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Modelling and techno-economic assessment of possible pathways from sewage sludge to green energy in India

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Abstract:

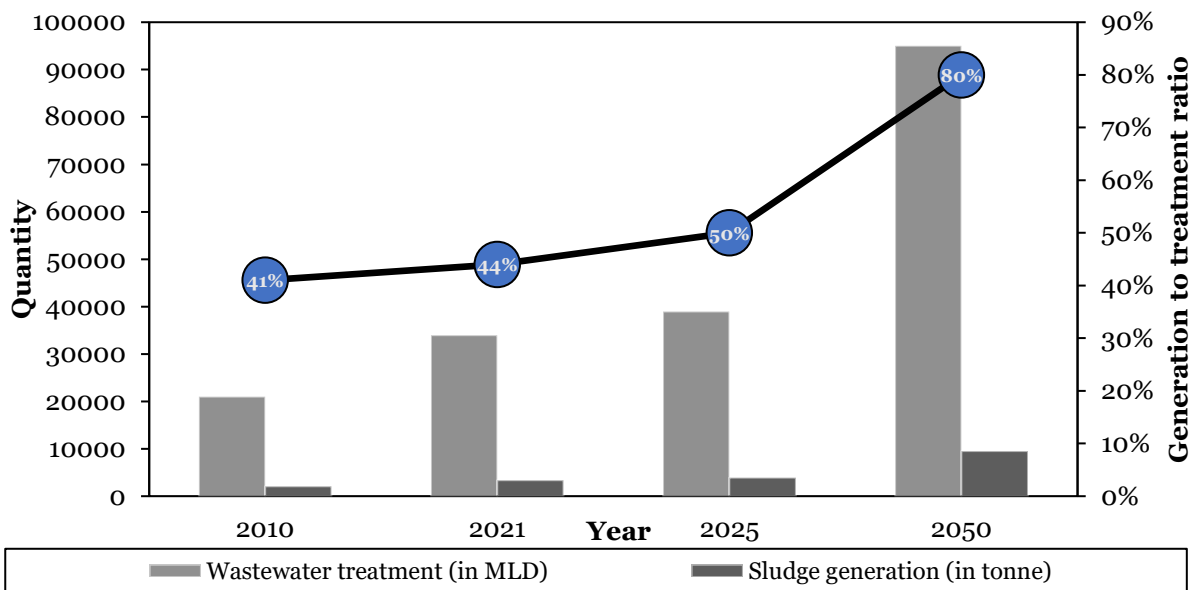
Efficient domestic wastewater management is essential for mitigating the impact of wastewater on human health and the environment. Wastewater management with conventional technologies generates sewage sludge. The present study considered a modelling approach to evaluate various processing pathways to produce energy from the sewage sludge. Anaerobic digestion, gasification, pyrolysis, and hydrothermal liquefaction are analysed in terms of their energy generation potentials with the Aspen Plus software. A techno-economic assessment is performed to assess the economic viability of each pathway. It reveals that gasification appears as the most promising method to produce electricity, with 0.88 kWh/kg_{drysludge}, followed by anaerobic digestion (0.66 kWh/kg_{drysludge}), pyrolysis (0.34 kWh/kg_{drysludge}), and hydrothermal liquefaction (0.13 kWh/kg_{drysludge}). In contrast, the techno-economic analysis underscores the viability of anaerobic digestion with levelized cost of electricity as 0.02 \$/kWh followed by gasification (0.10 \$/kWh), pyrolysis (0.14 \$/kWh), and hydrothermal liquefaction (2.21 \$/kWh). At the same time, if the products or electricity from the processing unit is sold, equivalent results prevail. The present study is a comprehensive assessment of sludge management for researchers and policymakers. The result of the study can also assist policymakers and industry stakeholders in deciding on alternative options for energy recovery and revenue generation from sewage sludge.

Keywords: Aspen Plus, bioenergy, gasification, pyrolysis, anaerobic digestion, hydrothermal liquefaction

1 **1. Introduction:**

2 Water is a necessary element for human health, animals, and ecosystems. The
3 rapid growth of the global population and the increasing water demand have raised
4 concerns about the accessibility of non-polluted and potable water. To fulfil the water
5 demand in densely populated areas, efficient wastewater management is required to
6 deliver clean water to the population and enrich the urban environment through water
7 reuse. Treatment plants make wastewater management a practical solution. The
8 domestic wastewater or sewage is collected through sewerage systems and conveyed
9 to assigned conventional wastewater treatment plants (WWTPs). The sewage
10 undergoes separation of organic and inorganic components, removes contaminants,
11 and reduces the microbial load within WWTPs. The treatment process result has two
12 components: the liquid content, which meets the national treated water quality
13 standard before discharging into nearby water bodies, and the semi-solid content,
14 commonly known as sewage sludge.

15 The wet sludge from the biological treatment unit of WWTPs is processed
16 further for dewatering in which water content is squeezed. After dewatering, typically,
17 2%-40% of the total solid content is left in the sludge, based on the wastewater
18 treatment technologies and dewatering systems employed (Singh et al., 2020). At the
19 world scale, the estimated annual sewage sludge generation ranges from 370 to 8910
20 thousand metric tonnes (dry basis) by different countries, which include the European
21 Union (EU)-27, China and the USA (Mateo-Sagasta et al., 2015). A developing country
22 like India, which has rapid population growth and urbanisation, generates
23 approximately 3955 thousand metric tonnes of sludge annually (dry basis) (Singh et
24 al., 2020). The sludge produced in India is about 44% of the EU-27 sludge generation.
25 A significant share of the sludge produced is dumped in open landfills due to the lack
26 of treatment facilities (Singh et al., 2020). Currently, approximately 44% of
27 wastewater generated is treated in India. This treatment rate is expected to increase to
28 80% by 2050, as shown in Fig 1 (Bassi et al., 2023). Sludge management is already a
29 challenge for governments and private enterprises. Increasing treatment through
30 conventional WWTPs will automatically increase sewage sludge generation and
31 become a massive management challenge.



32

33 Fig 1: Wastewater treatment (MLD), sludge generation (tonne/year), and wastewater
 34 treatment rate (%) in India

35

36 Since sewage sludge contains organic and inorganic contaminants and
 37 pathogens, it must be processed and handled carefully (Hoang et al., 2022). Processing
 38 of sewage sludge requires energy and capital. Traditionally, sewage sludge has been
 39 managed by open-field drying and dewatering processes, with the resultant sludge
 40 often used as a fertiliser or soil conditioner (Chojnacka et al., 2023). Although these
 41 methods provide some degree of sludge management, they do not fully capitalise on
 42 the energy potential locked within sludge. To fully capitalise on sewage sludge requires
 43 effective but sustainable management strategies. The sewage sludge has usable energy,
 44 which can be converted into valuable products. Sludge composition includes organic
 45 matter, which can be turned into valuable products like biogas, bio-oil, or syngas
 46 (Enebe et al., 2023). It will also provide a new energy source and economic benefits.

47 Worldwide, many WWTPs use anaerobic digestion (AD) to harness energy from
 48 sewage sludge. In the AD process, bacteria break down organic matter (specifically the
 49 volatile solids) without oxygen, and then the organic matter combines with water to
 50 produce biogas, which comprises methane and carbon dioxide (Khanh Nguyen et al.,
 51 2021). In India, AD plants generate up to 10,000 m³/day of biogas, which is used for
 52 cooking and electricity generation (Breitenmoser et al., 2019). While AD is a well-
 53 established sludge processing unit, making it feasible for commercial use, it still has
 54 some limitations. The process involves the various bacteria that need specific
 55 conditions to sustain, temperature needs to be regulated, and managing potentially

56 toxic materials; these elements can introduce complexities and operational challenges.
57 These factors can interrupt the adoption of large-scale AD plants as a primary waste-
58 to-energy method. Also, large-scale WWTPs have sludge quality issues for AD and lack
59 a waste storage unit (Mittal et al., 2018). Recognising the limitations of AD,
60 researchers have explored alternative approaches to convert sewage sludge into energy
61 with thermochemical methods. Among the emerging thermochemical processing
62 units, hydrothermal liquefaction (HTL), gasification, and pyrolysis have been
63 recognised (Pio et al., 2020). These processes offer rapid and efficient sewage sludge
64 transformation potential, creating operational advantages and novel opportunities for
65 energy production (Schnell et al., 2020). Additionally, thermochemical conversion
66 processes mitigate the sludge mass and decrease the pathogen load, lessening the
67 sludge's environmental impact (Hu et al., 2021; Ubando et al., 2021).

68 In the gasification process, the organic matter in biomass feedstocks (such as
69 crop residue, sewage sludge, and many more) is transformed into various products.
70 The process involves partial oxidation at high temperatures (typically 800-1000°C)
71 with gasifying agents like oxygen, carbon dioxide, steam, air, or combinations (Schmid
72 et al., 2018). The products include char, tar, and a combustible gas called syngas,
73 which comprises hydrogen, alkanes, carbon dioxide, carbon monoxide, and nitrogen.
74 On the other hand, pyrolysis is a thermal decomposition process at an operating
75 temperature ranging from 250°C to 600°C without any oxidising agent. Pyrolysis
76 produces pyrolysis gas, pyrolysis oil or bio-oil, and biochar (Rangabhashiyam et al.,
77 2022). Pyrolysis can be categorised into slow, fast, or flash pyrolysis, depending on
78 feedstock residence time and furnace heating rates (Quan et al., 2023). Slow pyrolysis,
79 in particular, produces superior quality and high quantity of biochar (Hu et al., 2023).

