Supplementary Information (SI)

for

Valorization of Tannery Fleshing Waste into High-Energy Biofuel Through Pyrolysis: Process Optimization and Fuel Properties Analysis

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Supplementary text 1:

$$HHV = 0.3383 \times C + 1.443 \times H - 0.1804 \times O + 0.0942 \times S \quad \ldots\ldots\ldots EqS1$$

$$LHV = HHV - (2.442 \times 8.936 \times (H/100)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots EqS2$$

$$\frac{dW}{dT} = \frac{W_{i+1} - W_i}{T_{i+1} - T_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots EqS3$$

Where W_i and W_{i+1} = Weight (%) of the sample at consecutive temperatures T_i and T_{i+1}, and dW/dT = the rate of mass loss per degree temperature, which forms the DTG curve.

$$\text{Specific gravity} = \frac{\text{Density of the biofuel}}{\text{Density of water}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots EqS4$$

$$\text{Acid value} = \frac{\text{Volume of KOH} \times \text{normality of KOH} \times 56.1}{\text{Weight of the biofuel sample}} \ldots\ldots\ldots\ldots EqS5$$

Table S1. Statistical comparison of regression models (Linear, two-factor interaction (2FI), quadratic and cubic) for biofuel process optimization.

Source	**Sequential p-value**	**Lack of fit p-value**	**Adjusted R^2**	**Predicted R^2**	**Remarks**
Linear	0.1511	0.0002	0.1391	-0.2572	
2FI	0.3058	0.0002	0.1900	-2.6451	
Cubic	0.0647		0.9906		Aliased
Quadratic	< 0.0001	0.0647	0.9664	0.8077	Suggested
Std. Dev.	1.8900				
Mean	38.1200				
Coefficient of variation	4.9500				
R^2	0.9823				
Adequate precision	29.4692				

Table S2. Cost analysis of biofuel production from fleshing waste (Lab-scale basis).

Item	Quantity	Total cost (USD)	Notes
Fleshing waste	200 g	0.00	Considered waste
N_2 gas	1 L	0.003	For inert environment
Electricity	0.5 unit	0.030	For heating to 555 °C
Transportation		0.010	
Total direct cost		0.043	

Biofuel yield from 300 g fleshing waste = 300 * 55.1 % = 110.2 g = 128.14 mL

Production cost per litre of biofuel = 0.0043 * 1000/ 128.14 = 0.33 USD

The laboratory-scale cost of biofuel production from fleshing waste is significantly lower than commercial fossil-based fuels, indicating a high potential of the process. With strategic scale-up and utilization of valuable by-products such as biochar and syngas, the overall production cost could be significantly reduced.

Table S3. Compounds identified in GC–MS analysis of biofuel produced from fleshing waste.

*MW = Molecular weight

Retention time	Possible compound name	MW*	Chemical formula	Area (%)
6.16	UREA, N-(2-METHYLCYCLOHEXYL)-N'-PHENYL	232	$C_{14}H_{20}ON_2$	0.607921
8.91	1R,2C,3T,4T-TETRAMETHYL-CYCLOHEXANE	140	$C_{10}H_{20}$	0.778242
11.81	TRANS-2-METHYL-4-N-PENTYLTHIANE, S, S-DIOXIDE	218	$C_{11}H_{22}O_2S$	0.807351
14.74	TRANS-2-METHYL-4-N-BUTYLTHIANE, S, S-DIOXIDE	204	$C_{10}H_{20}O_2S$	1.111013
17.61	1-NONANOL	144	$C_9H_{20}O$	1.662163
20.37	2-AZETIDINONE, 3,3-DIPENTYL	211	$C_{13}H_{25}ON$	2.620058
22.92	CYCLODODECYLAMINE	183	$C_{12}H_{25}N$	1.741779
24.93	CHLOROACETIC ACID, 10-UNDECENYL ESTER	246	$C_{13}H_{23}O_2Cl$	1.372146
25.42	N-[4-CYCLOOCTYLAMINOBUTYL] AZIRIDINE	224	$C_{14}H_{28}N_2$	3.587449
27.65	2H-PYRIDO[1,2F][1,6] DIAZACYCLOOCTADECIN-11(6H)-ONE, 10-(3-AMINOPROPYL)	379	$C_{23}H_{45}ON_3$	1.022638
29.48	CYANAMIDE, DI-2-PROPENYL	122	$C_7H_{10}N_2$	1.485159
30.28	DECAHYDRO-8A-ETHYL-1,1,4A,6-TETRAMETHYLNAPHTHALENE	222	$C_{16}H_{30}$	11.57388
32.16	DECAHYDRO-1,1,4A,5,6-PENTAMETHYLNAPHTHALENE	208	$C_{15}H_{28}$	1.042181
33.78	SILANE, CHLORODIETHYL(DODEC-9-YNYLOXY)	302	$C_{16}H_{31}OClSi$	2.075556
34.03	1-METHYL-2-PROPYL-PYRAZOLIUM BROMIDE	204	$C_7H_{13}N_2Br$	10.40997
35.92	2-PENTADECANONE	226	$C_{15}H_{30}O$	3.438095
39.26	Z-23-DOTRIACONTEN-2-ONE	462	$C_{32}H_{62}O$	3.062615
39.7	[1-(DIETHYLAMINO)ETHYLIDENIMINO] SULFUR PENTAFLUORIDE	240	$C_6H_{13}N_2F_5S$	1.933925
43.04	(2R,6R)-2-METHYL-6-NONYLPIPERIDIN-4-ONE	239	$C_{15}H_{29}ON$	0.816927
45.38	2,5-METHANOFURO[3,2-B] PYRIDINE, OCTAHYDRO	139	$C_8H_{13}ON$	0.696782
47.71	2(1H)-PYRIDINONE, 4-HYDROXY-6-METHYL-	125	$C_6H_7O_2N$	0.923240
52.13	2,5-METHANOFURO[3,2-B] PYRIDINE, OCTAHYDRO	139	$C_8H_{13}ON$	0.656114

Fig. S1. Purified biofuel fraction, isolated through fractional distillation based on boiling point differences (40 – 60 °C).

Fig. S2. Purified biofuel fraction, isolated through fractional distillation based on boiling point differences (60 – 80 °C).

Fig. S3. Biochar, synthesized at 550 °C via pyrolysis of fleshing waste.