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Comparing the environmental impacts of using bio-renewable and fossil- derived solvent in polymer membrane fabrications

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12 **Abstract**

13 Sustainable production methods for polymer membrane fabrication are gaining attention
14 due to concerns about the toxicity of conventional fossil-derived solvents in the
15 production process. In addition, the promotion of using chemicals from renewable source
16 for synthesis processes among industries and researches has increased to decelerate
17 resource depletion. As such, more benign and bio-renewable solvents,
18 dihydrolevoglucosenone (Cyrene™) and 2-methyltetrahydrofuran (2-MeTHF), have been
19 proposed as replacements for traditional fossil-derived solvents, n-hexane and
20 dimethylformamide (DMF). In this work, a life cycle assessment (LCA) was employed to
21 quantitatively evaluate the environmental impacts of using the aforementioned bio-
22 renewable solvents versus fossil-derived solvents for fabricating 1 g of polymer
23 membrane. The analysis adopted a cradle-to-gate perspective and assessed three
24 endpoint impact categories: Human health, Ecosystems and Resources. Despite lower
25 environmental impacts for producing bio-renewable solvents, using such solvents to
26 fabricate membranes displayed a higher environmental impact score in all endpoint
27 categories. This discrepancy was attributed to the lower yield of the membrane
28 fabrication process when using bio-based solvents. This indicated that further work is
29 needed to optimise membrane fabrication so that the benefits of using bio-based solvents
30 can be maximised.

31 **Keywords:** Membrane fabrication, bio-renewable solvent, life cycle assessment, LCA

32 **1. Introduction**

33 Organic solvent nanofiltration (OSN) is a sustainable pressure-driven membrane
34 separation process that enables organic solvent purification and valuable compound
35 recovery. This membrane-based process offers lower energy consumption, milder
36 operating conditions, and higher separation efficiency than traditional separation
37 processes, such as, distillation and chromatography. [1] At the heart of OSN is the thin
38 film composite polymer membranes, which are commonly fabricated *via* phase inversion
39 and interfacial polymerisation. [2] Phase inversion is used to produce porous support
40 layers while interfacial polymerisation is deployed for depositing a selective layer on the
41 porous support. In industry, the non-solvent-induced phase separation (NIPS) approach
42 is widely used for membrane production. [3] The NIPS process involves, first, producing
43 a porous support *via* phase inversion of a polymer dope solution containing a synthetic
44 polymer in an organic solvent. Following this, the porous support is soaked in an aqueous
45 polyamine solution and subsequently immersed in a water immiscible organic solvent
46 solution containing acyl chlorides, which react at the immiscible liquid interface to form
47 the selective layer. [4] Typically, the organic solvents used in NIPS are derived from fossil
48 fuels. Either dimethylformamide (DMF), dimethylacetamide (DMAc) or *N*-methyl-2-
49 pyrrolidone (NMP) is used to prepare the polymer solution in the porous support
50 production owing to their favourable physical properties, including their complete
51 solubility in water and high boiling points. [5, 6] Ascribing to its ability to dissolve acyl
52 chlorides whilst being water immiscible, n-hexane is used as the organic phase during
53 formation of the selective layer.

54

55 The use of fossil-derived solvents during membrane fabrication may compromise the
56 reported environmental sustainability of OSN. [7] These solvents contribute to
57 environmental pollution throughout their lifecycle, from production to disposal. One
58 well-known, long-term environmental issues is non-renewable resource exploitation,
59 which is consequently associated with global sustainability and climate change issues. [8]
60 Moreover, DMF, NMP and DMAc are categorised as 'substances of very high concern' per
61 the UK REACH regulation because of their reproductive toxicity and n-hexane presents
62 its own issues given its neurotoxic nature. [9, 10] Their use is subject to stringent
63 regulations and it is intended that they are gradually phased out of use. As a result,
64 traditional means of membrane fabrication is quickly becoming obsolete and the need for
65 a less hazardous and safer alternative is becoming more urgent.

66

67 Bio-renewable solvents, derived from bio-based feedstocks, have gained attention as
68 potential replacements for fossil-derived solvents in polymer membrane fabrication. [11-
69 13] These bio-renewable solvents comply with the principles of green chemistry, which
70 stipulate that hazardous solvents should be replaced with safer alternatives derived from
71 renewable feedstocks. [14] The use of bio-based feedstocks as raw material tackles
72 several of the issues associated with fossil fuel derived solvents, such as fossil fuel
73 depletion, carbon dioxide emissions and supply security. [15] Incorporation of bio-
74 renewable solvents has been reported in several organic synthesis processes, [16]
75 including thin film composite polymer membrane fabrication. The use of bio-renewable
76 solvents dihydrolevoglucosenone (Cyrene™) and 2-methyltetrahydrofuran (2-MeTHF) in
77 the membrane fabrication study has been reported. [17] Cyrene™, derived from sawdust
78 *via* the Furacell process, has physicochemical properties comparable to typically used

79 fossil-derived polar aprotic solvents during polymer solution preparation. [18] It does
80 not have any of the same carcinogenic, mutagenic or reproductive toxicity issues as its
81 fossil fuel derived counterpart. 2-MeTHF, a bio-based solvent derived from corncob,
82 exhibits partial miscibility in water, making it a potential replacement for n-hexane
83 during membrane fabrication. [19] This fabrication route represents a novel scenario
84 where benign solvent alternatives are used throughout the membrane fabrication
85 process, aiming to reduce the consumption of non-renewable resources, and
86 consequently, improve the overall process sustainability.