80 Dry feedstock basis processes like pyrolysis and gasification require extra
81 energy for feedstock dryers. To eliminate the need for extra energy, a wet feedstock
82 basis process like HTL is an alternative to the sludge processing unit. The HTL system
83 requires elevated temperatures and pressures to process the sludge into products.
84 Under controlled conditions, the feedstock undergoes a series of complex reactions,
85 generating a range of valuable by-products, such as thermally stable oil products
86 referred to as biocrude, aqueous phase, and solids like char (Hao et al., 2021).
87 However, HTL has not been extensively deployed in India.

88 The emergence of these thermochemical processes has paved the way for new
89 possibilities in sewage sludge management and energy generation. However, these

90 sludge processing units have remained limited to laboratory or pilot-scale
91 experimentation, raising questions about their scalability and economic feasibility for
92 commercial use. The originality of the research lies in a comparative assessment of
93 four well-known processing units to unlock the energy potential in sewage sludge. The
94 present research study addresses this critical knowledge gap by conducting a
95 comprehensive comparative and economic analysis employed for sewage sludge-to-
96 energy conversion. The analysis is performed on four sludge processing units, i.e., AD,
97 gasification, pyrolysis, and HTL. To the best of the author's knowledge, there has not
98 been a systematic comparison of the energy output derived from pyrolysis,
99 gasification, HTL and AD processes applied to sewage sludge. By modelling these
100 processes and quantifying their potential energy output from a typical WWTP, the
101 present study endeavours to provide new insights about both these processes' energy
102 generation potential and economic feasibility on a large scale. For energy modelling,
103 the Aspen Plus is used for chemical equations and thermodynamic equilibrium. The
104 study can inform decision-makers in sewage sludge management and energy
105 generation assessment about energy generation potential and economic feasibility
106 through processing units. The study can provide insights for potential large-scale
107 implementation. The study has been conducted using consistent parameters and
108 assumptions for uniformity.

109

110 **2. Methodology:**

111 The mechanism of different processing units is modelled to produce syngas, bio-oil,
112 biogas, biocrude, and electricity from sewage sludge. The fundamental path of energy
113 generation from each processing unit is illustrated through a comprehensive flow
114 diagram Fig 2. The present study examines various main products derived from
115 sewage sludge, which can be used as fuel or converted into electricity. The focus is
116 more on electricity as the demand for electricity is higher than the demand for heating
117 in India. However, the authors have also accounted for the heat generation from each
118 product but have not used it for further computation. Electricity is accounted for in
119 detail as its high demand is primarily supported through a mixed electricity grid; a
120 significant portion is from coal-based thermal plants. On average, 100-250 kilograms
121 of dry sewage sludge is produced per million litres per day (MLD) of wastewater
122 (Central Public Health & Environmental Engineering Organisation (CPHEEO), 2013).
123 The study considers a large-capacity WWTP of 100 MLD wastewater treatment and

146 The process model seamlessly integrated the Peng-Robinson equation with the
 147 Boston Mathias equation of state, ultimately contributing to a comprehensive
 148 understanding of the intricate processes involved (Pala et al., 2017). The processes are
 149 modelled considering some assumptions. A steady-state condition is also assumed,
 150 considering that the system's variables, like sludge composition, remain constant to
 151 assess energy balances. Additionally, it is assumed that the pressure remains constant
 152 throughout the operations without losses. The turbine operates with isentropic
 153 properties, with an assumed isentropic efficiency of 0.7 and a mechanical efficiency of
 154 0.9, simplifying the modelling process for the turbine's performance (Brachi et al.,
 155 2022). The discharge pressure of the compressor, gas turbine and steam turbine are
 156 10 bar, 2 bar and 1 bar, respectively. Lastly, the ash in the sludge is inert and not
 157 included in any potential reactions or interactions. The sewage sludge composition
 158 was adapted from the research conducted by Ghodke et al. (2021), with detailed
 159 ultimate and proximate analyses elucidated and organised in Table 1. The model's
 160 details are laid down further in the study for each process.

161 Table 1: Ultimate and Proximate Analysis of sewage sludge

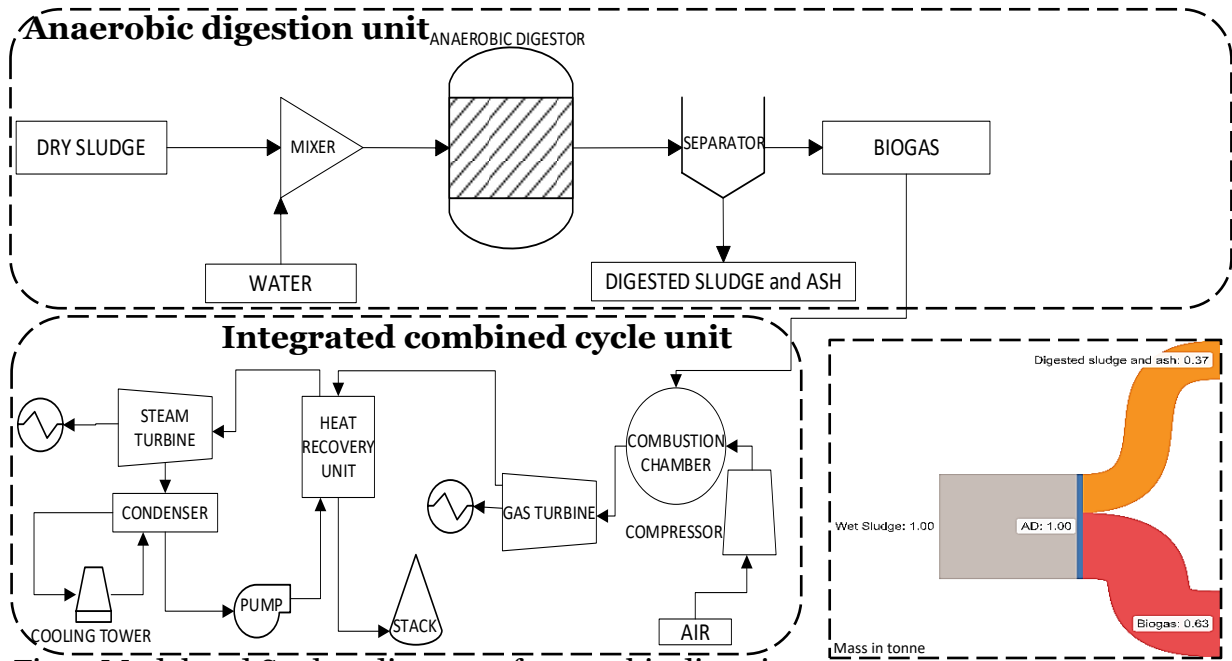
Ultimate analysis (weight %)		Proximate analysis (weight %)	
Carbon	37.95	Ash	27.7
Hydrogen	4.51	Volatile matter	50.9
Nitrogen	2.75	Fixed carbon	9.1
Sulphur	0.73	Moisture content	12.3

162

163 **2.1.1 Anaerobic digestion modelling**

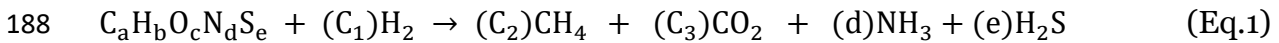
164 The AD process and mass flow (tonne/hr) illustrated in Fig 3 depicts the wet sludge
 165 (with 27% moisture content) that enters the AD reactor. In the model, an equation
 166 (Eq.1) has been used to conceptualise and represent the complex biological reaction in
 167 AD. The model is designed considering the assumption that the system is steady and
 168 that the temperature change or the microbial activity is not interrupting the process.
 169 Also, the authors assumed a complete conversion of the sludge into gases and digested
 170 sludge. Water and optional additives play pivotal roles in the process by facilitating the
 171 breakdown of organic matter in sewage sludge. The breakdown yields two valuable
 172 resources: biogas and digested sludge. Biogas, a renewable energy source generated
 173 through AD, holds significant potential for utilisation. The present study underscores
 174 the value of AD as a sustainable and multifaceted approach to sewage waste

175 management. Figure S1 and Table S1 of the supplementary document mention the AD
 176 model's mass flow details.



177
 178 Fig 3: Model and Sankey diagram of anaerobic digestion process

179 In the present study, the authors investigated the potential of the AD process
 180 for extracting products from sewage sludge. The process started by introducing sewage
 181 sludge under ambient conditions (25°C and 1 bar) into an anaerobic digester, which
 182 was combined with water to form a slurry. This slurry underwent controlled
 183 disintegration at 37°C, governed by the well-established Boyle-modified Buswell and
 184 Mueller reactions described in Eq.1 (Achinas and Euverink, 2016). Subsequently, a
 185 separator was employed to efficiently extract biogas from the resulting mixture,
 186 separating it from the digested sludge. The obtained biogas was then channelled into
 187 gas and steam turbines, serving as a feedstock for generating electricity.



