Bio-based Chemicals Climate Change Performance LCA Review

Carbon for Chemicals -
How can biomass contribute to the defossilisation of the chemicals sector?

Supplementary Materials Report

Author:

Andrew Welfle [1,2]

1) Tyndall Centre for Climate Change Research, Manchester Engineering Campus Development (MECD), The University of Manchester, M13 9PL, UK

2) UK Supergen Bioenergy Hub, Manchester Engineering Campus Development (MECD), The University of Manchester, M13 9PL, UK

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Table of Contents

1) Bio-based Chemical Research Publication Trends

A review of existing literature was undertaken to identify trends in bio-based chemicals research and the focus on environmental and sustainability themes.

1.1. Bio-based chemical Literature Database

A Bio-based Chemical Literature Database (BCLD) was developed as a method for analysing research publication trends between 1990 and 2021. 1990 marking a year where the UK first highlight GHG emissions as a potential problem, through introduction of the 'Non-Fossil Fuel Obligation', whilst 2021 represents the latest year with a complete publication database. The BCLD was developed following the methodology of the 'Bioenergy Literature Database' [1] – that collated a full list of all the biomass and bioenergy focused research papers and allowed assessment of how research themes changed over the timeframe.

Similarly, the BCLD was constructed sourcing references from The Web of Science [2], where a systematic process of publication searches was completed collating the results of all searches within a Microsoft Excel database (BCLD). The search terms used to construct the BCLD are included within the Appendix. The final BCLD captured 1,024,527 original research papers across chemical and bio-based chemical themes, published between 1990 and 2021.

1.1.1. Chemical Research Paper Trends

Figure 1 presents the total chemical research papers published annually between 1990 and 2021, also highlighting the total number of these papers that focus on environmental themes. An exponential rise in chemical research papers is shown over the timeframe, and roughly half of publications include some mention or analyses focusing on GHG emissions. Over the timeframe a rising proportion of publications also mention or include analyses of environmental and/ or sustainability themes.

Life cycle assessment (LCA) analyses is a primary method for assessing emissions and environmental performances. Despite the relatively large number of papers published annually that include GHG emissions, environmental or sustainability themes, the proportion of papers that mention or undertake LCA analyses is small. This suggests that although environmental and sustainability themes are widely covered within papers, research focusing on actual environmental or GHG assessments are comparatively rare.

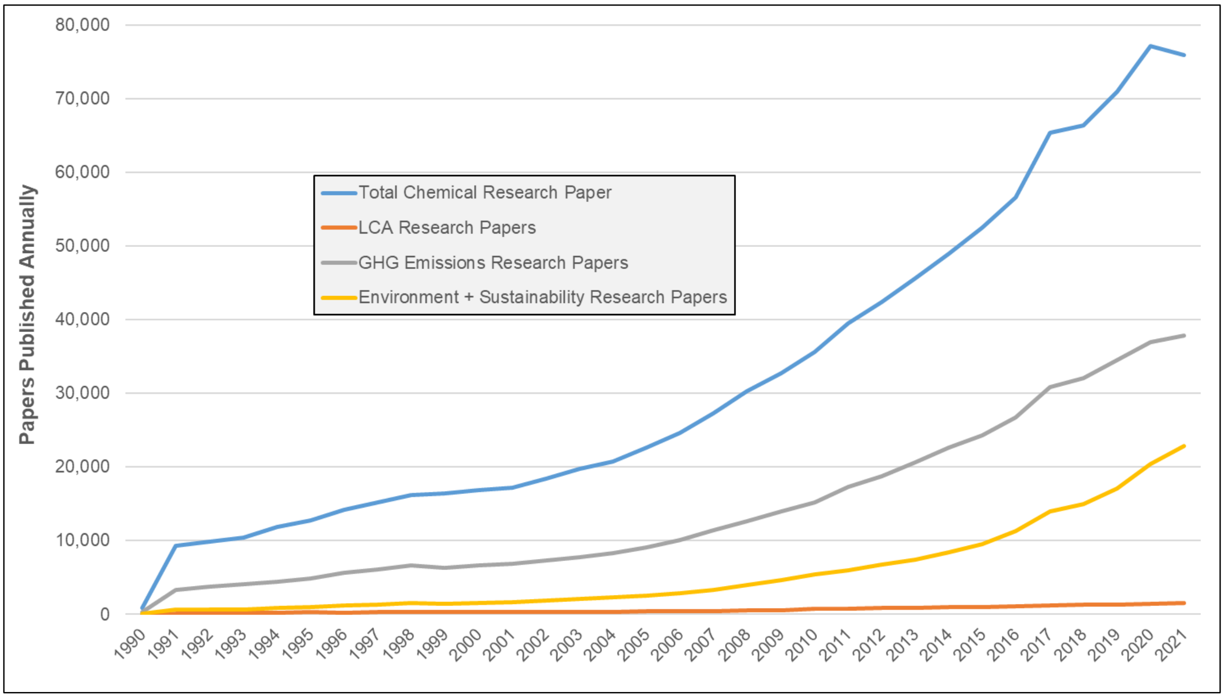

Figure 1: Total Annual Chemical and Environmental Assessment Research Publications 1990-2021

