electricity) (2020b)	$0.253/kwh (Industry-2020)

* Hydrochar price drastically depends on its quality and application.

4.2.3 Depreciation

The Modified Accelerated Cost Recovery System (MACRS) schedule was applied to measure the reduced value of an asset over time which depreciates because of wear and tear or obsolescence. The 7-years MACRS schedule was chosen in the Nth-plant assumptions and applied in this study.

Table 4 Annual depreciation of Fixed Capital Investment (FCI) in 7-year MACRS schedule.

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Schedule	14.29%	24.49%	17.49%	12.49%	8.93%	8.92%	8.93%	4.46%

4.2.4 Process Economics

The objective is to determine the net present value (NPV) for a period of 30 years. The discounted cash flow (DCF) analysis was performed to convert the wealth created in the future to its current value. All N^{th} plant assumptions are applied in this analysis, making it possible to see how different parameters can have direct effect on NPV.

5.0 PROJECT OUTCOMES

Laboratory scale investigation and product characterization

Laboratory experiments have for the first-time characterized different products generated from hydrothermal processing of paunch waste under different operating conditions and different solid content. The work demonstrated that hydrothermal processing can successfully convert paunch waste into high-value products like bio-oil and hydrochar.

Process modelling and techno-economic assessment

The process modelling and techno-economic assessment of hydrothermal processing of paunch waste was performed for a multispecies red meat processing facility producing 27 dry tonnes of paunch waste per day. It has been concluded that installing hydrothermal processing plant for such facility would require significant capital investment. Moreover, the NPV does not look attractive due to smaller scale operation (economy of scale not achieved). Catalytic hydrothermal processing might be commercially viable option at smaller scale. However, more research (i.e. both experimental and modelling work) is required to confirm this.

6.0 DISCUSSION

6.1 Effect of operating parameters

Table 5 presents the products distribution obtained from the hydrothermal treatment of paunch waste at different temperature, time and initial pressure. Hydrochar yield decreased from around 60% to 21% when temperature increased from 160 to 240℃ for 3% solids. When compared with other wet biomass or sewage sludge, paunch waste conversion in hydrothermal treatment was found to be relatively high. It is mainly attributed to higher volatile matter and lower ash content. When compared with microalgae, a feedstock similar to paunch waste in terms of proximate and ultimate analysis, the paunch waste still achieved higher conversion in hydrothermal treatment. It is mainly due to higher amount of carbohydrates (i.e. 70-75%), and lower protein (~10%) and ash content (Wang et al., 2017). It is reported in the literature that hydrolysis of carbohydrate needs milder conditions, which justifies why paunch waste performed even better than microalgae. When temperature was increased to 380ºC and residence time was kept zero min for paunch waste with 15% solids, a conversion of 79% was achieved. This confirms that higher solids content would have relatively lower conversion and requires either high temperature or longer residence time. This might be due to the reduced water content (water plays important role in hydrothermal treatment) and increased diffusional barrier for higher solids content. However, due to COVID-19, the team could not perform more experiments at higher temperatures at University of Alberta.

Residence time also plays a key role in the process as the macromolecules need some minimum time to break down and form the products. The heating time (for batch experiments) is also important as conversion starts occurring during the heating period. From Table 5, no significant change is observed in total bio-oil yield within the residence time range of 5-90 min, which suggests that carbohydrates such as amorphous cellulose and hemicellulose as well as protein might be completely hydrolysed during the heating phase and extractives and fat might be transferred to the liquid phase. Longer residence time helps enhance hydrolysis of crystalline cellulose and partial degradation of lignin.

An initial pressure of 10 bar of nitrogen was applied, and further increase in pressure is generated from the materials inside the reactor, called autogenous pressure. This pressure is mainly coming from the water. Pressure was found to have a minor effect on the conversion, however it slightly influenced the products distribution as evidenced from the data reported in Table 5.

Table 5 Product distribution in HTL of paunch waste at different operating conditions.

Parameter	HC, %	HBO, %	LBO, %	AQ., %	Gas, %	Loss, %
3% Solids, 10 bar initial pressure, 90 min residence time						
Effect of Temperature						
160°C	59.7	4.3	24.4	7	0.6	4
180°C	39.4	16	18.2	21.6	1.9	2.9
200°C	36	21.1	21.6	12.5	3.2	5.6
220°C	28.6	16.9	19.8	22.6	5.1	7
240°C	21.1	15.6	29.4	20.7	6.4	6.8
15% Solids, 10 bar initial pressure, 0 min residence time						
380°C*	21.1	41.5 (Combined HBO and LBO)		Not Measured	Not Measured	Not Measured
Effect of Residence Time						
3% solids, 240°C temperature, 10 bar initial pressure						
5 min	33.5	24.3	19.8	9.8	4.4	8.2
30 min	27.9	20.7	21.9	17.5	5.1	6.9
90 min	21.1	15.6	29.4	20.7	6.4	6.8
150 min	20.7	15.6	23.1	14.5	10.2	15.9
Effect of Initial Nitrogen Pressure						
3% solids, 240 °C temperature, 90 min residence time						
10 bar	21.1	15.6	29.4	20.7	6.4	6.8
20 bar	24.9	16.3	24.5	15.8	8.3	10.2
30 bar	24.4	20.2	20	12.2	10.8	12.4

* Experiment conducted at University of Alberta

6.2 Characterization of products

The concentration and representative composition of products obtained at 240°C, 10 bar and 5 min are listed in Table 6. Light bio-oil was found to be rich in phenolic compounds, while heavy bio-oil interestingly was composed of fatty acids and their derivatives. There is more to understand from the composition of bio-oil products as well as related reaction kinetics. Gas phase was found to be purely CO_2. Aqueous phase was found to be highly acidic with pH of 4. For modelling purposes, the composition of aqueous phase was obtained from the literature (Jones et al., 2014). It should also be noted that the mass loss happening in the lab-scale process is considered to be negligible in the model and the values from experiments were normalized.

