Life Cycle Assessment of Greenhouse Tomato (*Solanum lycopersicum* L.) Production in Southwestern Ontario.

by

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ABSTRACT

LIFE CYCLE ASSESSMENT OF GREENHOUSE TOMATO (*Solanum lycopersicum* L.) PRODUCTION IN SOUTHWEST ONTARIO

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Greenhouse tomatoes are the most widely grown greenhouse vegetable in Ontario, with southwestern Ontario having the largest concentration of greenhouse tomato operations in North America. However, there is little data concerning the environmental impacts of producing greenhouse tomatoes in Ontario. This study was conducted to evaluate the potential environmental impacts of greenhouse tomato production in southwestern Ontario by using a life cycle assessment (LCA). Data were collected from greenhouse tomato growers in Leamington, Ontario via a survey, with additional data from documents and databases. The major source of environmental impact came from the energy and source (i.e. fossil fuels) required for heating the greenhouse, followed by fertilization, electricity use, and if included, liquid CO_2. Different modelling scenarios proved effective in revealing the benefits and detriments of using various heating sources. This study revealed that energy saving methods should be investigated to mitigate the environmental burdens caused by heating the greenhouse.

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LIST OF ABBREVIATIONS

100BO: 100% Bunker Oil
100NG: 100% Natural Gas
100WC: 100% Wood Chips
50NG/50WC: 50% Natural Gas and 50% Wood Chips
80NG/20BO: 80% Natural Gas and 20% Bunker Oil
AD: Acidification
AVG: Average
BER: Blossom-End Rot
CBA: Cost Benefit Analysis
CED: Cumulative Energy Demand
CF_4: Tetrafluoromethane
C_2F_6: Hexafluoroethane
CFC-11: Trichlorofluoromethane
CH_4: Methane
CHP: Combined Heat and Power
CO_2 eq: Carbon dioxide equivalent
CO_2: Carbon dioxide
EU: Eutrophication
FU: Functional Unit
GHG: Greenhouse gases
GJ: Giga Joule
GW: Global Warming
H^+: Hydrogen Ion
IPCC: Intergovernmental Panel on Climate Change
ISO: International Organization of Standardization
K_2O: Potassium Oxide
L: Litre
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
MJ: Mega Joule
N: Nitrogen
NAFTA: North American Free Trade Agreement
NFT: Nutrient Film Technique
NH_3: Ammonia
NH_4^+: Ammonium
N_2O: Nitrous oxide
NO_3^-: Nitrate
NOx: Nitrogen oxides
OD: Ozone Depletion
OGVG: The Ontario Greenhouse Vegetable Growers
OMAFRA: Ontario Ministry of Agriculture, Food, and Rural Affairs

ON: Ontario
P_2O_5: Phosphorus Pentoxide
SE: Standard Error
SM: Smog
SO_2: Sulfur dioxide
STD: Standard Deviation
TOGA: The Ontario Greenhouse Alliance
TOV: Tomatoes On the Vine
TRACI: Tool for the Reduction and Assessment of Chemical and other environmental Impacts
US-EI: United States EcoInvent
USEPA: United States Environmental Protection Agency
USLCI: United States Life Cycle Inventory
UNEP: United Nations Environment Programme

CHAPTER 1- INTRODUCTION

Greenhouse tomato production in Leamington is an important part of Ontario's agricultural economy. With increasing environmental regulations and rising energy costs, the industry is seeking ways to remain competitive, while retaining production of quality tomatoes. Consumers are also demanding ecological-friendly food at fair prices, and will continue to do so in the future. Investigations into the environmental impacts of greenhouse tomato production are therefore necessary in order to assess the industry's environmental sustainability.

Life cycle assessment (LCA) is a constructive tool that can be used to evaluate the environmental load of a product, process, or activity throughout its life cycle (Roy, 2009). In other words, LCA analyzes the ecological impacts that stem from raw material acquisition, production, use/maintenance, and recycle/waste. Life cycle assessment can not only help guide changes in systems to reduce environmental impacts, but also make them more energy, carbon, water, and therefore cost efficient. The guidelines for conducting a proper LCA have been developed by the International Organization for Standardization (ISO) and have been further developed by the United Nations Environment Programme (UNEP).

There have been numerous LCA studies on food production and more specifically for greenhouse tomato production. However, the environmental impacts of greenhouse tomato production in southwestern Ontario are poorly documented or absent (TOGA, 2009). This research will help provide an understanding into the potential environmental impacts attributable to greenhouse tomato production and provide insight into the environmental sustainability of production systems as well as any challenges growers may face in terms of production.