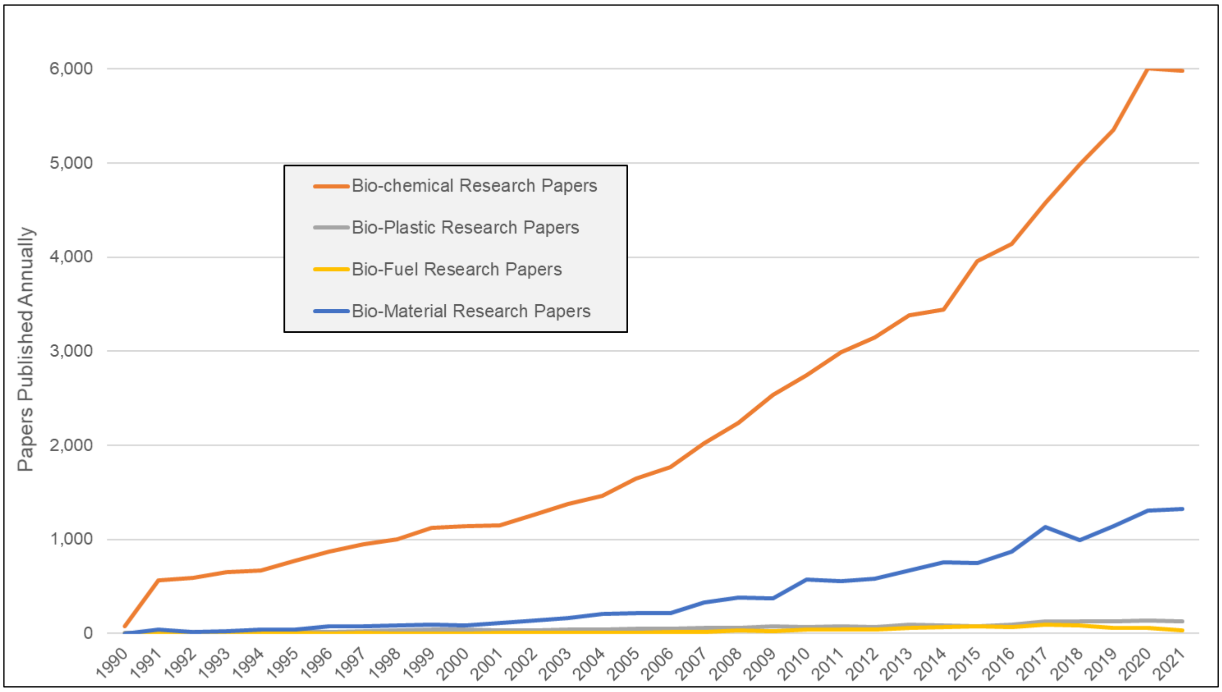

Figure 2: Total Annual Bio-based Chemical, Bio-Plastic, Bio-Fuel & Bio-Material Research Publications 1990-2021

Figure 2 presents the total research papers focusing specifically on bio-based chemicals, bio-plastics, bio-fuels and bio-materials published annually between 1990 and 2021. Papers focused of bio-based chemicals are the largest focus of research, with annual publications rising steadily over the timeframe. Papers focusing on bio-material themes gain the second highest focus. Papers published annually focused specifically on bio-fuels and bio-plastics are shown to be steady albeit much lower. Since 2016 there is shown to have been an increase in the annual rate of papers focusing on bio-plastics, albeit still only representing a small proportion of overall bio-based chemical focused papers.

2) Review of the Life Cycle Emission Performance of Bio-chemicals

A literature review was completed to build a greater understanding of existing life cycle assessment (LCA) research focusing on bio-based chemicals. The review aimed to i) assess the coverage of existing LCA research, to map the extent that different bio-based chemicals and related processes had been the focus of LCA analyses; ii) to build a database of LCA GHG emission performance values for different bio-based chemicals, to undertake a preliminary assessment of the potential for bio-chemicals to contribute to the decarbonisation of the chemical sector, and; iii) identify where there are gaps in current knowledge, specifically where future LCA research is needed to assess the decarbonisation potential of different bio-based chemicals.

1.2. UK Priority Bio-based chemicals

The review focuses on a list of bio-based chemicals (Table 1) which may be of interest for the UK, including platform chemicals, high value chemicals, and a number of polymers and plastics.

Table 1: Chemicals included within the Bio-based Chemical LCA Literature Review

Platform & High Value Chemicals	○ 1,3-Butanediol (1,3-BDO) ○ 1,3-Propanediol (1,3-PDO) ○ 2,5-Furandicarboxylic acid (FDCA) ○ 3-Hydroxypropionic acid (3-HP) ○ Acrylic acid ○ Acetic acid ○ Adipic acid ○ Ammonia ○ Ethylene	○ BTX - Benzene ○ BTX - Toluene ○ BTX - Ethylbenzene ○ BTX - p-xylene ○ Lactic acid ○ Propylene glycol ○ Succinic acid ○ Xylitol
Bio-Plastics	○ Polytrimethyleneterephthalate (PTT) ○ Polybutylene Succinate (PBS) ○ Polyethylene (PE) ○ Polypropylene (PP) ○ Polyvinyl Chloride (PVC) ○ Polystyrene (PS)	○ Polyethyleneterephthalate (PET) ○ Polyurethane (PU) ○ Polyamide (PA) ○ Poly (lactic acid) (PLA) ○ Polyhydroxyalkanoates (PHA)

1.3. Review of LCA Emission Literature

Previous research and studies included in the review are listed in Table 2. Based on the number of references identified for each. The number of references identified for each chemical clearly highlights the large variations in the extent that different bio-based chemicals have been the subject of LCA analyses. Key information derived from each study included climate change performance data and details of the LCA analyses boundaries.

- **Climate Change Performance Data:** taken from each of the studies for the relevant chemicals/ chemical processes. To allow ease of comparison in this review all values were converted to $kgCOe_2^{eqv.}$/kg as the functional unit. This is common unit used on LCA analyses, reflecting the levels of GHG emissions (converted to a CO_2 equivalency) generated per kg of chemical produced.
- **LCA Analyses Boundaries:** are an important assumption to record as they determine what is included within the assessment.
  - *Production to Gate:* LCA analyses that assess the climate change performance of producing the chemical up until it leaves the production site before being transported to costumers for use.
  - *Production to End of Use:* LCA analyses that assess the climate change performance of producing the chemical through to its eventual use and including the management/ disposal of any post-use materials.