189 i. $C_1 = a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}$

190 ii. $C_2 = \frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}$

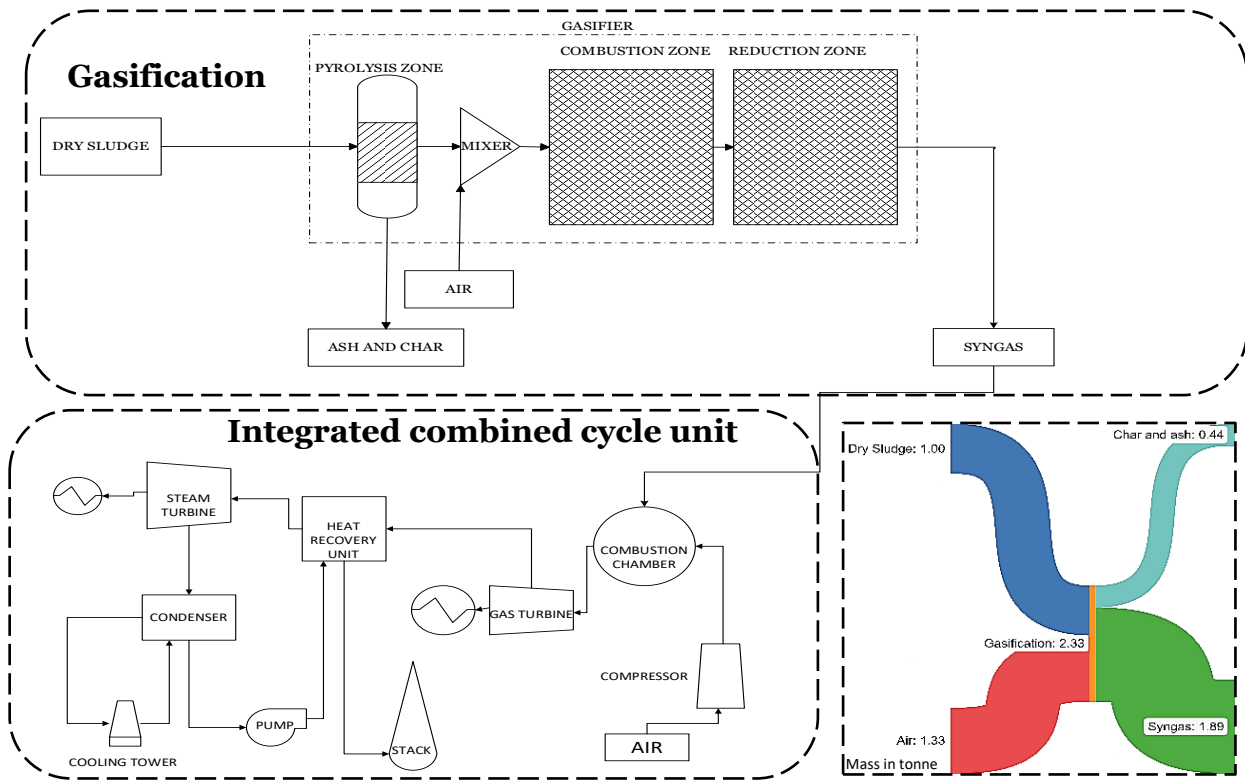
191 iii. $C_3 = \frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}$

192

193 2.1.2 Gasification modelling

194 Gasification is a well-known process used to gasify coal and biomass. The
 195 gasification model used for analysis and mass flow (tonne/hr) are depicted in Fig. 4.

196 Model simulation encapsulates three sequential stages: the pyrolysis, combustion, and
 197 reduction zones. Each stage is pivotal in orchestrating the intricate process of
 198 transforming sewage sludge into energy products like syngas and char. In the process,
 199 tar as a by-product is not considered. The details of the mass flow of the gasification
 200 model are mentioned in Figure S2 and Table S2 of the supplementary document.



201
 202 Fig 4: Model and Sankey diagram of the gasification process

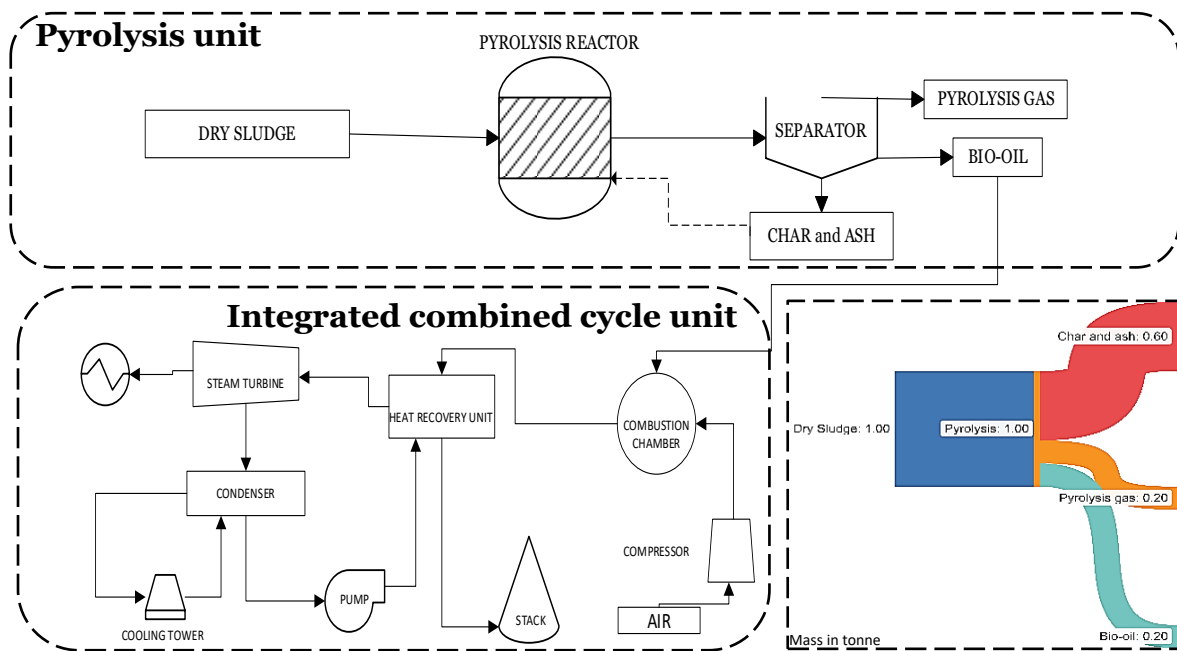
203 Sewage sludge is initially introduced into the pyrolysis block at ambient
 204 conditions (25°C and 1 bar). In the pyrolysis zone of the model, the sewage sludge
 205 effectively disintegrates into its constituent elements and products. The pyrolysis
 206 process's temperature profile aligns with the research insights of Kim et al. (2022),
 207 ensuring a robust correlation between the resultant product yield and temperature
 208 variations. Subsequently, the resulting gases from the pyrolysis stage blend with air to
 209 maintain an equivalence ratio (ER) of 0.25. ER is a critical factor in optimising the air
 210 gasification process. The significance of the ER in modulating the reaction mechanism
 211 and syngas composition is highlighted in the findings of Khan et al. (2022). The
 212 compound produced from the pyrolysis zone moves into the combustion and
 213 reduction zones. Specific kinetic reactions govern these zones. The reactions were
 214 adapted from the work of Puig-Gamero et al. (2021) offers deeper insights into the
 215 underlying mechanisms driving the gasification process. The reactions are in Table S3

216 with activation energy (E_a) and kinetic constant (k) values. The values govern the
 217 intricate reaction within the combustion and reduction zones. These reactions
 218 occurred at 800°C. Ultimately, the harnessed syngas is efficiently utilised to generate
 219 electricity and heat, facilitated by gas and steam turbines. This integrated approach
 220 optimally utilises the energy potential of syngas, highlighting a sustainable and
 221 efficient utilisation of sewage sludge-derived energy.

222

223 **2.1.3 Pyrolysis modelling**

224 The pyrolysis process and mass flow (tonne/hr) are depicted in Fig 5, which
 225 involves a one-step mechanism comprising the pyrolysis reactor for dry sludge and
 226 product. In the reactor, sewage sludge transforms into energy resources like bio-oil,
 227 pyrolysis, and bio-char. The details of the mass flow of the pyrolysis model are
 228 mentioned in Figure S3 and Table S4 of the supplementary document.