87

88 The concept of sustainability, which encompasses environmental, economic, and social
89 dimensions, has been vaguely claimed without quantitative measurement. To holistically
90 and quantitatively approximate one key aspect of sustainability, specifically the
91 environmental impact, in the context of membrane fabrication *via* the alternative bio-
92 renewable solvents, a life cycle assessment (LCA) framework was employed. An LCA is a
93 comprehensive environmental assessment technique developed to quantitatively
94 evaluate the environmental load of a system. [20] The principle of LCA is to compile data
95 on the material and energy flows exchanged with the environment over the life cycle of
96 the product, starting from raw material acquisition, through the production process,
97 product use, and final disposal or recycling, *i.e.* cradle-to-grave. This is then converted
98 into potential contributions to several environmental impact categories.

99

100 LCAs have been commonly used to assess the sustainability of bio-based processes. [21-
101 23] These studies are often carried out at various stages of process development to assess
102 the environmental feasibility of a given production route. [24] Per the ISO 14040 [25] and

103 ISO 14044 [26] standards, an LCA can be split into four distinct stages. Goal and scope
104 definition is the first step of an LCA, wherein the aim of the study is defined. Key
105 information, such as the intended application of the study, functional unit (parameter to
106 which all inlet and outlet flows are to be normalised) and system boundaries are
107 determined. The second step is the life cycle inventory analysis (LCI), where input and
108 output flow data are collected for each of the unit processes within the system boundary.
109 The unit processes can be categorised into foreground and background systems. The
110 foreground system encompasses the unit processes that are specific to the product
111 system being evaluated, while the background system is comprised of the unit processes
112 that are required to fulfil the foreground system, *e.g.* material inputs, waste
113 treatment/disposal. The next step is the life cycle impact assessment (LCIA), in which the
114 collected input and output data is used to calculate and assign results to several
115 environmental impact categories. Finally, in the life cycle interpretation, conclusions are
116 made from the findings and any limitations of the study are identified.

117 The purpose of this work was to investigate the environmental performance of a novel
118 membrane fabrication route, [17] referred to as the green route, which used bio-
119 renewable solvents (Cyrene™ and 2-MeTHF) compared to the conventional route
120 wherein fossil fuel-based solvents (DMF and n-hexane) were employed. The aim of this
121 green route was to replace the use of fossil-derived compounds, including solvents and
122 polymers, in TFC membrane fabrication with bio-renewable, benign alternatives. An
123 alternative material for fossil-derived polymers such as polyethersulfone,
124 polyacrylonitrile and crosslinked polyimide, that are widely used in the fabrication of
125 porous supports for TFC membranes is cellulose acetate. [27] A cradle-to-gate LCA was
126 carried out for 1 g of each membrane, considering the production of all input materials,
127 and employing the ReCiPe method to evaluate impact scores across three endpoint

128 categories: human health, ecosystems and resources. Despite the fact that the bio-based
129 solvents were in general more environmentally friendly than their fossil-derived
130 counterparts, it was found that across all endpoint impact categories, the green route
131 exhibited worse environmental impacts. This was attributed to the poor yield of
132 membrane fabrication when using bio-renewable solvents in traditional membrane
133 fabrication methods. This clearly indicated that novel membrane fabrication methods
134 should be developed to fully exploit the environmental benefits brought by bio-
135 renewable solvents. Incorporating membrane use, especially in the OSN application, into
136 the LCA was a suggestion for the future work, which may improve the environmental
137 performance of the green route. This is particularly relevant, given recently proposed
138 methods, such as spray coating, to enhance the separation performances of bio-
139 renewable-derived membranes. [28]

140

141 **2. Experimental method**

142 **2.1. Membrane fabrication**

143 ***2.1.1 Bio-renewable solvent employment (green route)***

144 The procedure for membrane fabrication comprised of two-steps: (1) preparation of a
145 porous support layer using one-step deacetylation-coagulation, (2) production of the
146 polyamide film using interfacial polymerisation (Figure 1).