Table 2: Literature Assessed within the Bio-based Chemical LCA Literature Review

Platform & High Value Chemicals	
1,3-Butanediol (1,3-BDO)	[3]–[5]
1,3-Propanediol (1,3-PDO)	[1], [6]–[15]
2,5-Furandicarboxylic acid (FDCA)	[8], [16]
3-Hydroxypropionic acid (3-HP)	[17]
Acrylic acid	[4], [5], [17]
Acetic acid	[5], [18], [19]
Adipic acid	[10], [19]–[21]
Ammonia	[22]–[25]
BTX - Benzene	[5][26], [27]
BTX - Toluene	
BTX - Ethylbenzene	
BTX - p-xylene	
BTX - m-xylene	
BTX - o-xylene	
Ethylene	[5], [7], [11]–[15], [28], [29]
Lactic acid	[5], [30]
Propylene glycol	[5], [11]
Succinic acid	[5], [11], [13], [15], [29], [31]
Xylitol	[32], [33]
Bio-Plastics	
Polyethylene (PE)	[11], [15], [18], [33]–[53]
Polypropylene (PP)	[7], [15], [25], [34], [36], [38]–[41], [45]–[51], [53]–[56]
Polyvinyl Chloride (PVC)	[5], [7], [12], [15], [34]–[41], [43]–[51], [53], [57]
Polystyrene (PS)	[5], [7], [15], [34], [36]–[41], [43]–[51], [53], [57]
Polyethyleneterephthalate (PET)	[7], [15], [36]–[53], [58]
Polytrimethyleneterephthalate (PTT)	[33], [35]–[43], [46], [47], [59]–[62]
Polyurethane (PU)	[7], [63]
Polyamide (PA)	[64]
Poly (lactic acid) (PLA)	[15], [34], [36]–[41], [43]–[51], [53], [57], [58], [65]
Polyhydroxyalkanoates (PHA)	[34], [36], [37], [39], [41], [43]–[51], [57], [61], [62]
Polyhydroxybutyrate (PHB)	[47], [66]
Polybutylene Succinate (PBS)	[23], [24], [45], [47], [66], [67]

1.4. Climate Change Performance of Biomass vs Fossil Derived Chemicals

Comparison of the climate change performance values obtained from literature for key chemicals are presented in Figure 3 and Figure 4. The Figures present ‘production to gate’ LCA GHG emissions intensity data (kg$CO_2^{eqv.}$/kg chemical product), comparing bio-based platform chemical and bio-plastics respectively, versus the existing fossil derived production processes. The review predominantly focuses on ‘Production to Gate’ LCA analyses due to the comparatively limited ‘Production to End of Use’ LCA data found (see Appendix Table 5).

For each chemical the ‘green’ plots in Figure 3 and Figure 4 highlight LCA values identified for bio-based production processed and the ‘orange’ plots highlight LCA values identified for the fossil-derived processes. The data values for all chemicals reviewed are included in Table 4 and Table 5 of the Appendix.

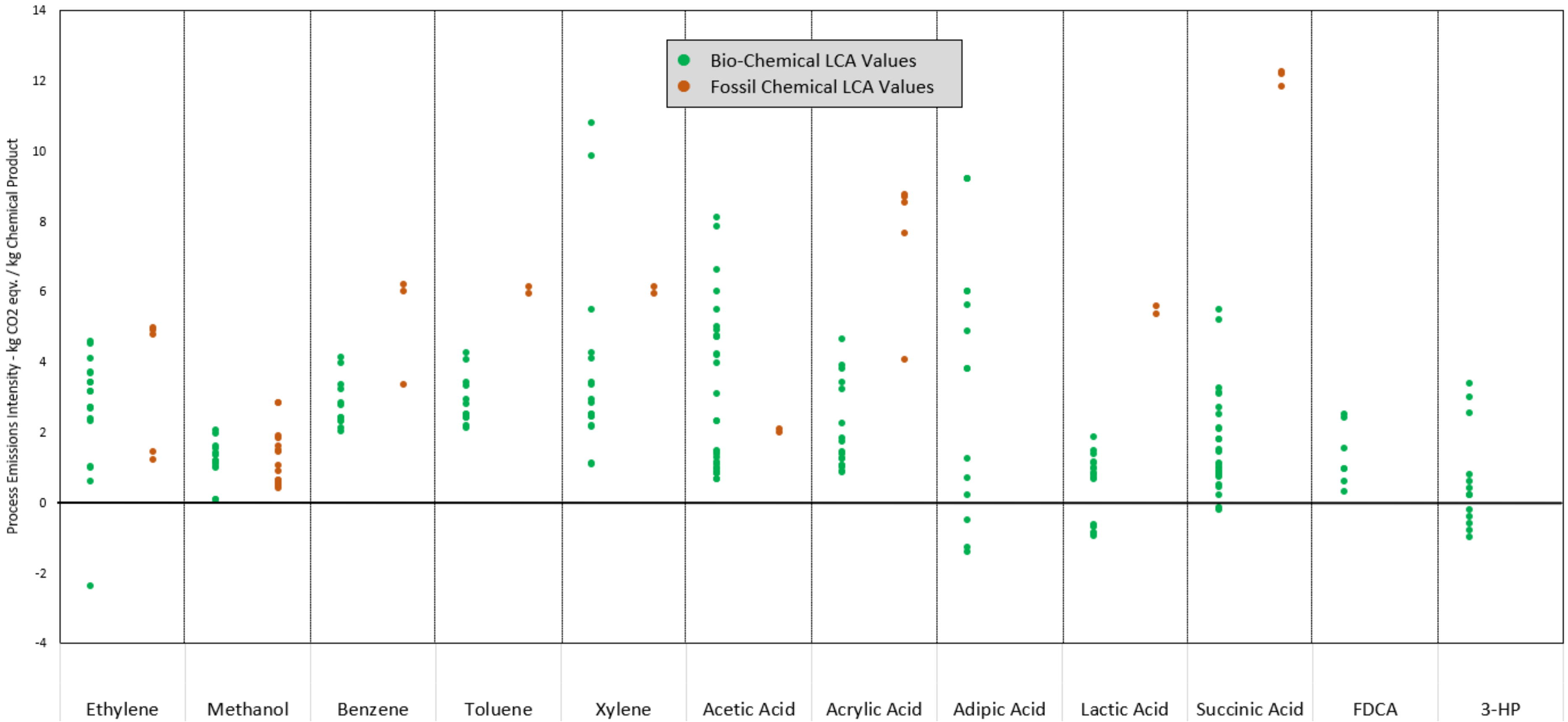

Figure 3: *Selected Platform & High Value Chemical LCA Climate Change Performance Values (kgCO_2 $^{eqv.}$/kg) derived from Literature. Comparisons of performance of biomass and fossil fuel derived chemicals and LCA analyses boundaries from 'production to gate'.*

