Life Cycle Assessment - Renewable and Sustainable Citrus Oils
Final Report

Renewable Citrus Products Association

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES AND DIAGRAMS

1.0 INTRODUCTION

1.1 STUDY BACKGROUND

The Renewable Citrus Product Association (RCPA) commissioned Environmental Resources Management (ERM) to conduct a streamlined Life Cycle Assessment (LCA) of citrus oils and associated products. Citrus oils are used in commercial and consumer products sold worldwide.

Citrus is a renewable crop that is harvested every year. Citrus oils are collected during the juicing process of oranges, grapefruits, and other citrus fruits. Cold pressed oils are extracted during the first squeezing of the fruit and d-limonene (citrus terpenes) is extracted during the second pressing and subsequent steam distillation of the peel. Utilizing the peel for citrus oils is a sustainable practice as it is a by-product of food production and does not require a choice to be made between crops for food or crops for feedstock.

Citrus oils are cradle-to-cradle products that sequester their carbon as carbon dioxide from the atmosphere (the cradle) and return their carbon to the environment at end-of-life as carbon dioxide where it is available for more biological processes. This cycle is commonly called the closed carbon cycle for biomass. Citrus oils offer a cradle-to-cradle solution in that the carbon sequestered through photosynthesis is made available again at end-of-life through the degradation pathways for the oils.

Citrus oils from oranges consist of 95 percent d-limonene and can be used as a naturally-occurring, biodegradable, biobased hydrocarbon replacing petroleum-based hydrocarbons.

Conducting an LCA is part of developing the renewable and sustainable profile for citrus oils such as orange oil and d-limonene.

Governmental agencies and consumers are showing increasing interest in sustainability issues and replacing petroleum-based materials with biobased resources. As more biobased products appear on the market there has been an increased interest in demonstrating their environmental credentials by evaluating the energy and environmental impacts of these products. The standard method of measuring these impacts is to conduct an LCA.

1.2 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a standardized technique for measuring and comparing the environmental consequences of manufacturing, using and disposing of a product or service. A cradle-to-grave LCA includes all stages up to and including use, recycling and disposal of the product and the subsequent releases to the environment. A cradle-to-gate study is performed to inform customers of the impacts of a product up to the point they take ownership. The types of environmental impacts appraised in a LCA include resource use, human health, ecological consequences and global warming potential (commonly referred to as a carbon footprint).

Citrus oils differ from petrochemical equivalents in that the building blocks (carbon dioxide and water) come from the environment through photosynthesis and most uses return them to the environment as part of the carbon cycle. LCA appraises the environmental impacts associated with this cycle for citrus oils, the uptake of carbon as carbon dioxide and its subsequent release being carbon neutral and does not contribute to global warming potential.

A key objective of performing this LCA on citrus oils was to provide a cradle-to-gate assessment of citrus agriculture, production and citrus processing, employing a carbon neutral approach as described below. The international standards for conducting LCAs are known as the ISO14040 series. This series states that LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system;
- Evaluating the potential environmental impacts associated with those inputs and outputs; and
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA may be used for a broad spectrum of applications. The individual use, adaptation and practice of LCA for all potential applications are based on the International Standards. Cradle-to-gate studies are conducted for products or an ingredient that will become an integrated part of another product (e.g., a household cleaning product with its own life cycle) once it enters a new organization or production facility.

A cradle-to-gate assessment of biobased products can generate favorable results when assessing the global warming potential because the main component (e.g., citrus, corn or soy beans) sequesters carbon during growth. Therefore cradle-to-gate assessments of biobased products can result in a negative global warming impact or a negative carbon footprint if the carbon cycle is not addressed. The cycle is completed, from cradle-to-cradle, when the sequestered carbon is oxidized to CO_2 either during use or disposal (e.g., combustion of biodiesel, metabolism of an ingested flavoring ingredient, biodegradation in a waste water treatment system or landfill, or through atmospheric oxidation mechanisms). However, the release process may contribute to global warming as a result of methane (a powerful greenhouse gas) production through degradation if not collected and used for energy generation. It is common LCA practice to assume that the carbon sequestered through photosynthesis is released at end-of-life, and to focus attention on the potential production of greenhouse gas (GHG) emissions other than carbon dioxide. This is often referred to as a carbon neutral approach. The exceptions to this include where long term carbon storage or sequestration at end-of life can be demonstrated. Additionally cradle-to-gate assessments do not provide the full life cycle impacts of products since the use and end-of-life life- cycle stages also contribute to the environmental impacts.

In this study, a streamlined LCA was conducted that is consistent with the Carbon Trust's PAS 2050:2008 Specification [(1)], which is derived from the ISO 14040 standards. A streamlined LCA involves limiting the scope of the LCA and, while not as detailed as a full LCA, still provides a clear and justified measure of the relative environmental impacts of the product systems.

The Building for Environmental and Economic Sustainability (BEES) [(2)] impact assessment methodology was used to interpret the results. The BEES methodology covers a broad range of environmental, health, and energy categories that meet the International Standards Organization (ISO) requirements and is used by the USDA for assessing biobased products for the Federal BioPreferred Program.

The key elements of a streamlined LCA, as defined in ISO 14040, are:

(1) http://www.bsigroup.com/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050
(2) http://www.bfrl.nist.gov/oae/software/bees

- Goal definition and scope;
- Life cycle inventory analysis;
- Life cycle impact assessment;
- Life cycle interpretation; and
- Reporting.

2.0 GOAL AND SCOPE

2.1 GOAL DEFINITION

The goal of this study is to perform a streamlined LCA that evaluates environmental impacts and performance from raw materials to distribution of the final products of citrus oils and other citrus-based products. The study was performed on behalf of RCPA. The data collected and used in the LCA covers greater than 80 percent of the processing industry and, as a result, the study can be considered representative for the industry.

Citrus oils are extracted during the juicing process of oranges, grapefruits and other citrus fruits. For the purpose of this study the focus was exclusively on citrus oils production from oranges. According to the Food and Agriculture Organization of the UN (FAO) (3), oranges account for more than 50 percent of all citrus fruit production. Approximately 33 percent of all citrus fruit is processed with orange having a dominant 80 percent share.

In conjunction with this study, the streamlined LCA gathered cradle-to-gate information for orange juice and other by-products. Orange juice production is the primary driver for other citrus by-products production; e.g., citrus oils and citrus-based cattle feed.

Citrus oils can be direct replacements for a variety of hydrocarbons, oxygenated hydrocarbons and chlorinated hydrocarbons. Therefore, the environmental impacts of orange terpenes and d-limonene are compared against petroleum-based counterparts. This provides the data required to make informed comparisons.

RCPA and the industry can use the study findings to communicate with stakeholders as to the environmental profile of citrus oils, including regulatory authorities and political/legislative entities. Additionally, the information generated by this LCA study will enable the citrus oils industry and the reader to review the balance of impacts across the life cycle of citrus oils to better understand where to focus attention in order to prioritize sustainability initiatives and ultimately minimize impact.

The findings of this study demonstrate the renewability and sustainability of citrus oils, and clearly show the advantage of using citrus oils over

(3) http://r0.unctad.org/infocomm/anglais/orange/market.htm

petroleum-based counterparts. This LCA focuses on the carbon and water impacts and the energy demand of the different products and includes 'traditional' life cycle impact categories such as abiotic depletion, acidification, smog formation, toxicity, etc., for each product system.

2.2 SCOPE OF THE STUDY

The scope of this study addresses the following items:

- Product system to be studied;
- Functional unit;
- System boundaries;
- Allocation procedures;
- Impact assessment;
- Interpretation to be used; and
- Data requirements.

2.2.1 Product Systems to Be Studied

The primary focus of this study is on the product systems for orange terpenes and d-limonene (citrus terpenes) which have been assessed from cradle-to-gate employing the carbon neutral approach described above. Cradle-to-gate information has been studied for orange juice, cold-pressed orange oil, 5-fold orange oil, and citrus-based dried cattle feed as a result of following citrus oils production. Additionally, for comparison purposes, generic petroleum-based counterpart systems have been studied.

2.2.2 Functional Unit

The functional unit provides a reference to which the input and output data are normalized. For this study, the functional unit is 1,000 kilograms of citrus oils which include cold pressed orange oil, d-limonene, orange terpenes, and 5-fold orange oil. All other associated products (orange juice and citrus-based cattle feed) have been normalized to 1,000 kilograms of their own products respectively.

For a fair comparison with petroleum–based counterparts, the environmental footprint of citrus oils has been compared to the other products on a kilogram-for-kilogram basis with the same functional unit.

2.2.3 *System Boundaries*

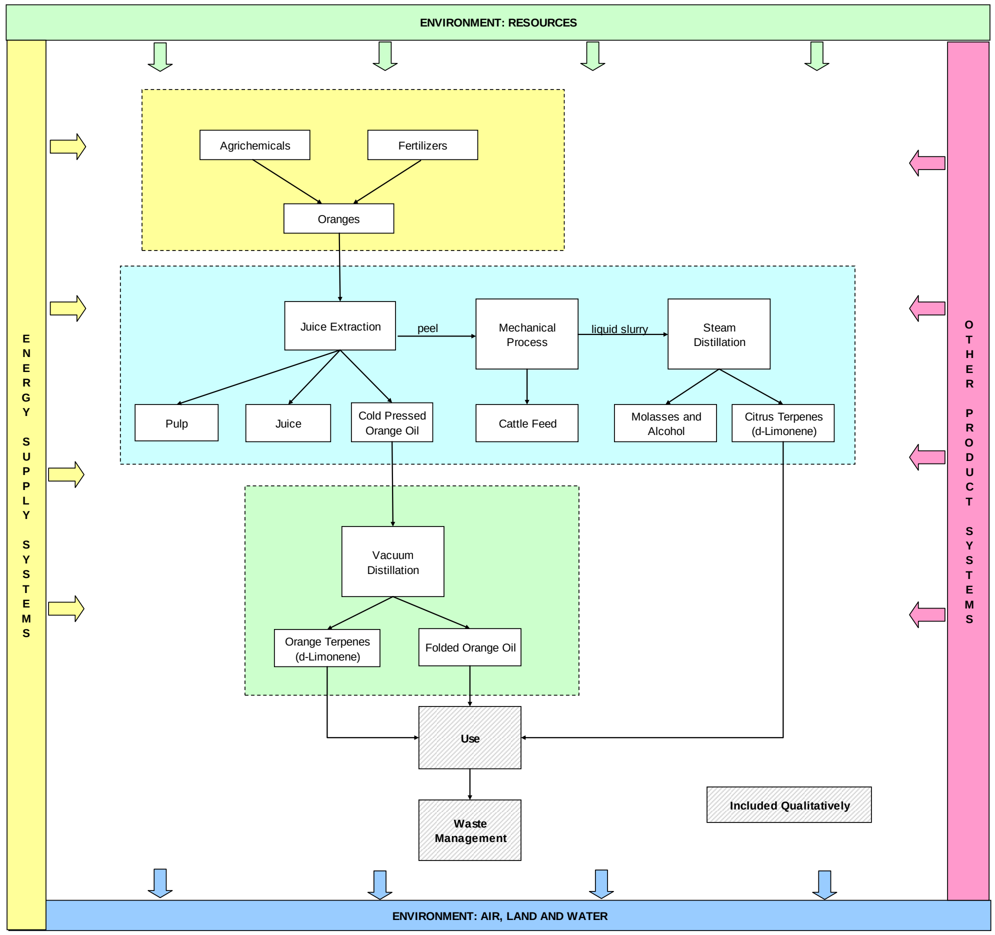
The system boundary defines which life cycle stages, materials and unit processes are evaluated in the streamlined LCA. The boundary also determines the environmental releases (e.g., CH_4, CO_2) and inputs (e.g., fossil fuels, water) to be included.