147 Cellulose acetate is typically dissolved in co-solvent systems comprising DMF or NMP and
148 acetone. [29, 30] In this work, we chose to use Cyrene™ to replace NMP or DMF for
149 membrane fabrication as this is a proven strategy that improves the sustainability of
150 membrane fabrication. [31-33] However, this is the first time Cyrene™ is used to fabricate
151 cellulose acetate membranes. As such, we compared the Hansen solubility parameters of

152 cellulose acetate, Cyrene™ and NMP and DMF revealed that the relative energy distance
153 (RED) values for cellulose acetate with Cyrene™, NMP and DMF were 1.05, 0.87 and 0.36,
154 respectively. [34] This indicated that Cyrene™ may not dissolve cellulose acetate as well
155 as NMP. To improve the solubility of cellulose acetate in Cyrene™, we added acetic acid
156 into Cyrene™, reducing the RED value from 1.05 to 0.89. Hence a 3:1 ratio of Cyrene™ and
157 acetic acid was chosen here. This co-solvent system only fully dissolved cellulose acetate
158 at 80 °C after 8 hours of continuous stirring. Based on these observations, we prepared a
159 50 mL polymer dope solution was prepared by dissolving 17.5 w/v % cellulose acetate in
160 mixture of Cyrene™ and acetic acid (3:1) at 80 °C for 8 hours using a heated stirrer. This
161 solution was rest overnight to allow any bubbles to dissipate. The dope solution was cast
162 onto a glass plate using a casting knife (Elcometer 3700) and immersed in the coagulation
163 bath containing 0.05 M KOH and DI water (10 L). After removing supports from the bath,
164 they were rinsed with 30 mL of DI. The porous support was then taped to a glass plate
165 and soaked in 30 mL aqueous solution of 3 w/v % piperazine for 2 minutes. The amine-
166 loaded support was then pressed with a roller and wiped to remove any excess solution.
167 Subsequently, it was immersed in 30 mL solution of 3 w/v % trimesoyl chloride in 2-
168 MeTHF for 4 minutes and then rinsed with 30 mL of DI water.

169

170 ***2.1.2. Fossil fuel-based solvent employment (conventional route)***

171 A similar protocol is followed with a few variations for the conventional route. The
172 polymer dope solution comprised of 17.5 w/v % cellulose acetate in DMF, the porous
173 support was soaked in a 2 w/v % piperazine solution for 2 minutes and the amine-loaded
174 support was soaked in 0.1 w/v % trimesoyl chloride in n-hexane for 2 minutes. It is

175 important to note that the conventional route did not necessitate the use of acetic acid
176 and involved lower concentrations of both piperazine and trimesoyl chloride.

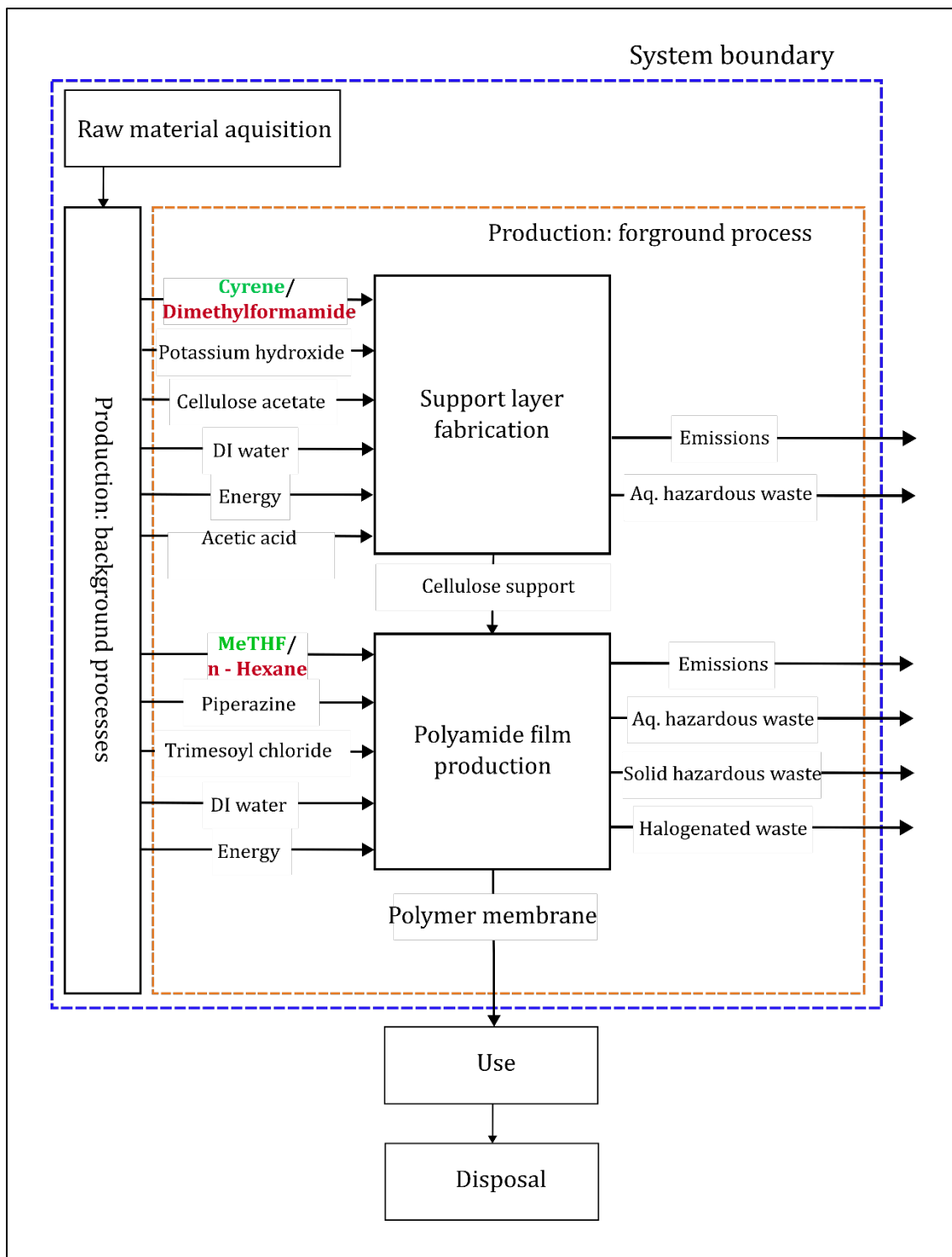
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178 **2.2. Goal and scope definition**