Table 6 The concentration and composition of different products in model.

Hydrochar	36.5 wt%	Aqueous phase	10.7 wt%
C	51.52 %	Methanol*	19 %
H	5.58 %	Formic acid*	38 %
N	1.39 %	Acetic acid*	12 %
S	0.32 %	Carbon dioxide*	26 %
O	34.1 %	Ammonia*	5 %
Ash	7.09 %		

Light Bio-oil	21.5 wt%	Heavy Bio-oil	26.5 wt%
Chloro-benzene	43 %	Undecanoic acid	57 %
2-Furancarboxaldehyde, 5-methyl-	10 %	Decanoic acid, ethyl ester	25 %
Phenol	6 %	1-Nonanol	18 %
Phenol, 2-methoxy-	15 %		
Apocynin	12 %	**Gas**	**4.8 wt%**
Phenol, 2,6-dimethoxy-	14 %	CO_2	100 %

* Aqueous phase composition was obtained from literature (Jones et al., 2014) for modelling purpose.

6.2.1 Proximate and ultimate analysis of hydrochar samples

Table 7 and 8 provides the details of proximate and ultimate analysis of paunch waste and hydrochars, respectively. The proximate analysis is used to determine the suitability of the material (in this case hydrochar) as a fuel. The first interesting fact to be noted is that both paunch waste and hydrochars contain less than 3% moisture, substantiating their hydrophobicity. This feature is of great importance when hydorchar is used as a coal substitute in a boiler. It is known that 1% moisture content can decrease the boiler efficiency by 0.1% (Hatt, 2012). It can be seen from Table 7 that volatile matter decreased with increase in temperature and residence time. In contrast, fixed carbon and ash content increased with increase in temperature and residence time. Initial pressure had no significant effect. The decrease in volatile matter and increase in fixed carbon suggests coalification of the paunch waste. A higher fixed carbon of hydrochar guarantees a steady flame with high firing temperature, hence a better quality hydrochar in terms of combustion (Liu et al., 2019).

Table 7 The results of proximate analysis of paunch waste and derived hydrochars.

Feedstock/ Parameter	Moisture[d], wt%	Volatile Matter[d], wt%	Fixed Carbon[d], wt%	Ash[d], wt%
Paunch waste	1.79	78.27	13.54	6.4
Effect of Temperature				
3% Solids, 10 bar initial pressure, 90 min residence time				
160℃	1.67	78.81	14.56	4.96
180℃	2.88	78.06	13.57	5.49
200℃	1.09	75.91	16.29	6.71
220℃	1.98	72.92	18.28	6.82
240℃	1.76	59.89	26.11	12.24
Effect of Residence Time				
3% solids, 240°C temperature, 10 bar initial pressure				
5 min	1.99	71.54	19.38	7.09
30 min	3.19	67.18	20.17	9.46
90 min	1.76	59.89	26.11	12.24
150 min	2.13	55.28	31.04	11.55
Effect of Pressure				
3% solids, 240°C temperature, 90 min residence time				
10 bar	1.76	59.89	26.11	12.24
20 bar	0.39	61.08	32.02	5.79
30 bar	0.82	61.14	31.85	6.19

Ultimate analysis shows that dry paunch waste is composed of carbon (45.25 %), hydrogen (6.52%), nitrogen (2.44%), sulphur (0.37%), oxygen (39.02%) and ash (6.4%). In the hydrochar samples, the carbon percentage increased up to 60% with increase in temperature and residence time. Similar to proximate analysis, the effect of initial pressure was insignificant. Hydrogen, nitrogen and sulphur percentages showed no profound changes in their contents. Hydrogen content decreased slightly. Nitrogen content was low in the paunch waste, and its percentage was roughly halved in hydrochar samples. Oxygen content however dropped down by around 45%, which is a deterministic factor of the hydrochar if it is to be used as a fuel. Similar observations were reported for HTL of loblolly pine where oxygen content decreased from 43.3% in the feedstock to 23.1% in the hydrochar derived at 260 ℃ (Reza et al., 2014). Reduction in oxygen content owing to the dehydration and decarboxylation reaction, increases the energy density of the fuel as well as quality of combustion. HHV is a suitable index to assess the suitability of hydrochar as a substitute to coal for energy production. It was found that HHV for hydrochar is in the range of 19.9 to 24.5 MJ kg^{-1} and this HHV value range is higher than the reported value for lignite in the literature (Liu et al., 2019) which clearly suggests the suitability of hydrochar as a replacement of lignite, if not sub-bituminous coal.

Table 8 The results of ultimate analysis of paunch waste and derived hydrochars.