This streamlined LCA study contains a cradle-to-gate assessment, which includes all life cycle stages from raw material production to distribution of the citrus oils products (4). Energy and materials have been traced back to resource extraction and emissions from each life cycle stage have been included. The cradle-to-gate information ending at the processor's gate is addressed in the sensitivity analysis section of the report.

The system diagram in Figure 2.1 shows the citrus oils system boundary for this study. An identical system boundary for the petroleum-based counterparts has been used for comparisons.

(4) The PAS 2050:2008 methodology specifies that distribution of the final product to the organization that will incorporate the ingredient into a new product includes the environmental impact of transporting the product to that organization. Therefore, the gate was set at the receiving organization's gate instead of the citrus processor's gate as this complies with PAS 2050:2008.

Figure 2.1 System Diagram



Note: Each arrow represents a transportation step

Geographic Boundaries

The geographic boundaries cover citrus oils produced from oranges grown in the U.S. Citrus oils are used in products that are sold worldwide. Where appropriate U.S. data for petroleum-based counterparts are not available, average European data has been used and adjusted to represent U.S. conditions. This is typical for U.S.-based LCA studies.

Time Boundaries

The systems investigated represent the situation for these markets during a representative 12-month period, the 2008-2009 growing season.

Landfill decomposition of wastes is assumed to take place within 100 years; the gas generation phase is considered to be complete within this timeframe [5].

Allocation Procedures

Few industrial processes yield a single output, or are based on a linear relationship of raw material inputs and outputs. In fact, most industrial processes yield more than one product, and they utilize intermediate or discarded products as raw materials for other processes (e.g., citrus oils from orange juice production). Allocation means that the resource (e.g., energy) consumption and the associated emissions are divided among the output products. For example, when specific data (such as energy consumption) is not available for a single process, the data can be generated by allocating a portion of the total energy used to the individual product or process.

Allocation is usually based on either mass or economic considerations. Mass allocation apportions the environmental burdens based on the weight of each production output and economic allocation apportions the environmental burdens based on the value of each production output. The PAS 2050:2008 methodology specifies that allocation must be based on economic value of the products and by-products and this is the allocation method used in the study. Mass allocation would allocate the majority of the environmental burdens to orange juice and cattle feed since the weight of these two products are excessive compared to citrus oils. Economic value of products and by-products is a more reasonable way of determining how much environmental burden is assigned to each product. The products with the most economic value are the primary reasons for growing and processing citrus and not low value products like cattle feed. This is the approach typically used in LCA and is the most appropriate allocation method for use in this study.

2.2.4 Life Cycle Stages

The life cycle stages included in the system boundaries are described below:

- Orange growing, cultivating and harvesting – The study includes water, energy, fertilizer and agrichemicals consumption for orange growing and cultivation in Florida, USA. It also includes fuel consumption for associated harvesting.

(5) PAS 2050:2008 Section 6.4.9.1

- Raw materials production and transport - The production and transport of all raw materials (fruit, chemicals, etc.) from point of extraction to point of use in juice and citrus oils processing is included. Where it was not possible to define a specific distance, a justifiable estimate was used.

- Production and transport packaging materials - This includes primary, secondary and transit packaging.

- Juice and citrus oils extraction and processing - This study includes raw material, water, energy, fuels, chemical, and packaging inputs for juice and citrus oils processing and production. The study also includes emissions to air, waste water, and solid waste generation.

- Transport of citrus oils to folding processors, flavor and fragrance houses - This study includes transport of the citrus oils to flavor and fragrance houses for further processing. In some cases, the citrus oils are first sent to refrigerated storage at the juicer where the wax content is removed prior to being sent for further processing. Dewaxing has been included in the extraction and processing stage.

- Citrus oils folding and processing – The citrus oils are further processed by the flavor and fragrance houses. This includes vacuum distillation, as well as mixing with other products and packaging.

- Commercial and consumer use – The commercial and consumer use phase has been assumed to result in the release of sequestered carbon and therefore conforms to the carbon neutrality approach described above. Ordinarily the use phase would not be considered in a cradle-to-gate study.

2.2.5 *Accounting for Carbon Sequestration*

When natural resources such as oranges are part of a product system, it is important to determine whether the CO_2 uptake during the growth of the orange (biogenic CO_2) should be included in the scope of the system boundaries. CO_2 that was absorbed as the orange grew (embedded carbon) ultimately returns to the atmosphere, and thus there is no net release of fossil-based carbon, only biobased-carbon, in the form of CO_2 (carbon neutral) as the cycle of growth and harvest is sustained. For the purposes of this study both the CO_2 uptake during the orange growing life cycle stage and the release of CO_2 during citrus oils use are assumed to be in balance; i.e., the system is carbon neutral reflecting the closed carbon cycle and renewability of the product. The PAS 2050 methodology was followed for the cradle-to-gate study.

Where a product remains in use for a period of greater than 12 months, PAS 2050: 2008 requires the calculation of the delayed release of CO_2 during the period of use up to 100 years. Should the product containing biogenic carbon remain for a period of more than 100 years, any carbon remaining in the product will be considered as a net removal. In the case of citrus oils, as they are likely to be used within 12 months of production, no further consideration of biogenic carbon is required under PAS 2050:2008.

A recent soy study, which is discussed in Section 6 of this report, is calculated according to the alternate ISO 14067 methodology. Unlike PAS 2050:2008, ISO 14067 prescribes reporting of carbon that originates from biogenic sources. This is reported separately to fossil carbon and, in the soy study discussed in Section 6, is represented by the negative values for the soy by-products (e.g., soy methyl esters). The positive values represent the CO_2 emissions that originate from fossil carbon sources and these should be considered when comparing to the results of this study.

2.2.6 *Exclusions*

In this study all life cycle stages that take place after the product has been received by a new production facility are excluded. These include:

- Packaging for distribution sale;
- Transport to distribution centers and retailers; and
- Post-consumer waste management.

Other generic exclusions in this study are:

- Carbon sequestered from the atmosphere into the wood of the roots, trunk and branches because sequestration beyond the 100-year point is not expected;
- The manufacture, maintenance and decommissioning of capital equipment, such as buildings or machines, was not included in the investigated system [6]; and
- Workforce burdens (e.g., driving to and from work).

(6) PAS 2050:2008 Section 6.4.3..

2.2.7 *Cut-off Criteria for Inputs and Outputs*

Ideally, cut-off criteria are based on environmental relevance. However, it is often impractical to define cut-off criteria based on environmental impact, since data for a process needs to be collected in order to understand the environmental impact of that process or the entire life cycle. So if data were collected it might as well be included in calculations. A more practical approach is to base cut-off criteria on mass or energy.

This study omits mass flows that contribute less than two percent of the inputs to a life cycle stage (e.g., grafting scions to rootstock in the nursery and planting in groves).

Based on LCA experience, the cut-off criteria defined above will not impact the final results. However, care was taken when excluding processes from the inventory; i.e., where inputs under the two percent threshold could have a significant environmental impact.

3.0 DATA

3.1 DATA CATEGORIES

The following data categories were included in the study:

- Raw materials and packaging inputs;
- Chemical inputs;
- Energy inputs (electricity and fuels);
- Other physical inputs, such as water;
- Emissions to air, water and soil;
- Products and by-products;
- Material outputs, including solid waste and wastewater; and
- Transportation.

3.2 DATA REQUIREMENTS

To ensure representative product systems, data collection questionnaires were prepared and distributed to the appropriate growers and processors to collect the primary data. The data used represent the production during a representative 12-month period.

The study used specific data when available, supplemented with generic data as necessary. Generic data from the U.S. LCI database [7], Ecoinvent[8] and Plastics Europe [9] database were used for the petroleum-based counterparts. These databases are the most up-to-date LCA database and consist of life cycle data for more than 4,000 different materials and processes including several different petroleum-based counterparts. A summary of the data required for the study are listed below.

(7) http://www.nrel.gov/lci/
(8) http://www.ecoinvent.org/database/
(9) http://www.plasticseurope.org/

Specific data were used for:

- Means of transport and distance associated with transportation of oranges and raw materials to juicing facilities, and citrus oils and raw materials to warehouses and/or folding facilities;
- Juice, citrus oils and other citrus products processing;
- Energy and water consumption;
- Chemical inputs;
- Production, transport and disposal of packaging; and
- Waste management.

Generic data were used for:

- Cradle-to-gate information on the petroleum-based counterparts;
- The mix of electricity generation in the geographical area where the product is produced, used, and disposed of was sourced from published data;
- Growing of oranges and production of citrus products (where generic data was of sufficient quality or when specific data was not available);
- Emission data from different means of transport per mile; and
- Fuel production.

3.3 DATA QUALITY REQUIREMENTS

The key requirements regarding data quality is that data are as accurate and representative as possible. Data quality requirements are defined in Table 3.1 below. These are based on the ISO standard for goal and scope definition and inventory analysis (EN ISO 14044:2006). Cases of missing data and assessed surrogate data quality were documented as needed.