Ontario's tomato greenhouse industry is important to the overall greenhouse vegetable output for Ontario and Canada. Furthermore, the industry has been growing to meet market opportunities and could continue to do so if it is progressive. Finally, the systems in Ontario are likely sufficiently different (i.e. climatic and technological) from those elsewhere that the results of LCA's elsewhere are not directly transferrable to the greenhouses in southwestern Ontario. Therefore, there is a need to conduct an LCA of tomato greenhouse production in Ontario. The objectives of this thesis are:

1. To quantify and identify the direct and indirect environmental impacts stemming from greenhouse tomato production in southwestern Ontario.
2. Identify the activities or processes that cause the major environmental burdens (i.e. hotspots) due to greenhouse tomato production.
3. Model different production scenarios, which can help reduce the environmental load caused by the hotspots.

The null hypothesis for this research thesis is that the greatest potential environmental burdens from tomato greenhouse production in southwestern Ontario are not primarily due to the energy use and source, for heating the greenhouse.

The Ontario Greenhouse Vegetable Growers (OGVG) can be considered pioneers in greenhouse food safety as can be seen in their ‘First in Food Safety’ campaign. With the application of LCA to greenhouse vegetable production in southwestern Ontario, the OGVG will have knowledge of the “hotspots” within the production systems. This will enable OGVG and its member growers to make informed decisions concerning greenhouse vegetable production and identify areas where it would be worthwhile to make changes to reduce environmental impacts. This thesis will also provide a template for further LCA studies in greenhouse production systems in Canada.

CHAPTER 2 - LITERATURE REVIEW

2.1.0. Growing Greenhouse Tomatoes (*Solanum lycopersicum* L.) in southwestern Ontario

2.1.1. Greenhouse Tomato Production

The tomato greenhouse industry has been active in Leamington, Ontario for approximately a century, beginning between the years of 1910-1920. During the 1950's many migrants from post-World War 2 Italy settled in southwestern Ontario, and contributed towards the tomato greenhouse industry (Papadopoulos and Gosselin, 2007). Decades later during the 1973-1974 energy crisis, many growers switched from coal-fired and oil-burning boilers to natural gas to provide heating for tomato production. The business really started to grow when the North American Free Trade Agreement (NAFTA) was signed, which immediately gave growers access to the entire continent (Papadopoulos and Gosselin, 2007). An additional benefit came with the introduction of soil-less media, which allowed growers to switch from pink coloured tomatoes to high yielding red tomatoes, while retaining the resistance to Fusarium crown and root rot, which were present in soil-grown produce (Papadopoulos and Gosselin, 2007).

The beefsteak tomato is the most commonly seen in greenhouse production in Ontario. The main cultivars include 'Dundee', 'Macarena', 'Heritage', 'Big Dina', and 'Grow Dina'. Furthermore, due to changing consumer demands, cluster tomato production has increased. These are marketed as tomato-on the-vine (TOV), and sold in bunches in grocery stores and markets. The main cultivars are 'Clarance', 'Trusco', 'Freesbie', 'Tricia', 'Grandella' (OMAFRA, 2010). Other types of tomatoes, such as cocktail, cherry, and Roma are grown for niche markets and are grown on a small-scale.

In terms of quantity, Ontario is Canada's leader in greenhouse tomato production, with Leamington having the highest concentration of greenhouses in North America. In 2010, the area occupied for greenhouse tomato production in Ontario was 3,379,391 m^2, with production at 165,782,754 kg (or 49 kg m^{-2}). Both figures represent 64% of the total Canadian market. Additionally, total farm gate value grew from \$260 million in 2009 to \$281 million in 2010, representing more than half (55%) of Canada's total greenhouse production (Statistics Canada, 2011). These figures are clear indications of the strength of Ontario's greenhouse tomato industry within Canada.

Canadian greenhouse tomatoes are generally available from March to December, with peak production occurring during the summer months (Agriculture and Agri-Food Canada, 2006). In Leamington Ontario, a single long-season crop is grown. Planting begins in December, with first harvest occurring in mid March, and a finished crop in October (OMAFRA, 2010). To increase production, there is a move toward trying to provide a year round supply, although the economics of producing a crop when light levels and temperatures are at their lowest will increase costs and limit supplies from December to February. To respond to continuous market demands, a small number of greenhouse tomato shippers have developed agreements with facilities in the U.S. and Mexico to supplement low supplies during winter months (Cook and Calvin, 2005).

The majority of greenhouses in Ontario are structurally composed of plastic (i.e. double layered polyethylene sheets) and are equipped with gutters that can be opened or closed to regulate greenhouse temperature without the use of forced-air ventilation (Agriculture and Agri-Food Canada, 2006). As opposed to glass greenhouses, the plastic structures are less expensive to install, growers save 10-20% on heating costs, reduce electricity consumption during the summer, and have the same productivity as their glass counterparts (OMAFRA, 2010).

