Avoiding greenhouse gas emissions

The essential role of chemicals

Life Cycle Assessment of circular systems

Approach and methodology

（日本語仮訳）

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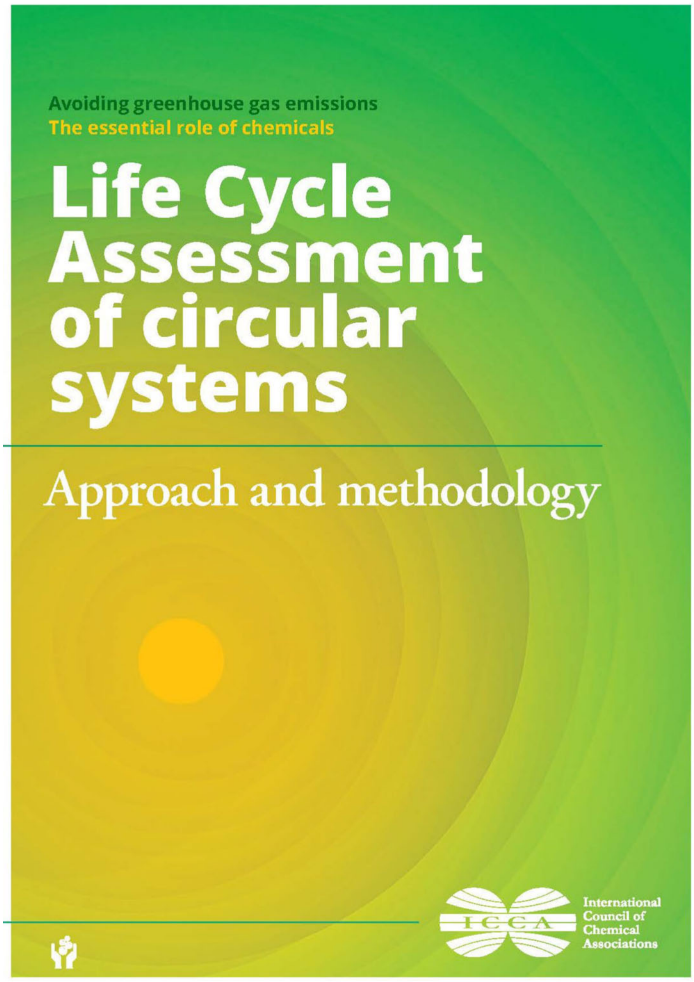

オリジナルの英文資料は以下の URL より入手できます。

https://icca-chem.org/wp-content/uploads/2022/03/ICCA-Life-Cycle-Assessment-of-Circular-Systems.pdf p.1

Introduction

はじめに

国際化学工業協会協議会（ICCA）は、ライフサイクルアセスメント（LCA）方法論が環境に関する意思決定を行うための強力な基盤となるように取り組んでいます。世界の化学産業は、新しい革新的な製品や技術の開発を通じて、循環経済の進展に伴う持続可能性の課題に取り組む上での重要な役割を果たしています。LCA は、環境への影響や社会的な便益に関して、これらのイノベーションが総合的に有益であることを確認するための必須の手段です。

ICCA は、意思決定者が LCA の事例についてより深く理解できるように、化学業界が提供する製品や技術によって実現される温室効果ガス（GHG）排出量の削減について、ライフサイクルの視点での定量化についての一連の事例研究を実施してきました。

この文書は、循環型ソリューションに関連する LCA アプローチと方法論及び ICCA とそのメンバー企業の事例紹介を示した「ICCA 循環型システムに対するライフサイクルアセスメント（日本語仮訳）(2021)」に続いて作成しました。

ICCA は Quantis 社に対し、インペリアルカレッジロンドン及びヴェオリア社によるプラスチック包装容器の LCA に関する 73 件の論文集（以下、「ヴェオリアレポート」[1]）について、LCA の原則を適用し、「Q＆A（質疑応答）」形式による検討・とりまとめを実施するよう依頼しました。

この文書では、実際の循環モデルであるビジネスケースを LCA 方法論を用いて評価を行う際に考慮すべき重要な点について概説します。

具体的には、ヴェオリア社とインペリアルカレッジロンドンで実施された広範な評価において、LCA 方法論がさまざまな状況でどのように適用されているかを概説します。ICCA は、この文書で、「ヴェオリアレポート」を引用し、LCA の評価を読む際に必要な共通事項について、質問に回答する形式で説明します。これらの質問に答えるための要点として、質問毎に、要点のチェックリスト及び意思決定者が LCA の評価を読む際に留意すべき論点を提供します。ICCA では、この文書を通じて、技術や製品の選択、更には政策や戦略が正しく判断されるように、LCA の評価結果を最大限に活用するための手段を提供したいと考えます。

[1] Voulvoulis, Nikolaos & Kirkman, Richard & Giakoumis, Theodoros & Metivier, Pauline & Kyle, Charlotte & Vicky, Midgley. (2020). Veolia Plastic White paper. 10.13140/RG.2.2.12793.70241.

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詳細な検討：プラスチック製ボトルとその他の材料を使用したボトルの環境への影響評価

「ヴェオリアレポート」では、プラスチック包装容器の LCA に関する 73 件の公開資料を取りまとめ、紙製容器、スチール缶、アルミニウム缶、ガラス瓶の 4 つの材料と比較して、プラスチック容器の環境影響に関する一般的な結論を導き出しています。各 LCA 事例に即した固有事項(specific context) を考慮した後、著者らはこれらの事例を基に、5 つの材料から作られた 500 ml の容器を製造する際の温室効果ガス排出量の平均比較を実施しています。

この比較の結果を説明するために、著者は 500 ml のペットボトルをある代替材料で製造した場合、2016 年に発生したであろう二酸化炭素排出量を算出しています[表 1]。この結果では、プラスチック製ボトルは、比較検討した他のバージン材料のボトルより二酸化炭素排出量（carbon footprint）が少なくなることを示しています[2]。2016 年*には、500 ml のペットボトルの生産に 25 百万 tCO2 eq を排出したと推定されています。これは、比較した代替品に全部置き換えたと仮定した場合の排出量、紙製容器（25.5 百万 t CO2 eq)、スチール缶（43.7 百万 t CO2 eq)、アルミニウム缶（105.9 百万 t CO2 eq)、ガラスボトル（112.4 百万 t CO2 eq）よりも少なくなります。

「ヴェオリアレポート」は、さらに、プラスチックリサイクルの重要性も明らかにしています。5 つの材料での比較には容器の廃棄段階（使用終了段階）が含まれていませんが、「ヴェオリアレポート」では、リサイクルの効果を強く示す複数の個別の LCA を引用しています。著者らは、代替材料に切り替えたり、まだ開発されていない技術を待つのではなく、「市場に投入されたプラスチック容器を回収（remove)、削減、再利用、またはリサイクルすることが、前進する方法である」と結論付けています。

それぞれが特有の事情を有する 73 件の LCA 事例から前述の一般的な結論を引き出すためには、各事例の詳細を慎重に検討し、結果に影響を与える可能性のある各 LCA 事例に即した固有の事項（contextual elements）を特定する必要がありました。結果として、次の 9 つの質問より、このような評価の枠組みを提供します。

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[2]「ヴェオリアレポート」に記載されているこれらの結果には、パッケージ使用後の最終処分（廃棄）の影響は含まれていないことに注意してください。このライフサイクルステージ（廃棄処分）を結果に追加すると、別の結論につながる可能性があります。

* 排出量は、各材料タイプの平均組成と重量を想定して計算されています。

検討結果、プラスチック製ボトルは、他のバージン材料のボトルと比較して二酸化炭素排出量が少ないことがわかりました。

表１：2016年の素材ごとの500ml容器を製造する際の温室効果ガス排出量

Container type (500ml bottle or can)	Composition	Weight per bottle (grams)	Tonnes in 2016 (485 billion bottles)	Tonnes CO_2-e per tonne of 500ml bottles/cans produced*	Million tonnes of CO_2 in 2016 from production if all plastic bottles were replaced by this format and material*
Plastic bottle (baseline)	Plastic (PET)	12.7	6,159,500	4.053	25.0
Liquid fiberboard packaging	Plastics (50% PET closure and 50% PE layer)	8	3,880,000	3.585	25.5 (+0.5)
	Aluminium	1	485,000	12.874	
	Carton	13	6,305,000	0.844	
Steel can	Steel	30	14,550,000	3.004	43.7 (+18.7)
Aluminium can	Plastics (PE layer)	4	1,940,000	3.116	105.9 (+80.9)
	Aluminium	16	7,760,000	12.874	
Glass bottle	Glass	259	125,615,000	0.895	112.4 (+87.4)

https://cdn.ca.emap.com/wp-content/uploads/sites/6/2020/07/Veolia-Plastic-Whitepaper.pdf

[表1]＊GHG排出量は、採掘、一次処理、製造、販売時点への資材の輸送をカバーするデフラ社の2019年換算係数を使用して算出しています。

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Q1： LCAを現実に適用するにはどうすればよいか？また、LCAから何を学ぶことができるか？

LCAは、製品やサービスの環境への影響を評価、比較するための強力なツールであり、意思決定の指針となります。LCAに基づいて決定を行う場合は、実施した各LCA事例に即した固有事項（the context of this specific decision）をしっかり確認することが重要です。

確認すべき事項の1つは、時間的、地理的、および技術的な背景などの前提条件を各種状況/条件を考慮した上で、このLCA結果を決定しているかどうかです。多くの場合、LCAは、消費されるエネルギー

の種類、工業プロセスの効率、評価対象製品の廃棄シナリオなどの事項を仮定する必要があります。LCAを意思決定のガイダンスとして使用する場合、これらの前提は各LCA事例に即した固有な事項が現実的である必要があります。例えば、プラスチックの容器の場合、「ヴェオリアレポート」では、「一部のLCAでは、すべての製品が回収、リサイクル、および使用終了段階で再利用されるという前提を用いています。しかし、現実はそれほど単純ではなく、特定の事例/国/都市のリサイクル率に依存することがよくあります。」と記しています。実際、リサイクル率が高いドイツのプラスチック製ボトルの LCA は、ライフサイクル全体の影響と利点が大きく異なるため、リサイクル率が低い国には、結論が変わる可能性があるため容易に適用できません。

また、公平な評価では、製品の機能性を考慮する必要があります。機能性の概念は、例えば2つの容器材料間の比較に適用できます。容器材料の機能とは、必要な容量の被包装材を保持するのに適した「入れ物」[3]であることが必要です。LCAでは、重量ベース（例： 1kgのガラスと1kgのプラスチック）で比較するのではなく、1つの製品単位（1リットルのミルクを梱包するために必要なガラスまたはプラスチックの質量など）を梱包するために必要な各材料の量の影響を比較する必要があります。これにより、意思決定者は、現実的な製品の機能性を考慮した比較に基づく選択の根拠とすることができます。