229

230 Fig 5: Model and Sankey diagram of the pyrolysis process

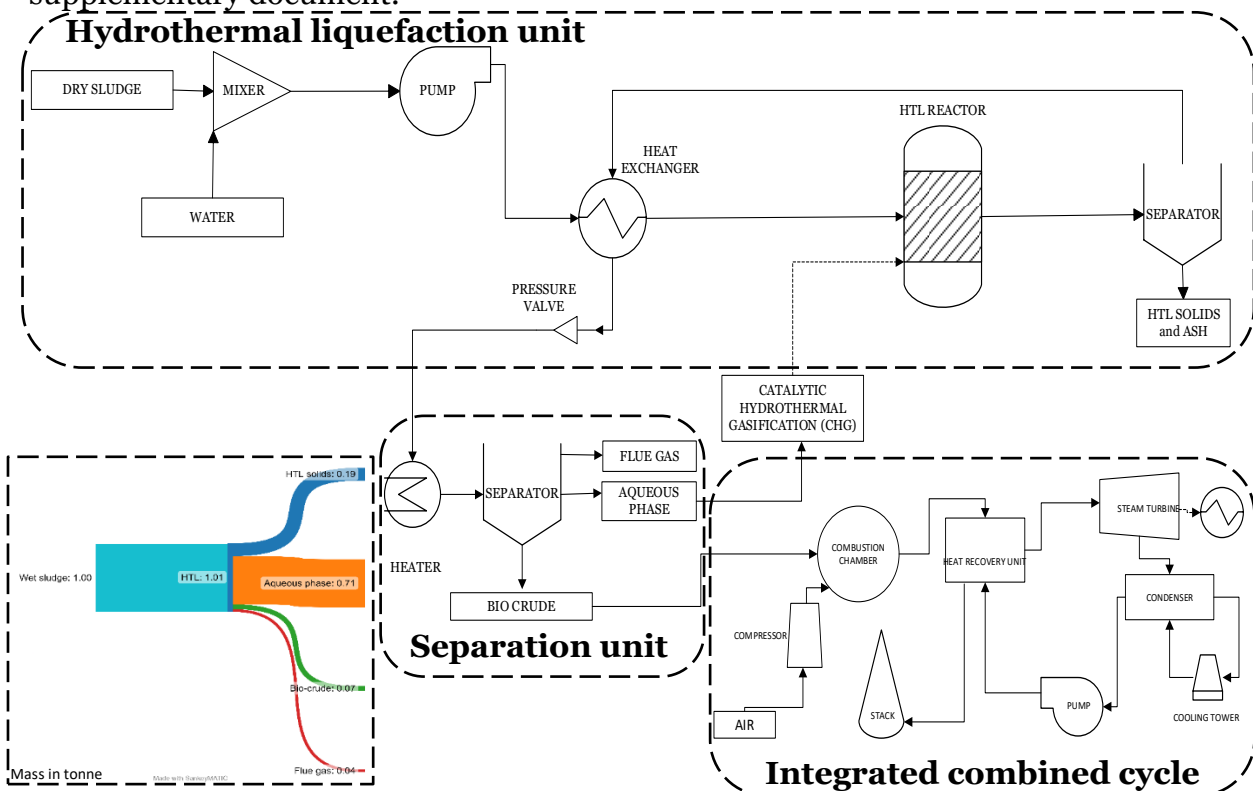
231 For the study, the pyrolysis model has adapted the yields from the experimental
 232 work on the pyrolysis of sewage sludge conducted by Ghodke et al. (2021). In the
 233 simulation, the initial introduction of sewage sludge into the reactor occurs under
 234 ambient conditions (25°C and 1 bar). Inside the reactor, the sewage sludge undergoes
 235 pyrolysis at 500°C, a process where the material is thermally decomposed in the
 236 absence of oxygen. This intricate thermal decomposition yields distinct products: char,
 237 bio-oil, and pyrolyzed gas. Bio-oil, a key output from pyrolysis, is directed towards
 238 energy production through combustion in a process that involves the utilisation of a

239 steam turbine. This combustion process harnesses the energy potential stored within
 240 the bio-oil, transforming it into electricity. Simultaneously, the char produced during
 241 the pyrolysis process is essential in sustaining the continuous thermal decomposition
 242 of sewage sludge to maintain the required temperature of the pyrolysis reactor. The
 243 unused or residual char is separated for potential further utilisation as a soil
 244 conditioner.

245

246 **2.1.4 Hydrothermal liquefaction modelling**

247 The HTL process and mass flow (tonne/hr) are illustrated in Fig 6 of the wet sludge
 248 (78% moisture content), a pivotal focus of investigation within this research. HTL
 249 involves a multi-stage mechanism centred around the HTL reactor, facilitating the
 250 transformation of sewage sludge into products. The crux of the HTL process resides in
 251 pressurising and subjecting the biomass to high-temperature heating within the HTL
 252 reactor, creating an environment conducive to efficient transformation. The study
 253 endeavours to illuminate the transformative potential inherent in the HTL process,
 254 emphasising its role in sustainable energy generation and effective waste utilisation.
 255 The details of the HTL model are mentioned in Figure S4 and Table S5 of the
 256 supplementary document.



257

258 Fig 6: Model and Sankey diagram of the hydrothermal liquefaction process

259 The HTL model developed by the Pacific Northwest National Laboratory (PNNL)
260 is replicated to show the HTL process for transforming sewage sludge into products
261 (Pacific Northwest National Laboratory, 2017). The wet sludge enters at ambient
262 conditions (i.e., 25°C and 1 bar), which is pressurised and heated before entering the
263 HTL reactor. Within the reactor, the sludge undergoes a liquefaction process at a
264 350°C temperature and 200 bar pressure (Pacific Northwest National Laboratory,
265 2017). HTL solids, i.e., ash and char, are separated from the fluid using a dedicated
266 separator. The process involves further pressurisation and heating to separate flue gas,
267 aqueous phase, and bio-crude in the fluid. The aqueous phase comprises high water
268 content and many components used for the heat requirements of the HTL reactor. The
269 aqueous phase is combusted in catalytic hydrothermal gasification (CHG). At the same
270 time, the bio-crude obtained from this process is then utilised to produce electricity,
271 typically via deployment in a steam turbine.

272

273 **2.2 Techno-economic assessment (TEA)**

274 Energy generation from waste plays a pivotal role in steering nations toward the global
275 goal of achieving net-zero emissions. Since environmental concerns and economic
276 considerations are intricately linked, TEA emerges as a crucial tool in evaluating the
277 economic viability of energy systems and the feasibility of each energy production
278 pathway: the influence of various factors can be analysed to gain insights into the
279 technology's potential lifespan, capital costs, operational expenses, and revenue
280 generation through electricity production and selling of end products.

281 The TEA model for wet biomass developed by PNNL has been adopted for the
282 HTL process (Pacific Northwest National Laboratory, 2017). The underlying
283 assumptions applied to the original model of PNNL are also applied to other
284 processing units for consistency. The Chemical Engineering Plant Cost Index (CEPCI)
285 factor is introduced to address the dynamic economic landscape for current pricing
286 adjustments, and the CEPCI is adapted from Chemical Engineering magazine (Gu et
287 al., 2023; The University of Manchester, 2022). The consumer price index is used to
288 adjust the different-year inflation rate (Ministry of Statistics and Programme
289 Implementation, 2024). The processing units are scaled down using the scaling factor
290 or power law. Also, the fixed cost is adjusted as per the plant's location in the case of
291 study, i.e., India. For India, the location factor of 0.65 is used. A location factor is
292 applied to represent the difference in construction cost of the plant from the original

293 location. The electricity selling price in India typically varies from 0.066 to 0.09
 294 \$/kWh. The price variation is due to different tariff rates of waste to electricity in
 295 different states of India. For instance, the Delhi electricity regulatory commission
 296 ordered a tariff rate of 7.38 INR/kWh (0.088 \$/kWh) (Bhawan, 2023). In the case of
 297 processing units, several assumptions are made to conduct a thorough TEA. The
 298 assumptions are tabulated in Table 2.

299

300 Table 2: Assumption for TEA

Parameter	Value	Reference
Plant Life	25 years	
Base year	2023	
Feed flowrate	20 tonne/day	
Operating hours	7920 hr/year	
Exchange rate (INR–USD)	0.012	based on November 2023
Electricity selling price	0.078 \$/kWh	
Char	0.15 \$/kg	(Govt of Uttarakhand-India, 2018)
Digested sludge	0.07 \$/kg	(Glivin and Sekhar, 2020)
Syngas	0.15 \$/kg	(IOCL, 2023)
Bio-oil	0.52 \$/litre	(Phusunti and Cheirsilp, 2020)
Biogas	0.30 \$/kg	(IOCL, 2023)
Bio crude	0.54 \$/litre	(Ministry of Petroleum & Natural Gas, 2023)
Electricity purchase price	0.10 \$/kWh	(Bernard et al., 2024)
Discount rate	10%	--

Silica sand	3\$/day	(Gu et al., 2023)
Polyelectrolyte	1.24 \$/kg	(Bernard et al., 2024)
Natural gas	9.20\$/mmBtu	(Ministry of Petroleum & Natural Gas, 2023)
Staff expense (SE)	0.08 million \$/year	--

301 Factors influencing purchase and installation are determined based on the
302 PNNL HTL economic model (Pacific Northwest National Laboratory, 2017). HTL
303 evaluation encompasses an in-depth analysis of numerous factors, and the equipment
304 cost is obtained from the PNNL HTL model, laying a robust economic assessment of
305 HTL within the waste-to-energy domain (Seiple et al., 2017). The purchase cost of the
306 CHG for HTL aqueous phase treatment was derived from the study by Zhu et al.
307 (2019). For a comprehensive evaluation of AD, equipment cost is sourced from the
308 study by Paritosh et al. (2021). The equipment cost of the gasification model is
309 obtained from the National Renewable Energy Laboratory (NREL) biomass
310 gasification model (Spath et al., 2005). Meanwhile, the pyrolysis process equipment
311 cost is obtained from the NREL biomass gasification model and the study by Gu et al.
312 (2023). For the drying of the sludge, polyelectrolyte is considered at 2 g/kg of dry
313 sludge, and the belt press filter is considered at 60 kWh/tonne of dry sludge (Hao et
314 al., 2020; Wójcik and Stachowicz, 2019). The details of the equipment used in
315 processing units are tabulated in Table 3.