Most Ontario greenhouse tomato growers use hydroponics for production. This method utilizes soil-less media such as coconut fibre (coir) or rockwool. Rockwool is an artificial media, composed of basaltic rock, coke, and limestone. It has excellent growth properties in that it does not interact with nutrient solutions, is lightweight, and it has a large water holding capacity. Coconut fibre is an organic growing media; it is recommended for its low price and ease of disposal. The majority of vegetable greenhouses in Ontario use rockwool (55%) as opposed to coir (35%). The remaining 10% are grown in other media such as Nutrient Film Technique (NFT), foam, expanded clay pellets, peat, saw dust and soil (OMAFRA, 2010).

There are certain requirements that are necessary for optimal tomato growth. The key requirements are light, carbon dioxide (CO_2), water, adequate temperature, and sufficient and proper nutrients. Light is typically the limiting factor for tomato greenhouse production in southwestern Ontario, which experiences dark winter months (OMAFRA, 2010). Carbon dioxide levels can be supplemented and maintained, due to the relatively sealed nature of modern greenhouses that resemble controlled environments. Depending on the season and light conditions, CO_2 concentration can sometimes vary between 400-1000 ppm in the greenhouse (OMAFRA, 2010).

A mature tomato crop uses 2-3L of water/plant/day during the summer months when light levels are high. However, an excess of water will be detrimental to normal plant growth and development, and subsequently lead to poor growth and later flowering (Jones, 1999). The optimum range in air temperature best suited for normal tomato plant growth is 18°C-26°C. Temperatures are adjusted depending on the stage of production (i.e. germination, transplanting, harvesting, etc). The soil (or growing media) pH should be approximately 5.8 to maintain productive tomato growth (Jones, 1999).

To sustain healthy and high yielding tomato production, a steady diet of nutrients in the form of fertilizer is required. Fertilization of greenhouse tomatoes, greatly aids in the development of the crop and consequently its yield. Nitrogen is the most important nutrient for tomatoes in terms of vegetative growth; however too much nitrogen can be detrimental to fruit production (OMAFRA, 2010). Tomatoes use nitrogen in two forms: ammonium (NH_4^+) and nitrate (NO_3^-). Ammonium is applied during earlier stages of plant development with a switch over to nitrate later in the season to encourage continued plant growth and fruit yield, while preventing blossom-end rot (BER) (Jones, 1999). Potassium is needed for aiding fruit quality and effectiveness in hardening growth; an inadequate supply causes uneven ripening. Phosphorus is needed for early root growth and continual vegetative growth and fruit set. Magnesium aids in fruit quality, while a deficiency in Calcium will lead to BER (Jones, 1999)

2.2.0. Trends and Issues for Greenhouse Tomato Production in southwestern Ontario

2.2.1. Production and Marketing

There is evidence that the greenhouse tomato industry is moving towards a future where larger, technically advanced growers, producing fresh, environmentally sustainable products, will continue to expand service to both the local Ontario market and a larger national and international market (TOGA, 2009). In addition, tomatoes continue to represent the largest component of greenhouse vegetable production, with the United States remaining as the primary destination for Canadian greenhouse tomato exports (TOGA, 2009).

Despite these positive trends, Ontario's tomato greenhouse market still has many challenges and issues. For instance, currency exchange rate swings, rising energy costs, and high operating expenses per hectare, are all issues beyond the control of growers that can create stress and worry in the sector (TOGA, 2009).

Additionally, low market prices and lack of available labour have affected profitability in the greenhouse tomato, and in general the greenhouse vegetable sector, in recent years (Agriculture and Agri-Food Canada, 2006). Table 2.1 is a summary of key costs in greenhouse vegetable production in Ontario.

Table 2.1 Gross average yearly greenhouse vegetable operating expenses in Ontario (Statistics Canada, 2011)

Costs	Plant material purchases for growing[1]	Gross yearly payroll[2]	Electricity[3]	Fuel	Other crop expenses	Other operating expenses	Total operating expenses
Amount ($)	45,820,745	130,426,520	18,085,130	92,635,710	65,848,235	159,939,430	512,873,445

1. Includes value of plants, seedlings, seeds and bulbs purchased (before sales tax)
2. Includes seasonal and permanent labour
3. Electricity expenses for lighting, airflow fans and heating

Besides labour (i.e. payroll), which is determined largely by provincial minimum wage legislation, operating expenses and fuel make up a large share of total expenses (Table 2.1). It has been noted that in many cases fuel for heating can easily represent 15-40% of total operating costs (Hughes, 2003).