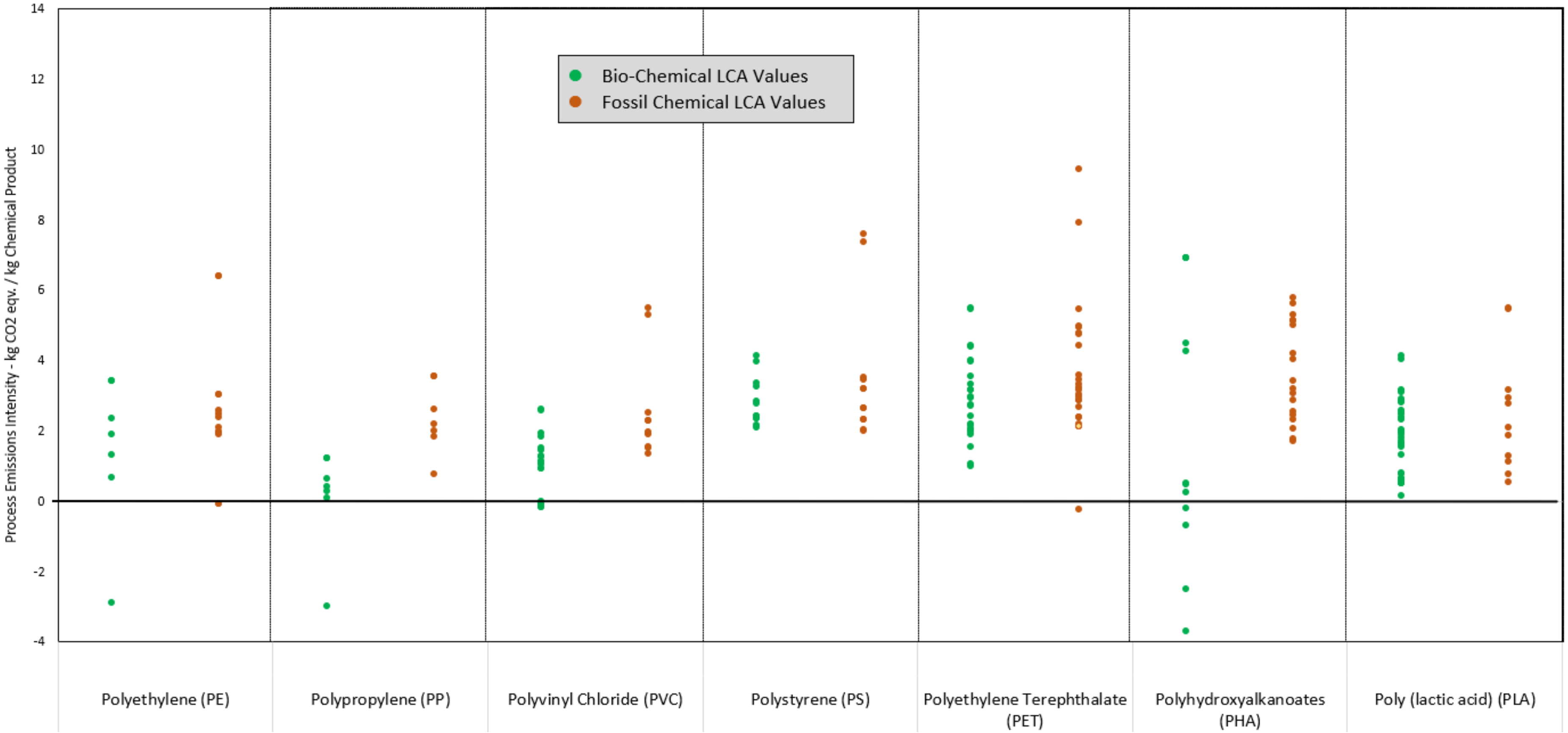

Figure 4: *Plastic and Bioplastic LCA Climate Change Performance Values (kg$CO_2$$^{eqv.}$/kg) derived from Literature. Comparisons of performance of biomass and fossil fuel derived chemicals and LCA analyses boundaries from 'production to gate'.*

1.5. Interpretation of LCA Climate Change Performance Values

1.5.1. Depth of the Literature

This review included data values from 66 previous LCA studies, collating many hundred individual LCA values for both bio-based chemical and fossil fuel chemicals. Although a cursory review of Table *2* demonstrates that some chemicals have been subject to a large number of LCA studies whereas others have received comparatively few or even no focus. Even though emissions and sustainability are widely discussed in chemical literature, chemical and bio-based chemical LCA literature is relatively niche.

There is a further clear distinction between 'to gate' and 'end of use' LCA assessments, many more LCA studies applying the former assessment approach. The depth of the literature and specifically the acute focus of LCA studies on specific chemicals rather than others is potentially problematic when attempting to draw broad conclusions, as in this review.

1.5.2. Performance of Bio vs Fossil Fuel Derived Chemicals

A leading finding from the Climate Change Performance LCA review is that for each of the chemicals assessed, there is potential for reducing the emissions generated through chemical use and production through using biomass feedstock compared to the conventional fossil fuel feedstocks. In some cases, as seen for Ethylene, Acrylic Acid and Succinic Acid high value chemicals and PHA, PE and PP plastics, bio- alternatives can provide significant GHG reductions and even opportunities for generating negative emissions where they replace fossil fuel derived production processes.