179 A comparative LCA was carried out per the ISO 14040 and ISO 14044 standards, to assess
180 the environmental impacts of bio-renewable (green route) and fossil fuel-based
181 (conventional route) solvent employment in membrane fabrication. A functional unit of
182 1 g of membrane was selected for both production routes.

183 This study took a cradle-to-gate perspective. The boundary covered the production of the
184 membrane including the raw material extraction process. The use of the membranes in
185 any application and end-of-life disposal were not considered as shown in Figure 1. A
186 cradle-to-gate assessment is similar, in terms of scope, to other studies, which consider
187 bio-based production routes at the laboratory scale. [21, 35]

188 Due to limited data availability, waste and emission flows, and transportation of materials
189 were omitted from the system boundary. The foreground process was modelled based on
190 UK-specific data, given that the membranes were produced within a laboratory at the
191 University of Edinburgh, Scotland. Average European data was used to model the
192 background processes.



193

194 *Figure 1 Block flow diagram of membrane fabrication for both green and conventional*
 195 *membrane fabrication. System boundary and foreground system are highlighted by blue*
 196 *and orange dotted lines respectively*

197 **2.3. Life cycle inventory analysis**

198 LCI data was collected in accordance with the system boundaries that were specified in
199 the goal and scope definition phase of the LCA. The laboratory scale membrane
200 fabrication process was defined as the foreground process. Primary data for chemical and
201 electricity inputs were provided by Akram. [17] Data for the background system was
202 collected from secondary sources such as published LCA studies, LCI databases, or
203 calculated.

204

205 **2.4. Life cycle impact assessment**

206 The LCIA was carried out using SimaPro (Version 8.0), a widely-used LCA software. This
207 software facilitates key steps of the LCIA, including classification (assigning flows to
208 relevant environmental impact categories), characterisation (determining magnitude of
209 each flow on a given impact category), and normalisation (comparing the values to a
210 reference value).

211

212 Within SimaPro, the LCIA method used was ReCiPe (Version 1.10). This method is a
213 “black-box” LCIA framework that allows the calculation of 18 midpoint indicators and 3
214 endpoint indicators, the widest set of impact categories by any LCIA method and the most
215 commonly used method in the chemical industry. [36, 37] The 18 midpoint impact
216 categories are as follows: climate change, ozone depletion, terrestrial acidification,
217 freshwater eutrophication, marine eutrophication, human toxicity, photochemical
218 oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater
219 ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban
220 land occupation, natural land transformation, water depletion, metal depletion, and fossil

221 depletion. These are grouped to determine 3 endpoint categories: human health,
 222 ecosystems and resources. The relationship between these midpoint and endpoint
 223 impact categories was presented in the supplementary Information. The reader can refer
 224 to the literature from Goedkoop *et al.* [38] for a comprehensive list of the ReCiPe
 225 characterisation factors (>70,000), midpoint impact categories, indicators, normalisation
 226 references and endpoint indicator normalisation references used in this study.