Table 3.1 Data Quality Requirements

Parameter	Description	Requirement
Time-related coverage	Desired age of data and the minimum length of time over which data should be collected.	Data should represent the situation for the most recent 12-month period for which data are available. Typically this will be for the financial year 2009 or the 2008-2009 growing season. General data and database data should represent the situation in 2009 where possible, and not be more than 10 years old.
Geographical coverage	Area from which data for unit processes should be collected.	Data should be representative of the situation in the respective product markets.
Technology coverage	Technology mix	Data should be representative of the situation in the respective product markets.
Precision	Measure of the variability of the data values for each data category expressed.	N/A
Completeness	Consider the percentage of data that are measured and the degree to which the data represents the population of interest.	Specific datasets will be compared with literature data and databases.
Representativeness	Degree to which the data represents the identified time-related, geographical and technological scope.	The data should fulfill the defined time-related, geographical and technological scope.
Consistency	How consistently the study methodology has been applied to different components of the analysis.	The study methodology will be applied to all the components of the analysis.
Reproducibility	Assessment of the methodology and data and whether an independent practitioner would be able to reproduce the results, if tasked to do so.	The information about the methodology and the data values should allow an independent practitioner to reproduce the results reported in the study.
Sources of the data	Assessment of data sources used.	Data will be derived from credible sources and databases.

Source: PAS 2050:2008 Section 7.2

These criteria were used to assess the quality of the data obtained for each product. Furthermore, the time related, geographical and technological coverage of the secondary data used to represent these flows were assessed to determine the degree to which they are representative of the data used in the study.

4.0 RESULTS INTERPRETATION

The contributions were assessed and reported on each system for impact indicators listed in section 4.1 below. The study provided high-level results, indicating the key underpinning assumptions and limitations of the analysis were correct. Additionally, the results of the study were interpreted to indicate the scale and significance of the cradle-to-cradle environmental profiles of orange terpenes and d-limonene and the selected petroleum-based counterparts with specific emphasis on the renewability and sustainability of citrus oils.

4.1 LCA METHODOLOGY AND TYPES OF IMPACTS

This LCA was carried out using the Carbon Trust's PAS 2050:2008 Specification. The PAS 2050:2008 methodology takes an LCA approach, focusing on estimating carbon equivalent emissions from a product across its life cycle, from the production of raw materials used in its manufacture through disposal of the finished product. The PAS 2050:2008 methodology also includes specific guidelines on how to conduct a cradle-to-gate LCA.

The output of an LCA carried out using the PAS 2050:2008 methodology is a carbon footprint measured in CO_2-eqivalents. However, this LCA study also addressed those environmental impacts and indicators that were most relevant to RCPA and its members. The Building for Environmental and Economic Sustainability (BEES) impact assessment methodology was used to assess all other impact categories. The BEES methodology covers a broad range of environmental, health, and energy categories that meet the International Standards Organization (ISO) requirements and is used by the USDA for assessing biobased products for the Federal BioPreferred Program.

Water resource depletion has not been routinely assessed in LCAs to date; however, researchers are beginning to address this issue to account for areas where water is scarce, such as the western and southwestern United States. It is important to recognize that this impact addresses only the depletion aspect of water intake, not the fact that activities such as agricultural production and product manufacture may generate water pollution. However, water pollution impacts, such as nitrate and phosphate run off from agricultural production, were addressed in other impact categories in this study, such as eutrophication. The BEES impact assessment method utilizes the direct use of inventories approach to assess water resource depletion. Water intake is recorded in the BEES life cycle inventory for each product (in liters per functional unit), and is used directly to assess this impact [10].

Although carbon and water demand of products provide a good indication of a product's sustainability profile, there are other environmental impacts that should be included in an LCA to provide robust scientific evidence for important decision-making regarding sustainability and renewability. Therefore, the LCA assessed a range of other environmental impacts which are consistent with standard LCA practice. The study assessed, albeit with less detail, the following impacts:

- Land use/biodiversity;
- Resource depletion;
- Acidification;
- Nitrification/eutrophication;
- Aquatic toxicity;
- Human toxicity; and
- Photochemical smog.

The listed impact categories address a breadth of environmental issues and are based on thorough methodologies developed for these categories. However, the contributions calculated for each system were limited by the data available.

4.2 SENSITIVITY ANALYSIS

A critical part of the results interpretation is the use of sensitivity analysis to test the robustness of the conclusions. The sensitivity analysis is often referred to as a "what if" analysis where different scenarios are tested. The sensitivity analysis focuses on the environmental hotspots of the lifecycle and assessed the underlying data points and assumptions and their impacts on the overall conclusions. Examples of sensitivity scenarios in this study included:

(10) NISTIR 7423, BEES 4.0 Technical Manual and User Guide

- Calculation of carbon footprint excluding transport to the receiving organization which will incorporate the ingredient into a new product (classic cradle-to-gate assessment);

- Substituting synthetic fertilizer for orange growing with biobased compost;

- Landfilling orange peel instead of using it for citrus oils and cattle feed production; and

- The use of different LCA environmental impact methodologies such as ReCiPe.

5.0 *INVENTORY ANALYSIS*

5.1 *INTRODUCTION*

The following inventory analysis serves two purposes:

1. An assessment of the appropriateness and completeness of the data collected; and

2. A quantitative assessment of the data collected.

This section describes the life cycle of the citrus oils assessed and the data collection procedure for generation of the life cycle inventory. The data was combined to protect confidential business information. For each of the systems assessed, inventories of a few significant environmental flows to and from the environment, and internal material and energy flows were produced.

Data sources included both specific and generic data. Specific data relating to the production of inputs used to produce the citrus products were sourced.

Generic data from life cycle databases were mainly used for the materials and products used in the life cycle impact comparison of citrus oils to petroleum-based counterparts. However, generic databases were also used to model common processes, materials, transport steps and electricity generation.

5.2 *SPECIFIC DATA COLLECTION, MODELING AND ASSUMPTIONS*

Questionnaires were used to collate information on the quantities of raw materials, energy, etc., sourced by suppliers, as well as the geographical location that they are sourced from. The specific data used is considered to be fully representative as it is sourced directly from the suppliers.

In terms of reproducibility, the data collected from processors of juice and other citrus products is very specific to this study. The data received from the processors will allow an independent practitioner to reproduce the results calculated using this data. Most suppliers stated that they are using best available technology in their production.

In Table 5.1, the specific data collection is presented by life cycle stage. It includes the geographic, technological and temporal representativeness of the data, the main assumptions and estimates, and the data sources.

The data are described per life cycle stage: orange growing and harvesting; manufacturing and packaging of citrus oils; transport to a receiving organization; use; and end of life.

Table 5 Specific Data Collection and Life Cycle Inventory Analysis

Life Cycle Stage	**Geographical, Technological and Time Coverage**	**Data Quality Assessment**
Orange growing and harvesting	Data for orange growing and harvesting were provided by a major U.S. orange juice producer. Most of these raw data used are from the University of Florida, Citrus Research & Education Center reports. Data include land use; water use for irrigation; tractor mileage for agrichemicals/fertilizer application; mileage for harvesting; material input data for agrichemicals and fertilizer use and transport of oranges to processing plants.	Primary data for orange growing and harvesting in Florida were gathered from a major U.S. orange juice producer. Transport data that represented the estimated distances and transport mode from orange growing in Florida to the orange juice producers – Citrosuco, Florida's Natural Growers, Southern Gardens – were used. Major U.S. orange juice producers provided expert guidance on the data for citrus production. The data are considered representative and appropriate for the study.
Production of Orange Juice, d-limonene, Cold Pressed Orange Oil and Cattle Feed	Data for Orange Juice, Cold Pressed Orange Oil, Citrus Terpenes and Citrus-based Cattle Feed were sought from three suppliers: • Citrosuco; • Florida's Natural Growers (Citrus World); and • Southern Gardens Citrus. All three suppliers returned detailed and comprehensive questionnaires. The data included: raw material and packaging use; energy consumption; water consumption; waste water emissions; emissions to air; solid waste management; incoming transport of raw materials; and details on by-products for allocation. Most suppliers stated that they are using best available technology in their production.	The data collected are considered best available. The data were collated by internal environmental and operations experts from each company. The data collected from the three suppliers were compared to previous orange juice LCAs. The production and consumption data for the three suppliers are considered complete for this study. Average economic data for allocation of products and by-products were provided by the companies supplying data. The data are considered representative and appropriate for the study.
Production of Orange Terpenes, 5-Fold Orange Oil and Compounded flavors	Data for Orange Terpenes, 5-Fold Orange Oil and Compounded Flavors were sought from two suppliers: • Florida Chemical Company; and • Firmenich. Both suppliers returned detailed and comprehensive questionnaires. The data included: raw material and packaging use; energy consumption; water consumption; waste water emissions; emissions to air; solid waste management; incoming transport of raw materials; and details on by-products for allocation.	The data collected are considered best available. The data were collated by internal environmental and operations experts from each company. Average economic data for allocation of products and by-products was provided by the companies supplying data. The data are considered representative and appropriate for the study.

Life Cycle Stage	Geographical, Technological and Time Coverage	Data Quality Assessment
	Most suppliers stated that they are using best available technology in their production.	
Transport to end user	An average value of 1200 miles was assumed for distribution by road from the citrus processor to the receiving organization or end user.	The citrus oils are transported to the customer in reusable steel drums. Since the drums are being reused numerous times, the impact from these is negligible and has therefore been excluded from this study. For truck, average emission data per ton-mile were used from the U.S. LCI database. The data are considered representative and complete for the study.
Use	Citrus oils are incorporated into many different products as an ingredient. These products have their own use phase, e.g., cleaning products. The impact from cleaning, e.g., a kitchen, cannot be assigned to the citrus oils because the impact of that cleaning process must be assigned to the entire product and all the ingredients of it. However, the use phase was considered only in terms of the carbon cycle and the need to address biogenic carbon.	It is assumed that 100% of the citrus oils would be oxidized as a result of combustion, metabolism of an ingested flavoring ingredient, biodegradation in a waste water treatment system or landfill, or through atmospheric oxidation mechanisms. Thus the carbon uptake during orange growth is emitted during use resulting in a carbon neutral situation.
End-of-life	Not included in the current LCA (100% of citrus oils are released during use so no impact from waste management would be expected).	

Other data quality indicators include: Completeness, Consistency, Precision and Reproducibility.

Completeness

The data provided by suppliers are mainly generated by direct site measurements or internal calculations made by the suppliers so these data are considered complete. Furthermore the specific data fit within acceptable ranges of other orange juice studies.

Consistency

The method used for data collection, such as allocation and cut-off criteria, is consistent with the overall methodology described in the goal and scope.

Precision

An area where there is data variability is in the use of data from one year. Although specific and complete data were collected these data represent the data of one specific year. The data might not be fully representative for average production data since these could represent a good/bad production year that would be completely different the following year. This is very common challenge when doing LCAs of seasonal products like orange juice and other citrus products.

Reproducibility

In terms of reproducibility, the data is very specific to this study as it was collected by specific processors of orange juice and by-products. The data received from the supplier will allow an independent practitioner to reproduce the results calculated using this data.