For a significant number of the chemicals the ranges of LCA values for bio-based chemicals are extremely large in comparison to the fossil fuel equivalent – typically including LCA values both far below and above the fossil fuel chemical. The narrower range of LCA values for the fossil fuel chemicals suggests these chemical production processes are well established and optimised, thus there is greater certainty in predicting levels of the GHG emissions that may be generated. In contrast the wider range of LCA values for many of the bio-based chemicals, highlights the comparative development stage of the bio-based chemical sector – many of these processes are still being developed and are not yet optimised.

Further research and development will be required to reduce the potential range of bio-based chemical GHG emissions, and a targeted and supportive policy framework may be required to prevent specific activities that result in some of the higher GHG emission performance values.

1.5.3. Production to Gate vs Production to End of Use

Despite the discrepancy in availability of 'end of use' data compared with 'to gate' LCA data, the review does highlight that $kgCO_2$ climate change performance values are greater where an 'end of use' assessment boundary is applied. This is an expected finding as there are more activities to analyse where the assessment boundary extends to the end of use, thus it is logical that more GHGs are likely to be omitted linked to these additional life cycle activities.

In some cases, the differences between the 'to gate' and 'end of use' LCA values are significant, highlighting the need to assure that comparisons between LCA values from different studies are like-for-like in terms of the LCA boundary assumptions.

1.5.4. Drivers of Variation in LCA Climate Change Performance Values

The variation in the climate impacts of bio-based chemicals is the cause of some hesitancy when it comes to implementing bio-based products. The reality is that some variation in the potential GHG savings will always exist (and is also seen in products derived from carbon dioxide or recycled material, and biofuels and hydrogen [69]–[72]. It should be emphasised that this variability in GHG impacts is not unique to bio-based processes. For example, hydrogen has gained much attention as a potential alternative low carbon fuel, but how it is produced has a significant impact on whether it will support GHG reductions [73]. Also, in some cases the variability in GHG impact between alternative fossil fuel production processes is even greater than that of the biobased alternative – as shown for both PET and PS in Figure 4. This variability likely comes from the choice of feedstock and processes used, demonstrating the importance of prioritising/preventing given processes in order to maximise GHG performances. It would be more beneficial to focus on how technology developers and policymakers can develop or incentivise those products that deliver GHG savings over those that do not.

1.5.5. Explaining Negative LCA Climate Change Performance Values

Negative LCA values are found for a number of chemicals included in the review. Both Figure 3 and Figure 4 highlight several net negative GHG emissions values - careful interrogation of the LCA methodologies and assumptions is required for such values, to determine if these truly deliver permanent removal of carbon from the atmosphere.

The amount of carbon permanently stored must exceed that emitted across the whole product lifecycle, and it is essential to understand the system boundaries used and how temporal aspects are accounted for [74]. A cradle to gate LCA could return a negative GHG emissions value for a short lifetime bio-based product because it excludes emissions associated with use and end-of-life and so does not consider the re-release of the embedded carbon. Also as discussed previously, the inclusion of certain counterfactual assumptions can also result in negative emission LCA values.

Sometimes LCA data for fossil-based chemicals may also result in a negative GHG emissions value, but it is important to be clear that the use of fossil carbon can never result in net transfer of carbon from the atmosphere to storage. The negative emissions values presented for the fossil-based chemicals can only be down to features of the LCA method applied, and is likely a consequence of assumptions relating to the temporality of carbon storage and emissions [75]. Explanations for this are not always clear in the literature, although are likely attributed to assumptions where recycled materials (carbon) is used or where there is further use of the material (carbon) after the chemicals use such as CCS/CCU activities.

1.5.6. Recommended Further Work

Based on the Climate Change Performance LCA review, further work recommendations include:

- **Coverage of Chemicals in Literature** – There is large discrepancies in the extent that different LCA studies have assessed chemicals, with certain 'high priority' chemicals gaining very little and in some cases no coverage. Further LCA studies are required to build a greater understanding of how bio-based chemicals may provide low and even net-zero carbon alternatives for the leading chemicals and plastics required by the UK.
- **Optimisation** – The range of LCA values for bio-based chemicals is large compared to the fossil fuel equivalent in many cases. Work is required to further develop and optimise bio-based chemical processes allowing greater certainty in the prediction of life cycle emissions.
- **High GHG Impact Activities** – In some cases the LCA values for the bio-based chemical are higher than that of the fossil fuel equivalent. Work is required to identify the specific activities linked to these high GHG emissions, and policy frameworks should be considered to prevent/ mitigate high GHG impact activities.
- **Influence of Location** – This review did not assess the influence of geographic location on LCA values. This is potentially important when considering the feedstocks used and any policy constraints that limit/ promote certain activities. Work is required to investigate the potential influence of location on climate change performance.
- **Influence of Feedstock** – This review did not assess the influence of how specific feedstocks influence the climate change performance of different chemicals. For both bio-based chemicals and fossil fuel derived chemicals, there are an array of potential feedstocks – the sourcing and chemical properties of feedstocks will have an influence on climate change performance. Work is required to investigate the influence of feedstocks and to potentially support certain feedstocks and restrict use of others based on performance.
- **Chemical Production Processes** – The chemical sector is extremely complicated and based on feedstocks used, desired products etc. the combinations of production technologies used may vary greatly. This research did not review LCA performance values linked to different technologies, therefore work may be required to identify the influence of technology choices.
- **Consistent LCA Approach** – This review has assessed LCA values from a large number of studies that each apply different approached to assessing climate change performance.

Comparison of the ‘to gate’ versus the ‘end of use’ LCA values highlights the importance of comparing like-for-like values when assessing performance. A key recommendation is to develop a uniform LCA method framework to ensure comparability in LCA output values.

- **Consistency in Negative Emissions Accounting –** This review identifies a number of processes that highlight the potential for generating negative emissions. Either linked to the LCA accounting assumptions (e.g. use of recycled materials, biogenic carbon) or through inclusion of carbon capture and or utilisation (CCS/CCU) technologies. To provide a true assessment of performances and a fair comparison of LCA values, work is required to develop a uniform approach for accounting negative emissions.