The use of CO_2 for aiding growth in greenhouse production can also be a major cost, and this cost is dependent upon the size of the greenhouse as well as type of CO_2 generation used and its distribution. Liquid CO_2, natural gas, and propane can each cost approximately $100/day (Blom *et al*, 2009). In addition, when CO_2 equipment costs are added, the annual costs of liquid CO_2 equipment for a 10-acre greenhouse is $10,500; flue gas CO_2 is $80,000; and for a CO_2 burner the cost is $50,000 (Blom *et al*, 2009). Efficient use of CO_2 is essential for high productivity at low cost.

Production levels are also dependent upon consumer demand and economic conditions, both nationally and internationally. Although the tomato greenhouse industry in Ontario has a large local market (38% of Canada’s population lives in Ontario), it is heavily reliant upon the U.S. markets, and therefore it can be impacted by the value of the Canadian dollar relative to the U.S. dollar (Cook and Calvin, 2005; Hughes, 2003). For instance in 2006, 70% of Ontario’s greenhouse tomatoes were exported to the U.S. (Papadopoulos and Gosselin, 2007), when the Canadian dollar was far below the U.S. dollar. Since that time, the Canadian dollars relative value has risen greatly and this has influenced the value equation for tomato exports from Canada to the U.S.

Another issue that growers are concerned about is disease. Managing disease within dense greenhouse production scenarios can be a challenge and given the lack of genetic diversity within the industry, it can be devastating if an outbreak occurs. Growers tend to choose cultivars based on yield, consumer qualities (taste and appearance) and reliability of source. Disease resistance has not been a key attribute for choice. There are some new varieties being developed with resistance to common diseases including grey mould (*Botrytis cinerea*) or corky root rot (*Pyrenochaeta lycopersici*), but growers are not using them because they do not deliver in terms yields and quality (Papadopoulos and Gosselin, 2007). Growers in Ontario would like to see a greater availability of high yielding and high quality disease resistant cultivars.

The entire Ontario greenhouse tomato industry will face new challenges as it continues to expand. To-date the main issues remain the rising cost of energy (particularly in colder months), the rising costs of labour, and the fluctuating value of the Canadian dollar relative to the U.S. dollar. The latter two issues are largely beyond the control of growers, but the first issue (energy), is something that growers can do something about either through source or through greenhouse design and growing approaches.

2.2.2 Environmental Concerns

During greenhouse tomato production, large amounts of waste are produced, which can potentially cause environmental issues. The major sources of wastes are: plant debris, soil-less growing substrate, and plastics. Table 2.2 shows the level of waste that one hectare of a tomato crop produced in Ontario in non-recirculating rockwool, can potentially produce.

Table 2.2 Output of Greenhouse Tomatoes/Hectare (OMAFRA, 2002)

Product	Output
Tomato (40 kg/m^2/yr)	400 tonnes/yr
Leached Fertilizer Salts	7.5 tonnes/yr
Leached Irrigation Water	4000 m^3/yr
Used Rockwool	76 m^3/ha/yr
Plant Debris	40-60 tonnes/yr
Plastic Greenhouse Covering	1.3 tonnes/ha/yr

Leached fertilizer salts and irrigation water are also environmental concerns because they have the potential to pollute groundwater and negatively affect aquatic ecosystems. Re-circulation of the nutrient solution is environmentally beneficial and can potentially reduce water consumption by 25-30% and fertilizer usage by 30-40% (OMAFRA, 2010). The recommended approach to managing plant debris waste is to compost or apply it directly to cropland as green manure.

Well over half of all vegetable greenhouses in Canada use plastic instead of glass (Mailvaganam, 2010; Statistics Canada, 2011). Every year, plastic vegetable greenhouses are re-covered resulting in hundreds of tonnes of plastic waste (OMAFRA, 2002). Landfills are the primary destination for this plastic. The problem is that, most landfills are filling up (with certain landfills refusing to accept agricultural and greenhouse plastic waste) and there are now large tipping fees of $80-160/tonne (Clarke, 1996). Alternative options exist, such as recycling and using the plastic as a fuel source, but these too have their drawbacks. In order for the plastic to go through recycling, no more than 5% of its weight can be comprised of contaminants (Clarke, 1996). This condition is not feasible for most greenhouses, as the cleaning and proper sorting requires labour and capital, which is why most growers still used landfills for plastic disposal (Clarke, 1996). However, over the last few years, some growers have been recycling their plastics on the international market, in countries such as China, where the rules and regulations concerning plastic quality are generally less stringent.