227

228 3. Results and discussion

229 3.1. Life cycle inventory

230 3.1.1 Foreground process

231 A summary of the LCI results for membrane fabrication *via* both production routes was
 232 presented in Table 1.

233 *Table 1 Life cycle inventory for the production of 1 g of polymer membrane.*

	Conventional route	Green route
Material inputs		
Cellulose acetate (g)	8.21×10^1	3.62×10^2
Cyrene™ (g)	-	1.28×10^3
DMF (g)	3.87×10^2	-
Acetic acid (kg)	-	4.26×10^2
Potassium hydroxide (g)	4.74×10^2	2.09×10^3
Water, deionised (L)	1.69×10^2	7.46×10^2
Piperazine (g)	5.63×10^0	3.72×10^1
Trimesoyl chloride (kg)	2.81×10^{-1}	3.72×10^1
2-MeTHF (mL)	-	1.240×10^3
n-Hexane (mL)	2.81×10^2	-
Utilities		
Electricity (kWh)	2.10×10^0	9.26×10^0
Other information		
Mass of support produced (g)	6.72×10^0	2.96×10^1
Yield (g _{membrane} /g _{support})	1.49×10^{-1}	3.40×10^{-2}

234

235 **3.1.2 Background system**

236 The background processes data were primarily collected from the ecoinvent v3.0
237 database. [39] This is a widely used LCI database, containing flow input and output data
238 on over 12,000 processes and products. The absent data of some processes from
239 ecoinvent library was determined from a combination of industrial sources, literature
240 and stoichiometric calculations. A summary of the data collection methods was provided
241 in Table 2 and a detailed account of all new LCI datasets were presented in the
242 Supplementary Information.

243 Where relevant, biogenic carbon neutrality was assumed. By definition, biogenic carbon
244 is the carbon accumulated in biomass or other renewable feedstocks during growth. For
245 any unit process wherein materials derived from renewable feedstocks were incinerated,
246 the carbon dioxide emissions were neglected. [40] Furthermore, sequestration of any
247 emitted carbon dioxide following incineration was taken as an overall credit to the
248 process. Such an analysis is commonly used in LCA studies. [41] Allocation procedures
249 for the modelled processes varied on a case-by-case basis, and an account of this can be
250 found in the relevant Supplementary Material. Of note is the allocation procedure
251 associated with biomass cultivation. Often the biomass used in the production of green
252 solvents are waste products from other processes, *e.g.* corncob used for 2-MeTHF
253 production and sawdust for Cyrene™ production. In this study, it is assumed that in the
254 relevant processes, biomass is a waste co-product stream in its production process.
255 Hence, any environmental load associated with its cultivation can be omitted from the
256 study.

257 *Table 2 Summary of life cycle inventory data collection methods for background unit*
 258 *processes*

Material	Production route	Specificities	Source
Green membrane production	Non-solvent induced phase separation	Very high	First-hand collection
Conventional membrane production	Non-solvent induced phase separation	Very high	First-hand collection
Cellulose acetate	Acetylation of cellulose	Medium	Calculated from patent literature [42, 43]
Cyrene™	Hydrogenation of levoglucosenone	Medium	LCI data from industry
DMF	Reaction of dimethylamine with carbon monoxide	Medium	ecoinvent v3.0
Acetic acid	Carbonylation of methanol	Medium	ecoinvent v3.0
Potassium hydroxide	Electrolysis of potassium chloride	Medium	ecoinvent v3.0
n-Hexane	Molecular sieve separation of naphta	Medium	ecoinvent v3.0
2-MeTHF	Hydrogenation of 2-methylfuran	Medium	LCI in literature [44]
Piperazine	Reaction of 1,2-dichloroethane with ammonia	Medium	Stoichiometric calculation
Trimesoyl chloride	Reaction of trimesic acid with thionyl chloride	Medium	ecoinvent v3.0
DI water	Ion exchange	Medium	ecoinvent v3.0
Electricity	Electricity mix	Medium	ecoinvent v3.0

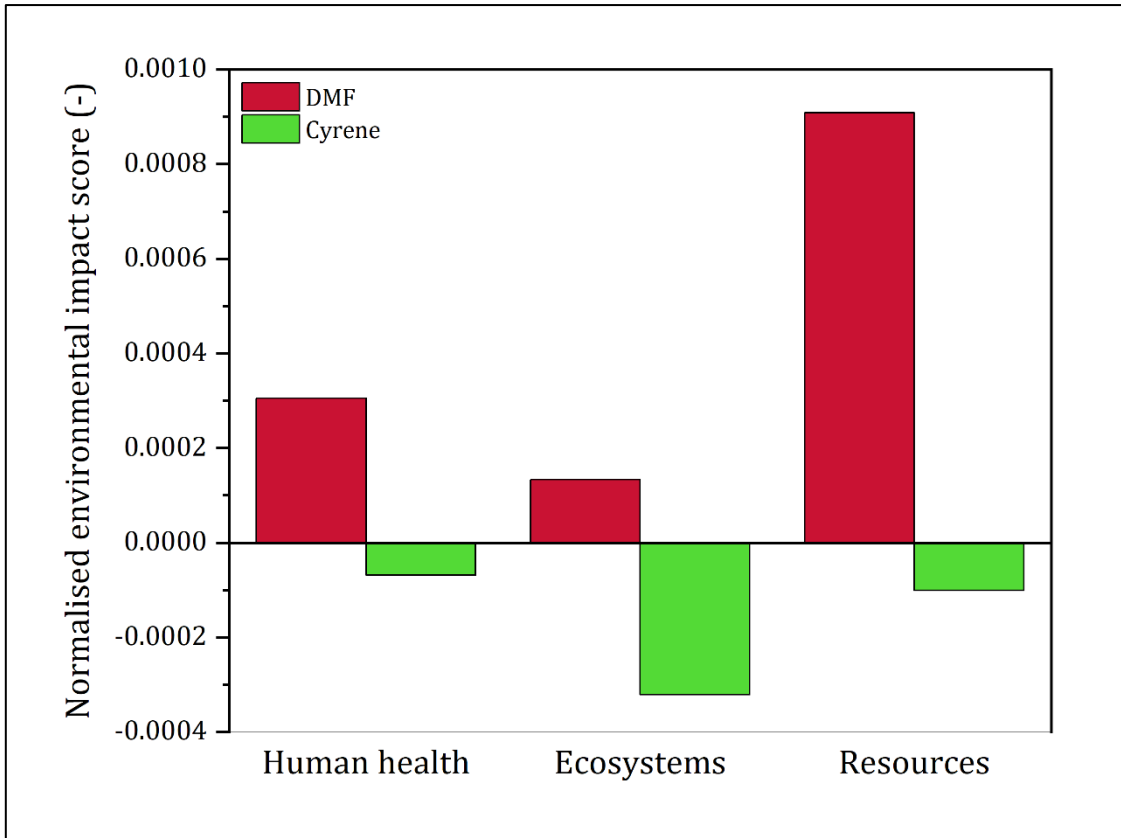
259 * LCI data calculation framework used in this study was developed and implemented by ecoinvent
 260 (the primary database used for this LCA). [45-47]