316 Table 3: Details of equipment unit

Processing unit	Equipment	Equipment		
		cost (million USD)	Capacity (tonne/day)	Location factor
Common	Feed Handling & Drying	\$18.90	2000	0.65
Common	Steam System and Power Generation	\$14.20	2000	0.65

Gasification	Gasification, Tar Reforming, and quench	\$16.80	2000	0.65
	Cooling Water and Other Utilities	\$3.40	2000	0.65
Pyrolysis	Pyrolysis reactor	\$0.16	997.90	0.65
	Cyclone	\$0.03	997.90	0.65
HTL	HTL Reactor System: Pumps, heat integration, HTL reactor, knockout drums	\$11.34	99.79	0.65
	Phase separation	\$1.12	99.79	0.65
	Hot oil system for reactor and trim heater	\$0.64	99.79	0.65
	Sludge dewatering	\$1.43	99.79	0.65
	other equipments	\$0.62	99.79	0.65
	CHG	\$28.55	7100	0.65
Anaerobic digestion	Grinder	\$0.01	68.58	1.00
	Solid-liquid separator	\$0.01	68.58	1.00
	SSAD digester with insulation	\$0.04	68.58	1.00
	Mixer, Pump, and other accessories	\$0.02	68.58	1.00

317 In addition to purchasing cost of equipment, costs are incurred to put the
 318 equipment in place at the plant site. The details of the breakout of the cost component
 319 are mentioned in Table 4 and Figures S5 and S6.

320 Table 4: Breakout of cost component

Cost component of capital investment		Cost component of operation cost	
Total installed cost (TIC)	Obtained from equipment installed and purchase cost	Overhead & maintenance cost (OMC)	90% of SE
Building cost (BC)	4% of TIC	Maintenance capital cost (MCC)	3% of TIC
Site development cost (SDC)	10% of TIC	Insurance and taxes cost (ITC)	0.7% of FCI
Additional piping cost (APC)	4.5% of TIC	Total Fixed Cost	OMC+MC C+ITC
Total direct cost (TDC)	TIC+BC+SDC+APC		
Total indirect cost (TiC)	60% of TDC		
Fixed capital investment (FCI)	TDC+TiC		
Working capital (WC)	5% of FCI		
Total capital investment (TCI)	FCI+WC		

321

322 **3. Results and discussion:**

323 The present study rigorously examined the intricate hurdles and potential
 324 opportunities inherent in sewage sludge management, recognising its untapped
 325 potential as an energy source.

326

327 **3.1. Validation of models**

328 The results of the gasification model are compared to the results of the study by Brachi
 329 et al. (2022) for a temperature of 800°C and an equivalence ratio of 0.25, as shown in
 330 Figure S7. The comparison shows a close agreement between both studies on the
 331 syngas flow rates: 0.72 kg/s in the present work; Brachi et al. (2022) reported a slightly

332 higher value of 0.78 kg/s. However, the presented model provides a similar trend of
333 mole fraction as Brachi et al. (2022). The reasons for these differences are probably
334 linked to the temperature, which was fixed to a uniform value of 800°C, while in
335 reality, the temperature is varying in the reactor, changing the reaction constants.

336 The pyrolysis process is versatile and capable of yielding various products
337 simultaneously. While numerous studies have centred on producing char for
338 agricultural applications, the present study focuses on harnessing energy specifically
339 from the bio-oil generated (Racek et al., 2020; Raj et al., 2021). To ensure the
340 credibility and reliability of the findings, the outcomes obtained from the present
341 model from pyrolysis have been validated against the results presented by the Ghodke
342 et al. (2021) experiment. The product yield quantity composition from the present
343 model is similar to the study of Ghodke et al. (2021). Table S6 shows the bio-oil
344 composition through the model.

345 The AD process is used for sewage sludge management, and its primary output
346 is biogas. Biogas comprises methane, carbon dioxide, and traces of gases (such as
347 hydrogen sulphide and ammonia), with a general spanning composition range of 50–
348 75% methane and 25–50% carbon dioxide (Khanh Nguyen et al., 2021). The present
349 model shows a composition of 49% methane, 45% carbon dioxide, and 6% trace of
350 hydrogen sulphide and ammonia. As per the International Energy Agency (IEA)
351 report, biogas production consists of around 63-64% of methane generated from
352 sewage sludge (Bachmann, 2015). 0.15 ML/hr of methane is computed against 0.17
353 ML/hr of methane as per the IEA.

354 The HTL model in the present study is a replica of the Aspen Plus model
355 developed by PNNL (Pacific Northwest National Laboratory, 2017). The parameters
356 and calculations within the present model are well-validated simulations. Moreover,
357 the flow rates derived from the present model are consistent with those derived from
358 the PNNL model, affirming the accuracy and reliability of the model's predictions
359 regarding the HTL process. The bio-crude production rate in the HTL process in the
360 present study is 3896.52 kg/hr, equivalent to the 3897 kg/hr of the PNNL model. Table
361 S7 shows the bio-crude composition through the model.

362 The sensitivity of various processing units to different parameters significantly
363 affects their output. The pyrolysis zone's unconverted char factor is critical in
364 gasification. A 10% decrement in the unconverted char factor results in change in NPV
365 to 12.66M\$. Meanwhile, a 10% increase in the unconverted char factor results in

366 doesn't show any increase in NPV. The limited increment in hydrogen mole fraction is
367 probably due to the restriction of reactions at an equivalence ratio (ER) of 0.25. For
368 pyrolysis, a $\pm 10\%$ variation in the char mass yield within the reactor NPV to 5.49 M\$,
369 and 5.17 M\$ respectively. As in pyrolysis, NPV is governed by bio-oil production rather
370 than char. So, any change in bio-oil has an impact on NPV. While in anaerobic
371 digestion, a $\pm 10\%$ variation in water content in the sludge within the digester variate
372 the NPV from 12.93 to 14.03 M\$. As in AD, NPV is governed by biogas production
373 rather than digested sludge. So, any variation in biogas has a significant impact on
374 NPV. In the HTL process, changing the water content by $\pm 10\%$ results in NPV change
375 ranging from -2.52 to -2.39 M\$. Additionally, a 10% decrease in sludge mass leads to
376 a NPV reduction to 12.71 M\$, 11.38 M\$, 4.87 M\$ and -3.08 M\$ of AD, gasification,
377 pyrolysis and HTL with their primary and by-product, respectively. While a 10%
378 increase in sludge mass to leads to increment in NPV to 14.26 M\$, 13.15 M\$, 5.76 M\$
379 and -1.83 M\$ of AD, gasification, pyrolysis and HTL with their primary and by-
380 product, respectively.

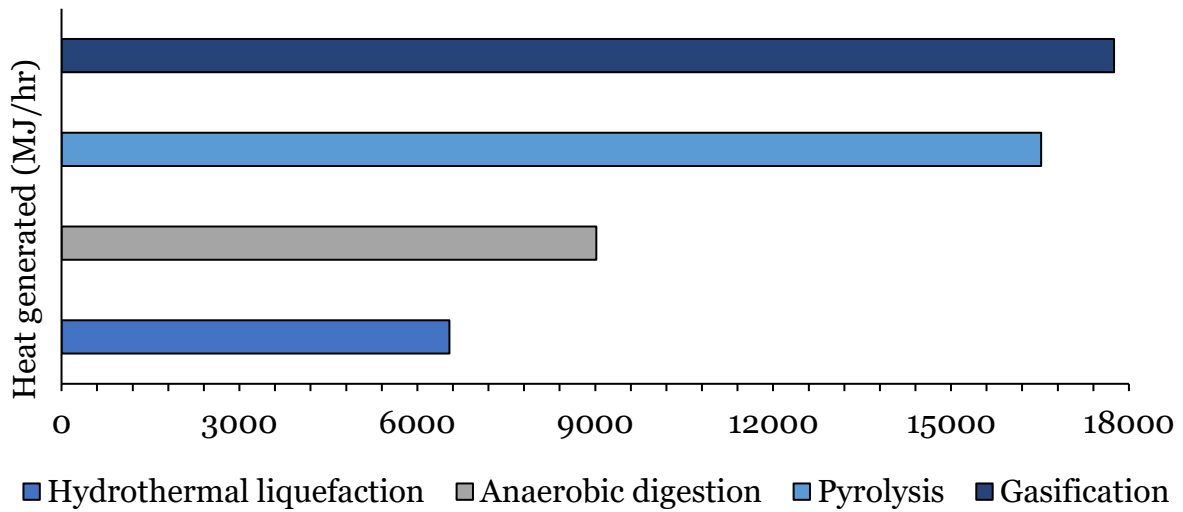
381

382 **3.2. Analysis of feedstock to heat:**

383 The processing unit's primary product's lower heating values have been
384 illustrated in Figure S8, distinctly showing their energy content. The specific low
385 heating values of bio-oil from pyrolysis, the syngas from gasification, biogas from AD,
386 and biocrude from HTL show the variations in the inherent diversity in energy content
387 from the same feedstock. Such distinctions highlight the applications and
388 potentialities inherent in energy production and utilisation strategies derived from
389 sewage sludge, emphasising the significance of considering these variations in
390 optimising energy recovery methods.