Parameter	C^a, wt%	H^a, wt%	N^a, wt%	S^b, wt%	O^c, wt%	Ash^d, wt%	HHV, MJ kg^{-1}
Paunch waste	45.25	6.52	2.44	0.37	39.02	6.4	19.31
Effect of Temperature							
3% Solids, 10 bar initial pressure, 90 min residence time							
160°C	48.84	6.14	2.17	0.42	37.47	4.96	20.32
180°C	50.11	6.03	1.3	0.31	36.76	5.49	20.69
200°C	50.26	5.94	1.11	0.28	35.7	6.71	20.72
220°C	52.62	5.66	1.09	0.24	33.57	6.82	21.43
240°C	58.06	5.69	1.91	0.38	21.72	12.24	24.48
Effect of Residence Time							
3% solids, 240°C temperature, 10 bar initial pressure							
5 min	51.52	5.58	1.39	0.32	34.1	7.09	20.89
30 min	50.15	5.17	0.87	0.26	34.09	9.46	19.89
90 min	58.06	5.69	1.91	0.38	21.72	12.24	24.48
150 min	55.75	4.83	1.87	0.39	25.61	11.55	22.27
Effect of Pressure							
3% solids, 240°C temperature, 90 min residence time							
10 bar	58.06	5.69	1.91	0.38	21.72	12.24	24.48
20 bar	59.86	4.94	0.9	0.29	28.22	5.79	23.69
30 bar	58.66	4.87	1.58	0.3	28.4	6.19	23.16

[a] from CHN instrument
[b] from XRF
[c] by difference: O = 100 – (C + H + N + S + ash)
[d] from TGA instrument

6.2.2 Mechanistic study

FTIR spectroscopy is of great importance to characterize unknown compounds in terms of their organic functional groups. This analysis was performed under middle IR region (650-4000 cm^{-1}), and spectra of raw paunch waste and different hydrochars derived from the HTL at various temperatures are shown in Fig. 5. They illustrate similar spectrum in general, but different in intensity. The difference in intensity is elucidates the physico-chemical transformations and reaction mechanism.

FTIR spectroscopy is also able to monitor the fate of cellulose, hemicellulose and lignin in the lignocellulosic paunch waste (Jindal and Jha, 2016, Yang et al., 2007). The onset of hydro-treatment is 180℃, as the spectra begins to show some difference. According to its structure, cellulose can be identified by the bands at 3331, 2917 and 1000-1500 cm^{-1}, representing –OH, aliphatic –CH and C-O bonds, respectively. Higher temperature resulted in the meaningful reduction in the intensity of cellulose characteristic peaks, indicating the deconstruction of cellulosic structure during HTL process. C=O stretching vibration assigned to 1741 cm^{-1} is a characteristic band for hemicellulose which is easily seen in the raw material but completely disappeared during HTL process. The decreased intensity of this peak showed its highest decrease in spectrum of samples produced above 180℃, indicating that hemicellulose is mostly converted at temperatures as low as 180℃. This is also supported by the fact that CO_2 is liberated from the decomposition of carbonyl and carboxyl functional groups (Funke and Ziegler, 2010). The bands at 2917, 1610 and 1420 cm^{-1} respectively assigned to aliphatic -CH, aromatic C=C groups and saturated aliphatic hydrocarbons can show lignin (Bonds at around 1610, 1520 and 1420 cm^{-1} are benzene peaks). Lignin pieces are also proved to be present for the peaks around 1513 and 898 cm^{-1}. Their low intensity proves the low content of lignin in the samples. It appears that lignin decomposition also happens in such processing conditions, however at higher temperatures.

Moreover, decreased intensity of the broad band 3000 – 3600 cm^{-1} in the spectra of hydrochars compared to that of raw material can be a valid sign of dehydration during which the number of –OH functional group decreases. The decreased intensity of this peak also indicates the hydrophobicity of hydrochars.

6.2.3 Morphology study

The images of micro structures of raw material and derived hydrochars reveal the information on the morphological transformations occurred during process. Fig. 6a shows the morphology of untreated paunch waste with smooth encrusting layer presumably made of hemicellulose and lignin, which covers the cellulosic core. Hemicellulose was seen as small non-uniform particles. Porous monolithic structure of the raw paunch allows for transferring of water throughout the feedstock, hence perhaps expediting the hydrothermal treatment. Water at elevated temperatures can dissolve volatile matter in the cell wall through which it creates a web-like structure. Orderly arranged 3D structures resembling honeycomb were observed in the hydrochars as highlighted in Fig. 6b, possibly formed through the combination of –OH and –COOH functional groups as in dehydration reaction. This can significantly contribute in improving the porosity of the material, as will be shown in the next section. The diameter of Xylem vessel is around 13 µm and process could degrade it as shown in Fig. 6c. Morphologies different from the initial raw paunch were also observed in the derived hydrochar such that the hypothesis of creation of new solid structures is corroborated. Fig. 6d shows a particle which is visually obtained from the fusion of tiny pieces. This irregular sponge-like shape is formed from the aggregation of fiber bundles. In summary, it is observed that HTL process can effectively break down paunch waste into its constituents, and perhaps can even allow for recombination and production of new structures.

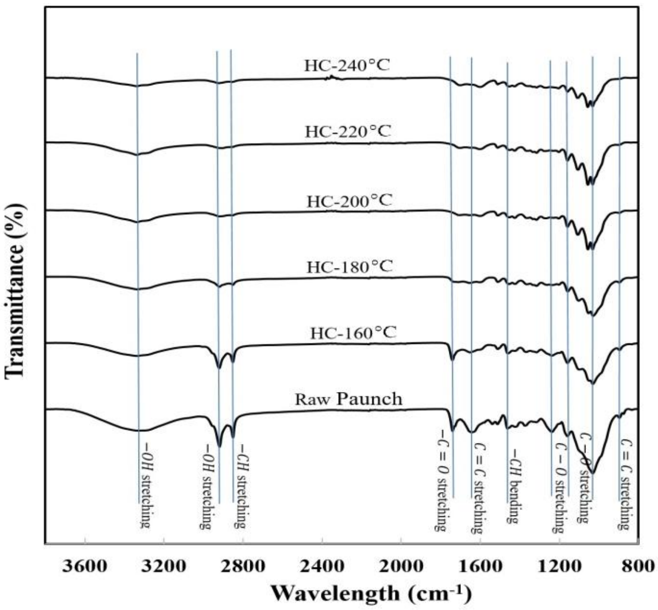

Fig. 5 FTIR spectra of paunch waste and derived hydrochars at different temperature.