比較評価の結果は、どのような前提（仮定）を置いたかや製品の機能性（機能単位）をどのように置いたかに左右されます。比較LCAの結果を用いて決定を行うためには、次の質問/確認が必要です。

•LCAの仮定は、各事例に即した固有の事項とどの程度整合しているか？
•比較は、各LCA事例に即した固有の事項において、理にかなっているか？

Q2：材料の品質はどのように考慮されますか？

LCAを使用して2つの製品またはサービスの環境パフォーマンスを比較する場合、評価の比較基準は機能に基づいて定義されます。この概念は材料の品質に依存します。

材料によっては特定の用途に適していない場合があります。プラスチックの場合では、高分子鎖（polymer chains）の劣化です。すなわち、一部の再生プラスチックは、特定の用途では品質が不十分であると見なされるということです。実際、すべてのリサイクル技術が同じ品質のリサイクル製品に再生されるわけではありません。ケミカルリサイクルはバージン材料の製品と同じ品質のものを製造できると考えられますが、マテリアルリサイクルは品質が低下する可能性があります。食品に接触する用途では、プラスチックの品質が重要な要素であるため、ケミカルリサイクルされたプラスチックとマテリアルリサイクルされたプラスチックは機能的に同等ではない場合があります。したがって、LCAを検討する場合には、このような特定の状況（ここでは、用途）において材料の品質が問題になるかどうかを確認

[3] ここでの容器の概念には、製品プロバイダのニーズに応じて、内容物（牛乳）を保持、保護、および輸送可能性を確保することが含まれます。

することが重要です。

ただし、材料の品質に関する問題は必ずしも重要であるとは言えません。例えば、「ヴェオリアレポート」は、ボトルの製造に、未使用/バージンの PET 繊維とリサイクル PET 繊維を比較した事例が示されています。この事例で、著者らは、マテリアルリサイクルの場合には、リサイクル繊維はある特性（例えば、染色性の点）では品質が劣っている場合がよくあることを認めています。しかし、純粋な廃棄物（端材などの廃棄物）回収の流れでは、マテリアルリサイクルが、ペットボトルの製造に十分な品質のリサイクル PET 繊維につながると主張しています。このような状況では、潜在的な品質の違いは問題ではなく、未使用の PET とリサイクル PET を同等と見なすことができます。ただし、別の場合、明るい色の子供のおもちゃの製造などは、マテリアルリサイクルされた PET の染色性が劣っているため、その比較の意味合いが低下することがあります。このため、製品の最終的な用途における品質の観点からみて比較が適切かどうかを決めることになります。LCA を評価する場合は、次の質問/確認が重要です。

•評価で材料の品質は考慮されているか？
•材料の品質を考慮する必要があるか？
•材料の品質に言及した場合、結果にどのような影響があるか？

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Q3: 計算での仮定は、結果に大きな影響を与える可能性があるか？ その場合、LCA に感度分析が含まれているか？

LCA 解析は、一次ソースからのデータと、二次データを提供するために使用されるデータベースに基づいて行います。バリューチェーンは複雑であり、LCA を実施する個々人が事例に即した詳細な事項を完全には特定できないため、LCA の共通部分は仮定になります。工業プロセスで消費されるエネルギーの種類、その効率、製品の廃棄シナリオなどの事項については、多くの場合、LCA 実施者にその産業の背景や最も一般的な事例に関する知識に基づいて仮定を行うよう要求しています。

このように仮定は、結果に大きな影響を与える可能性があります。前提が LCA の結果に大きな影響を与えると考えられる場合は、感度分析を行うことをお勧めします。感度分析では、「最善ケース」シナリオと「最悪ケース」シナリオを定義して、仮定に潜在的な変動と不確実性を反映させます。これらのシナリオの定義は、LCA 実施者の対象プロセスに関する知識に基づいているため、潜在的な変動がよく知られている場合は、信頼できるシナリオを設定するのが容易です。

例えば、PET ボトルの LCA で、リサイクル率が国内平均として定義されている場合、「最悪のケース」はリサイクル率 0%、「最良のケース」はリサイクル率 100%で対応できます。このような分析により、背景/条件が変化した場合に LCA の結果がどのように異なるかを示唆できます。すなわち、プロセスが別

の場所で実現されたり、時間の経過とともに前提が変化したときも、感度分析によるケーススタディによって示唆を得ることができます。

LCA の結果を読む場合は、次の質問/確認が重要です。

•計算での主要な仮定は何か？
•これらの仮定は堅牢であるか、それとも課題を持つ可能性があるか？
•これらの仮定は結果にどのような影響を与え、感度分析は行われたか？
•シナリオ分析は公平か（「最良ケースシナリオ」だけに焦点を当てていないか）？

Q4：評価の範囲は、事例の目的に沿っているか？

LCA の定義は、製品またはサービスの環境への影響を、生産に必要な原材料の採掘（「ゆりかご（cradle）」）から使用終了（「墓場（grave）」）まで、ライフサイクル全体にわたって考慮することです。実際には、この「ゆりかごから墓場まで（cradle-to-grave）」アプローチは必ずしも必要ではありません。また、調査の目的に関連しない段階は、分析からそのライフサイクル段階を省略することもできます。

例えば、「ゆりかごからゲート（cradle-to-gate）」の事例は、原材料の採掘から工場のゲートまでの部分的なライフサイクルの評価です。このような事例では、製品の変換、輸送、使用、廃棄を行うライフサイクル段階は省略されています。「ゆりかごからゲート」アプローチは、特定の原材料または製品のユーザーに情報を提供することを目的としている場合には適切と言えるでしょう。例えば、PVC 樹脂の「ゆりかごからゲート（cradle-to-gate）」までの LCA の結果は、電気ケーブルメーカーが PVC 絶縁ケーブルの LCA を実施するために再利用できます。

ただし、部分的な評価を用い比較を行う場合、2 つの製品比較の決定を行うために必要な全体像などの LCA 結果が常に提供されるわけではありません。「ヴェオリアレポート」は、プラスチックまたは紙素材から 500ml の飲料容器を製造した場合の影響を比較した LCA 結果の例を示しています。CO2 排出量を見ると、どちらの容器も同じ量の排出量をその生産時に排出しています。ただし、LCA の結果には使用が終了した段階は反映されていません。「ヴェオリアレポート」に記載されているように、プラスチック製ボトルはリサイクルが容易で、プラスチックのリサイクルが一般的な地域では、プラスチック製ボトルの二酸化炭素排出量はリサイクルされていない紙製容器包装よりも低くなる可能性があります。したがって、意思決定にはこれらの材料の使用が終了するまでの段階を考慮する必要があります。

LCA の結果を解釈する際には、評価の範囲を考慮する必要があります。調査の目的によっては、一般的で広く適用可能な結果を提供するため、部分評価が最も適切な選択肢となる場合があります。2 つの複雑な製品を比較することを目的としている場合、ライフサイクルの各段階ですべての環境影響を把握するためには、完全な評価が必要です。このため、LCA の範囲に関して考慮する場合は、次の質問/確認が重要です。

•評価は材料の選択に使用されているか、または同じ製品タイプのメーカーを選択するために使用されるのか？
•評価で考慮されていないライフサイクル段階はあるか。また、その理由は何か？
•ゆりかごからゲート（cradle-to-gate）までの評価において、ライフサイクルのある段階を省略した場合、結果に大きな影響を与える可能性はあるか？

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Q5：LCA は厳密な代表的なデータを使用しているか？

LCA 方法論は、モデル化されたデータと評価対象の製品またはサービスを特徴付けるプロセス固有のデータの組み合わせに依存します。固有のデータが欠落している場合は、LCA データベース、文献、またはシミュレーションから代替（surrogate）データを取得します。

プロセス固有のデータは常に優先されますが、新しい技術では特定のデータがまだ利用できない場合は、信頼性の高い代替データを選択することになります。例えば、新しいリサイクル技術がまだ運用されていない場合や、エネルギー消費量やその収量を定量化するのに十分なデータが得られていない場合などです。

このような場合は、既存のデータセット（データベース）から外挿する必要があります。つまり、LCA の結果と結論は、プロセスの代表性が劣っている可能性があります。LCA を読み解く場合、特に新しい技術を LCA で評価する場合は、次の質問/確認が重要です。

•LCA は外挿データを使用しているか？
•その場合、適切に文書化され、信頼性が高く、正当化されているか？
•結果にはかなりの不確実性が生じる可能性があるか？
•このギャップは認識され、著者はそれについて詳しく説明しているか？

Ｑ６：LCA には、将来のシナリオの分析が含まれているか？

LCA の結果は、評価が行われる背景に影響されます。PET ボトルなどの製品では、製品に即した固有な事項が LCA の結果に影響を与える可能性があります。例えば、再生原材料の調達、グリーンエネルギー由来の電力供給、使用が終了したとき（廃棄段階）のリサイクルオプションなどです。さらに、これらのパラメータは時間の経過とともに変化するため、LCA の結果を期限付きにします。

実際、国がグリーンエネルギー、リサイクル、廃棄物回収、エネルギー効率、循環社会に投資するにつれて、影響力のあるいくつかのパラメータが今後数年間で大きく変化すると予想されます。「ヴェオリア

レポート」の中の評価では、発電のための新しい電源の例について説明しています。各国の電源構成がより環境に配慮したものになると予想されるため、電力消費型製品やサービスの環境フットプリントも変化すると予想しています。

LCA 実施者は、将来、いくつかの重要なパラメータがどのように進化するかという仮定についての将来シナリオを用いる場合は、このような潜在的な進展を調査することがあります。このアプローチは、意思決定を行う手助けとなり、LCA の結果が将来の利用者にも役立つような追加情報（additional layer）を提供します。ただし、将来のシナリオは常に不確実であることを考慮する必要があります。LCA の結果を理解する場合は、次の質問/確認が重要です。

•将来シナリオの分析はあるか？
•違ったシナリオにより、結果はどのような影響を受けるか？
•将来のシナリオは過度に楽観的でなく、適切か？

LCA 方法論は、モデル化されたデータと評価対象の製品またはサービスを特徴付けるプロセス固有のデータの組み合わせに依存します。

p. 7

Q7. 全ての関連する環境影響カテゴリーを考慮しているか？

LCA は、地球温暖化、水の消費、資源の枯渇、酸性化などの環境基準について、製品やサービスの影響を評価するのに役立ちます。LCA の結果は、地球温暖化については、広く理解されている単位である kg 当たりの二酸化炭素（CO2）換算排出量で示されています。他の環境基準の結果は、あまり議論されておらず、しばしば無視されます。その理由は、他の環境基準が余り理解されていないことと、結果の提示を容易にするためです。