5.3 GENERIC DATA COLLECTION, MODELING AND ASSUMPTIONS

Generic data have been used for common processes, material, transport steps and electricity generation. The key life cycle databases used were the U.S. LCI database (11) and Ecoinvent Version 2.2 (12). The U.S. LCI database and Ecoinvent are peer-reviewed databases developed to provide sets of unified and generic LCI data of high quality. Aggregated data from Plastics Europe was also used for toluene and acetone information as shown in Table 5.2 below.

(11) http://www.nrel.gov/lci/
(12) http://www.ecoinvent.ch/

The U.S. LCI and Ecoinvent data were adapted, as required, to be representative of the relevant geographical locations. Different states or countries have different energy mixes for the provision of electricity used by industrial end users at a medium voltage. The supply mix consists of various sources such as coal, gas, oil, nuclear, hydro and others. The losses from transmission and distribution are also different for each country/state. Where required, data were amended to represent the U.S grid electricity mix.

The data from the U.S. LCI and Ecoinvent do not include transport to end user. It is assumed that citrus oils producers transport the products an average of 1200 miles by road to the receiving organization. Generic data used to represent petroleum-based counterparts were adapted to include transport to the receiving organization based on the same assumption.

Table 5.2 presents the data and data sources for the products and materials used for the comparison of life cycle impacts from citrus oils to petroleum-based counterparts. Although these generic data vary in geography, technology, time etc. they are considered to be complete and representative for this study.

Table 5.2 Products and Material Data for Comparison to Citrus Oils

Data	Geographical, Technological and Time Coverage	Data Source
Tap water	Infrastructure and energy use for water treatment and transportation to the end user. Data are European average adjusted for U.S. conditions and are from 2000.	Ecoinvent 2.2
Naphtha	Co-product from crude oil refining. Data are European average adjusted for U.S. conditions and are from 2000.	Ecoinvent 2.2
Kerosene	Co-product from crude oil refining. Data are European average adjusted for U.S. conditions and are from 2000.	Ecoinvent 2.2
Xylenes	Data represent catalytic reforming of paraffinic hydrocarbons in North America (U.S. and Canada).	U.S. LCI Database
Benzene	Production of benzene with co-production of heat. All emissions are allocated to benzene production. Data represent U.S. and Canada.	U.S. LCI Database
Toluene	Production by catalytic reforming out of naphtha. Average European production.	Aggregated data from Plastics Europe. Average of 11 toluene producing plants.

Data	Geographical, Technological and Time Coverage	Data Source
Ethyl benzene	Production by alkylation of benzene with ethylene with a yield of 97 percent. Average European production.	Ecoinvent 2.2
Acetone	Production by oxidation of cumene. Average European production.	Aggregated data from Plastics Europe. Average of 4 Acetone producing plants.
Dichloromethane	Data from various plants in Europe. Production represents the actual technology of the plants. Data are from 2000.	Ecoinvent 2.2
Perchloroethylene	Data from various plants in Europe. Production represents the actual technology of the plants. Data are from 2000.	Ecoinvent 2.2

Other data quality indicators include: Completeness, Consistency, Precision and Reproducibility.

Completeness

All relevant inputs and outputs have been included in the data sets. Furthermore they fit within acceptable ranges of other literature data.

Consistency

The method used for data collection, such as allocation and cut-off criteria, is consistent with the overall methodology described in the goal and scope

Precision

The use of the average data sets in the U.S. LCI, Ecoinvent and Plastics Europe databases potentially introduce some variability in the data. Most of these values have been obtained on a weighted average basis, so while there is variability in the data, it has been averaged on a production-output basis.

Reproducibility

The U.S. LCI, Ecoinvent and Plastics Europe databases are public and will thus allow an independent practitioner to reproduce the calculated results if necessary.

5.4 *BURDEN ANALYSIS*

The burden analysis provides an overview of the actual emissions and resource use from the life cycles before calculating the contribution of emissions to environmental impact categories; e.g., in this burden analysis the emission of carbon dioxide was used before it is calculated into global warming potential.

The burden analysis is an important intermediate step where key elementary flows are presented before they are translated into environmental impacts. This is particularly useful when comparing LCAs that have been calculated using different impact assessment methods.

For d-limonene and orange terpenes, and each petroleum-based counterpart, a summary inventory of environmental flows is presented for the following:

1. Crude petroleum consumption (feedstock)
2. Non-Methane VOC
3. Carbon dioxide, fossil
4. Sulfur oxide
5. Nitrogen oxides
6. Land occupation
7. Water

Table 5.3 shows the result of the burden analysis. The petroleum-based counterparts have high consumption of crude petroleum as a raw material compared to the citrus oils. Furthermore the petroleum-based counterparts have significant emissions of non-methane VOCs (NMVOC) and CO_2 compared to the citrus oils when considered on a cradle-to-gate basis.

The citrus oils dominate the consumption of water and the occupation of land when compared to petroleum-based counterparts.

Table 5.3   Life Cycle Burden Analysis

Unit (per 1,000 kg)	**Crude petroleum** kg	**NMVOC** kg	**CO_2, fossil** kg	**SO_2** kg	**NOx** kg	**Land occupation** m^2a	**Water** m^3
Tap water	0.0065	0.000085	0.22	0.00079	0.00039	0.02	2.9
d-Limonene	26.79	0.08	157.79	0.31	0.69	1.02	233.3
Orange terpenes	72.01	0.16	315.37	0.38	1.64	1.68	261.9
Dichloromethane	138.48	4.63	2,466.23	13.08	15.08	0.15	46.2
Perchloroethylene	225.91	12.83	2,169.86	9.48	9.88	0.14	137.4
Acetone	632.81	3.74	1,946.91	6.95	5.66	0.51	87.3
Toluene	821.00	1.99	1,340.76	2.35	3.13	0.21	93.9
Benzene	961.41	2.05	893.47	10.89	4.45	0	0
Ethyl benzene	971.70	4.60	1,975.37	4.55	4.36	1.86	1,503.8
Naphtha	1,111.14	1.47	460.22	4.19	2.22	0.53	406.1
Kerosene	1,134.50	1.50	517.44	4.07	2.31	0.35	274.5
Xylenes	1,136.27	2.37	704.95	2.96	4.54	0	0

All results are provided correct to two significant figures.

6.0 LIFE CYCLE IMPACT ASSESSMENT

6.1 METHODOLOGY

In the following section of the report, the data that has been collated and analyzed in the life cycle inventory will be further interpreted using the BEES life cycle impact assessment methodology.

The BEES methodology was used for the following reasons:

- BEES has adopted the U.S. EPA-developed Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), a set of peer-reviewed U.S.-based LCA methods;

- BEES addresses a comprehensive set of impacts to meet ISO's requirements for a range of impact categories; and

- The BEES framework and impact categories are used for other government programs, such as the USDA's BioPreferred program and were used in a similar study of soy-based products.

Table 6.1 shows the life cycle results according to the BEES method of producing and using 1,000 kg of each product/material. The BEES method addresses a wide range of environmental impacts; some impacts are associated with larger uncertainties than others. Impacts like global warming, acidification, water consumption, etc., are all based on internationally recognized scientific methods endorsed by organizations like the Intergovernmental Panel on Climate Change (IPCC).

Other impacts, especially the toxicity impacts, are associated with greater uncertainty. The human and ecotoxicity science is very different from other sciences. When determining lethal doses (e.g., LC50 or LD50) that determine the impact on humans and ecosystems, a difference of a factor 1,000 is considered to be good data, so any LCA results (not only BEES) for toxicity must be used with caution.

When comparing the citrus oils with the petroleum-based counterparts, there are tradeoffs across the impact categories. The citrus oils have lowest contribution to global warming, acidification, smog formation and natural resource depletion. These are all impacts associated with energy consumption. For other impacts, especially water consumption, the citrus oils are contributing most because of the significant water consumption for irrigation and in the production of orange juice and its by-products.

Table 6.1 LCA Results (BEES)

Impact category	**Global warming**	**Acidifi-cation**	**HH cancer**	**HH non-cancer**	**HH criteria air pollutants**	**Eutrophi-cation**	**Eco-toxicity**	**Smog**	**Natural resource depletion**	**Habitat alteration**	**Water intake**	**Ozone depletion**
per 1,000 kg	kg CO_2 eq	H+ moles	g C_6H_6 eq	kg C_7H_7 eq	Micro-DALYs	kg N eq	kg 2,4-D eq	kg NOx eq	MJ surplus	T&E count	m^3	kg CFC-11 eq
Tap water	0.24	5.68E+01	0.00025	0.48	0.02	0.000065	0.002	0.001	0.21	1.43E-15	2.851	2.87E-09
d-Limonene	321.26	8.83E+04	0.32	495.77	17.85	1.17	0.32	1.80	478.93	0	226	4.86E-06
Orange terpenes	369.51	1.04E+05	0.33	527.96	20.57	0.98	0.41	2.22	577.01	0	258	4.93E-06
Naphtha	505.89	3.10E+05	2.69	631.77	80.40	1.58	1.81	2.90	7,140.71	0	405	3.67E-04
Kerosene	563.27	3.08E+05	2.73	722.98	79.51	1.61	1.87	3.01	7,276.00	0	273	3.75E-04
Xylenes	833.92	4.91E+05	1.88	1,566.01	120.68	0.32	1.49	5.75	7,658.64	0	0	5.03E-07
Benzene	1,114.52	8.92E+05	2.02	1,608.14	230.54	0.39	1.02	5.64	9,456.33	0	0	1.34E-07
Toluene	1,629.36	2.53E+05	0.59	559.92	72.28	0.35	0.55	3.91	9,212.03	2.88E-13	93.36	4.04E-08
Ethyl benzene	2,292.24	4.16E+05	4.35	1,169.34	124.28	1.37	2.46	6.40	10,471.31	1.51E-12	1,503.10	4.47E-06
Acetone	2,345.96	5.90E+05	0.60	1,293.94	155.72	1.63	2.15	7.22	9,795.26	5.74E-13	86.95	7.62E-08
Dichloro-methane	3,505.02	1.28E+06	2.17	22,855.14	576.96	2.04	60.48	22.07	4,294.97	2.12E-12	46.23	6.70E-02
Perchloro-ethylene	3,937.41	8.90E+05	35.17	22,813.72	458.46	1.58	60.39	16.61	3,737.03	1.75E-12	137.44	1.50E-01

* Note: Incomplete water usage data for crude oil exploration and production prevents accurate meaningful results for many of the petroleum-based counterparts in the water intake category.