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Appendix

Table 3: *Search themes used within the Web of Science for constructing the BCLD*

Overarching Search Terms	**Biochemical**	○ Biochemical ○ Biochemicals	○ Bio-chemical ○ Bio-chemicals
	Chemicals	○ Base Chemicals ○ Base-Chemicals	○ Platform Chemicals
	Bio-Plastics	○ Bio-plastics ○ Bio-plastic ○ Bio plastic	○ Aliphatic Polyester ○ Bio polymer ○ Bio-polymer
	Bio-Fuels	○ Bio fuels ○ bio fuel	○ Bio-fuel ○ Bio-fuels
	Bio-Materials	○ Biomaterials ○ Biomaterial	○ Bio-material ○ Bio-materials
	LCA	○ LCA ○ ALCA	○ CLCA ○ Life Cycle Assessment
	Emissions	○ Carbon ○ GHG ○ GHGs	○ Emission ○ CO2 ○ Emissions
	Emissions	○ Sustainable ○ Sustainability	○ Environment
Bio-based Chemicals	**1,3-Butanediol (1,3-BDO)**	○ 1,3-Butanediol ○ 1,3-BDO	○ 1,3-butanediol ○ 1,3-butandiol
	1,3-Propanediol (1,3-PDO)	○ 1,3-Propanediol ○ 1,3-PDO ○ 1,3-Propanediol	○ 1,3-PDO ○ Propane-1,3-diol
	2,5-Furandicarboxylic acid (FDCA)	○ 2,5-Furandicarboxylic acid ○ Furan-2,5-dicarboxylic acid	○ Dehydromucic acid ○ FDCA
	3-Hydroxypropionic acid (3-HP)	○ 3-Hydroxypropionic acid ○ 3-HP	○ Hydracrylic acid
	5-Hydroxymethylfurfural (HMF)	○ 5-Hydroxymethylfurfural ○ Hydroxymethylfurfural ○ HMF	○ 5-(Hydroxymethyl)furan-2-carbaldehyde ○ 5-(Hydroxymethyl)-2-furaldehyde
	Acrylic acid	○ Acetic acid ○ Ethanoic acid	○ Vinegar ○ Hydrogen acetate
	Acetic acid	○ Acrylic acid ○ Prop-2-enoic acid	○ Acroleic acid ○ Ethylenecarboxylic acid
	Adipic acid	○ Adipic acid ○ hexanedioic acid	○ Butane-1,4-dicarboxylic acid ○ Hexane-1,6-dioic acid
	Ammonia	○ Hydrogen nitride ○ NH3	○ Ammonia
	BTX	○ BTX ○ Benzene ○ Benzol ○ Cyclohexa-1,3,5-triene ○ Toluene ○ Phenyl methane ○ Toluol ○ Ethylbenzene ○ Ethylbenzol ○ Phenylethane ○ alpha-Methyltoluene ○ p-xylene	○ 1,4-Xylene ○ dimethylbenzene ○ 1,4-Dimethylbenzene ○ m-xylene ○ 1,3-Xylene ○ dimethylbenzene ○ 1,3-Dimethylbenzene ○ o-xylene ○ 1,2-Xylene ○ dimethylbenzene ○ 1,2-Dimethylbenzene
	Butadiene	○ Butadiene ○ 1,3-Butadiene ○ Buta-1,3-diene ○ Biethylene ○ Erythrene	○ Divinyl ○ Vinylethylene ○ Bivinyl ○ Butadiene
	D-Mannitol	○ D-Mannitol	○ Mannite
	Epichlorohydrin	○ Epichlorohydrin ○ ECH ○ 2-(Chloromethyl)oxirane ○ (Chloromethyl)oxirane	○ Epichlorohydrin ○ 1-Chloro-2,3-epoxypropane ○ γ-Chloropropylene oxide ○ Glycidyl chloride
	Fatty alcohols	○ Fatty alcohols ○ Fatty alcohol ○ long chain alcohol	○ lauryl alcohol ○ stearyl alcohol ○ oleyl alcohol
	Fumaric acid	○ Fumaric acid ○ (2E)-But-2-enedioic acid ○ Lichenic acid ○ Donitic acid	○ Boletic acid ○ Allomaleic acid ○ 2-Butenedioic acid ○ rans-Butenedioic acid