本来、LCA の結果を見る際には、関連するすべての環境基準の結果を考慮することが重要です。2 つの基準の間でトレードオフが発生する場合があるからです。この場合、1 つの環境への影響が減少すると、もう 1 つの基準が増加します。バイオ燃料は一般的な例であり、GHG 排出量の削減につながることが多いですが、農業への需要の増加により毒性や富栄養化、土地利用の増加につながる可能性があります。

「ヴェオリアレポート」は、主に CO2 を中心にした LCA 報告書の例です。これは、「カーボンフットプリント」というタイトルから明確に説明できます。1 つまたは 2，3 の環境基準に評価を集中させることは、評価が部分的であることが明確である限りは問題ではありません。ただし、この集中は、結果の選択的な提示にはならず、最も肯定的な結果のみを示していると言えます。その他の環境影響カテゴリー

を含めることは、負荷の転換がある場合には推奨します。

このように評価を読む際には、関連するすべての環境基準から恣意的な選択を行うのではなく、同等の重要性を示しているかどうかを確認することが重要です。不完全な評価では、全体像が示されず、潜在的なトレードオフが隠れている可能性があります。

Q8. LCA によって把握されない影響や効果はあるか。

LCA では、製品やサービスに関連する主な環境上の課題を把握できます。この分析では、地球温暖化から土地利用まで、いくつかの環境基準を評価することができます。この方法論は、地球温暖化などの十分に研究されたトピックでは強力ですが、いくつかの複雑な課題については LCA では十分に把握できない場合があります。

LCA を検討する場合は、負の影響が評価で把握されているかいないかを識別することが重要です。LCA は包括的で総合的な優れたツールですが、意思決定者は、LCA を全ての側面を網羅できる他のツールと補完することをお勧めします。

p.8

異なる二つの LCA 事例で用いられた方法に大きな違いはあるか？

Q9 これらの結果を他の LCA 事例と比較するにはどうすればよいか？

全述の 8 つの質問は、各 LCA が評価の範囲、想定される前提、および評価を行う時の方法論の選択が全て異なることを示しています。特にリサイクルの場合は、方法論の決定が重要な違いをもたらす可能性があります。

これらの違いの下、相違点が特定され、結果に対する影響が明確である限り、LCA 事例は比較可能となる場合があります。例えば、PET ボトルの「ゆりかごからゲート（cradle-to-gate)」までの事例は、共通となるライフサイクルフェーズでのみ比較する限り、「ゆりかごから墓場（cradle-to-grave)」までの評価とも比較可能となります。

同様に、2 つの異なる背景の下に実行された 2 つの研究結果は、背景が結果にどのような影響を与えるかを説明している場合に限り、比較できることがあります。例えば、2 つの異なる生産国間の評価では、電力構成が全体的な結果にどのように影響するか、国ごとの製品輸送時の環境負荷影響が両国間にどのように影響するか、国ごとで廃棄段階の処理にどのような違いがあるのかといったことを考慮する必要があります。

類似する題材で 2 つの異なる LCA を比較しようとすると、結果が異なる場合があります。このような

場合は、分析する前に次の質問/確認が重要です。

•両方の事例で実施した方法論的な選択により大きな違いはあるか？
•分析で使用されるデータは、確実性、信頼性が高く、十分に検証されているか？
•両方の事例における評価の背景は類似しているか？
•これらの違いは結果にどのような影響を与える可能性があるか？相違について説明がなされているか？

p.10

結論

LCA の結果は、頻繁に LCA に携わっていない人にとっては解釈が困難な場合があります。この方法論をより深く理解することで、意思決定者は LCA の結果をいつ、どのように特定の意思決定の背景に適用するかを理解することができます。

LCA は、LCA 方法論に関する一般的で包括的な文書を提供することで意思決定プロセスのための有用な情報を提供します。ICCA は本書のようなチェックリストを提供することができ、LCA の解釈において意思決定者にお力添えができれば幸いです。

この日本語訳については出来る限りオリジナルの英文に忠実で、わかりやすい翻訳に努めましたが、日本語訳の内容に疑問等がある場合には、本資料 1 ページ目に紹介しておりますオリジナルの英文資料にて、直接、内容をご確認いただくようお願いいたします。
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今後の検討課題：
・LCA における「context」の解釈と日本語訳

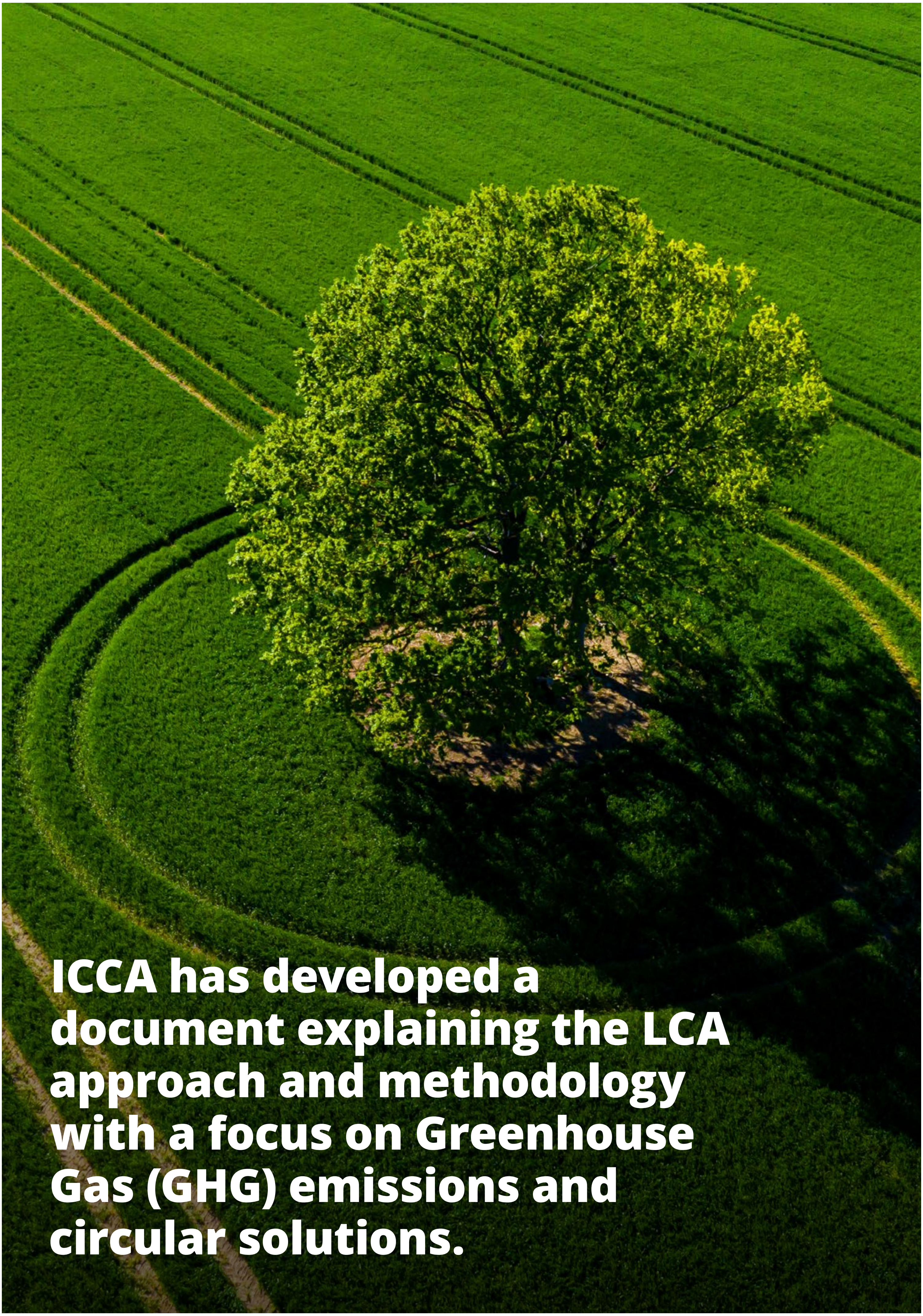
Avoiding greenhouse gas emissions

The essential role of chemicals

Life Cycle Assessment of circular systems

Approach and methodology

International Council of Chemical Associations



ICCA has developed a document explaining the LCA approach and methodology with a focus on Greenhouse Gas (GHG) emissions and circular solutions.

Introduction

The International Council of Chemical Associations (ICCA) is committed to ensure that Life Cycle Assessment (LCA) methodology provides a strong basis for environmental decision-making. The global chemical industry plays an important role in addressing sustainability challenges through the development of new, innovative products and technologies in the context of a growing circular economy. LCA is an essential step to check that these innovations are beneficial overall, regarding environmental impacts, and societal benefits.

To help decision-makers better understand life cycle assessment studies, ICCA has developed a series of studies on the quantification, with a life cycle perspective, of greenhouse gas (GHG) emissions savings enabled by products of the chemical industry.

This document follows the first edition ICCA LIFE CYCLE ASSESSMENTS TO CIRCULAR SYSTEMS (2021), which focuses on the LCA approach and methodology relevant for circular solutions,and was illustrated by case studies by ICCA and its member companies.

ICCA commissioned Quantis to apply these principles when reviewing through "Questions & Answers" an assessment by Imperial College London and Veolia of 73 publications on LCA of plastic packaging (referred to as Veolia's Report[1]).

The document provides a critical overview of the main elements to take into consideration when performing LCA methodology applied on existing circular model business cases.

The extensive assessment performed by Veolia and Imperial College provides an overview of how LCA methodology has been applied in a wide variety of situations. With this document, ICCA builds on Veolia's Report and aims to answer common questions that must be asked when reading through an LCA. The key to answering these questions is given by providing, for each question, a checklist of elements and questions that a decision-maker should keep in mind when reading an LCA. Through this document, ICCA hopes to give decision-makers the tools to make the most of LCA results to select technologies and projects, and/or to orient policies and strategies.

[1] Voulvoulis, Nikolaos & Kirkman, Richard & Giakoumis, Theodoros & Metivier, Pauline & Kyle, Charlotte & Vicky, Midgley. (2020). Veolia Plastic White paper. 10.13140/RG.2.2.12793.70241.

An in-depth review: assessing the environmental impacts of bottles made from plastic vs other materials

Veolia's Report compiles 73 publications on LCA of plastic packaging, aiming to draw general conclusions on its environmental performance relative to four other materials - liquid fiberboard, steel cans, aluminum cans, and glass bottles. After consideration of the specific context of each LCA, the authors are able to build on these studies to generate an average comparison between 500 ml containers made from the five materials.