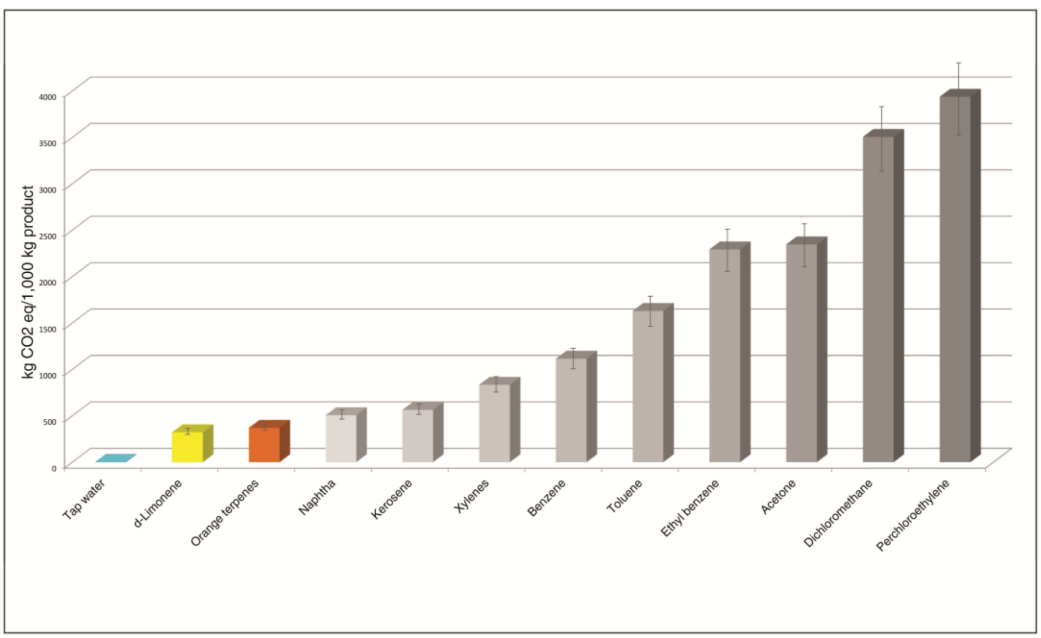
Table 6.1 presents the results of the LCA 'per 1,000 kg' of product for each of the environmental indicators included in the assessment. Where a product is made by more than one supplier, the results are provided as an average. In Table 6.1, this refers to the following:

- d-Limonene is produced by three suppliers – Citrosuco, Florida's Natural Growers (Citrus World) and Southern Gardens Citrus; and

- Orange terpenes are produced by two suppliers – Florida Chemical and Firmenich.

Figure 6.1 shows the comparative results for global warming potential. The contribution from the production and transportation of tap water to global warming is negligible compared to the other products. The contributions to global warming from orange terpenes and d-limonene are significantly lower than the other petroleum-based and biobased counterparts.

Figure 6.1 Results of the Global Warming Potential Levels



Includes a 10% margin of error

As shown in Table 6.1 the contribution from d-limonene and orange terpenes are approximately 321 and 370 kg CO_2-eq per 1,000 kg, respectively. These positive numbers are considerably different to the carbon footprint of soy methyl esters recently reported by United Soybean Board. The published study, *Life Cycle Impact of Soybean Production and Soy Industrial Products*, reports a carbon footprint of -2,100 kg CO_2-eq per 1,000 kg using mass allocation and -1,500 kg CO_2-eq per 1,000 kg using economic allocation. However, the United Soybean Board LCA includes carbon uptake from plant growth which, in accordance with PAS 2050:2008, this LCA does not include in the calculation of global warming potential. The United Soybean Board LCA calculated carbon uptake to be -2,955 kg CO_2-eq per 1,000 kg of product.

In contrast to the approach taken by the recent United Soybean Board LCI, this LCA considers the use (release) phase, where it is assumed that 100% of the carbon uptake from plant grown is released and returned to the carbon cycle.

The differences between the citrus oils and the petroleum-based counterparts are demonstrated using averages. The results for d-limonene and orange terpenes were averaged and the results for all the non-chlorinated petroleum-based products found in Table 5.2 were averaged.

Table 6.2 shows a comparison between the average of citrus oils and the average petroleum-based counterpart. In this LCA a statistical treatment of the data was not possible and throughout the LCA, estimations and assumptions are made that potentially introduce uncertainty into the final results. All data used in this study have a level of uncertainty caused by:

1. Missing information in the questionnaires received;

2. Inappropriate modeling for the necessary inputs and outputs; e.g., European data for U.S. conditions; and

3. Mistakes imposed by human errors.

This 'noise', which is inevitable in any LCA study, must be considered when comparing product systems to determine whether differences in environmental impact are real differences or caused by this noise. If the differences are the result of noise, the environmental impact from the two systems would be equivalent within the accuracy of the evaluation. On that basis, an environmental difference of 10% or more is considered meaningful. If the difference is less than 10%, the systems are considered equivalent.

Table 6.2 Difference in Life Cycle Impacts between Average of Citrus Oils and Average Petroleum-based Counterparts

	Units (per 1,000 kg)	Average Citrus Oils	Average Petroleum-based Counterparts	Citrus to Petroleum Ratio
Global warming	kg CO_2 eq	345	1,859	0.19
Acidification	H+ moles eq	96,380	603,954	0.16
HH† cancer	kg C_6H_6 eq	0.33	5.80	0.06
HH non cancer	kg C_7H_7 eq	512	5,913	0.09
HH criteria air pollutants	microDALYs	19	211	0.09
Eutrophication	kg N eq	1.07	1.21	0.88*
Ecotoxicity	kg 2,4-D eq	0.37	14.69	0.03
Smog	kg NOx eq	2.01	8.17	0.25
Natural resource depletion	MJ surplus	528	7,671	0.07
Habitat alteration	T&E count	1.48E-12	7.73E-13	1.91
Water intake**	m^3	242	283	**
Ozone depletion	kg CFC-11 eq	4.89E-06	2.42E-02	0.0002

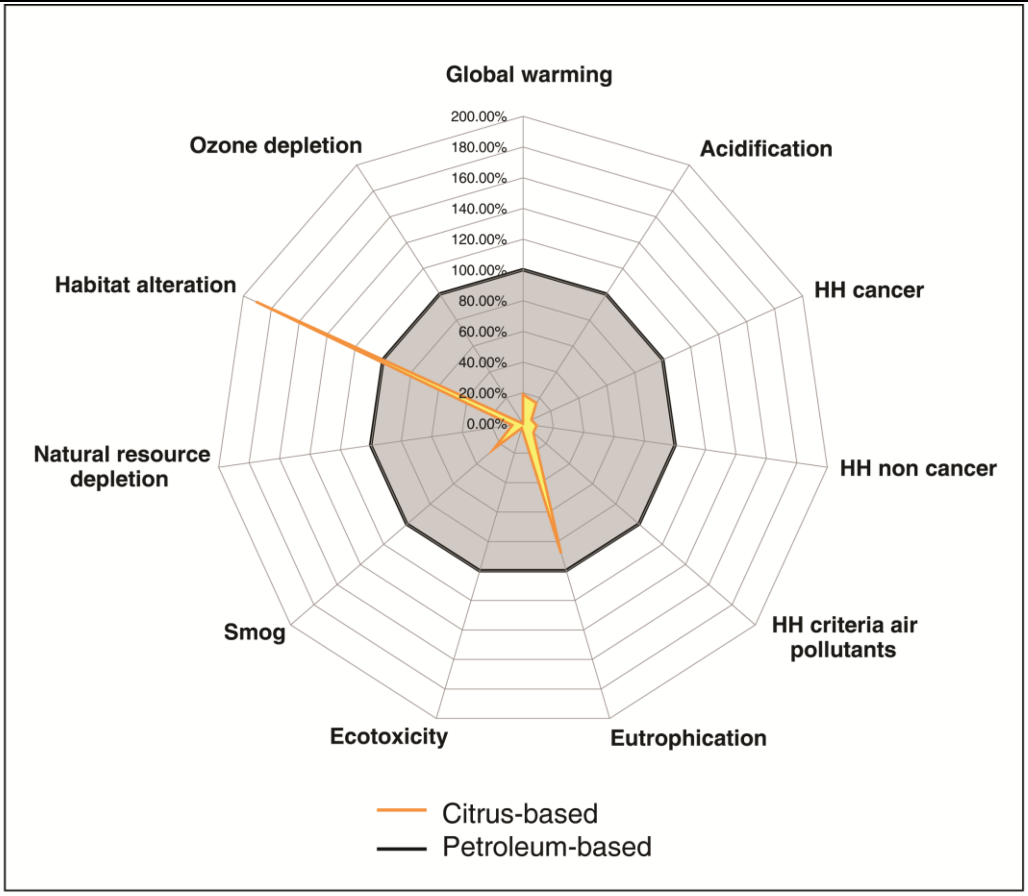
Citrus oils are better
Areas of possible improvement

* Cells shaded yellow suggest areas of possible improvement because the relative differences are not considered significant and therefore citrus oils likely do not perform better than petroleum-based counterparts in eutrophication impacts.

** Missing water usage data for electricity production (cooling water) and crude oil exploration and production prevents a meaningful comparison for this impact category.

†HH is the impact on human health

Figure 6.2 Difference in Life Cycle Impacts between Average of Citrus Oils and Average Petroleum-based Counterparts



As Table 6.2 and Figure 6.2 show, the citrus oils average has lower environmental impacts except for habitat alteration caused by direct land use from the orange groves. The significant water consumption from citrus oils is attributed to irrigation when growing oranges (2,429 m^3 per acre per year [(13)]); however, it cannot be accurately compared to petroleum-based counterparts due to gaps in data (no water consumption availability during crude oil production) and therefore is not depicted in Figure 6.2.

6.2 RELATIVE CONTRIBUTION PER LIFE CYCLE STAGE

The following two tables show the contribution per life cycle stage for d-limonene and orange terpenes. The objective of this is to identify where the environmental hotspots are in the life cycle of the two products and

(13) Data provided by Growers and used for the Tropicana carbon footprint study.

thereby where citrus oils producers could focus their efforts to reduce environmental impacts.

The major life cycle stages of petroleum-based counterparts are not presented in the tables since citrus oils producers have no influence or incentive for reducing the impacts. The main contributor in the life cycle of the petroleum-based counterparts is energy consumption from petroleum refining and crude oil production (e.g. together they are 94% of global warming potential).