	Furfural	Furfural Furan-2-carbaldehyde furan-2-carboxaldehyde fural	furfuraldehyde 2-furaldehyde pyromucic aldehyde
	Glucaric acid	Glucaric acid Saccharic acid glucaric acid	D-glucaric acid (2R,3S,4S,5S)-2,3,4,5-tetrahydroxyhexanedioic acid
	Glycerol	Glycerol Glycerin Glycerine	Propanetriol 1,2,3-Trihydroxypropane 1,2,3-Propanetriol
	Ethylene	Ethylene	ethene
	Isoprene	Isoprene 2-Methylbuta-1,3-diene	2-Methyl-1,3-butadiene
	Itaconic acid	Itaconic acid methylidenesuccinic acid 2-Methylenesuccinic acid	Methylenesuccinic acid 1-Propene-2-3-dicarboxylic acid
	Lactic acid	Lactic acid	Milk acid
	Levoglucosenone	Levoglucosenone (1S,5R)-6,8-Dioxabicyclo[3.2.1]oct-2-en-4-one	Levoglucosenone
	Levulinic acid	Levulinic acid β-Acetylpropionic +R43acid 3-Acetopropionic acid	β-acetylpropionic acid γ-ketovaleric acid
	L-Lysine	L-Lysine (2S)-2,6-Diaminohexanoic acid (L-lysine) D-lysine	L-lysine LYS h-Lys-OH
	Malic acid	Malic acid 2-Hydroxybutanedioic acid Hydroxybutanedioic acid 2-Hydroxysuccinic acid	(L/D)-Malic acid (±)-Malic acid (S/R)-Hydroxybutanedioic acid
	Methyl methacrylate	Methyl methacrylate MMA Methyl 2-methylpropenoate	methyl methacrylate 2-(methoxycarbonyl)-1-propene
	Muconic acid	Muconic acid	(2E,4E)-Hexa-2,4-dienedioic acid
	n-Butanol	n-Butanol Butan-1-ol n-Butyl alcohol n-Butyl hydroxide	n-Propylcarbinol n-Propylmethanol 1-Hydroxybutane Methylolpropane
	Propylene glycol	Propylene glycol Propane-1,2-diol Propylene glycol α-Propylene glycol	1,2-Propanediol 1,2-Dihydroxypropane Methyl ethyl glycol Methylethylene glycol
	Succinic acid	Succinic acid Butanedioic acid	1,4-Butanedioic acid
	Terpenoids	Terpenoids Terpenoid Isoprene Monoterpenes	Sesquiterpenes Diterpenes Sesterterpenes Tetraterpenes
	Xylitol	Xylitol (2R,3R,4S)-Pentane-1,2,3,4,5-pentol (2R,3R,4S)-Pentane-1,2,3,4,5-pentaol	1,2,3,4,5-Pentahydroxypentane Xylite
Bio Plastics	**Cellulose-Plastic**	Cellulose-Plastic Cellulose Plastic Cellulose bioPlastic	cellulose esters cellulose acetate nitrocellulose
	Starch-plastic	Starch-plastic Starch plastic chitosan	Bio-Polyethylene Bio Polyethylene renewable polyethylene
	Polylactic acid	Polylactic acid Poly(lactic acid)	Polylactide PLA
	Poly(L-lactic acid)	Poly(L-lactic acid) Poly(L-lactide)	L-PLA Polylactide
	Poly(DL-lactic acid)	Poly(DL-lactic acid) DL-lactic acid Poly(DL-lactide)	DL-lactide DL-PLA
	Poly(glycolic acid)	Poly(glycolic acid) Polyglycolic acid	Polyglycolide PGA
	Poly(ε-caprolactone) (PCL)	Poly(ε-caprolactone)	(1,7)-Polyoxepan-2-one

		Polycaprolactone PCL	2-Oxepanone homopolymer 6-Caprolactone polymer
	Poly(hydroxybutyrate	Poly(hydroxybutyrate PHB	PHA polyhydroxyalkanoate
Bio Fuels	**Bio-ethanol**	Bio-ethanol Bioethanol	Bio ethanol
	Bio-hydrogen	Bio-hydrogen Biohydrogen	Bio hydrogen
	Bio-methanol	Bio-methanol Biomethanol	Bio methanol
	Bio-methane	Bio-methane Biomethane	Bio methane
	Bio-ethane	Bio-ethane Bioethane	Bio ethane
	Bio-Propane	Bio-Propane BioPropane	Bio Propane
	Bio-Butane	Bio-Butane Bio Butane	BioButane
	Bio-Naphtha	Bio-Naphtha BioNaphtha	Bio Naphtha
Bio Materials	**Bio-metals**	Bio-metals Bio metals	Biometals
	Bio-ceramics	Bio-ceramics Bio ceramics Bio ceramics	Bio-ceramic Bio ceramic Bio ceramic
	Bio-glass	Bio-glass Bio glass	Bioglass
	Bio-asphalt	Bio-asphalt Bioasphalt	Bio asphalt
	Bio-cement	Bio-cement Biocement	Bio cement
	Bio-Bitumen	Bio-Bitumen BioBitumen	Bio Bitumen
	Bio-concrete	Bio-concrete Bioconcrete	Bio concrete

Table 4: *Production to Gate LCA Climate Change Performance Values (kg$CO_2^{eqv.}$/kg) derived from Literature*