To illustrate the results of this comparison, the authors calculate the carbon emissions that would have occurred in 2016 if all 500 ml PET bottles had been made from an alternative material [Table 1]. The results indicate that bottles made from plastic would have a lower carbon footprint in comparison to other virgin materials considered[2]. In 2016*, it is estimated that 500 ml PET bottles generated 25 million tons of CO_2 eq for their production, which is less than the alternatives that are liquid fiberboard packaging (25.5 millions t CO_2 eq), steel cans (43.7 millions t CO_2 eq), aluminum cans (105.9 millions t CO_2 eq), and glass bottles (112.4 millions t CO_2 eq).

The study also displays the importance of plastic recycling. Although container end-of-life is not included in the average comparison between the five materials, Veolia's Report cites several individual LCA that demonstrate the strongly positive effects of recycling. The authors conclude that "removing, reducing, reusing or recycling the plastic packaging placed on the market is the way forward", rather than switching to alternative materials or waiting for solutions that are not developed yet.

In order to draw such general conclusions from 73 different LCA, each corresponding to a specific context, the authors had to carefully examine the particularities of each study, identifying contextual elements that could have an impact on the results. The nine questions that follow provide a framework for such an assessment.

PDF **https://cdn.ca.emap.com/wp-content/uploads/sites/6/2020/07/Veolia-Plastic-Whitepaper.pdf**

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[2] It should be noted that these results presented by Veolia's paper do not include the end-of-life impacts of the packaging. Adding this life cycle stage to the results could lead to different conclusions.

*** Emissions have been calculated assuming average compositions and weights for each material type.**

Their results indicate that bottles made from plastic would have a lower carbon footprint in comparison to other virgin materials considered.

[Table 1] Calculating greenhouse gases emissions for producing all 500ml containers in 2016 from alternative materials

Container type (500ml bottle or can)	Composition	Weight per bottle (grams)	Tonnes in 2016 (485 billion bottles)	Tonnes CO_2-e per tonne of 500ml bottles/cans produced*	Million tonnes of CO_2 in 2016 from production if all plastic bottles were replaced by this format and material*
Plastic bottle (baseline)	Plastic (PET)	12.7	6,159,500	4.053	25.0
Liquid fiberboard packaging	Plastics (50% PET closure and 50% PE layer)	8	3,880,000	3.585	25.5 (+0.5)
	Aluminium	1	485,000	12.874	
	Carton	13	6,305,000	0.844	
Steel can	Steel	30	14,550,000	3.004	43.7 (+18.7)
Aluminium can	Plastics (PE layer)	4	1,940,000	3.116	105.9 (+80.9)
	Aluminium	16	7,760,000	12.874	
Glass bottle	Glass	259	125,615,000	0.895	112.4 (+87.4)

* Emissions have been calculated using the 2019 Conversion Factors from Defra that covers the extraction, primary processing, manufacturing and transporting materials to the point of sale.

Q1. How can this LCA be applied to reality and what can be learned from it?

LCA is a powerful tool to evaluate and compare the environmental impacts of products or services, providing guidance for decision-making. When making a decision based on an LCA, it is important to ensure that this LCA can be applied to the context of this specific decision.

One element to check is whether the assumptions taken in the LCA apply to the specific context of this decision from a temporal, geographic and technological context. Often, LCA must make assumptions on elements such as the type of energy consumed, the efficiency of industrial processes or the end-of-life scenario for the product assessed. These assumptions must be realistic for the specific context if the LCA is to be used as guidance for decision-making. In the case of plastic packaging, for example, Veolia's Report mentions that "some LCA maintain the assumption that all products are collected, recycled, and reused in the end-of-life phase. The reality, however, is not that simple; and often depends on recycling rate in a particular study/country/city". Indeed, an LCA of a plastic bottle in Germany, where recycling rates are high, cannot be easily applied to countries where the recycling rates are much lower since the impacts and benefits of the life-cycle stage would be significantly different, potentially altering the conclusions.

Furthermore, fair assessments should take product functionality into consideration. The notion of functionality applies, for example, to the comparison between two packaging materials. The function of a packaging material is to be a proper vehicle[3] for a given volume of product. An LCA should compare the impacts of the amount of each material that is necessary to package one unit of product (e.g. the mass amount of glass or plastic necessary to package 1 liter of milk), rather than comparing the materials on a weight basis (e.g. 1 kg of glass versus 1 kg of plastic). Therefore, decision-makers should base choices on a comparison that corresponds to the reality of product functionality.

Results of a comparative assessment are influenced by the choices made in the methodological assumptions, and by the way in which product functionality was taken into account. In order to base a decision on a comparative LCA, the questions to ask are the following:

- To **what extent** are the LCA assumptions coherent with the specific context of the decision?
- Does the **comparison make sense** in the specific context of this decision?

Q2. How is material quality taken into consideration?

When LCA is used to compare the environmental performance of two products or services, the basis of comparison of the assessment is defined based on functionality. This notion is dependent on material quality.

Some materials may not be suitable for specific applications. In the case of plastics, the degradation of polymer chains mean that some recycled plastics are deemed to be of insufficient quality for certain applications. In fact, not all recycling technologies lead to the same quality of recycled product. Chemical recycling is considered to produce virgin-quality outputs, whereas mechanical recycling may lead to quality degradation. For food-contact applications, where plastic quality is essential, chemically, and mechanically recycled plastic may not be functionally equivalent. Thus, when reviewing an LCA, it is important to ask whether material quality could be an issue in this specific situation.

However, the question of material quality is not always relevant. For example, Veolia's Report cites a study comparing virgin and recycled PET fibers for the production of bottles. The authors acknowledge that, in the case of mechanical recycling, recycled fibers are often inferior for some properties such as dyeability. However, they argue that, with a pure waste stream, mechanical recycling leads to recycled PET fibers that are of far sufficient quality for making plastic bottles. In this situation, potential quality differences are not an issue and virgin and recycled PET can be considered as equivalent. In another situation, however, such as producing brightly colored children's toys, the comparison may be less relevant given the limited dyeability of mechanically recycled PET. Thus, the final usage of the product determines whether the comparison makes sense or not from a quality standpoint.

When reviewing an LCA, it is important to check the following points:

- Is **material quality** taken into account in the assessment?
- Is it **necessary to take material** quality into account?
- If material quality is addressed, how does it **affect results**?

[3] The notion of vehicle here includes holding, protecting, and ensuring transportability according to the needs of the product provider.

Q3. Are some assumptions made in the calculation likely to have a strong impact on results? If so, does the LCA include a sensitivity analysis?

LCA analyses are based on data coming from primary sources and databases used to provide secondary data, which are often completed with assumptions. Assumptions are a common part of LCA, as the complexity of value chains makes it so that no individual member could fully characterize each element in detail. Elements such as the type of energy consumed by an industrial process, its efficiency or the end-of-life scenario for a product often require the LCA practitioner to make assumptions based on knowledge of the context and the most common practices in the industry.

Such assumptions can have a large impact on results. When an assumption is presumed to have a large impact on LCA results, the best practice is to carry out a sensitivity analysis. In a sensitivity analysis, "best case" and "worst case" scenarios are defined to reflect the potential variations and uncertainty in the assumption. The definition of these scenarios is based on the LCA practitioner's knowledge of the studied process, thus it is easier to set credible scenarios when the potential variations are well-known.

For example, in an LCA of PET bottles in which the recycling rate is defined as the national average, the "worst case" could correspond to 0% recycling and the "best case" to 100% recycling. Such analyses provide insight on how LCA results may be different if the context evolves, because a process is carried out in a different location or because of changes over time.

When reading through an LCA, it is important to ask the following questions:

- What are the **main assumptions** made in the calculations?
- Are these **assumptions robust** or could they be questioned?
- How could these **assumptions affect results** and is there a sensitivity analysis?
- Is the scenario **analysis unbiased** (i.e. not focusing on the "best case scenario")?

Q4. Is the scope of the assessment in line with the objectives of the study?

By definition, Life Cycle Assessments take into account environmental impacts of a product or service across its full life cycle, from the extraction of the raw materials necessary for production ("cradle") all the way to end-of-life ("grave"). In practice, this "cradle-to-grave" approach is not always necessary, and life cycle steps might be omitted from the analysis if they are not relevant to the objectives of the study.

For example, "cradle-to-gate" studies are the assessment of a partial life cycle, from resource extraction to factory gate. Such studies omit the life cycle phases in which the product is transformed, transported, used and discarded. The cradle-to-gate approach may be relevant if the purpose is to provide information to the user of the specific raw material or product. For example, a cradle-to-gate LCA of a PVC resin generates results that can be reused by an electric cable manufacturer for an LCA of PVC-insulated cables.

For the sake of comparison, however, partial assessments do not always provide the full picture that is needed to make an informed decision between two products. Veolia's Report gives the example of LCA results comparing the impact of producing a 500-ml beverage container from plastic or from liquid fiberboard. When looking at CO_2 emissions, both containers generate a similar amount of emissions for their production. However, the LCA results do not reflect the end-of-life phase and, as stated in the Report, plastic bottles are much easier to recycle and thus, in regions where plastic recycling is common, plastic bottles could have a lower carbon footprint than non-recycled liquid fiberboard packaging. Thus, end of life for these materials should be taken into consideration in decision-making.

The scope of the assessment must be kept in mind when interpreting the results of an LCA. Depending on the study objective, a partial assessment may be the most appropriate choice as it provides results that are generic and widely applicable. If the aim is to compare two complex products, a full assessment is necessary to capture all environmental impacts at every life cycle stage. Thus, the following questions are important to consider regarding the scope of an LCA:

- Is the assessment being **used for material selection** or to choose between manufactures of the same product type?
- Are there any **life cycle stages** that are not accounted for in the assessment and why?
- If any life cycle **stages are omitted**, for example in a cradle-to-gate assessment, are they likely to have a strong impact on results?

Q5. Does the LCA make use of rigorous, representative data?

LCA methodology relies on a combination of modeled and process-specific data characterizing the product or service that is assessed. Whenever specific data is missing, surrogate data may be obtainable from LCA databases, from the literature or from simulations.

While process-specific data are always preferred, reliable surrogate data may be an option when specific data is not yet available for a new technology. Novel recycling technologies, for example, may not yet be operational or have generated enough data to quantify their energy consumption or their yield.

In such cases, it may be necessary to extrapolate from existing datasets, meaning that the results and the conclusions of the LCA might be less representative of the process under study. When reading through an LCA, and especially if it is an LCA of a new technology, it is important to ask the following questions:

- Does the LCA make use of **extrapolated data**?
- If so, is it **well-documented**, reliable, and justified?
- Could it introduce **a significant amount** of uncertainty in the results?
- Is this **gap acknowledged** and do the authors elaborate on it?

Q6. Does the LCA include an analysis of a future scenario?

LCA results are influenced by the context in which the assessment is taking place. For a product such as a PET bottle, many contextual elements can have an impact on LCA results, such as the availability of recycled input material, of green energy to power production, or of recycling options at end-of-life. Moreover these parameters can evolve over time, making LCA results time-bound.