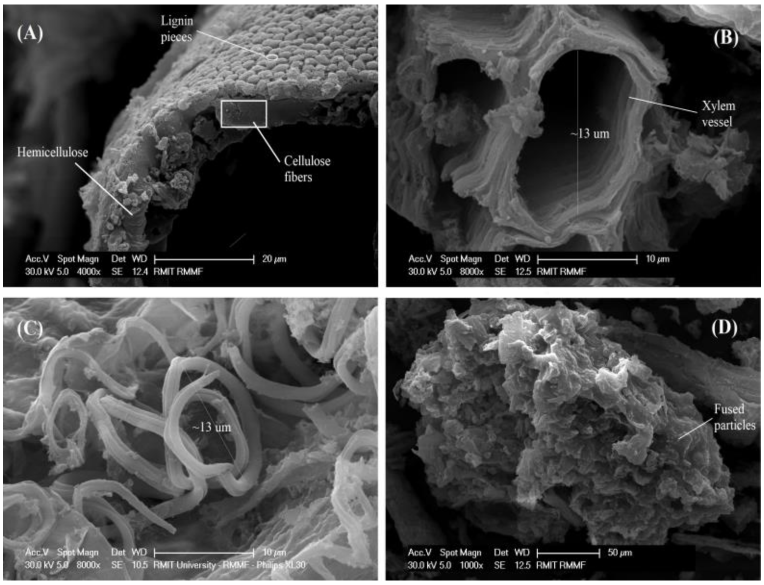

Fig. 6 Morphology of raw paunch waste and derived hydrochar: (A) the lignocellulosic structure of feedstock, (B) 3D honeycomb structure and Xylem vessels found in the hydrochar, (C) deconstructed xylem vessel after HTL process, (D) new solid structure observed in hydrochar.

6.2.4 Porosity study

The textural properties of hydrochars and paunch waste are presented in Table 10. The BET surface area for paunch-derived hydorchar is much higher than that of raw paunch waste. The BET surface area of hydrochar increases to 50.8 $m^2\ g^{-1}$ with the temperature raised up to 220°C where lignin wall is still preserved, but decreases at 240°C to 29.6 $m^2\ g^{-1}$, showing partly destruction of developed porous media. Pore volume also shows the same trend with temperature. With increasing the residence time from 5 to 150 min, the BET surface area decreased from 68.1 to 37 $m^2\ g^{-1}$. This demonstrates that hydrolysis and deconstruction of paunch waste molecular structure requires enough time, which will diminish porous area. Pressure also was shown to have effect on porosity, as higher pressure contributed to developing porous media. As optimum, processing at 220°C under 30 bar initial pressure for 5 min should presumably lead to the highest specific surface area.

Table 9 Textural properties of raw paunch waste and derived hydrochars.

Parameter	BET*, m^2g^{-1}	Pore volume**, cm^3g^{-1}	Pore size, nm
Paunch waste	3.3	0.0009	2.667
Effect of Temperature			
3% Solids, 10 bar initial pressure, 90 min residence time			
160°C	5.2	0.0055	4.220
180°C	9.1	0.0089	5.415
200°C	24.7	0.0406	7.597
220°C	50.8	0.0947	6.080
240°C	29.6	0.0500	6.425
Effect of Residence Time			
3% solids, 240°C temperature, 10 bar initial pressure			
5min	68.1	0.1285	6.470
30min	32.1	0.0585	5.885
90min	29.6	0.0500	6.425
150min	37.0	0.0617	6.290
Effect of Initial Pressure			
3% solids, 240°C temperature, 90 min residence time			
10bar	29.6	0.0500	6.425
20 bar	39.1	0.0656	7.495
30bar	48.9	0.0922	6.840

* BET surface area estimated using P/P0 in the range of 0 - 0.2

** Volume of pores between 17.000 and 3,000.000 Å width.

Pore size was found to be increased during HTL from 2.7 nm in raw paunch waste to the range of 4.2 to 7.6 nm for hydrochar, demonstrating the mesoporosity of hydrochar. Similar porous media found applications in supercapacitor (Fuertes et al., 2005), dye-sensitized solar cells (Wang et al., 2009) and wastewater treatment (Zhang et al., 2011). Employing hydrochar obtained from biomass in supercapacitor electrodes was thoroughly investigated by Wei et al (Wei et al., 2011), and shown that by tuning the conditions of hydrothermal synthesis and producing sought-after micro-porous structure it is achievable to double the energy density of supercapacitors.

6.3 Assessment of economic viability

Appendix 2 summarizes the capital costs involved in this project. As expected, hydrothermal reactor solely shows the greatest share in the capital investment of the plant. Handling paunch waste with higher total solids in hydrothermal reactor leads to a smaller volume of reactor i.e. lower capital investment, however it requires higher operating cost as the reactants would need either harsher operating conditions (i.e. high temperature) (Fig. 7) or longer residence time. The effect of solids content in paunch waste on the techno-commercial feasibility is investigated in this report.