261 **3.2. Environmental impact comparison of solvent production**

262 Figure 2 presents the normalised environmental impact score for each of the end-point
 263 impact categories for both Cyrene™ and DMF production. A higher impact score indicates
 264 that the route created more environmental impact compared to another route and is
 265 thereby worse. A score below zero indicates that the process receives a credit or benefit
 266 that offsets the environmental load from all previous stages. It can be seen that the
 267 production of 1 kg of Cyrene™ has a lower environmental load compared to the

268 production of 1 kg of DMF across all three impact categories. This difference is influenced
269 by two key factors. Firstly, the production of Cyrene™ involves the incineration of waste
270 char to generate the required heat and electricity. The study, as detailed in the
271 background system datasheet (Supplementary Information), treats biogenic carbon
272 emissions from this process as neutral. In contrast, DMF production faces environmental
273 consequences due to emissions associated with process energy generation. This is
274 particularly important given the energy-intensive nature of DMF purification during
275 production – attributed to its high boiling point and solubility characteristics. Secondly,
276 the production of Cyrene™ receives an additional credit earned from excess energy
277 exports. This results in a consistently lower (and below zero) environmental load of
278 Cyrene™ production.

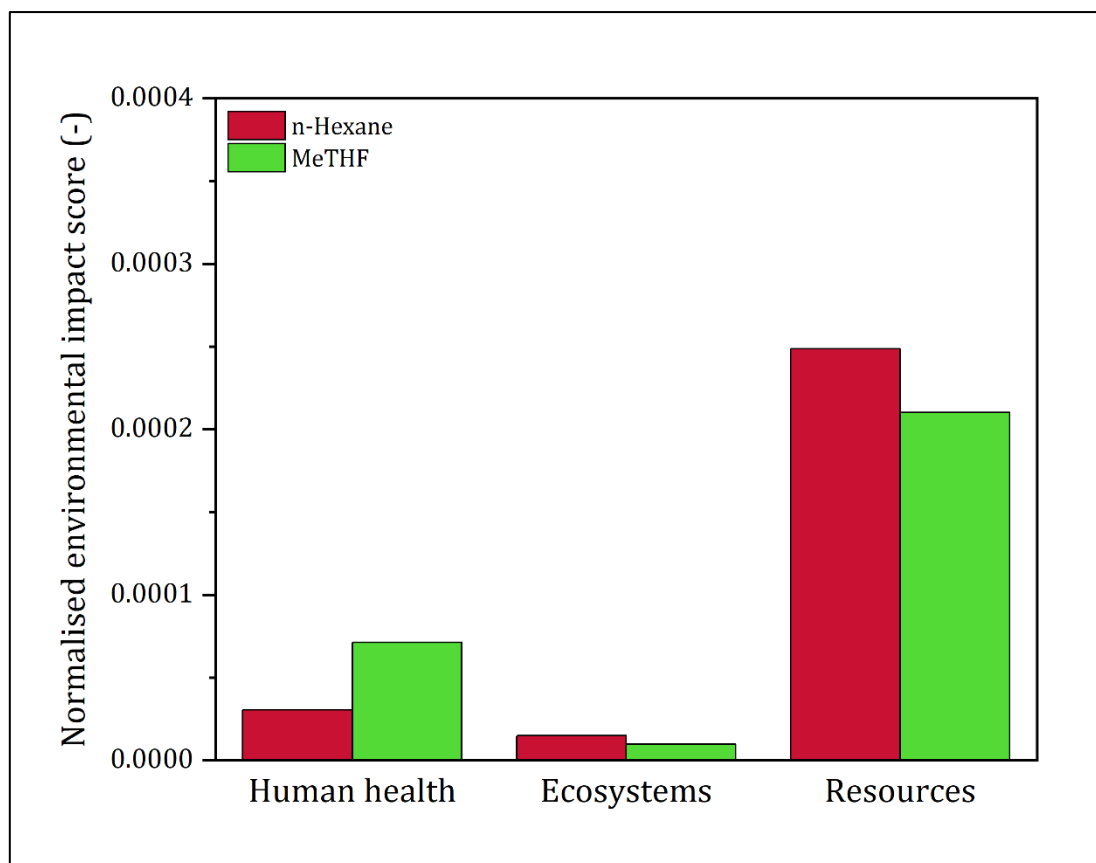
279 It is worth noting that Cyrene™ production *via* the Furacell process (as modelled in this
280 study) is currently the only industrial-scale production process. However, this process
281 remains at the pilot-scale. There are plans to develop a scaled-up plant, increasing the
282 production capacity from 50 tonnes to 1000 tonnes. The LCA practitioner has been
283 informed that the data provided for Cyrene™ production does not reflect the scaled-up
284 plant and that further reductions in environmental load are anticipated. It is challenging
285 to incorporate this information into the LCA at this time as the plant is not operational
286 yet. Future iterations of the LCA should incorporate the most up-to-date process data
287 available to accurately assess the environmental impact of the scaled-up production.