In fact, several influential parameters are expected to change greatly in the coming years as countries invest in green energy, recycling, waste collection, energy efficiency and circularity. Veolia's Assessment mentions the example of evolving sources of electricity generation. As the electricity mix of countries is expected to become greener, the environmental footprint of electricity-consuming products and services is expected to change as well.

LCA practitioners sometimes investigate such potential evolutions by using a future scenario, which is an assumption on how several important parameters may evolve in the future. This approach provides an additional layer of information which can help guide decision-making and ensures the results of the LCA can be also useful for future users. It should however be considered carefully, as future scenarios are always uncertain. When reading through an LCA, it is thus important to ask the following questions:

- Is there **an analysis** of a future scenario?
- How are **results affected** by this different scenario?
- Is the **future scenario** plausible without being too optimistic?

LCA methodology relies on a combination of modeled and process-specific data characterizing the product or service that is assessed.

Q7. Are all relevant environmental impact categories taken into consideration?

LCA is useful to evaluate the impacts of products and services on several environmental criteria, including global warming, water consumption, resource depletion or acidification. Often, LCA results are presented with a focus on global warming expressed in kg of CO_2 equivalents emitted, a widely understood metric. Results for other environmental criteria are much less discussed and are often neglected, perhaps because they are less widely understood and because it facilitates the presentation of results.

It is nevertheless important to consider results for all relevant environmental criteria when looking at LCA results. Tradeoffs may occur between two criteria, where the reduction of one environmental impact leads to the increase of another. Biofuels are a common example, as they often are shown to lead to a reduction of greenhouse gas emissions, but may lead to increased toxicity, eutrophication, or land use due to the demand for more agricultural inputs.

Veolia's Report is an example of an LCA document centering chiefly on CO_2. This is made explicit from the title, "The Carbon Footprint". Focusing an assessment on one or a few environmental criteria is not an issue per se, as long as it is explicit that the assessment is partial. However, this focus should not lead to a selective presentation of results, showing only the most positive outcomes. Inclusion of other impact categories is recommended to help indicate if there are shifting of burdens.

When reading such an assessment, it is important to check whether all relevant environmental criteria are presented with equal importance, rather than in a "pick-and-choose" fashion. Incomplete assessments do not provide the full picture and may be hiding a potential trade-off.

Q8. Are some impacts and effects not captured by LCA?

LCA provides insight into key environmental challenges associated with a product or service. Several environmental criteria may be evaluated in the analysis, ranging from global warming to land use. While the methodology is strong on well-researched topics such as global warming, some complex topics may not be well captured in LCA.

When reviewing an LCA, it is thus important to check whether any adverse effects have been identified that are not captured in the assessment. LCA is a great tool as it is comprehensive and holistic, it would however be wise for decision-makers to complement LCA with other tools to ensure all aspects are covered.

Are there major differences in the methodological choices made in both studies?

Q9. How can these results be compared to other LCA studies?

The eight questions above demonstrate that each LCA differs in the scope of the assessment, the assumptions that are taken, and general methodological choices that are made in the assessment. Especially in the case of recycling, methodological decisions can lead to significant variations.

Despite these differences, some LCA studies may be comparable so long as their differences are identified and their impact on results is clear. For example, a cradle-to-gate study of PET bottles can be comparable to a cradle-to-grave assessment, so long as they are only compared on the life cycle phases they have in common.

Similarly, the results of two studies carried in two different contexts may be comparable in some cases, as long as the interpretation highlights how the context impacts the results. For example, assessments considering two different production countries would need to, among other things, consider how the electricity mix plays into the overall results, how the transportation distances might evolve between countries and how the end-of-life management can differ from one region to another.

When attempting to compare two different LCAs on a similar topic, some results may differ. In such cases, ask the following questions before relying on the analyses:

- Are there **major differences** in the methodological choices made in both studies?
- Are the data used in the analyses **reliable**, **credible**, and **well validated**?
- Is the context of the **assessment similar** in both studies?
- **What impact** could these differences have on results? Does it explain discrepancies?

Conclusion

LCA results can be difficult to interpret for those who do not work with LCA often. A better understanding of the methodology can help decision-makers appreciate when and how LCA results can be applied to a specific decision-making context.

LCAs can provide valuable information for a decision-making process, by providing a general, comprehensive document on LCA methodology followed by a checklist of elements to keep in mind when reviewing an LCA, ICCA hopes to support decision makers in their interpretation of LCA results.

About ICCA

The International Council of Chemical Associations (ICCA) is the worldwide voice of the chemical industry, representing chemical manufacturers and producers all over the world.

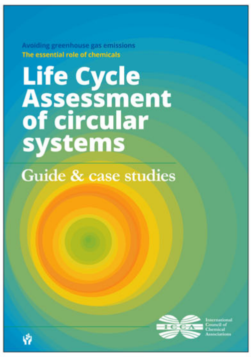
Responding to the need for a global presence, ICCA was created in 1989 to coordinate the work of chemical companies and associations on issues and programs of international interest. It comprises trade associations and companies involved in all aspects of the chemical industry.

ICCA is a chemical industry sector with a turnover of more than 3,600 billion euros. ICCA members (incl. observers & Responsible Care members) account for more than 90 percent of global chemical sales. ICCA promotes and co-ordinates Responsible Care® and other voluntary chemical industry initiatives.

ICCA has a central role in the exchange of information within the international industry, and in the development of position statements on matters of policy. It is also the main channel of communication between the industry and various international organizations that are concerned with health, environment and trade-related issues, including the United Nations Environment Programme (UNEP), the World Trade Organization (WTO) and the Organisation for Economic Co-operation & Development (OECD).

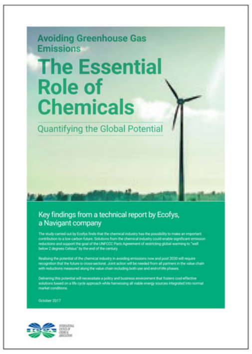
Related ICCA documents

This document on **LIFE CYCLE ASSESSMENTS APPLIED TO CIRCULAR SYSTEMS** is the latest of a series of studies on the quantification, with a life cycle perspective, of greenhouse gas (GHG) emissions savings enabled by products of the chemical industry:

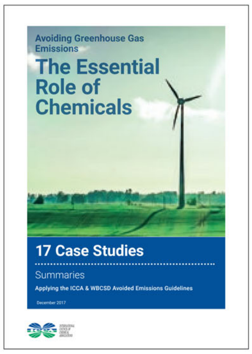


LIFE CYCLE ASSESSMENT OF CIRCULAR SYSTEMS: GUIDE & CASE STUDIES (2020): This document complements a series of studies by ICCA and its members companies, including a range of case studies and methodological documents, highlighting the importance of Life Cycle Assessments (LCA), especially when it comes to quantifying and reporting on the chemical industry's own footprint (scope 1 emissions), and the enabling role of its products in lowering CO_2 emissions in value chains.

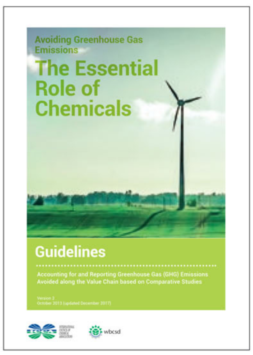
ENABLING THE FUTURE: CHEMISTRY INNOVATIONS FOR A LOW-CARBON SOCIETY (2019): Commissioned to KPMG and fors, the study reveals that 450 generic technologies are enablers of GHG savings, of which 137 are highly feasible. The 17 innovative solutions featured in the report could develop emission reductions of about 5-10 Gigaton by 2050 – which is about one quarter of the total world emissions today. These solutions will require robust transformation of entire sectors, such as power generation and storage, industry and production, mobility and transportation, nutrition and agriculture, and building and housing.



AVOIDING GREENHOUSE GAS EMISSIONS: THE ESSENTIAL ROLE OF CHEMICALS. QUANTIFYING THE GLOBAL POTENTIAL (2017): Commissioned to Ecofys, the report illustrates how efficient processes and chemical industry solutions can contribute to GHG savings. ICCA estimates that by 2030, light materials for transportation, efficient buildings and lighting, electric cars, wind and solar power and improved tires, at global scale, have the potential to avoid 2.5 Gigatons of GHG emissions globally every year.



AVOIDING GREENHOUSE GAS EMISSIONS: THE ESSENTIAL ROLE OF CHEMICALS - 17 CASE STUDIES (2017): Commissioned to Quantis, this report assembles 17 examples of Life Cycle Assessment case studies. The purpose is twofold: to motivate all stakeholders to discuss climate change using robust studies, taking the full life cycles into account, and to encourage all chemical companies to generate high quality assessments.



AVOIDING GREENHOUSE GAS EMISSIONS: THE ESSENTIAL ROLE OF CHEMICALS – GUIDELINES (UPDATED IN 2017): Prepared jointly with the World Business Council for Sustainable Development (WBCSD) the guidelines define how to measure avoided GHG emissions via LCA methodologies applied to entire value chains.

EXAMINING MATERIAL EVIDENCE THE CARBON FINGERPRINT

Voulvoulis N.[a], Kirkman R.[b], Giakoumis T.[a], Metivier P.[b], Kyle C.[b], Midgley V.[b]

HIGHLIGHTS

If all plastic bottles used globally were made from glass instead, the additional carbon emissions would be equivalent to 22 large coal-fired power plants producing enough electricity for a third of the UK.

If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to shutting between 8 and 40 coal-fired power plants globally.

KEY WORDS

Circular Economy
Climate Change
Net Zero
Sustainable Packaging
Plastics
Life-cycle Assessment

Executive Summary

Only 2% of British people consider plastic, compared to other materials used in packaging, to contribute the least greenhouse gases to the environment from its production, use, and post use treatment. Whilst in absolute numbers it is a fact the least impactful. Plastics do have a large carbon impact - accounting for 3.8% of global greenhouse gases emissions - but it is wrong to assume that alternative packaging materials would perform better, and it is important to consider the carbon benefits that arise from plastics use.

When considering the production and manufacturing of the main alternatives to plastic for a 500ml bottle, other packaging types (fibre, glass, steel and aluminium) emit more greenhouse gases than plastic bottles, with glass bottles being the highest emitter overall. By way of example, if all plastic bottles used globally were made from glass instead, the additional carbon emissions would be equivalent to powering around 22 large coal-fired power plants. This is equivalent to the electricity consumed by a third of the UK.

Life-cycle assessment (LCA) is a useful tool which should be more widely used to evaluate environmental impacts of packaging alternatives over their life-time, from the extraction of raw material to the disposal or recycling of packaging at the end of its life. Undertaking LCAs to compare the environmental performance of alternative materials for different packaging applications is essential if we want to take into account the environmental impacts associated with the whole life-cycle of packaging (mining, manufacturing process, logistics, usage and end-of-life route).