391 Countries above the tropic of cancer, like the EU, experience longer periods of
392 wintry weather, leading to significant and continuous heat requirements throughout
393 the year. 44% of the primary energy supply for residential heating for EU-28 is fulfilled
394 by natural gas (Bertelsen and Vad Mathiesen, 2020). Sludge processing units can
395 generate heat through the combustion of various products, each with its unique lower

396 heating value and, hence, its heating capacity. The data in Fig 7 shows the potential for
 397 heat production by the daily processing of 20 tonnes of dry sludge.



398
 399 Fig 7: Heat generated by processing units (MJ/hr)

400
 401 **3.3. Analysis of feedstock to products:**

402 NPV is performed based on the prices of different outputs from different
 403 processing units. NPV is computed based on sales of primary and secondary products
 404 from different processing units. The equation for NPV is mentioned in Eq.2. The
 405 results of NPV are in Table S8 for a large-capacity treatment plant processing for 100
 406 MLD wastewater treatment. AD proves favourable economic results, followed by
 407 gasification regarding financial viability and positive economic implications.

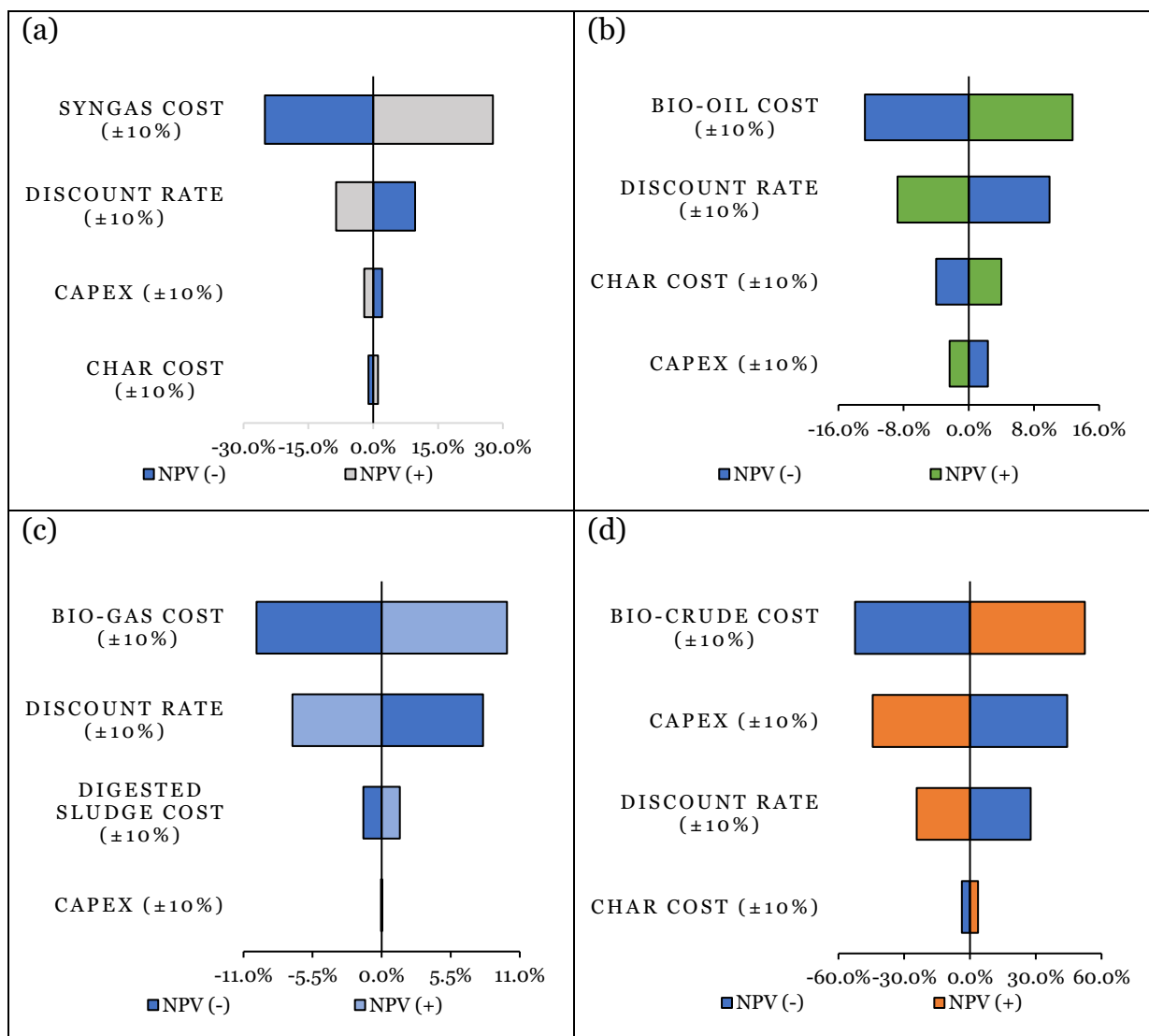
408
$$NPV = \sum_{t=0}^N \frac{(TR-TC)_t}{(1+discount\ rate)^t} \quad (Eq.2)$$

409 TR= Revenue from products and by-products

410 TC= Capital cost and operational cost

411 t= time (years)

412 The sensitivity analysis conducted on various parameters affecting the techno-
 413 economic aspects of different processes reveals the influence of specific factors on the
 414 NPV. Understanding the sensitivity of the NPV to ±10% of the variation of primary
 415 and secondary product cost, discount rate, and capital cost is crucial for
 416 comprehending a processing unit's economic viability and resilience as a sewage
 417 sludge management method. The sensitivity analysis in Fig 8 (a)-(d) provides crucial
 418 insights into the techno-economic analysis of gasification, pyrolysis, AD and HTL.



419 Fig 8: Sensitivity analysis of NPV for different parameters in the techno-economic
 420 analysis of (a) Gasification, (b) Pyrolysis, (c) Anaerobic digestion and (d) Hydrothermal
 421 liquefaction

422 Gasification reveals that minor shifts in char cost marginally impact NPV, while in
 423 pyrolysis, a $\pm 10\%$ change in char cost triggers a noticeable change of $\pm 1.1\%$ NPV. AD,
 424 conversely, displays slight sensitivity as digested sludge cost induces a $\pm 1.4\%$ NPV
 425 fluctuation. HTL, however, diverges significantly with a $\pm 10\%$ alteration in char cost,
 426 resulting in a substantial NPV change of $\pm 3.7\%$. In these processes, the influence of
 427 secondary product, i.e., char and digested sludge cost, on NPV seems limited, except
 428 in pyrolysis, where the significant production volume of biochar notably contributes
 429 to revenue. Gasification and pyrolysis show moderate impacts, with variations in $\pm 10\%$
 430 CAPEX affecting NPV by around $\mp 2.1\%$ and $\mp 2.4\%$, respectively. AD contrasts these
 431 findings by showing no sensitivity to CAPEX, while HTL significantly varies,

432 witnessing NPV influence of $\mp 44.4\%$ for $\pm 10\%$ CAPEX change, highlighting its
433 considerable impact on project feasibility. HTL's initial higher investment than other
434 processes drive the high NPV variation. The discount rate emerges as a pivotal factor
435 across all processes. Gasification, pyrolysis, and AD showcase NPV change ranging
436 from a -8.6% decrease to an 9.7% increase, a -8.8% decrease to a 9.9% increase, and a
437 -7.1% decrease to an 8.1% increase, respectively with $\pm 10\%$. HTL stands out, exhibiting
438 substantial NPV fluctuations from a -24.4% decrease to a 27.3% increase, emphasising
439 its significant role in determining economic feasibility. This rate heavily influences
440 these processes by governing the system's interest returns and financial costs.
441 Moreover, primary products like syngas, bio-oil, biogas, and bio-crude play pivotal
442 roles, significantly contributing to overall revenue generation. This complex
443 interaction of diverse factors underlines their varying impacts on the economic
444 feasibility of sewage sludge processing methods.