288

289 *Figure 2 Normalised environmental endpoint impacts for Cyrene™ and DMF production (1*
 290 *kg)*

291 Figure 3 presents the normalised environmental impact score for each of the end-point
 292 impact categories for 2-MeTHF and n-Hexane production. 2-MeTHF presents a lower
 293 environmental impact score for two of three environmental impact categories, namely
 294 ecosystems and resources. However, the impact to the human health is higher than that
 295 of n-hexane. Raw material manufacturing, specifically 2-methylfuran, stands out as the
 296 primary contributor to this impact category. The root cause of this impact lies in poor
 297 yields in further upstream background processes. Similar to Cyrene™ production, 2-
 298 MeTHF production utilises biogenic waste solvent and accrues additional credits for
 299 excess energy exports. These credits, although favourable, are insufficient to fully offset
 300 the environmental impact of 2-MeTHF production.



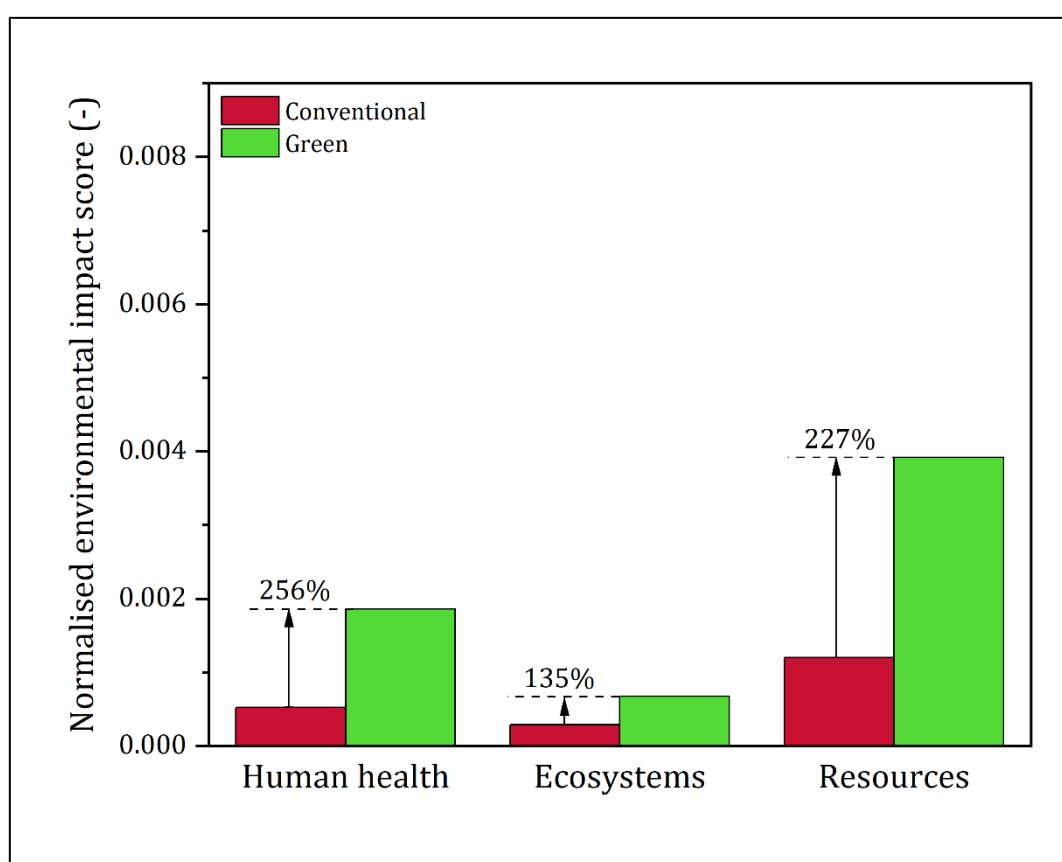
301

302 *Figure 3 Normalised environmental endpoint impacts for 2-MeTHF and n-Hexane*
 303 *production (1 kg)*