			Production to Gate LCA Climate Change Performance Values (kg$CO_2^{eqv.}$/kg)									
			Biomass Derived Chemicals					Fossil Fuel Derived Chemicals				
			Min	Q1	Mean	Q3	Max	Min	Q1	Mean	Q3	Max
Platform & High Value Chemicals	1,3-Butanediol (1,3-BDO)		*1.04*	*1.45*	*2.11*	*2.61*	*4.00*	*1.65*	*3.66*	*4.39*	*5.76*	*5.84*
	1,3-Propanediol (1,3-PDO)		*-1.70*	*1.13*	*2.10*	*2.65*	*8.11*	*11.21*	*11.42*	*11.93*	*12.29*	*12.94*
	2,5-Furandicarboxylic acid (FDCA)		*0.32*	*0.77*	*1.32*	*1.97*	*2.50*					
	3-Hydroxypropionic acid (3-HP)		*-1.00*	*-0.40*	*0.62*	*0.80*	*3.38*					
	Acrylic acid		*0.87*	*1.05*	*2.00*	*2.99*	*4.63*	*4.07*	*7.65*	*7.54*	*8.70*	*8.76*
	Acetic acid		*0.65*	*1.02*	*3.09*	*4.74*	*8.11*	*1.99*	*2.01*	*2.03*	*2.06*	*2.08*
	Adipic acid		*-1.40*	*0.45*	*3.78*	*6.00*	*9.20*	*0.00*				*0.00*
	Ammonia		*0.00*	*0.41*	*0.80*	*1.26*	*1.44*	*0.08*	*1.22*	*2.07*	*2.66*	*4.90*
	BTX - Benzene		*2.04*	*2.33*	*2.83*	*3.26*	*4.13*	*3.36*	*4.69*	*5.20*	*6.11*	*6.21*
	BTX - Toluene		*2.11*	*2.40*	*2.91*	*3.34*	*4.25*	*5.94*	*5.99*	*6.03*	*6.08*	*6.12*
	BTX - Ethylbenzene		*2.14*	*2.43*	*2.88*	*3.22*	*4.10*	*6.89*	*6.89*	*6.89*	*6.89*	*6.89*
	BTX - p-xylene		*1.10*	*2.43*	*3.67*	*3.93*	*10.80*	*5.94*	*5.99*	*6.03*	*6.08*	*6.12*
	BTX - m-xylene											
	BTX - o-xylene											
	Ethylene		*-2.39*	*2.34*	*2.59*	*3.60*	*4.57*	*1.21*	*1.44*	*3.46*	*4.91*	*4.95*
	Lactic acid		*-0.94*	*-0.65*	*0.47*	*1.06*	*1.87*	*5.37*	*5.42*	*5.48*	*5.54*	*5.60*
	Propylene glycol		*1.12*	*1.95*	*2.62*	*3.16*	*4.57*	*5.31*	*5.44*	*6.53*	*7.63*	*7.77*
	Succinic acid		*-0.20*	*0.78*	*1.53*	*2.12*	*5.50*	*11.83*	*12.00*	*12.08*	*12.21*	*12.25*
	Xylitol		*-0.93*	*1.38*	*2.16*	*3.65*	*3.83*	*37.16*	*37.52*	*37.88*	*38.24*	*38.60*
Bio-Plastics	Polytrimethyleneterephthalate (PTT)		*1.10*	*2.56*	*3.83*	*5.00*	*10.24*					
	Polyhydroxybutyrate (PHB)		*-4.00*	*-1.91*	*0.28*	*2.01*	*3.97*					
	Polybutylene Succinate (PBS)		*2.28*	*2.29*	*3.63*	*5.04*	*5.40*					
	Polyethylene (PE)	Bio-	*-2.90*	*0.66*	*1.30*	*2.36*	*3.42*					
		LDPE						*-0.07*	*1.92*	*1.96*	*2.48*	*3.03*
		HDPE						*-0.07*	*1.88*	*2.38*	*2.59*	*6.40*
	Polypropylene (PP)		*-3.00*	*0.29*	*0.08*	*0.65*	*1.23*	*0.76*	*1.84*	*2.18*	*2.60*	*3.53*
	Polyvinyl Chloride (PVC)		*-0.19*	*-0.02*	*1.00*	*1.45*	*2.61*	*1.34*	*1.81*	*2.50*	*2.35*	*5.48*
	Polystyrene (PS)		*2.08*	*2.36*	*2.84*	*3.27*	*4.13*	*1.99*	*2.32*	*3.52*	*3.46*	*7.59*
	Polyethyleneterephthalate (PET)		*1.00*	*2.04*	*2.94*	*3.64*	*5.49*	*-0.25*	*2.38*	*3.63*	*4.74*	*9.45*
	Polyurethane (PU)							*3.52*	*3.80*	*4.33*	*4.58*	*5.70*
	Polyamide (PA)		*1.90*	*2.95*	*3.33*	*4.05*	*4.10*	*6.96*	*7.60*	*8.02*	*8.30*	*9.16*
	Poly (lactic acid) (PLA)		*0.14*	*0.76*	*1.86*	*2.58*	*4.13*	*0.54*	*1.20*	*2.50*	*3.05*	*5.49*
	Polyhydroxyalkanoates (PHA)		*-3.70*	*-0.34*	*1.96*	*5.09*	*6.90*	*1.69*	*2.47*	*3.64*	*5.09*	*5.77*

***Table 5**: Production to End of Use LCA Climate Change Performance Values ($kgCO_2^{eqv.}/kg$) derived from Literature*

			Production to End of Use LCA Climate Change Performance Values ($kgCO_2^{eqv.}/kg$)										
			Biomass Derived Chemicals						Fossil Fuel Derived Chemicals				
			Min	Q1	Mean	Q3	Max		Min	Q1	Mean	Q3	Max
Platform & High Value Chemicals	1,3-Butanediol (1,3-BDO)												
	1,3-Propanediol (1,3-PDO)		*4.04*	*5.38*	*6.72*	*8.06*	*9.40*						
	2,5-Furandicarboxylic acid (FDCA)												
	3-Hydroxypropionic acid (3-HP)												
	Acrylic acid												
	Acetic acid												
	Adipic acid		*0.50*	*3.02*	*4.89*	*5.52*	*11.00*		*16.70*	*18.78*	*20.85*	*22.93*	*25.00*
	Ammonia												
	BTX - Benzene												
	BTX - Toluene												
	BTX - Ethylbenzene												
	BTX - p-xylene												
	BTX - m-xylene												
	BTX - o-xylene												
	Ethylene								*3.80*	*4.07*	*4.35*	*4.62*	*4.89*
	Lactic acid												
	Propylene glycol												
	Succinic acid								*3.43*	*4.72*	*6.01*	*7.30*	*8.59*
	Xylitol												
Bio-Plastics	Polytrimethyleneterephthalate (PTT)												
	Polyhydroxybutyrate (PHB)		*1.43*	*1.43*	*1.43*	*1.43*	*1.43*						
	Polybutylene Succinate (PBS)		*0.80*	*2.70*	*3.96*	*4.90*	*6.10*						
	Polyethylene (PE)	Bio-	*-1.00*	*1.70*	*2.49*	*3.70*	*4.74*						
		LDPE							*1.87*	*1.90*	*1.93*	*1.95*	*1.98*
		HDPE							*-0.13*	*0.60*	*1.88*	*2.55*	*5.00*
	Polypropylene (PP)								*0.74*	*1.62*	*2.23*	*2.60*	*4.20*
	Polyvinyl Chloride (PVC)												
	Polystyrene (PS)								*3.51*	*3.56*	*3.60*	*3.65*	*3.69*
	Polyethyleneterephthalate (PET)		*2.21*	*2.61*	*2.80*	*3.10*	*3.19*		*-0.30*	*2.50*	*2.94*	*3.99*	*5.00*
	Polyurethane (PU)		*3.03*	*3.03*	*3.03*	*3.03*	*3.03*		*3.57*	*3.57*	*3.57*	*3.57*	*3.57*
	Polyamide (PA)												
	Poly (lactic acid) (PLA)		*0.10*	*1.28*	*2.02*	*2.45*	*6.59*						
	Polyhydroxyalkanoates (PHA)												

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