Table 6.3 ***Relative Contributions to Life Cycle Impacts of d-Limonene Production (Cradle-to-Gate)***

	Transport of raw materials	Raw materials production	Electricity use	Natural gas use	Transport to receiving organization
Global warming	3%	23%	9%	10%	56%
Acidification	5%	16%	7%	4%	68%
HH cancer	2%	47%	19%	8%	25%
HH noncancer	0.4%	48%	32%	7%	13%
HH criteria air pollutants	7%	24%	17%	5%	48%
Eutrophication	1%	71%	21%	2%	5%
Ecotoxicity	2%	26%	41%	10%	20%
Smog	6%	6%	4%	3%	81%
Natural resource depletion	3%	10%	3%	15%	69%
Habitat alteration	0.03%	43%	33%	24%	0%
Water intake	0.4%	51%	46%	3%	0%
Ozone depletion	22%	72%	4%	2%	0.15%

Table 6.4 ***Relative Contribution per Life Cycle Stage for Orange Terpenes Production (Cradle-to-Gate)***

Calculation as a percentage	Transport of raw materials	Raw materials production	Electricity use	Natural gas use	Transport to receiving organization
Global warming	12%	19%	12%	4%	54%
Acidification	16%	11%	9%	2%	62%
HH cancer	5%	29%	33%	4%	29%
HH noncancer	3%	33%	50%	1%	13%
HH criteria air pollutants	12%	18%	23%	2%	45%

Calculation as a percentage	Transport of raw materials	Raw materials production	Electricity use	Natural gas use	Transport to receiving organization
Eutrophication	2%	42%	48%	1%	8%
Ecotoxicity	4%	25%	50%	4%	17%
Smog	19%	6%	5%	1%	69%
Natural resource depletion	14%	10%	4%	11%	61%
Habitat alteration	0%	44%	56%	0.1%	0%
Water intake	0%	34%	64%	1%	0%
Ozone depletion	0.04%	43%	23%	33%	0.6%

Table 6.3 shows that the main contributors (high percentages) to the environmental impact of the production of d-limonene across all impact categories are production and application of fertilizer and tractor transport during orange growing (raw materials production). In most cases electricity use during production also contributes significantly to the life cycle environmental impacts. In some cases, transportation of the final product to the end user also results in a significant contribution to the life cycle environmental impacts.

Table 6.4 shows that the main contributors (high percentages) to the environmental impact of orange terpenes production across all impact categories are production of cold pressed orange oil (raw materials production) and electricity consumption for orange terpenes production. Transportation of the final product to the receiving organization also results in a significant contribution to the life cycle environmental impacts.

6.3 NORMALIZATION

In order to gain a better understanding of the relative size of an impact, normalization is a useful step. During normalization, an impact is related to a known size or activity contributing to the same impact. For example, global warming potential can be directly related to the energy consumed in the life cycles, which makes it directly comparable with other energy consuming activities such as miles driven in a car. This approach has been used to put the differences in global warming between the products into perspective.

The GHG impact of one mile of travel in a gasoline passenger car with a 1.4 to 2.0 liter engine is 0.402 kg CO_2-eq [14].

The difference in the GHG impact of the production of orange terpenes and the production of petroleum was assessed relative to traveling one mile in the passenger car described above.

The cradle-to-gate GHG emissions for d-limonene and orange terpenes are 321 and 370 kg CO_2-eq per 1,000 kg, respectively.

Table 6.5 Normalization of GHG Impact

	GHG emissions (cradle-to-gate)	Difference in GHG emissions with d-Limonene	Equivalent number of passenger car miles saved	Difference in GHG emissions with orange terpenes	Equivalent number of passenger car miles saved
	kg CO_2-eq per 1,000 kg	kg CO_2-eq per 1,000 kg		kg CO_2-eq per 1,000 kg	
Acetone	2,346	2,025	5,037	1,976	4,917

Table 6.5 shows that, when compared on a mass-to-mass basis, the difference in GHG impact of 1,000 kg orange terpenes and 1,000 kg acetone is equivalent to the GHG impact of travelling 4,917 miles in a passenger car. The difference in GHG impact of 1,000 kg d-limonene and 1,000 kg of acetone is equivalent to the GHG impact of travelling 5,037 miles. These distances are comparable to about one-half of the total annual mileage of one passenger car [15] in the U.S. in 2009 [16].

6.4 *GLOBAL WARMING RESULTS FOR OTHER ORANGE PRODUCTS*

In addition to the global warming impacts of d-limonene and orange terpenes, the LCA also calculated the impacts of other orange products; i.e., orange juice, cold pressed orange oil, 5-fold orange oil, citrus terpenes and citrus-based cattle feed. The total values of the citrus-based products (including d-limonene and orange terpenes) are much less than orange juice. Consequently more than 99% of the environmental impacts are allocated to the production of orange juice and the remaining 1% is

(14) 2011 Guidelines to Defra/ DECC's GHG Conversion Factors for Company Reporting
(15) The annual vehicle mileage per capita in the U.S. in 2009 was 9,548 miles. U.S. Department of Energy, Transport Energy Databook (Table 8_02: Vehicles and Vehicle-Miles per Capita, 1950–2009a) (http://cta.ornl.gov/data/chapter8.shtml)
(16) It is possible that comparison of the products on a mass-to-mass basis is not appropriate due to differences in their functionality. No assessment of the functionality of the citrus oils or their petroleum/ biobased counterparts has been undertaken as part of this study.

divided between the other orange products. This allocation method is consistent with other LCAs of orange juice products.

Table 6.6 shows the global warming potential (GWP) results for the other orange products compared to orange terpenes and d-limonene:

Table 6.6 *Global Warming Potential or Carbon Footprints* for Orange Products*

Orange Juice kg CO_2-eq per 1,000 kg	**Cold Pressed Orange Oil** kg CO_2-eq per 1,000 kg	**d-Limonene (Citrus Terpenes)** kg CO_2-eq per 1,000 kg	**Orange Terpenes** kg CO_2-eq per 1,000 kg	**5-Fold Orange Oil** kg CO_2-eq per 1,000 kg	**Citrus-based Cattle Feed** kg CO_2-eq per 1,000 kg
584	**362**	**321**	**370**	**1,359**	**8**

* The carbon footprints in this table are consistent with the PAS 2050:2008 Specification and include transportation of 1,200 miles to the receiving organization's door or "gate".

To calculate the relative contribution from d-limonene compared to orange juice it is therefore necessary to multiply these results with the absolute quantity produced at each facility. This will result in a relative contribution, based on economic value, of 0.1% from d-limonene compared to 99.2 % from orange juice to the total carbon footprint of orange juice producers. The remaining 0.7 % is associated with the production of the remaining by-products including cold pressed orange oil.

As a comparison, the GWP results for orange juice in this LCA are very similar to the Tropicana study by the Carbon Trust which increases confidence in the results of this LCA (17).

A 64-ounce carton of orange juice is equivalent to 1.87 kg of OJ. Therefore a 64-ounce carton of OJ results in 1.09 kg CO_2-eq (0.584 kg CO_2-eq per kg orange juice multiplied by 1.87 kg OJ per 64 ounces). The Tropicana LCA showed that 60% of the total life cycle CO_2 emissions are contributed by the production of orange juice (18). The total Tropicana footprint is 1.7 kg CO_2-eq 64 ounce carton and 60% of this is 1.02 kg CO_2-eq which is comparable to the results of the RCPA LCA.

6.5 SENSITIVITY ANALYSIS

The sensitivity analysis is a process where key input parameters and method choices about which there may be uncertainties are deliberately

(17) Further information relating to the Tropicana carbon footprint study is available at: http://www.tropicana.com/pdf/carbonFootprint.pdf.
(18) http://www.tropicana.com/pdf/carbonFootprint.pdf

varied in the modeling in order to show the effect that such variation could have on the results of the assessment.

The following parameters were investigated in the sensitivity analysis:

1. Calculation of the carbon footprints excluding transport to the end user of citrus oils (classic cradle-to-gate assessment);

2. Substituting fertilizer use when growing the oranges;

3. Landfilling of orange peel instead of using it for citrus oils and cattle feed production; and

4. Use of a different impact assessment methodology (ReCiPe).

Scenario 1- Excluding Transport to Receiving Organizations

The baseline calculation of this study includes the emissions from transporting the citrus oils and other citrus products to a receiving organization (19).

- For d-limonene, it was estimated that the product was transported an average of 1,200 miles by truck to the receiving organization. The cradle-to-gate carbon footprint of d-limonene totals 321 kg CO_2-eq per 1,000 kg, of which 56% is attributable to transportation to the receiving organization.

- For orange terpenes, it was estimated that the product was transported an average of 1,200 miles by truck to the receiving organization. The cradle-to-gate carbon footprint of orange terpenes totals 370 kg CO_2-eq per 1,000 kg, of which 54% is attributable to transportation to the receiving organization.

Average transportation to the receiving organization is shown to account for a significant proportion of the total cradle-to-gate carbon footprints of both d-limonene and orange terpenes. However, citrus oils are shipped to various geographic locations and therefore the transport distance can vary considerably. This variation would cause a significant variation in the carbon impact from this life cycle stage, as well as the total carbon footprint results.

(19) This is required by the PAS 2050:2008 standard and is in accordance with the ISO standards.

In this sensitivity scenario, transportation to the receiving organization is excluded. This represents the carbon footprint of the production of the d-limonene and orange terpenes products. This sensitivity scenario removes the uncertain element from the assessment and enables a better understanding of the carbon impact associated with production.

As Table 6.7 shows, transportation to the receiving organization contributes a significant proportion to the total carbon footprint. The table also shows the cradle-to-gate carbon footprint which can be provided to potential users independently of the user's geographical location.

Table 6.7 Impact of Transport/Cradle-to-Gate Analysis

	d-Limonene	**Orange Terpenes**
	kg CO_2-eq per 1,000 kg	kg CO_2-eq per 1,000 kg
Baseline: Cradle-to-Gate (Receiving Organization's Gate) including Transportation	321	370
Cradle-to-Gate (Producer's Gate) without Transportation	142	191
Difference	56% Reduction	54% Reduction

Scenario 2 - Substituting Fertilizer Used for Growing Oranges

The fertilizer used for growing oranges accounts for approximately 50% of the total carbon footprint of citrus oils. Therefore, any efforts to reduce the impact from fertilizer, with a more efficient orange growing process or reduced fertilizer application, is a key way in which the total carbon footprint of citrus oils can be reduced.

The production of synthetic fertilizers is a relatively energy intensive process which results in relatively high GHG impacts per kg of fertilizer. Based on Ecoinvent data for the production of compost, biobased compost requires much less energy and consequently the GHG impact per kg of compost is significantly lower than for synthetic fertilizers. However, emissions of greenhouse gases from application and storage of organic fertilizer (i.e. N_2O) can be higher than for synthetic fertilizers.

The use of biobased fertilizers could present an opportunity to reduce the carbon footprint of citrus oils and therefore the impact of substituting of synthetic fertilizers with organic compost was investigated.

The substitution of synthetic fertilizer with organic compost was estimated based on their relative nitrogen content and using Ecoinvent data for compost production.

- Data for synthetic fertilizer inputs for orange growing were provided as kg of nitrogen – 5.62 lb of nitrogen per 1,000 lb of oranges.