304 **3.3. Environmental impact comparison of membrane fabrication via green and**
 305 **conventional methods**

306 Figure 4 presented three environmental end-point impacts of the membrane fabrication
 307 process *via* conventional and novel green routes. From the figure, membranes produced
 308 from green route showed significantly higher environmental impact scores across all
 309 categories. The green synthesis impact scores were 256 %, 135 % and 227 % higher for
 310 human health, ecosystems and resources, respectively. These higher impacts can be
 311 attributed to the approximately 4.4 times lower yield of the green production route
 312 (Table 1). However, Akram reported that 10-fold more trimesoyl chloride was required
 313 to fabricate a dense polyamide selective layer when 2-MeTHF was used instead of n-
 314 hexane as the organic phase during interfacial polymerisation. This was most likely

315 attributed to the better water solubility of 2-MeTHF than n-hexane, where organic
316 solvents with water solubility tend to require more monomer reactants to form dense
317 polymer films. [48] Optimisation of the yield is necessary to reduce the overall
318 environmental impact of this fabrication route. Considering the challenges associated
319 with the replacement of both solvents (i.e., incomplete polymerization and bubble
320 formation), exploring Cyrene™/hexane and DMF/2-MeTHF systems, where only one
321 solvent is replaced, presents a promising path for further research.



322

323 *Figure 4 Normalised environmental endpoint impacts for membrane fabrication (1 g)*
324 *using bio-renewable and fossil fuel-based solvents. The percentage increase is noted.*

325

326 **4. Conclusions and Suggestions**

327 The environmental impact assessment of the thin film composite polymer membrane
328 fabrication process employing novel green solvents (Cyrene™ and 2-MeTHF) was
329 conducted. The traditional membrane fabrication using fossil fuel-derived solvents (DMF
330 and n-hexane) was used as a benchmark for the comparative assessment. Through the
331 standard LCA framework, the overall environmental impact of the fabrication process of
332 the membranes produced from bio-renewable solvents was higher. This was due to lower
333 membrane yield from the green route. This outcome indicated that the substitution of the
334 bio-renewable solvent in a process could not ensure that the process would automatically
335 become more sustainable, and further process development is crucial.

336 However, this work only considered a partial stage of the membrane's life-cycle, the
337 possibility that the environmental impact contribution from the membrane produced
338 from Cyrene™ and 2-MeTHF would trade-off in later stages of life. According to Akram's
339 research, the membranes from the green route displayed higher permeance and rejection
340 rates than the membrane from the traditional route. An increased permeance
341 corresponded to lower energy consumption and, consequently, reduced environmental
342 impact. Hence, consideration of membrane use could potentially serve as a benefit to the
343 green production route.

344 Several suggestions should be taken into consideration for the future work in order to
345 improve the feasibility and reliability of the assessment. Monte Carlo simulation should
346 be carried out to account for uncertainties and variability in the input parameters and
347 model assumptions. It is also recommended that an LCA should be carried out for a
348 scaled-up version of the process presented here. This would involve implementing a
349 pilot-scale production. By doing so, it would become possible to identify any differences

350 between the two processes, such as the use of different equipment, chemicals, and
351 reagents. Additionally, heat integration and solvent recycling should be taken into
352 account to maximise the sustainability of the process.

353 Beside the improvement for the future environmental assessment, the suggestions for
354 experimental section has also been provided as following. Other than improving
355 membrane fabrication yield, there is also a need to explore the use of alternative
356 membrane fabrication technologies to improve the green metrics of using bio-renewable
357 solvents for membrane fabrication. For e.g., the use of green solvents in membrane
358 fabrication typically results in lower separation performances. We have recently
359 overcome this trade-off between sustainability and membrane separation performances
360 by using spray-coating to fabricate thin film composite membranes. [28] Another strategy
361 that can potentially address the challenges of improving green metrics of membrane
362 fabrication is to identify alternative materials for both the selective and porous support
363 layers. [7]

364

365 **CRedit authorship contribution statement**

366 **Aiman Arif:** Software, Formal analysis, Writing – Original Draft, Writing – Review &
367 Editing, Visualisation; **Nadhita Chanchaona:** Conceptualisation, Methodology, Writing –
368 Review & Editing; **Cher Hon Lau:** Conceptualisation, Writing – Review & Editing,
369 Supervision.

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