(a) Centre for Environmental Policy, Imperial College London (b) Veolia UK

Results can vary significantly from one study to another, depending on key parameters and assumptions. For example, the risk of producing more food waste because of the packaging design and shelf life is not always considered in LCAs while this can have a large impact on the packaging carbon contribution.

In this study, a total of 73 publications on LCAs comparing different types of packaging were identified and reviewed. By assessing many different studies we can draw some general conclusions about the range of results and what the majority of analysis determined. Findings indicate that in the applications it is used, most of the time, plastic packaging performs better than its alternatives, and mainly due to its very lightweight properties.

Transport distance and method, sources of electricity generation, packaging shape and weight, all significantly influence the LCA results and should be considered on a case by case basis. It is also important to consider the full life cycle of the material, such as, for plastic the prospecting and mining stages.

The waste management route in place to treat packaging at its end of life, is also shown to be a critical factor explaining variations of LCA results for the same packaging. Recycling always wins over virgin production on all environmental indicators. For plastics, there seems to be consensus that recycling saves between 30% and 80% of the carbon emissions that virgin plastic processing and manufacturing generate.

If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to stopping between 8 and 40 coal-fired power plants globally.

The findings of this study demonstrate that if we really want to tackle the environmental issues we face with plastics today then removing, reducing, reusing or recycling the plastic packaging placed on the market is the way forward. This approach is more certain and reaps better results than waiting and hoping for solutions not yet commercialised or switching to alternative available materials respectively.

Considering that only around 9% of plastics are currently being recycled worldwide, there is a lot that can be done to improve things. We can see that where the right policy drivers are in place, this is already happening, with regulatory statutes that themself deliver fiscal actions on business. In the UK, the various measures planned in the UK Waste and Resources Strategy planned by DEFRA, such as the extended producer responsibility scheme, the deposit return scheme and the harmonisation of waste collection associated with a clear labelling system, as well as HM Treasury proposals for a plastic packaging tax are all good steps for creating a fully functioning circular and sustainable system for packaging.

In concert with the widespread application of renewable energy and demand-management strategies, increasing the recycling of plastics have the potential for both curbing the growing life-cycle GHG emissions from plastics, and also preventing them from entering the marine environment.

If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to stopping between 8 and 40 coal-fired power plants globally.

Introduction

Plastic production, use, and disposal all emit significant amounts of greenhouse gases, but the situation is complex and one would be wrong to assume that reducing plastic use or switching to alternative materials would automatically result in curbing emissions.

In a paper published in 2019 in the journal Nature Climate Change[1], the global assessment of the life cycle of greenhouse gas emissions from all plastics was presented. The overwhelming majority of plastic resins come from petroleum, which requires extraction and distillation. Then the resins are formed into products and transported to market. All of these processes emit greenhouse gases, either directly or via the energy required to undertake them. The carbon footprint of plastics continues after their end of life, since landfilling, incinerating, recycling and composting (for certain plastics) all release carbon dioxide either directly or via the energy and consumables used to undertake the treatment (in the case of landfill for example). Emissions from plastics in 2015 were equivalent to nearly 1.8 billion metric tonnes of CO_2[2]. Across their lifecycle, plastics account for 3.8% of global greenhouse gas emissions[3]. Plastics production has risen from 2 million tonnes per annum in 1950 to 381 million tonnes per annum in 2015, with an estimated 9% of plastic discarded since 1950 considered to have been recycled[4]. Rising plastic production will exacerbate both problems with pollution and climate change. Production is set to increase. If current trend continues, by 2050, it is estimated that total plastics ever produced will reach 34,000 million tonnes[5]. By then, if the production and recycling systems for plastics do not change, the accumulation of greenhouse gas emissions from plastic could reach 15% of the amount of global carbon emissions permissible to keep temperature rise under 1.5°C[6] . With around 8 million tonnes of plastic ending up in the oceans every year, and 3,000 pieces of plastic litter found in every square kilometre of seawater, this not only represents a significant hazard to marine species and human health, but considerable wastage of resources and inefficiency[7].

Looking at the entire life cycle of fossil fuel-based plastics today, nearly two thirds of its greenhouse gas emissions are produced in the early stages from fossil fuel extractions to the production of resin, while converting resin to pipes, bottles, bags and other products generates just under one third of its emissions, with the remainder coming from the disposal phase. This indicates there are high carbon benefits of recycling plastics, avoiding those 61% of greenhouse gases emissions from the extraction and resin production process, discussed further throughout this paper. Despite the large impact of plastics on the environment, their application for packaging offers some environmental benefits. Reducing its usage or switching to different materials may have unintended negative consequences.

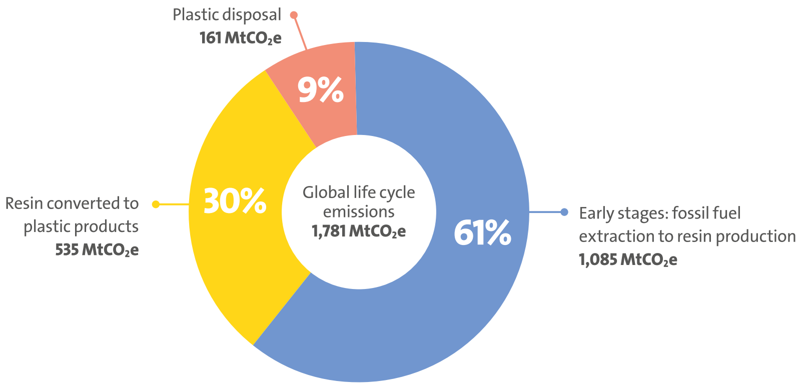


Figure 1. Life cycle emissions of fossil fuel-based plastics in metric tons of CO_2 equivalent, 2015[1]

"If we recycle plastics we avoid the 61% contribution of plastics emissions"

[1] J. Zheng and S. Suh, 'Strategies to reduce the global carbon footprint of plastics', Nature Climate Change , 9/5 (2019), 374–78.

[2] Zheng and Suh, 'Strategies to reduce the global carbon footprint of plastics'.

[3] J. G. J. Olivier, K. M. Schure, and J. A. H. W. Peters, 'TRENDS IN GLOBAL CO_2 AND TOTAL GREENHOUSE GAS EMISSIONS Summary of the 2017 report', 2983 (2017).

[4] S. Cheriyedath, 'What Counts as Plastic Waste?', (2019).

[5] J. M. Simon, Zero Waste Europe, F. Rosa, C. Allen, M. Wilson, and D. Moon, 'Changing trends in plastic waste trade: Plastic waste shipments report', November (2018).

[6] J. Y. S. Leung, B. D. Russell, and S. D. Connell, 'Adaptive Responses of Marine Gastropods to Heatwaves', One Earth , 1/3 (2019), 374–81.

[7] IUCN, 'Marine Plastics: What is the issue? Why is this important? What can be done?', International Union for Conservation of Nature Issues Brief , (2018), 1–2.

[8] Center for International Environmental Law, Fueling Plastics. Fossils, Plastics, & Petrochemical Feedstocks. , (2017).

[9] B. Brandt and Harald Pilz, 'The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe. Executive Summary', July (2011), 1–7.

[10] Bright Blue, 'lastics and climate change: unwrapping the evidence', (2018).

[11] STATISTA, 'Production of polyethylene terephthalate bottles worldwide from 2004 to 2021', (2020).

The benefits of plastic

Plastic is a versatile material which can easily be made thin and lightweight. It is durable and provides protection from contaminants and the elements. It reduces food waste by preserving food and increasing its shelf life. It protects food against pests, pathogens and humidity. Plastic packaging is more flexible and lighter than alternatives such as glass and card, which reduces transportation costs and the carbon emissions that come with them.

Without packaging, food is more likely to get damaged and become unusable. Since food waste contributes to climate change, water and energy consumption, deforestation and biodiversity loss, every effort we make to mitigate those effects makes a big difference, and plastic packaging helps make that possible. Plastic packaging is useful for keeping products fresh and insulated. Removing plastic entirely from our food supply may not be the best solution when it comes to protecting the environment and conserving valuable resources. Plastic packaging is used in the food supply chain because it supports the safe distribution of food over long distances and minimises food waste by keeping food fresh for longer.

A lot of food is air freighted, so prolonging its shelf life has important benefits for the environment. Plastic minimises food waste and conserves all valuable resources involved from farm to shelf. A 2016 review of studies on food waste found that 88m tonnes of food is wasted every year in the EU – that's 173kg per person and equals about 20% of food produced[12]. Minimising this wastage is crucial for environmental protection, as well as food security. Several factors must be considered when determining how useful plastic packaging is in the food supply chain, as it has the potential to preserve food and prevent its wastage. For example, the use of just 1.5g of plastic film for wrapping a cucumber can extend its shelf life from three days to 14 days and selling grapes in plastic bags or trays has reduced in-store wastage of grapes by 20%[13]. Recent estimates from Zero Waste Scotland suggest that the carbon footprint of food waste generated can be higher than that of plastic, with 456,000 tonnes of food waste produced in Scottish households contributing to around 1.9m tonnes of CO_2, three times higher than that of the 224,000 tonnes of plastic waste generated[14].

[12] M. Dora and E. Iacovidou, 'Why some plastic packaging is necessary to prevent food waste and protect the environment', (2019).

[13] Dora and Iacovidou, 'Why some plastic packaging is necessary to prevent food waste and protect the environment'.

[14] BBC, 'Scotland's food waste causing more greenhouse gas than plastic', (2019).

The carbon impact of plastic bottles compared to other material type containers

All food and drink packaging, whether plastic or another material, has an environmental impact. There is a lot of emphasis on plastic waste and pollution, but other impacts such as carbon emissions must also be considered when determining which materials are most suitable for different packaging applications. When considering reductions in the use of plastics, it is therefore important to consider the carbon footprint of things that could replace plastic — materials such as paper, aluminium, or glass.

It is also worth noting that aluminium cans and carton containers, despite often being explicitly depicted as alternatives to plastic bottles, still contain considerable amounts of plastic. Aluminium cans often have a complex plastic closure weighing around 4g (nearly half the weight of a single use plastic bottle); glass containers usually include a relatively heavy plastic lid – 14g (meaning they weigh more than a lightweight plastic water bottle); and multilayer cartons usually include nearly 10g of plastic (roughly the weight of a plastic water bottle)[15]. In addition, virtually all metal cans used for food and beverage products are also lined on the inside with a coating that uses Bisphenol A (BPA) as a base protective material, while most plastic bottles are made from polyethylene terephthalate (PET) plastic, which does not contain BPA.

To illustrate the difference of carbon impacts from the production of bottles from plastics and alternative materials, we calculated carbon emissions that would have been incurred in 2016 if every 500ml PET bottle produced worldwide was replaced by alternative material. The results are shown in Table 1 and Figure 2.