445 The sensitivity analysis of various processing units can be effectively compared
446 with in-depth studies conducted on each specific processing unit. Considering the
447 gasification unit, the present study shows a similar result as Alves et al. (2021) for
448 $\pm 10\%$ change in capital cost. Whereas for the pyrolysis unit, the present study shows
449 2.6 times less change for $\pm 10\%$ change in capital cost as Patel et al. (2022). The Patel
450 et al. (2022) study has more equipment than the present study. However, while
451 considering the AD unit, the results can be compared with the study by Ogbu et al.
452 (2023). A $\pm 10\%$ fluctuation in discounted prices reveals a 14% increase in NPV and a
453 12% decrease, a deviation that is half the magnitude reported by the authors. This
454 deviation from the author's findings could be attributed to the high revenue flow in the
455 present study. Additionally, when examining a $\pm 10\%$ change in capital costs, Ogbu et
456 al. (2023) observed a corresponding $\pm 10\%$ alteration in NPV, contrasting with the
457 authors' findings, which indicated no change. This discrepancy could be due to the
458 lower capital cost associated with AD technology in India, which is a well-established
459 technology in the country.

460

461 **3.4. Analysis of product to electricity:**

462 Considering the utilisation of sewage sludge to derive main products alongside
463 secondary products such as char from HTL, gasification, pyrolysis, and digested sludge
464 from AD in each process, the focus lies on transforming these into electricity. The

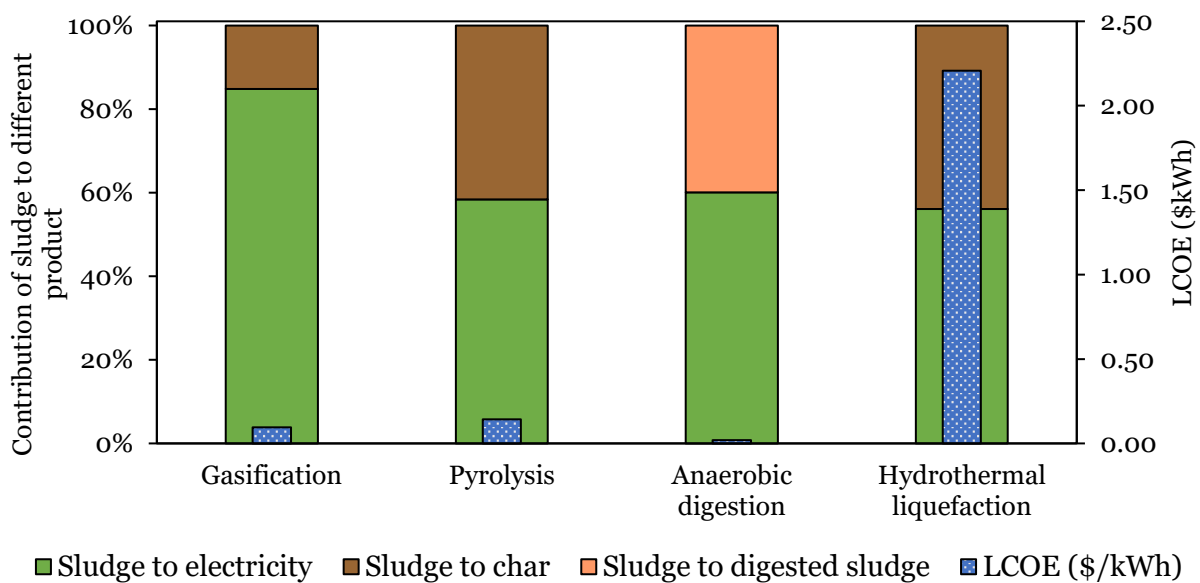
465 models account for heat integration and detailed analysis. Electricity generation can
 466 utilize combined heat and power (CHP) or combined-cycle gas turbine (CCGT)
 467 technologies, each with distinct advantages: CHP is less expensive, while CCGT
 468 generates more electricity. The difference can be seen in the Fig S9. In the context of
 469 India, where the demand for heat is relatively low compared to regions like the EU-27
 470 and the USA, CCGT is more suitable due to the higher electricity demand. The present
 471 study focuses on electricity generation, aligning with India's energy needs. CCGT
 472 cycles offer higher efficiency and output in electricity generation than CHP processes,
 473 making them a better fit for our objectives. Additionally, standardizing CCGT
 474 technology across all processes allows for a more straightforward comparison of their
 475 techno-economic feasibility, ensuring an accurate evaluation of each process's
 476 performance and economic viability.

477 The authors also tried to explain that the extraction of electricity from the
 478 primary products aligns with maximising the energy potential of sewage sludge while
 479 streamlining the analysis by prioritising primary product conversion. The details are
 480 depicted in Fig 9 (where by-products are neglected for the analysis), and the figure
 481 also depicts each processing unit's levelized cost of electricity (LCOE). The equation
 482 used to compute the LCOE is expressed in Eq. 3.

$$483 \text{ LCOE} = \frac{(\text{TCI} \cdot \text{CRF}) + \text{operating cost}}{\text{Net electricity generated}} \quad (\text{Eq.3})$$

484 TCI= Total capital investment

485 CRF= Capital recovery factor



486

487

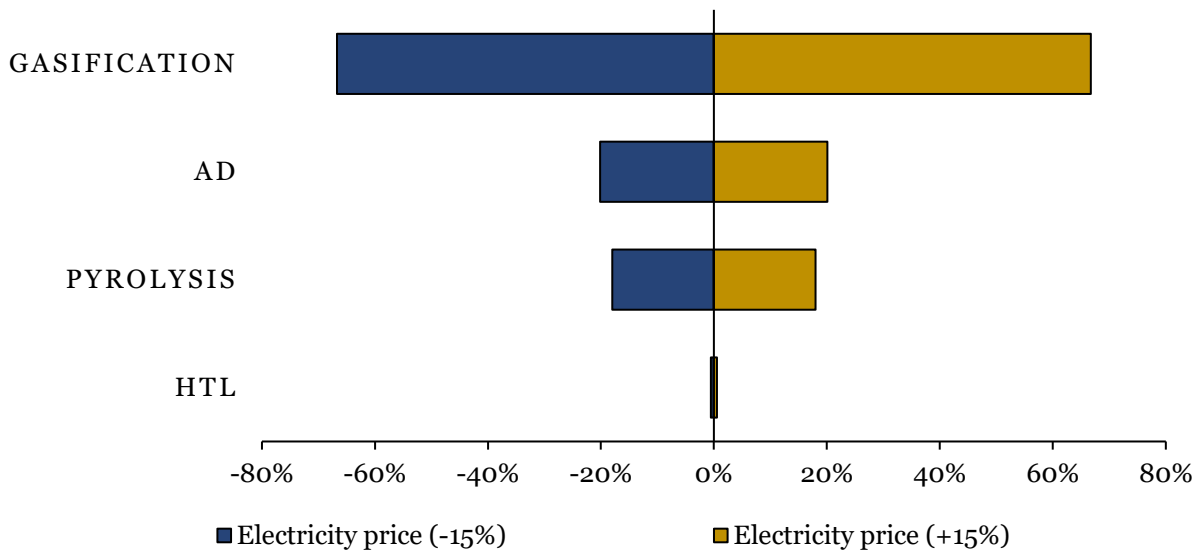
Fig 9: Conversion of sludge to product and LCOE (\$/kWh)

488 The technical analysis reveals that gasification appears to be the most
489 promising method, producing 0.88 kWh/kg_{drysludge} using approximately 85% of the
490 sewage sludge. Using 57% and 58% of the sludge, HTL and pyrolysis generate 0.13
491 kWh/kg_{drysludge} and 0.34 kWh/kg_{drysludge}, respectively. Meanwhile, AD produces 0.66
492 kWh/kg_{drysludge}, which uses 61% of the sludge while producing 39% of the digested
493 sludge (including ash content). However, when assessing the LCOE, AD demonstrates
494 the lowest value, falling below the sale price range for the waste-to-electricity range in
495 India. While considering electricity pricing and the cost of secondary products, AD
496 appears to be the only process displaying positive results in NPV. The outcome for
497 electricity and secondary product sales is shown in Table S9. AD exhibits favourable
498 results, followed by gasification, regarding financial viability and positive economic
499 implications.

500 The LCOE for the gasification process can be compared with the study
501 conducted by Ram et al. (2023), which investigated the LCOE for biomass gasification
502 across different states in India. The study by Ram et al. (2023) reported an LCOE of
503 \$0.10/kWh for air gasification. In the present work, the authors obtained an LCOE of
504 \$0.10/kWh for the gasification process, considering that the sludge feedstock is
505 available at no cost. However, the authors' LCOE appears to be elevated due to the
506 inherent characteristics of sludge, which possesses a lower Carbon-to-Hydrogen
507 (C/H) ratio. This lower ratio adversely impacts electricity production, thus
508 contributing to the observed higher LCOE value. AD results can be compared with the
509 study conducted by Ogbu et al. (2023). In their study, they demonstrated the potential
510 of AD in comparison with incineration. The sludge generation was considered to be
511 approximately 1 kg per 100 L, leading to the generation of around 0.04 kWh/kg of wet
512 sludge. Considering 5% dry sludge content obtained from wet sludge, the energy
513 generation potential is approximately 0.98 kWh/kg_{dry sludge}. Notably, this calculated
514 value might be higher than reported in the authors' work due to certain assumptions
515 about methane generation and electricity conversion.