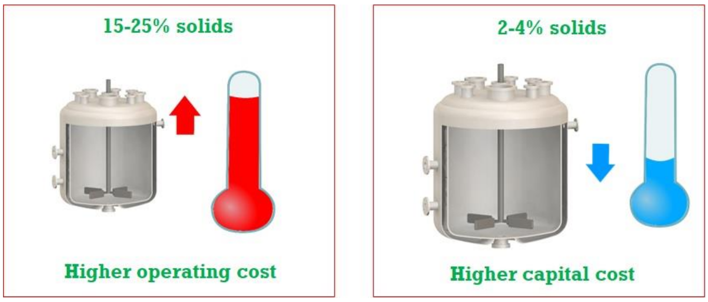

Fig. 7 Dependence of capital and operating cost on total solid content.

Three different cases were considered which include reaction severity and total solid content:

Case 1: Hydrothermal treatment of sample with 3% total solid at 240°C

Case 2: Hydrothermal treatment of sample with 15% total solid at 240°C

Case 3: Hydrothermal treatment of sample with 15% total solid at 380°C

The complete worksheet of the discounted cash flow analysis for Case 1 can be found in Appendix 3.

Fig. 8 shows the variation of NPV of three above-mentioned cases for a period of 30 years.

Case 1

Case 1 results are displayed in Fig. 8A and 8B. Fig. 8A shows that if hydrochar sale price is kept at $1000/tonne, it requires bio-oil sale price to be at least $5/gal for the NPV to become positive. Average crude oil market price in the last decade is estimated to be ~$1.5/gal (Macrotrends, 2020). herefore, bio-oil sale price was fixed as $1.5/gal and hydrochar sale price was varied in Fig. 8B. It shows that at least $2000/tonne of hydrochar sale price is essential to achieve positive NPV. Moreover, for NPV to become positive in 5 years, hydrochar sale price is estimated to be $3000/tonne. This is also far from reality as hydrochar on its own has limited benefits to offer.

Case 2

Case 2 results are displayed in Fig. 8C and 8D. For Case 2, hydrochar is expected to be of inferior quality due to additional diffusional barrier because of higher solids content. Therefore, in Fig. 8C, hydrochar sale price is kept at $500/tonne (lower than Case 1). It was found that at $500/tonne hydrochar sale price, it requires bio-oil sale price to be at least $5/gal for the NPV to become positive. In Fig. 8D, the bio-oil sale price is kept at $1.5/gal and hydrochar sale price was varied. It was found that at $1000/tonne of hydrochar sale price, NPV becomes positive in approximately 10 years.

Case 3

Case 3 results are displayed in Fig. 8E and 8F. For Case 3, due to elevated condition, it is assumed that similar conversion values and morphology in hydrochar as obtained in Case 1 is achievable. Fig. 8E kept the hydrochar sale price as $1000/tonne and varied bio-oil sale price. It was found that NPV becomes slightly positive at bio-oil sale price of $3/gal. However, for NPV to look attractive and become positive in 5 years, it requires bio-oil sale price of $5/gal. Fig. 8F has kept bio-oil sale price at $1.5/gal and varied hydrochar sale price and observed that NPV becomes positive under 15 years at hydrochar sale price of $2000/tonne.

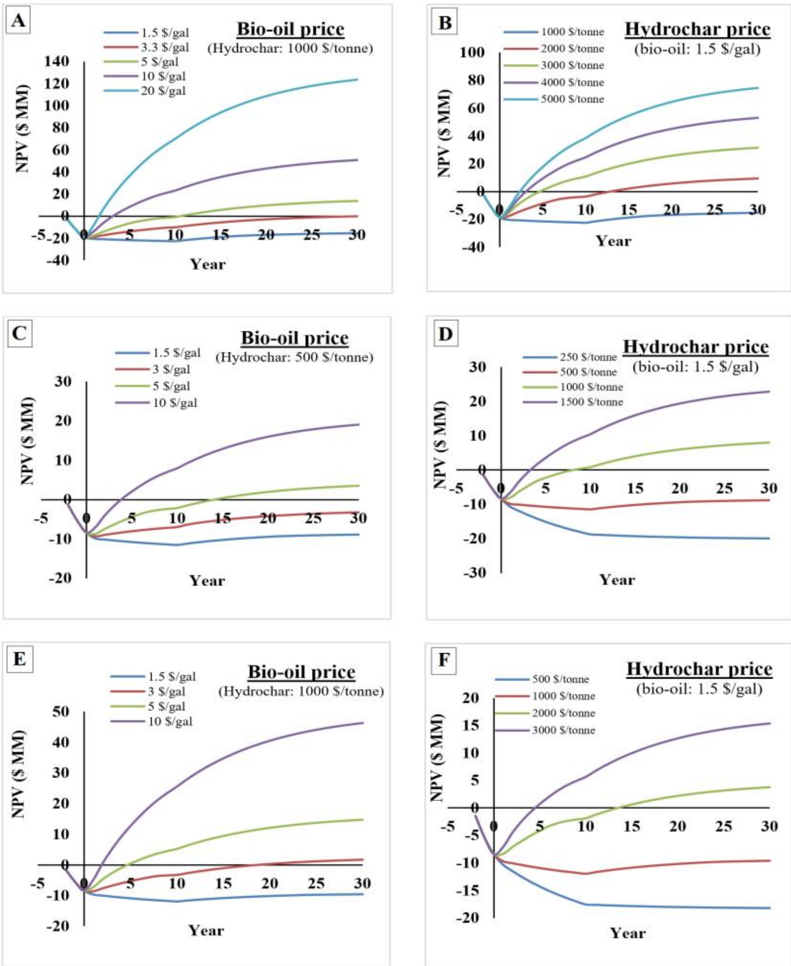

Fig. 8 Variation of net present value for different bio-oil and hydrochar sale price: case 1 (A and B), case 2 (C and D), case 3 (E and F).