Carbon emissions from the production of plastic bottles are lower than all other materials equivalent: glass, aluminium and steel in particular, glass bottle being the worst alternative from a carbon perspective. If all plastic bottles used globally were made from glass instead, the additional carbon emissions (87.4Mtonnes of CO_2eq annually) would be equivalent to powering 22 coal-fired plants[16]. Although plastic bottles perform similarly to liquid fibreboard packaging in terms of carbon impact during the production process, they are much easier to recycle and thus should have a lower carbon impact if we were considering their end of life.

The necessity to capture all environmental impacts of a packaging full life (including its end of life), and to capture the complexity of each specific packaging design produced in a specific supply chain and disposed in a specific waste management system, advocates to use a more detailed life cycle approach to assess the environmental impact of one particular packaging.

Note: It is important to note that there will be examples when alternative materials still make sense, for example the widely cited reusable milk glass bottles case where it is evident that emissions can be lower when the farm is local, bottles are filled and distributed by electric milk floats (running on low carbon electricity) in a locality close to the milk distribution centre, and are then cleaned and reused (not forgiving the detergent and water required for the cleaning)[17].

Therefore, every case must be assessed in its own merits, since there will be examples of Liquid Fibre Board, Metals and Glass presenting better packaging solutions on a carbon basis.

[15] Green Alliance, 'Losing the bottle: why we don't need single use containers for water'.

[16] EPA Greenhouse Gas Equivalencies Calculator (March 2020 update)

[17] WRAP, Life cycle assessment of example packaging systems for milk, (2010)

Table 1. Calculating greenhouse gases emissions for producing all 500ml containers in 2016 from alternative materials

Container type (500ml bottle or can)	Composition	Weight per bottle (grams)	Tonnes in 2016 (485 billion bottles)	Tonnes CO_2-e per tonne of 500ml bottles/cans produced*	Million tonnes of CO_2 in 2016 from production if all plastic bottles were replaced by this format and material*
Plastic bottle (baseline)	Plastic (PET)	12.7	6,159,500	4.053	25.0
Liquid fiberboard packaging	Plastics (50% PET closure and 50% PE layer)	8	3,880,000	3.585	25.5 (+0.5)
	Aluminium	1	485,000	12.874	
	Carton	13	6,305,000	0.844	
Steel can	Steel	30	14,550,000	3.004	43.7 (+18.7)
Aluminium can	Plastics (PE layer)	4	1,940,000	3.116	105.9 (+80.9)
	Aluminium	16	7,760,000	12.874	
Glass bottle	Glass	259	125,615,000	0.895	112.4 (+87.4)

*Emissions have been calculated using the 2019 Conversion Factors from Defra that covers the extraction, primary processing, manufacturing and transporting materials to the point of sale[18]

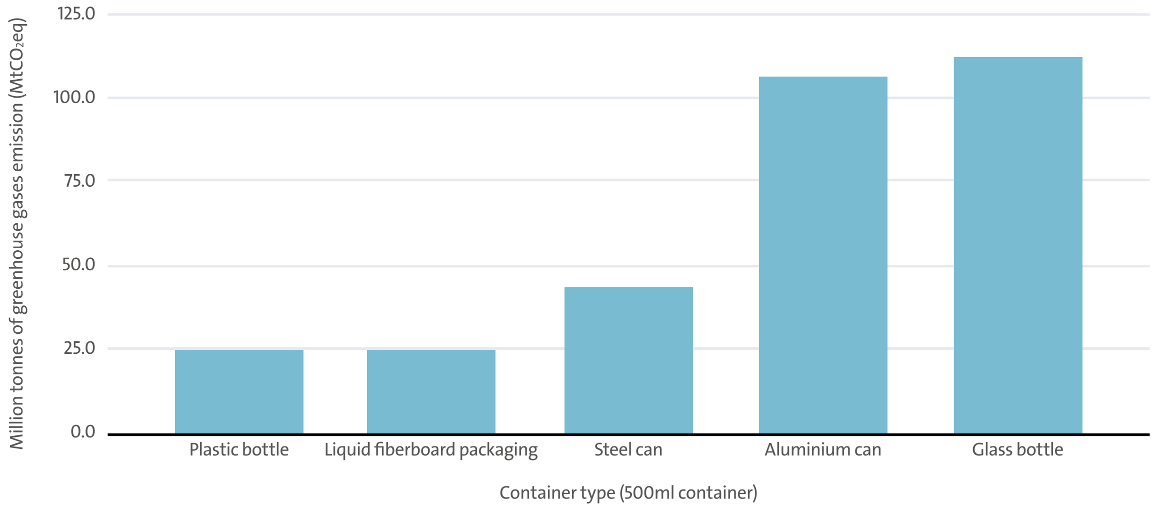


Figure 2 - Greenhouse gases emissions for producing all 500ml containers in 2016 from alternative materials

[18]Defra, 'Greenhouse gas reporting: conversion factors 2019', (2019).

Life cycle assessment (LCA)

Life cycle thinking is increasingly seen as a key concept for ensuring the sustainability of resources production and consumption. Over the years, life cycle assessment has been used extensively to assess products from "cradle to grave" - from extraction of resources to end of life management. The assessment has been formalized by the International Standard Organization (ISO) (Geneva, Switzerland). LCA is based on an iterative process with four steps, i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation.

In January 2018, when the European Commission adopted the European Strategy for Plastics in a Circular Economy, they proposed a vision in which alternative materials and feedstocks should only be developed and used where evidence clearly shows that they are more sustainable compared to the non-renewable alternatives[19]. In particular, they promoted specified specific actions aiming at better understanding the life-cycle impacts of alternative feedstock for plastics production.

LCA provides a quantified methodology to assess the environmental performance of goods and processes. The cradle-to-gate LCA study usually starts with raw material extraction and ends with the final products leaving the factory gate[20]. A cradle-to-grave study starts with raw material extraction and ends with the disposal of product in landfill, incineration or recycling. A cradle-to-cradle study starts with the same process and considers not only the final disposal but also the energy recovery from incineration or the raw material replacement due to recycling of the studied products[21]. In the assessment, the burdens imposed on the environment by plastic packaging is ascertained by accounting for the resources and energy (inputs) consumed at each stage of the system and the resulting pollutants and wastes (outputs) emitted.

Unlike issues such as energy, water, and material use, which can be measured during the production process, "impact of plastic litter on the environment" is not easy to express in figures. Plastic crumbles into smaller and smaller pieces that enter the food chain, resulting in unknown effects on our health. Despite the increasing concerns regarding the impacts of plastic in the marine environment, including the long-term impacts associated with their durability under marine conditions of cold and dark which inhibit degradation, there is a stark lack of literature on the LCA end-of-life impact in the marine environment. Woods et al. (2016) examined the use of LCA for marine ecological impacts, and singled out key stressors such as ocean acidification, over exploitation and invasive species in order to examine approaches to quantifying their effects on the biodiversity of the marine environment[22]. However, for marine plastic debris they concluded that no methods have yet been proposed to quantify the effect of plastic waste on biodiversity at any scale greater than the individual organism. The Medellin Declaration in 2017 has addressed this need but it remains unmet[23].

Keeping this limitation in mind, LCA still remains the best existing assessment tool to compare the environmental impact of packaging alternatives. In the following section, we review existing LCAstudies on plastic packaging and its alternatives and discuss the main factors driving its environmental impact.

Comparing packaging alternatives - a review of existing life cycle assessments

A total of 73 LCAs (see Annex 1) were identified, and information on LCA procedures including scope and boundary, functional units and analysed life cycle impacts were reviewed and summarized. Most LCA undertaken for various plastic uses show plastic performing better than the alternatives from a carbon perspective. Even if, ounce for ounce, some kinds of plastic have a higher carbon footprint than other kinds of packaging, less quantity is used reducing overall impact, as plastic is light. Plastic performs better most of the time (for example heavier-duty plastics, such as low density polyethylene or woven polypropylene bags, do have a bigger climate and energy impact than paper, but they're more durable and you get more use out of them). Several studies have shown many materials used as alternatives to plastic in packaging, such as cotton, glass, metal or bioplastics, to have significantly higher CO_2 impact or water usage compared to plastic packaging. On average over current food packaging, replacing plastic packaging with alternatives, would increase the weight of the packaging by 3.6 times, the energy use by 2.2 times, and the carbon dioxide emissions by 2.7% but these can vary significantly for different cases[24]. Some examples are 23 highlighted in Figure 3.

[19] European Commission, 'A European Strategy for Plastics', European Comission , (2018).

[20] S. Madival, R. Auras, S. P. Singh, and R. Narayan, 'Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology', Journal of Cleaner Production , 17/13 (2009), 1183–94.

[21] Madival, Auras, Singh, and Narayan, 'Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology'.

[22] J. S. Woods, K. Veltman, M. A. J. Huijbregts, F. Verones, and E. G. Hertwich, 'Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA)', Environment International , 89–90 (2016), 48–61.

[23] G. Sonnemann, S. Valdivia, M. Prox, P. Wiche, C. Hasenstab, M. Diaz, C. Peña, N. Suppe, I. Vázquez-Rowe, I. Quispe, C. Ugaya, A. Barona, E. Cadena, J. R. Vieira, A. Moeller, H. Harris, S. Humbert, N. Duque-Ciceri, M. Goedkoop, J. R. Pons, and C. Naranjo, 'Medellin Declaration on Marine Litter in Life Cycle Assessment and Management', 2017.

[24] Committee for the Environment Food and Rural Affairs, Plastic food and drink packaging , (2019).

Plastic versus glass

Humbert et al. (2009) showed that plastics perform better than glass packaging in terms of production and waste treatment processes based on global warming scores [24]. The steam consumption with ultra-high temperature process used in plastic packaging system is lower that those with retort process in glass packaging systems. Though Accorsi et al. (2015) showed than PET bottling line compromising many automated working stations is more energy consuming compared to glass bottling lines, but also more efficient when dealing with input materials [25]. Plastic packaging is lighter, and this leads to a significant reduction in packaging transportation. Glass packaging performs worse for impact categories such as primary energy demand, abiotic depletion, acidification potential, human toxicity potential, terrestrial toxicity potential and photochemical oxidant creation potentia [26]. A 2L PET soft drink packaging in the same study was shown to perform best across most of the impact categories.

Plastic versus aluminium

According to El CA studies on beverage packaging, plastic bottles perform better than aluminium cans. Amienyo et al (2013) Pointed that aluminium can production causes higher global warning potential than PET bottle production [26]. Due to high emissions of PAH and hydrogen fluoride during aluminium can production, the human and marine toxicity are disproportionately higher for aluminium cans than PET bottles compared with their market share in the study area. Pasqualino et al. (2011) as well as Simon et al. (2016) had similar findings with the aluminium cans intensive thermal production performing worse for the environment [27,28]. Plastic product saved 57% more energy and 61% more GHGs emissions compared to alternatives.