516 The study explored the impact of varying electricity selling prices Through a
517 sensitivity analysis, within the range of 0.066 to 0.09 \$/kWh ($\pm 15\%$) on the NPV
518 associated with different processing units by selling electricity with secondary
519 products. Higher electricity selling prices corresponded to increased NPV for specific
520 processing methods, whereas lower prices resulted in reduced NPV figures. The
521 findings underscored the significance of electricity selling prices in determining each

522 processing unit's economic feasibility and attractiveness in sewage sludge
 523 management for energy generation. These insights, visually represented in the
 524 accompanying Fig 10, offered a clear depiction of the sensitivity of NPV to changes of
 525 $\pm 15\%$ in electricity selling prices.



526

527 Fig 10: Sensitivity analysis of NPV on electricity price selling change ($\pm 15\%$)

528 Gasification shows remarkable sensitivity to changes in electricity selling prices,
 529 displaying a strong positive correlation. A 15% change in electricity selling price yields
 530 a substantial $\pm 67\%$ NPV change. This responsiveness indicates gasification's potential
 531 as an economically favourable option, particularly under scenarios with higher
 532 electricity selling prices, because revenue generation is balanced between char and
 533 electricity production. However, when the present study is compared with the Alves et
 534 al. (2021) study, the present study results show double the fluctuation. This is possibly
 535 due to the higher influence of electricity prices on the NPV. AD and pyrolysis also show
 536 sensitivity to electricity price changes, albeit to a lesser extent than gasification. Both
 537 processes show positive correlations between electricity selling price change and NPV.
 538 A $\pm 15\%$ change in electricity price results in a $\pm 20\%$ NPV change for AD, which is
 539 comparable to a study by Ogbu et al. (2023). The Ogbu et al. (2023) studies show $\pm 24\%$
 540 NPV change for $\pm 20\%$ electricity selling price change. Whereas $\pm 18\%$ change for
 541 pyrolysis, as its high char production from sewage sludge processing. In contrast, HTL
 542 displays minimal sensitivity to changes in electricity selling prices among the studied
 543 processing units. HTL demonstrates minimal NPV fluctuations in response to
 544 electricity price variations, indicating a minor impact of these changes, likely due to its

545 higher initial investment, which contributes less significantly to NPV through
546 electricity revenue.

547 By-products such as biochar and digested sludge not only generate revenue but
548 also have a significant positive impact on the environment. The present study shows
549 that a $\pm 10\%$ change in the cost of these by-products can lead to a notable $\pm 1-4\%$
550 variance in the NPV. Commercializing biochar, produced through gasification,
551 pyrolysis, and hydrothermal liquefaction (HTL), is financially profitable. Biochar from
552 thermochemical processes like pyrolysis and gasification has specific applications
553 based on its properties. Due to its neutral to alkaline pH, biochar can be used to
554 modulate soil pH and lock carbon for extended periods, making it reliable for carbon
555 sequestration. When applied to soil, biochar improves environmental restoration and
556 increases soil quality and fertility (Oliveira et al., 2017). Additionally, biochar helps
557 reduce nutrient leaching and effectively removes organic pollutants from soil,
558 including fungicides, herbicides, pesticides, and insecticides (Oliveira et al., 2017; Oni
559 et al., 2019). Its environmental benefits include carbon sequestration and reduced
560 N₂O emissions (Cayuela et al., 2014; Yang et al., 2016).

561 Similarly, digested sludge enhances soil quality, improves agricultural practices,
562 and fosters soil fertility. There is a significant potential for nutrient recovery from
563 digested sludge, particularly essential nutrients like nitrogen (N), phosphorus (P), and
564 potassium (K). Anaerobic digestion (AD) degrades organic matter, increasing the
565 concentration of total ammonia nitrogen (TAN) and ortho-phosphate, which plants
566 easily assimilate. This process not only recycles valuable nutrients back into the soil
567 but also supports sustainable agriculture by reducing the need for synthetic fertilizers
568 (Di Costanzo et al., 2021). However, quantifying the direct environmental benefits of
569 these by-products remains a challenging aspect that requires further research.

570 Recovering minerals and nutrients in the sewage sludge benefits the environment.
571 In particular, phosphorus from sludge holds significant environmental and economic
572 potential. Excess phosphorus in wastewater can lead to eutrophication, negatively
573 impacting aquatic ecosystems. Recovered phosphorus can be utilized for soil
574 fertilizers, which can lower the extraction of traditional phosphorus fertilizers
575 (Montalvo et al., 2020). This will help boost the production rate of phosphorus
576 fertilizers, which declines due to the depletion of available phosphorus resources, so
577 searching for new, sustainable sources of phosphorus is essential. Phosphorus
578 recovery typically involves several stages: solubilization or release, enrichment,

579 precipitation, and subsequent separation (Zhu et al., 2023). The economic feasibility
580 of phosphorus recovery is mainly dependent on the chosen process. Generally, the
581 operational costs associated with recycling phosphorus from sewage sludge are higher
582 than extracting it from the supernatant (Zhu et al., 2023). Thus, selecting an efficient
583 and cost-effective recovery process is crucial for the economic viability of phosphorus
584 recycling initiatives. The authors have kept the nutrient recovery out of the scope as
585 there is less possibility of recovery due to the lower quantity of sewage wastewater, and
586 it is less cost-effective.

587

588 **4. Limitations and future work:**

589 Anaerobic digestion displays promising attributes in terms of energy content,
590 electricity production, and positive economic analysis. However, its efficiency is
591 hindered by inherent limitations arising from biological treatment and the potential
592 presence of pathogens in the by-products (Zhao and Liu, 2019). Limitations like lower
593 carbon-nitrogen ratio lead to less generation of biogas and slow hydrolysis rate limit,
594 which leads to lower biodegradation efficiency and hydraulic retention time and
595 requires a large reactor size. ((Balasundaram et al., 2022; Gahlot et al., 2022; Park et
596 al., 2016). Gasification shows results closer to anaerobic digestion, and it can emerge
597 as a possible alternative if the capital investment is low.

598 As a thermochemical conversion process, gasification nullifies pathogen risks,
599 presenting potential benefits for India's hydrogen production plans (Tezer et al.,
600 2023). Despite the potential rise in syngas price, gasification's role in hydrogen
601 production can be significant. Pyrolysis offers a different route for sewage sludge
602 utilisation, yielding bio-oil and biochar. The bio-oil can be used as a transportation
603 fuel, especially in the context of growing fuel prices; it can be an alternative solution.
604 Conversely, hydrothermal liquefaction (HTL) appears less suitable for electricity
605 generation or transportation fuel from sewage sludge due to high capital and operating
606 costs. Overall, bioenergy produced from sludge can minimise GHG emission levels in
607 the environment (Srivastava et al., 2021). A detailed impact analysis is needed to
608 understand the contribution of each processing unit's product in mitigating the
609 emission.

610

611 **5. Conclusion:**

612 In the context of India, which is symbolic of a fast-growing economy with rapid
613 urbanisation, sewage sludge management emerges as an escalating challenge. As
614 sewage sludge production escalates, urgent utilisation solutions become imperative.
615 One critical question addressed in the present study is selecting the most suitable
616 processing unit, considering whether to sell the product or generate electricity directly.
617 Through a model-driven approach, this research sheds light on transforming sewage
618 sludge into green energy, unveiling its substantial potential for energy generation. The
619 findings underscore that pyrolysis has the highest energy content and gasification has
620 the lowest. However, when sludge is converted into electricity or heat, gasification
621 stands out by producing the highest electricity and heat output. However, when
622 economic considerations are factored in, AD emerges as the most economically viable
623 option in both scenarios—direct product sales and electricity generation. Gasification
624 is the second most economical among all the processing units. On the other hand, HTL
625 appears economically unfeasible and less viable for both energy generation and
626 economic returns. While these findings demonstrate the energy potential and
627 economic potential of these approaches, it is imperative to conduct further
628 environmental impact studies to ensure their sustainable implementation.

629 The present study contributes significantly to Sustainable Development Goal 7
630 (SDG 7) by exploring avenues for sustainable energy production from waste sources.
631 As India navigates the complexities of sewage sludge management, the present study
632 underscores the urgency for sustainable and pragmatic approaches to address
633 production challenges and leverage this resource's potential for sustainable energy
634 generation, aligning with broader sustainability goals.

635

636 **Credit author statement**

637 **Praveen Kumar Vidyarthi:** Conceptualisation, Methodology, Modelling, Analysis
638 and interpretation, Writing- Original draft; **Pratham Arora:** Supervision,
639 Conceptualisation, funding acquisition, Editing and Reviewing, Writing, Validation;
640 **Nadège Blond:** Supervision, funding acquisition, Editing and Reviewing; **Jean-Luc**
641 **Ponche:** Supervision, Editing and Reviewing

642

643 **Declaration of Competing Interest**

644 The authors declare that they have no known competing fiscal interests or personal
645 relationships that could have influenced the research work presented in this paper.

646

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654

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