From all above three cases, it was concluded that to keep the NPV attractive and become positive in 5 years with bio-oil sale price of $1.5/gal, it requires hydrochar sale price at least to be $1500/tonne. This will be difficult to achieve unless hydrochar are functionalized. One of the reasons for such less encouraging cost-economics is due to smaller scale operation (i.e. economy of scale is not achieved). Also, heat integration with waste heat available in abattoir is not considered in this study. However, it will only have effect on the operating cost and not on the capital cost.

Further to this, a sensitivity analysis was performed to identify the most sensitive (i.e. critical) factor among hydrochar sale price, capital cost (CAPEX) and operating cost (OPEX). The results are displayed in Fig. 9. It can be seen that CAPEX is the most sensitive factor followed by hydrochar sale price and then OPEX. Their order can be defined as: CAPEX > Hydrochar price > OPEX.

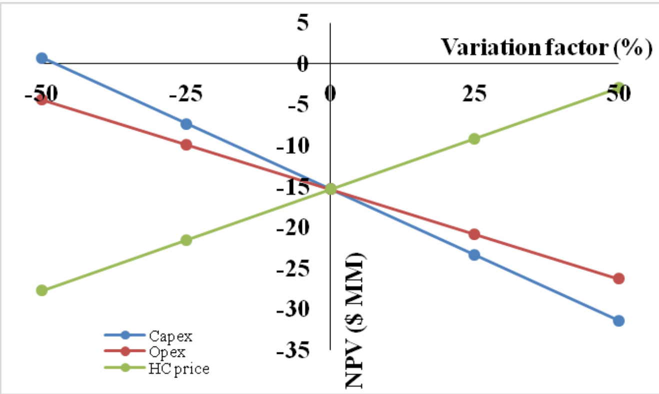

Fig. 9 Sensitivity analysis for Case 1.

An additional case study (Case 4) of the production of functionalized hydrochar via catalytic hydrothermal processing in the presence of nano iron oxide catalyst is studied. It is expected that nano iron oxide catalyst will not only lower down the requirement of operating temperature (and hence reducing capital cost) but also helps functionalizing the hydrochar by converting them to magnetic hydrochar (and hence help increasing their sale price). The idea of producing magnetic hydrochar from hydrothermal processing is not new and has been proposed by our group and others (Siddiqui et al., 2019a, Siddiqui et al., 2019b). More work in this direction should be carried out in future.

Fig. 10 provides a comparison among three underlying cases and Case 4 which is production of magnetic hydrochar through hydrothermal processing at 240°C, 15% total solid with 5%

impregnation of iron oxide. As seen, Case 4 appears to be the most superior option with NPV reaching >$20M and becomes positive under 5 years.

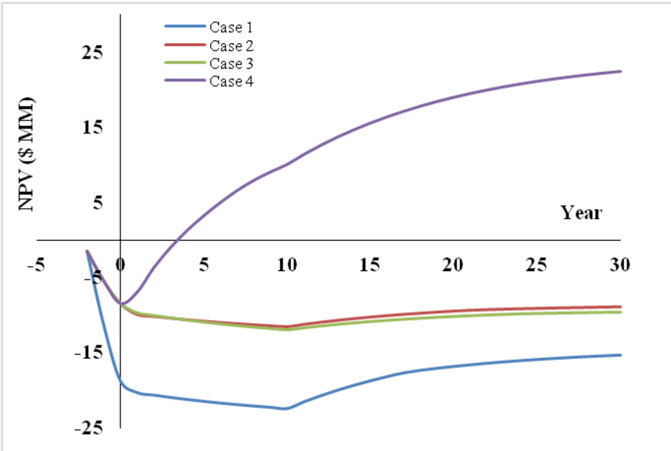

Fig. 10 Comparison among all proposed cases in terms of net present value calculations.

7.0 CONCLUSIONS/RECOMMENDATIONS

- Paunch Waste resembles characteristics of algae and food waste and will require much lower temperature and residence time for bio-oil production. Hydrothermal processing of paunch waste offers great potential due to (i) initial high water content in the waste, (ii) very high volatile matter and low ash content, and (iii) lowest emission profile due to extremely low temperature operation (below 400°C).

- Low ash and therefore low heavy metal content makes paunch waste ideal for blending with sewage sludge or municipal solid waste to produce hydrochar of lowest contamination grade (C1) from stand point of Victorian biosolids guideliens.

- The experimental work demonstrated that for paunch waste high yields of bio-oil can be achieved under milder hydrothermal carbonization conditions. This is mainly due to high volatile matter and carbohydrate content and low ash content. Paunch waste is found to be a better (i.e. superior quality) feedstock when compared with other similar wet waste materials such as sewage sludge, municipal solid waste and microalgae. It is expected to behave similar to food waste in hydrothermal processing.

- The calorific value of hydrochar produced from hydrothermal processing of paunch waste is appreciably enhanced after treatment, making it a possible candidate as coal substitute.