Plastic versus paper

Comparing plastic to paper bags, the global warming potential of paper bag production was shown to be much higher due to the need for fertiliser during the tree farming and plantation [30]. Moreover, cardboard production, as a common stage of paper packaging production, has significant water depletion potential. Paper packaging production is also responsible for greater ecosystem quality damage due to the land use required for wood pulp as a paperboard production input [31].

Figure 3. Comparing packaging alternatives [25, 26, 27]

[25] S. Humbert, V. Rossi, M. Margni, O. Jolliet, and Y. Loerincik, 'Life cycle assessment of two baby food packaging alternatives: Glass jars vs. plastic pots', International Journal of Life Cycle Assessment , 14/2 (2009), 95–106.

[26] R. Accorsi, L. Versari, and R. Manzini, 'Glass vs. plastic: Life cycle assessment of extra-virgin olive oil bottles across global supply chains', Sustainability (Switzerland) , 7/3 (2015), 2818–40.

[27] D. Amienyo, H. Gujba, H. Stichnothe, and A. Azapagic, 'Life cycle environmental impacts of carbonated soft drinks', The International Journal of Life Cycle Assessment , 18/1 (2013), 77–92.

[28] J. Pasqualino, M. Meneses, and F. Castells, 'The carbon footprint and energy consumption of beverage packaging selection and disposal', Journal of Food Engineering , 103/4 (2011), 357–65.

[29] B. Simon, M. Ben Amor, and R. Földényi, 'Life cycle impact assessment of beverage packaging systems: Focus on the collection of post-consumer bottles', Journal of Cleaner Production , 112 (2016), 238–48.

[30] Brandt and Harald Pilz, 'The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe. Executive Summary'.

[31] J. B. M. M. Biona, J. A. Gonzaga, A. T. Ubando, and H. C. Tan, 'A comparative life cycle analysis of plastic and paper packaging bags in the Philippines', 2015 International Conference on Humanoid, Nanotechnology, Information Technology,Communication and Control, Environment and Management (HNICEM), (2015), 1–6.

[32] J. Cleary, 'Life cycle assessments of wine and spirit packaging at the product and the municipal scale: A Toronto, Canada case study', Journal of Cleaner Production , 44 (2013), 143–51.

Important factors impacting a packaging LCA

While LCAs are widely used to inform discussions on packaging, the inherent complexity in capturing the environmental impacts of packaging means that results will vary based on the details of the methodology used. For example, food waste can or not be taken into account in a food packaging LCA via shelf-life extension or via other drivers linked to the packaging design (e.g. trimming and multipack). The shape of the packaging container also influences the overall environmental performance of the system since the amount of resin used per container varies in different shapes. The stackable container consumes more resin for enabling distribution without any crates, resulting in high greenhouse gases emission and energy consumption associated with the production process. Containers with different plastic materials also have various scores in impact categories due to the container mass. PET strawberry packaging with higher container weight is worse for the environment compared with similar PLA or PS packaging[33].

Though some LCA studies claimed that transport-induced environmental impacts are much smaller than the environmental impacts of packaging production[34] most pieces of literature have considered transportation within the life cycle impacts. The results of the country-scale LCA study in the United States also suggest that railway transportation has a better environmental performance than the truck one[35]. Different weight of packaging material types also influences the transporting related impacts. The heavier the packaging type is, the higher impact is generated within the transportation phase[36]. Another LCA study on olive oil packaging suggested that the preferable packaging changed with distribution distance. Glass bottles were more suitable for local transportation while tinplate cans were chosen for long-distance distribution. Besides, a reduction in the average distance travelled to market can improve the overall environmental performances of heavier packaging containers[38]. In summary, transport-efficient packaging depends on several factors including food ingredient, type and amount of used packaging materials, and more importantly, travel distance between producer and retail as well as transportation mode[39].

Technological advances and changes can also alter LCA results, as materials improve over time. Over the past years the gram weight of the 16.9 ounce "single serve" bottled water container has dropped by 32.6%[40]. The average PET bottled water container weighed 18.9 grams in 2000 and by 2008, the average amount of PET resin in each bottle has declined to 12.7 grams[41]. The amount of aluminium and steel used to produce cans has also been reduced by around 50% in the past 40 years: a 500ml aluminium can now weighs around 16 grams, while a steel can weighs around 30 grams[42]. Transport costs are a function of weight, so this further reduces outgoings and also CO_2 emissions. Another important factor in the LCAs is the source of electricity and the type of energy supplied during the whole product life which can dramatically influence the total environmental impacts[43].

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Importance of recycling

Finally, considering the waste management capabilities of locations/countries where waste is collected at the end of its life is essential to have a full and accurate LCA. Many environmental impacts, such as environmental leakage and chemical migration, are not captured well by LCA when real-life waste scenarios are not considered. Changing waste management practices for food waste, including increasing redistribution, or separate collection of organic waste for composting and anaerobic digestion, for example has the potential to reduce the impact of waste and LCAs could be used to explore the waste reduction potential of these activities.

Some LCAs maintain the assumption that all products are collected, recycled, and reused in the end-of-life phase. The reality, however, is not that simple; and often depends on recycling rate in a particular study/country/city. End of life scenario has a great impact on the LCA results and on what can be done to reduce impacts, as currently 79% of plastic worldwide ends up in landfills or the environment[44]. Similarly, in some studies [26], where plastics perform better, it is assumed that the PET material recycling systems are operated with a high share of high-grade recycled PET in a closed loop. Assuming a high proportion of recycled PET in bottle production might not be a realistic assumption in some countries on one hand, on the other it shows the importance of closed loop recycling in improving the environmental performance of plastics. Amienyo et al. (2013) showed that increasing recycling rate to 60% of PET bottles would save approximately half of the emissions, equivalent to 445,000 tonnes of CO_2 eq. every year in that study[45].

Recycling wins over virgin production on all environmental measurements, especially when it comes to carbon emissions. Estimates vary with the type of recycling process used, but researchers agree that recycling and remanufacturing plastic saves between 30% and 80% of the carbon emissions that original processing and manufacturing produces. That could mean annual savings of 30 to 150 million tons of CO_2, given our previous calculations of carbon emissions from plastics production. An LCA study showed that the environmental impact of PET bottle-to-fibre recycling compared to virgin PET fibre and other commodity fibre products, i.e. cotton, viscose, PP (polypropylene) and PLA (polylactic acid) offer important environmental benefits[46]. Depending on the allocation methods applied for open-loop-recycling, non-renewable energy use savings of 40–85% and global warming potential savings of 25–75% can be achieved[47]. Recycled PET fibres produced by mechanical recycling performed better than virgin PET in at least eight out of a total of nine categories used in the study, with recycled fibres produced from chemical recycling performing better in six to seven out of nine categories compared to virgin PET fibres.

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Discussion

According to a recent YouGov poll[49], only 2% of British people consider plastic, compared to other materials used in packaging, to contribute the least greenhouse gases to the environment from its production, use, and post use. The survey findings prompted a better understanding of the issues amongst the wider public to help them make "informed" decisions. Indeed, as reviewed in this work, in terms of carbon emissions, plastic is often the packaging material that is least damaging to the environment from a whole life cycle perspective, particularly when used in closed loop recycling, and most alternative packaging are actually not plastic free.

It should not be dismissed that plastics have a large and unacceptable impact on the marine environment and potentially impacts to human and ecosystem health that are not yet well understood and which cannot be easily expressed in figures and incorporated into life-cycle assessments. This complicates the choice made between carbon emissions versus marine pollution, environmental and health impacts in terms of deciding what to choose for packaging.

However, we believe this dilemma must be pragmatically managed. Environmental bodies and industry are already supporting the view that climate is one of the most serious threats to the ocean, certainly in the long term, which indirectly restricts most of the options for replacing plastics. On the other hand, global demand for plastics is expected to increase by some 22% over the next five years, with GHG emissions from plastics reaching 15% of the global carbon budget by 2050[50]. This anticipated growth of plastic production is of real concern, but we need to recognise that production is growing in response to increasing global demand for lightweight automotive parts, building insulation, and product packaging—all of which will play an important role in reducing greenhouse gas emissions and helping people live more sustainably around the world. We must be mindful to not fix a problem by removing one of the solutions.

What is clear is that we need to **reduce** plastics production while ensuring that any alternatives do not contribute more to climate change, and this is **where recycling comes in**. The emissions reductions from eliminating the need for new plastic outweigh the slightly higher emissions that come from processing wastes to recover plastics.

The findings of this study indicate that if we really want to tackle the environmental issues we face with plastics today, removing, reducing, reusing or recycling the plastic packaging placed on the market is an important part of the way forward, and a better option to replacing it with current alternative materials or waiting and hoping for solutions not yet available. Considering that only around 9% of plastics are currently being recycled worldwide, there is a lot that can be done to improve on this. We can see that when the right policy drivers are in place, this is happening already, with regulatory statutes that themself deliver fiscal actions on business. In the UK, the various measures planned in the UK Waste and Resources Strategy planned by DEFRA, such as the extended producer responsibility scheme, the deposit return scheme and the harmonisation of waste collection associated with a clear labelling system, as well as HM Treasury's proposed plastic packaging tax are all good steps for creating a fully functioning circular and sustainable system for packaging. Increasing the levels of recycled content in plastic packaging can reduce both the need for manufacturing plastics and the amount of plastic wastes produced[51]. As recycled plastic is more expensive than virgin plastic, the future plastic packaging tax announced by the UK government will be a key initiative to drive the market, increasing the recycling infrastructure and ultimately improving plastics recycling rate.

Widespread application of renewable energy, recycling and demand-management strategies in concert, have the potential to curb the growing life-cycle GHG emissions from plastics. Recycling can also play a key role in stopping plastics entering the marine environment, as once collected the chances of plastic waste entering the environment are reduced or at least there is clear accountability in what ultimately happens to plastic waste. Whilst it is not the only way to address the packaging conundrum, we can - at least in part - **recycle our way out of this problem**.

Building a sustainable system for packaging and all the products we use every day is achievable, but only if we accept to continue using plastic when it is the most carbon efficient option, supporting any material choice with scientific facts and not led by popular beliefs. Still, heightened public awareness of the growing and unsustainable plastics production provides policy makers with a unique mandate for change and businesses with opportunities for using packaging that can be easily recycled and reused. Making the transition to a sustainable circular economy is an important goal for society, yet, the complexity and interdependencies of such an undertaking mean that ecosystem-wide orchestration is necessary. Strong regulations and policies have a clear role to play in supporting recycling if we are ever to reach as a society a truly circular sustainable state.

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Annex 1 - The 73 Life Cycle Studies of plastics reviewed in this study.

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