- The average nitrogen content of compost is assumed to be 4% [20]. Therefore, 140.5 lb of compost required to equate to a nitrogen input of 5.62 lb.

- The yield of oranges in Florida has been shown to increase by 10% using biobased compost rather than synthetic fertilizer. Therefore the output of oranges was uplifted by 10% [21].

The results of this sensitivity analysis are presented in Table 6.8.

Table 6.8 Impacts on Cradle-to-Gate GHG Emissions of Citrus Oils of Substituting Synthetic Fertilizer for Orange Growing with Biobased Compost

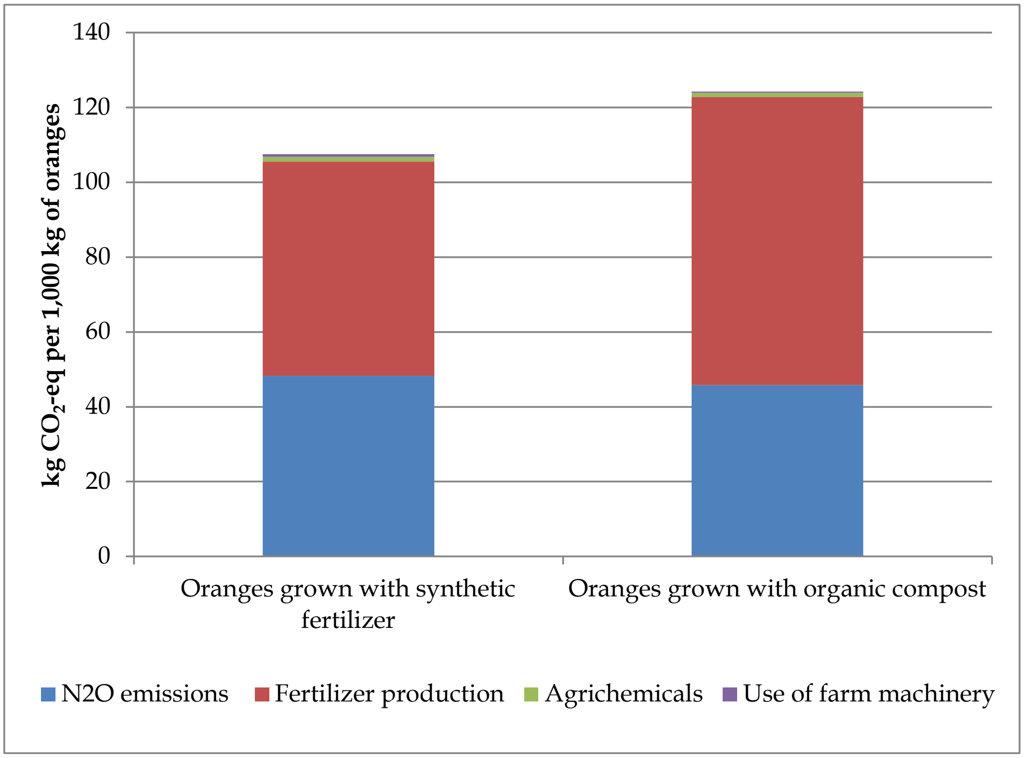
	Total GHG emissions *synthetic fertilizer* kg CO_2-eq per 1,000 kg	**Total GHG emissions** *organic compost* kg CO_2-eq per 1,000 kg
d-Limonene	321	385
Orange terpenes	370	398

Table 6.8 suggests that the cradle-to-gate carbon footprints of citrus oils made from oranges using compost are greater than from using synthetic fertilizer. This is indicative as secondary data has been used to appraise compost production and methods for producing compost will vary significantly in reality. Although on a mass-to-mass basis the production of compost typically has a lower carbon footprint than the production of synthetic fertilizer, there are other factors that influence the impact on the total carbon footprint. The carbon footprint of one kg of organic compost is much lower than one kg of nitrogen fertilizer. However, as organic compost has a much lower nitrogen content than synthetic nitrogen fertilizer, much more is needed to deliver the same quantity of nitrogen to the soil.

Figure 6.3 provides a breakdown of orange growing per 1,000 kg of oranges, comparing oranges grown with synthetic fertilizer and oranges grown with biobased compost. This clearly shows how the production of a large quantity of compost impacts on the carbon footprint per 1,000 kg of oranges.

(20) http://horttech.ashspublications.org/content/12/3/332.full.pdf (Table 3)
(21) http://horttech.ashspublications.org/content/12/3/332.full.pdf (Table 3)

Figure 6.3 ***GHG Emissions from Growing Oranges with Synthetic and Organic Fertilizers – per 1,000 kg of Oranges***



It should be noted that the carbon footprint results for cultivation of oranges will differ with varying yields.

Scenario 3 – Landfill of Orange Peel

In this scenario the potential global warming impact of landfilling the peel from orange juicing instead of making it into useful products has been calculated. For the landfill scenarios the PAS 2050:2008 landfill model developed by the Carbon Trust for their Footprint Expert tool was used. The landfill model calculates the CO_2 equivalent value of CO_2 and CH_4 released from landfilling orange peel based on its carbon content and biodegradability rate. The results of the model show an emission factor of 812 kg CO_2-eq/1,000 kg wet orange peel.

Table 6.9 below shows the impact of landfilling the orange peel by-product from orange juicing rather than making use of it in the production of other products.

Table 6.9 Impact on Cradle-to-Gate GHG Emissions of Orange Juice of Landfilling Orange Peel

Cradle-to-gate GHG emissions of 1,000 kg of orange juice	**GHG emissions** *kg CO_2-eq per 1,000 kg*
Orange juice with disposal of orange peel to landfill	812
Orange juice with use of orange peel for production of other products	583
Difference in GHG emissions	229
% Reduction in GHG emissions by using orange peel	28.2%

The production of 1,000 kg of orange juice produces an average of 1,000 kg of orange peel (based on the production of orange juice from the three suppliers). The impact of landfilling this peel and not using it for the production of other products results is an additional 229 kg CO_2-eq. In other words, for every 1,000 kg of orange juice produced the contribution to global warming is reduced by 229 kg CO_2-eq or 28.2% when using the orange peel for citrus oils and cattle feed instead of landfilling as waste. The absolute reduction in global warming potential is significant when the total amount of orange juice production in Florida is considered (together, the three companies in this study produce billions of kilograms of orange juice per year).

Scenario 4 - Using Different Impact Assessment Methodology

Another way of testing the results and subsequent conclusions is to calculate the results using other impact assessment methods. The results were tested using the ReCiPe method (22). ReCiPe was created by the RIVM (23), CML (24), PRé Consultants, Radboud Universiteit Nijmegen and CE Delft and was developed to provide a single impact assessment method that combines both mid-point and end-point analysis. ReCiPe was most recently updated in July 2010.

Table 6.10 presents the LCA results of the citrus oils and the petroleum and biobased counterparts using the ReCiPe method. Table 6.11 shows a comparison between the average of citrus oils and the average petroleum-based counterparts and Figure 6.3 compares this figuratively.

(22) ReCiPe Mid/Endpoint method, version 1.05 July 2010 (www.lcia-recipe.net)
(23) The Dutch National Institute for Public Health and the Environment
(24) Centre for Environmental Science, Leiden University (www.cml.leiden.edu)

Table 6.10 LCA Results using ReCiPe

Unit (per 1,000 kg)	**Climate change** kg CO_2-eq	**Water depletion** m³	**Metal depletion** kg Fe eq	**Fossil depletion** kg oil eq	**Terrestrial acidifi-cation** kg SO_2 eq	**Fresh water eutrophi-cation** kg P eq	**Marine eutrophi-cation** kg N eq	**Terrestrial ecotoxicity** kg 1,4-DB eq	**Fresh water ecotoxicity** kg 1,4-DB eq	**Marine ecotoxicity** kg 1,4-DB eq	**Human toxicity** kg 1,4-DB eq	**Ozone depletion** kg CFC-11 eq	**Photo-chemical oxidant formation** kg NMVOC
Tap water	0.240	1.13	5.50E-04	0.07	0.001	1.47E-06	0.00015	0.000053	0.0021	0.00060	0.031	1.19E-08	0.00055
d-Limonene	207	0.75	3.71E-01	51.89	0.83	4.84E-02	0.28	0.006	0.468	0.54	49.97	9.42E-06	0.81
Orange terpenes	350	0.58	3.64E-01	105.92	1.55	3.90E-02	0.65	0.004	1.082	1.13	130.23	8.95E-06	1.90
Naphtha	510	3.11	1.03E+00	1,270.86	5.60	6.78E-04	0.89	0.035	2.166	1.71	112.31	4.43E-04	3.98
Kerosene	567	3.00	1.76E-01	1,292.38	5.52	5.64E-04	0.92	0.038	2.124	1.69	114.33	4.52E-04	4.08
Xylenes	845	0	0	1,389.04	8.61	0.00E+00	1.84	0.006	13.698	14.13	2,118.86	3.93E-07	8.16
Benzene	1,134	0	0	1,614.36	16.51	0.00E+00	1.81	0.007	12.770	13.20	1,976.13	1.21E-07	8.31
Toluene	1,654	1.03	8.92E-01	1,525.79	4.25	6.87E-03	1.22	0.016	0.860	0.99	90.23	8.28E-08	5.57
Ethyl benzene	2,320	14.86	1.54E+00	1,774.41	7.15	9.97E-03	1.71	0.039	1.284	1.43	106.28	3.19E-05	8.99
Acetone	2,381	3.22	1.63E+00	1,595.71	10.27	1.47E-01	2.21	0.259	15.875	2.02	109.01	1.28E-07	10.25
Dichloro-methane	3,590	5.66	2.27E+00	780.97	21.68	5.00E-02	5.87	0.074	2.813	2.72	615.01	8.80E-02	17.96
Perchloro-ethylene	4,023	8.26	1.24E+00	697.66	15.17	4.11E-02	3.86	0.090	3.205	2.76	829.66	1.65E-01	13.23

Note – All values are correct to two significant figures

Table 6.11 Difference in Life Cycle Impacts between Average of Citrus Oils and Average Petroleum-based Counterparts using ReCiPe