- The specific surface area is also greatly improved, which is important when it comes to using it as a soil amendment or porous media (such as catalysis, wastewater remediation agent etc.)

- It was also concluded that paunch waste hydrothermal processing would require high capital investment when handling low total solid content (~3%) or high operating costs when treating high total solid content (~15%).

- Upgrading would be required if the bio-oil is to be sold for blending with gasoline and diesel due to higher oxygen content present in the crude bio-oil. AMPC members, if takes this pathway, should not consider bio-oil upgrading onsite and aim to sale crude oil to the nearby refineries at average market price.

- Potential direct immediate use of crude bio-oil in boiler (on-site) is quite attractive. However, its combustion characteristics will need to be investigated mainly for identifying operational issues (if any) and obtaining emissions profile (mainly around clean burning of the fuel). NG would still be much cheaper at its current price compared to crude oil prices at $1.5/gal.
- Unless hydrochar sale price reaches values in the range of $1500-2000/tonne, hydrothermal process does not look commercially attractive for paunch waste.
- Catalytic hydrothermal processing of paunch waste with iron oxide nano catalyst might improve the commercially viability as it will help reducing capital cost by lowering the temperature requirement and functionalize hydrochar by converting them into high value magnetic hydrochar. More work in this direction should be carried out in future.
- Commercially available technologies have yet not tested paunch waste. Also, they have not looked at using catalyst to functionalize hydrochar and improve the conversion rate. Therefore, it is recommended that more laboratory work is needed in this area before conducting pilot-scale demonstration program.

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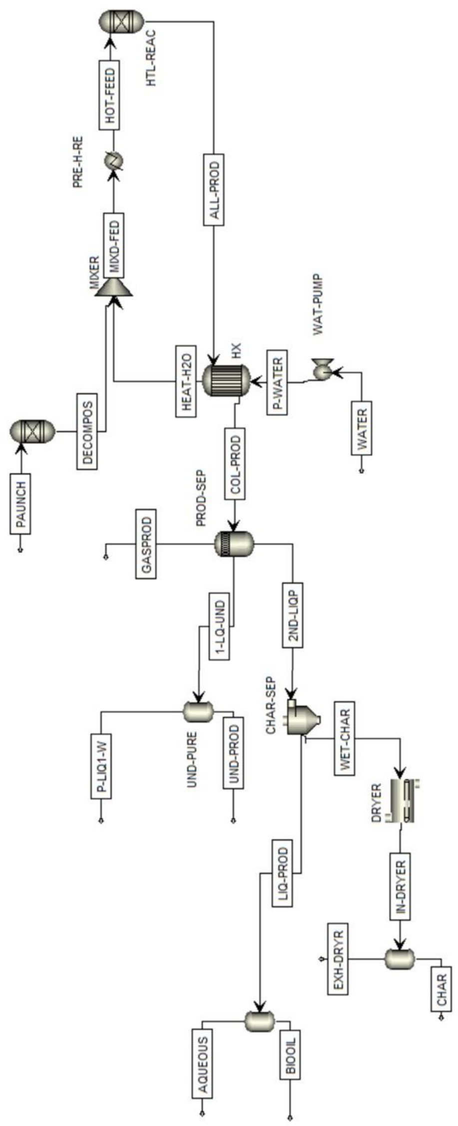
9.0 APPENDICES

9.1 Appendix 1

The process modelling developed by Aspen plus software.



9.2 Appendix 2

Capital investment of all proposed cases are as follows (2020 M AU$):

	Case 1	*Case 2, 3 and 4*
HTL setup	9.74	2.8
Hot Oil System	4.62	1.78
Phase Separation	1.9	0.63
Dryer	1.6	1.96
Balance of Plant	0.7	0.29
Total Installed Cost (TIC)	18.57	7.46
Buildings	0.18	0.75
Site development	1.67	0.67
Additional piping	0.83	0.34
Total Direct Cost (TDC)	21.27	8.54
Prorated expenses	2.1	0.85
Home office and construction fees	4.2	1.7
Field Expenses	2.12	0.85
Project Contingency	2.12	0.85
Start-up and Permits	1.06	0.85
Total Indirect Cost	11.7	0.42
Fixed Capital Investment (FCI)	33	13.24
Working Capital	1.6	0.66
Land- Assumed to be provided by red meat processing facility	0	0
Total Capital Investment (TCI)	34.6	13.9

9.3 Appendix 3

The worksheet of discounted cash flow analysis of case 1 (year -2 to 6)