	Units (per 1000 kg)	**Average Citrus Oils**	**Average Petroleum-based Counterparts**	**Citrus to Petroleum Ratio**
Climate change	kg CO_2-eq	278.33	1891.49	0.15
Water depletion	m^3	0.67	4.35	0.15
Metal depletion	kg Fe eq	0.37	0.98	0.38
Fossil depletion	kg oil eq	78.90	1326.80	0.06
Terrestrial acidification	kg SO2 eq	1.19	10.53	0.11
Freshwater eutrophication	kg P eq	0.044	0.028	1.57
Marine eutrophication	kg N eq	0.47	2.26	0.21
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0051	0.063	0.08
Freshwater ecotoxicity	kg 1,4-DB eq	0.77	6.09	0.13
Marine ecotoxicity	kg 1,4-DB eq	0.84	4.52	0.19
Human toxicity	kg 1,4-DB eq	90.10	674.65	0.13
Ozone depletion	kg CFC-11 eq	9.18E-06	2.82E-02	0.0003
Photochemical oxidant formation	kg NMVOC	1.36	8.95	0.15

Citrus oils are better
Areas of possible improvement

Figure 6.4 Difference in Life Cycle Impacts between Average of Citrus Oils and Average Petroleum-based Counterparts using ReCiPe

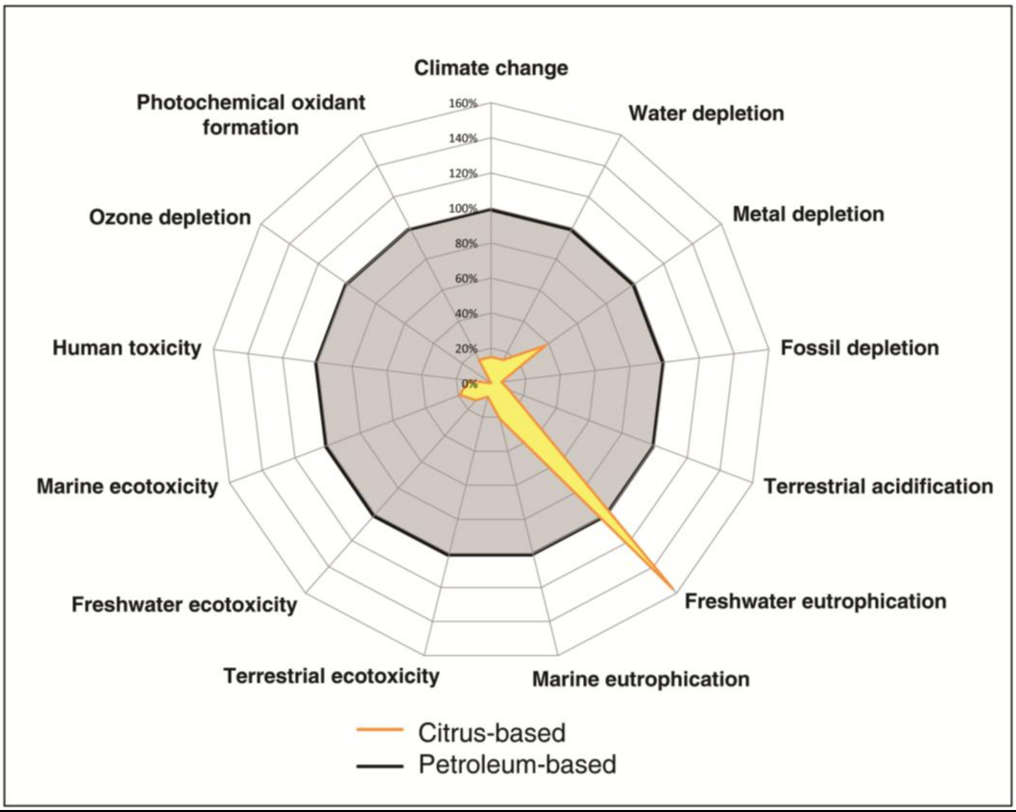


Figure 6.4 shows the difference in the results of average of citrus oils and average petroleum-based counterparts using the ReCiPe method, rather than BEES as was used in Figure 6.2.

With the exception of freshwater eutrophication, the impact from average citrus oils is lower than for the average petroleum-based counterparts, as for the BEES results.

For freshwater eutrophication, the assessment using ReCiPe results in a higher impact for average citrus oils than for the average petroleum-based counterparts. This is compared to average citrus oils resulting in a slightly lower eutrophication impact than average petroleum-based counterparts using the BEES method. ReCiPe characterizes eutrophication as two separate impacts – marine and freshwater – whilst BEES characterizes these two impacts as one. The unit of measurement for ReCiPe freshwater eutrophication (kg P eq) is different to ReCiPe marine eutrophication and BEES eutrophication (kg N eq) and therefore the impacts are not directly comparable. Using either impact assessment method, the impact from eutrophication (freshwater and marine) is predominantly from the use of fertilizers and agrichemicals for growing oranges.

ReCiPe does not include an equivalent land use/ biodiversity impact category to the BEES 'habitat alteration' category and this has therefore been excluded from the comparison.

7.0 CONCLUSION

7.1 LIFE CYCLE ENVIRONMENTAL IMPACTS

Citrus is a renewable crop that is harvested every year. Citrus oils can be direct replacements for a variety of hydrocarbons, oxygenated hydrocarbons and chlorinated hydrocarbons. Therefore, the environmental impacts of orange terpenes and d-limonene were compared against petroleum based counterparts. This provided the data required to make informed comparisons.

This assessment included the calculation and analysis of the life cycle environmental impacts for the full 11 citrus-based and petroleum-based counterparts:

- Orange terpenes
- d-Limonene (Citrus terpenes)
- Naphtha
- Kerosene
- Xylenes
- Benzene
- Toluene
- Ethyl benzene
- Acetone
- Dichloromethane
- Perchloroethylene

7.2 ` FINDINGS SHOW ENVIRONMENTAL BENEFITS

In general the results indicate that citrus oils have a more favorable and more sustainable environmental profile when compared to petroleum-based counterparts.

These conclusions are based on an overall assessment of all the following environmental impacts, which were assessed in the study:

- Global warming potential;
- Water intake;
- Land use/biodiversity (represented by 'habitat alteration');
- Resource depletion (represented by 'natural resource depletion');
- Acidification;
- Nitrification/eutrophication;
- Aquatic toxicity (represented by ecotoxicity);
- Human toxicity (represented by 'HH cancer', 'HH non-cancer' and 'criteria air pollutants'); and
- Smog.

Results of the LCA indicate that across a wide range of impact categories petroleum-based counterparts have significantly higher environmental impacts than citrus oils.

Table 7.0 Difference in Life Cycle Impacts between Average of Citrus Oils and Average Petroleum-based Counterparts

	Units (per 1,000 kg)	Average Citrus Oils	Average Petroleum-based Counterparts	Citrus to Petroleum Ratio
Global warming	kg CO_2 eq	345	1,859	0.19
Acidification	H+ moles eq	96,380	603,954	0.16
HH† cancer	kg C_6H_6 eq	0.33	5.80	0.06
HH non cancer	kg C_7H_7 eq	512	5,913	0.09
HH criteria air pollutants	microDALYs	19	211	0.09
Eutrophication	kg N eq	1.07	1.21	0.88*
Ecotoxicity	kg 2,4-D eq	0.37	14.69	0.03
Smog	kg NOx eq	2.01	8.17	0.25

	Units (per 1,000 kg)	Average Citrus Oils	Average Petroleum-based Counterparts	Citrus to Petroleum Ratio
Natural resource depletion	MJ surplus	528	7,671	0.07
Habitat alteration	T&E count	1.48E-12	7.73E-13	1.91
Water intake**	m^3	242	283	**
Ozone depletion	kg CFC-11 eq	4.89E-06	2.42E-02	0.0002

Citrus oils are better
Areas of possible improvement

* Cells shaded yellow suggest areas of possible improvement because the relative differences are not considered significant and therefore citrus oils likely do not perform better than petroleum-based counterparts in eutrophication impacts.
** Missing water usage data for electricity production (cooling water) and crude oil exploration and production prevents a meaningful comparison for this impact category.
†HH is the impact on human health

The specific case of greenhouse gas emissions is useful for illustrating the magnitude of differences in environmental impacts between citrus oils and petroleum-based counterparts. 1,000 kg of citrus oils products is associated with the average of 321 kg CO_2-eq and 370 kg CO_2-eq emissions from d-limonene and orange terpenes, respectively. When compared on a mass-to-mass basis, the difference in GHG impact of 1,000 kg orange terpenes and 1,000 kg acetone is equivalent to the GHG impact of travelling 4,917 miles in a passenger car. The difference in GHG impact of 1,000 kg d-limonene and 1,000 kg of acetone is equivalent to the GHG impact of travelling 5,037 miles. These distances are comparable to about one-half of the total annual mileage of one passenger car [25] in the U.S. in 2009.

7.3 *EXTERNAL COMMUNICATION OF BENEFITS*

The LCA demonstrates that citrus oils have lower environmental impacts than petroleum-based materials. Citrus oils due to their composition clearly have benefits in terms of impacts from the use of biogenic carbon representing a closed carbon cycle with carbon being sequestered in the making of oranges and being released at the end of life. Petroleum based materials are derived from crude oil and as such result in the release of carbon dioxide to the environment that had previously been locked in place. It should be noted that all processing of materials has associated impacts and that the processing will result in the release of some fossil-based carbon dioxide. Utilizing citrus peel for production of citrus oils is

(25) The annual vehicle mileage per capita in the U.S. in 2009 was 9,548 miles. U.S. Department of Energy, Transport Energy Databook (Table 8_02: Vehicles and Vehicle-Miles per Capita, 1950–2009a) (http://cta.ornl.gov/data/chapter8.shtml)

a sustainable practice that promotes or contributes to sustainability and sustainable outcomes, since sustainability is a process or goal.

The use of the term "cradle-to-cradle" requires support with the appropriate clarifications and caveats. This LCA is not associated with the Cradle to Cradle© product design philosophy and certification process, and does not infer the physical collecting and recycling or reuse of citrus oils at their end-of-life. The study does not appraise the use of citrus oils by customers, their environmental impacts, nor the environmental impacts that result from release of citrus oils to the environment. The study assumes that the carbon in citrus oils is part of the closed carbon cycle for biomass and therefore in the specific case of biogenic carbon could be described as a "cradle-to-cradle" assessment. To reiterate, citrus oils contributes to global warming, however, their contribution is significantly less than that of the petroleum-based and biobased counterparts, and are therefore a low carbon alternative.

It is suggested RCPA focus on promoting citrus oils as a low carbon, sustainable solution to the petrochemical alternatives.

7.4 OPPORTUNITIES FOR IMPROVEMENT

One of the benefits of conducting an LCA is that it identifies environmental impact areas where there is potential for improvement. The LCA shows water intake, habitat alteration and fertilizer consumption are potential areas for improvement when growing citrus for orange juice and citrus by-products. It is important to point out that these impacts are inherent in growing and cultivating agricultural crops like citrus.

RCPA is committed to continuous improvement and incorporating sustainable agriculture practices that are economically viable, socially responsible and ecologically sound.

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