Year		-2	-1	0	1	2	3	4	5	6
Fixed Capital Investment		1054812	7911093	4219249						
Working Capital		0	0	1648144						
Loan Payment		0	0	0	2947465.44	2947465.44	2947465.44	2947465.44	2947465.44	2947465.44
Loan Interest Payment		126577.49	1075908.7	1582218.6	1582218.64	1472998.896	1355041.572	1227647.663	1090062.241	941469.985
Loan Principal		1582218.6	13448858	19777733	18412486.2	16938019.66	15345595.79	13625778.01	11768374.81	9762379.357
BioOil Sales					2993068.892	3990758.523	3990758.523	3990758.523	3990758.523	3990758.523
Hydrochar Sales					2690820	3587760	3587760	3587760	3587760	3587760
Total Annual Sales					5683888.892	7578518.523	7578518.523	7578518.523	7578518.523	7578518.523
Annual Manufacturing Cost										
Raw Paunch Waste					-467775	-534600	-534600	-534600	-534600	-534600
Natural Gas					586777	670602	670602	670602	670602	670602
Electricity and Utilities					137879	157576	157576	157576	157576	157576
Fixed Operating cost					2586114	2586114	2586114	2586114	2586114	2586114
Total Product Cost					2842995	2879692	2879692	2879692	2879692	2879692
Annual Depreciation										
Total Plant MACRS Schedule					14.29%	24.49%	17.49%	12.49%	8.93%	8.92%
Depreciation					4710396.552	8072611.026	5765208.936	4117064.586	2943585.809	2940289.52
Net Revenue					-3451721.3	-4846783.399	-2421423.986	-645885.7264	665178.473	817067.0176
Losses Forward					0	-3451721.3	-8298504.699	-10719928.69	-11365814.41	-10700635.9
Taxable Income					-3451721.3	-8298504.699	-10719928.69	-11365814.41	-10700635.94	-9883568.92
Income Tax					0	0	0	0	0	0
Annual Cash Income					-106571.5478	1751361.083	1751361.083	1751361.083	1751361.083	1751361.083
Discount Factor		1.21	1.1	1	0.909	0.826	0.751	0.683	0.621	0.564
Annual Present Value	18764794.8				-96873.5369	1446624.255	1315272.173	1196179.62	1087595.233	987767.6508
Total Capital Investment + Interest		1429481.3	9885701.8	7449611.6						
Net Present Value				0						

Continued: The worksheet of discounted cash flow analysis of case 1 (year 7 to 18)

7	8	9	10	11	12	13	14	15	16	17	18
2947465.44	2947465.44	2947465.44	2947465.44	0	0	0	0	0	0	0	0
780990.3486	607672.3413	420488.8934	218330.82	0	0	0	0	0	0	0	0
7595904.266	5256111.167	2729134.621	0	0	0	0	0	0	0	0	0
3990758.523	3990758.523	3990758.523	3990758.523	3990758.52	3990758.52	3990758.523	3990758.523	3990758.523	3990758.52	3990758.52	3990758.523
3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760
7578518.523	7578518.523	7578518.523	7578518.523	7578518.52	7578518.52	7578518.523	7578518.523	7578518.523	7578518.52	7578518.52	7578518.523
-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600
670602	670602	670602	670602	670602	670602	670602	670602	670602	670602	670602	670602
157576	157576	157576	157576	157576	157576	157576	157576	157576	157576	157576	157576
2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114
2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692
8.93%	4.46%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2943585.809	1470144.76	0	0	0	0	0	0	0	0	0	0
974250.3653	2621009.422	4278337.63	4480495.703	4698826.52	4698826.52	4698826.523	4698826.523	4698826.523	4698826.52	4698826.52	4698826.523
-9883568.921	-8909318.556	-6288309.13	-2009971.5	0	0	0	0	0	0	0	0
-8909318.556	-6288309.134	-2009971.5	2470524.198	4698826.52	4698826.52	4698826.523	4698826.523	4698826.523	4698826.52	4698826.52	4698826.523
0	0	0	864683.4695	1644589.28	1644589.28	1644589.283	1644589.283	1644589.283	1644589.28	1644589.28	1644589.283
1751361.083	1751361.083	1751361.083	886677.6135	3054237.24	3054237.24	3054237.24	3054237.24	3054237.24	3054237.24	3054237.24	3054237.24
0.513	0.467	0.424	0.386	0.35	0.319	0.29	0.263	0.239	0.218	0.198	0.18
898448.2356	817885.6258	742577.0992	342257.5588	1068983.03	974301.68	885728.7996	803264.3941	729962.7003	665823.718	604738.974	549762.7032

Continued: The worksheet of discounted cash flow analysis of case 1 (year 19 to 30)

19	20	21	22	23	24	25	26	27	28	29	30
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
3990758.523	3990758.52	3990758.52	3990758.52	3990758.52	3990758.52	3990758.5	3990758.52	3990758.5	3990758.52	3990758.5	3990758.52
3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760	3587760
7578518.523	7578518.52	7578518.52	7578518.52	7578518.52	7578518.52	7578518.5	7578518.52	7578518.5	7578518.52	7578518.5	7578518.52
-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600	-534600
670602	670602	670602	670602	670602	670602	670602	670602	670602	670602	670602	670602
157576	157576	157576	157576	157576	157576	157576	157576	157576	157576	157576	157576
2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114	2586114
2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692	2879692
0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0	0	0	0	0	0	0	0	0	0	0	0
4698826.523	4698826.52	4698826.52	4698826.52	4698826.52	4698826.52	4698826.5	4698826.52	4698826.5	4698826.52	4698826.5	4698826.52
0	0	0	0	0	0	0	0	0	0	0	0
4698826.523	4698826.52	4698826.52	4698826.52	4698826.52	4698826.52	4698826.5	4698826.52	4698826.5	4698826.52	4698826.5	4698826.52
1644589.283	1644589.28	1644589.28	1644589.28	1644589.28	1644589.28	1644589.3	1644589.28	1644589.3	1644589.28	1644589.3	1644589.28
3054237.24	3054237.24	3054237.24	3054237.24	3054237.24	3054237.24	3054237.2	3054237.24	3054237.2	3054237.24	3054237.2	3054237.24
0.164	0.149	0.135	0.123	0.112	0.102	0.092	0.084	0.076	0.069	0.063	0.057
500894.9074	455081.349	412322.027	375671.181	342074.571	311532.198	280989.83	256555.928	232122.03	210742.37	192416.95	174091.523