In typical tomato greenhouse production, rockwool is thrown out and replaced every 1-3 years, yet rockwool does not decompose in landfills and a method for recycling rockwool is not fully developed in Canada. Composting of rockwool is still being researched and there are not yet effective protocols (OMAFRA, 2002; Zheng and Dixon, 2009).

The sustainability of the tomato greenhouse sector will depend on how it copes with the environmental regulations imposed by legislation for production and how it manages its waste as well the rising costs for fossil fuels.

2.3.0. Life Cycle Assessment

2.3.1. Life Cycle Assessment Methodology

Increasingly, society is expecting industrial production to become more sustainable. This requires the employment of practical tools and/or methods to evaluate the environmental impacts associated with the provision of goods and services. Environmental impacts can include, for example, climate change, stratospheric ozone depletion, tropospheric ozone creation, eutrophication, acidification, depletion of resources and, toxicological stress on human health (Rebitzer *et al.* 2004).

Depending on the use of the product, which will determine its length of use, all products share a similar "life cycle". A life cycle starts with design/development of the product, followed by resource extraction, production of materials, use/consumption, and finally end-of-life activities (i.e. waste, recycle, collection, etc) (Rebitzer *et al.* 2004). A "Life cycle assessment (LCA) is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO1440, 2006). For this concept many names have been used, including eco-balancing (Germany, Switzerland, Austria, Japan), resource and environment profile analysis (USA), environmental profiling and cradle-to-grave assessment (Roy *et al*. 2009).

An LCA can help inform decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign). In addition, LCA can aid in "the selection of relevant indicators of environmental performance, including measurement techniques, marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental declaration)" (ISO14044, 2006). LCA studies usually consider all four stages of a product life cycle: raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/ waste management (USEPA, 2001). The outcome of an LCA study is dependent upon the goal of the study, the required accuracy of the results, and the available time and resources.

LCA is now a valuable tool for businesses and industries searching for ways to convert production practices into more environmentally sustainable processes. Society has itself become more conscious of activities that might cause harm to the environment.

The LCA method is structured and systematic with four primary phases: goal definition and scoping, inventory analysis, impact assessment, interpretation. The first phase of LCA, goal and scope definition, outlines the purpose of conducting an LCA (USEPA, 2001). The goal and scope definition helps to determine how much time and resources should be used in an LCA. It is perhaps the most important component of an LCA because the study is carried out and interpreted according to the statements made in this phase (Roy *et al*. 2009). According to ISO 14044 (2006), the goal definition "shall unambiguously state the intended application, the reasons for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public" (ISO14044, 2006). The scope of the study should describe the functional unit (FU), choice of impact categories and method for impact assessment, system boundaries and principles for allocation and data quality requirements (Baumann and Tillman, 2004; ISO14044, 2006).

The FU represents the "quantified performance of a product system for use as a reference unit" (ISO14040, 2006). Its purpose is to provide a reference to which inputs and outputs are related and to ensure comparability of LCA results (Reap *et al*, 2008). Defining a functional unit can be difficult, because describing the function of a product is not always easy. For instance, an LCA study might look to compare different floor constructions: wood and concrete. The functional unit may be based on the load bearing capacity of the constructions, noise reduction, or fire protection (Baumann and Tillman, 2004).

The system boundary determines which processes will be included in the LCA and determines whether the LCA will be a 'cradle-to-grave', 'cradle-to-gate' or 'gate-to-gate' project (ISO14044, 2006). A selection of environmental impact categories should be made, such as acidification, eutrophication, and global warming (Baumann and Tillman, 2004). A mixture of measured, calculated, and estimated data can be included in an LCA. The quality of the data must be determined following ISO standards of relevance, reliability, and accessibility (ISO14044, 2006). Lastly, an allocation procedure must be applied and explained when several products share the same industrial process and the environmental load of the process is to be expressed in relation to only one of the products (ISO14044, 2006).

The second phase of LCA, life cycle inventory (LCI), is a methodology for "estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a products life cycle" (ISO14044, 2006; Rebitzer *et al*. 2004). LCI involves data collection and is considered the most time consuming stage of an LCA. The data that is used can be retrieved from generic data sources or supplied by large databases found in LCA software. For example, data on transport, extraction of raw materials, processing of materials, manufacturing of materials such as plastic and cardboard, and disposal can normally be found in an LCA database (Roy *et al*. 2009).

Similar to the goal definition and scope stage of LCA, an LCI can be broken down into smaller components. The first step is to create a flow diagram in order to identify all the inputs (i.e. raw materials, energy, etc) and outputs (i.e. emissions, finished products, etc) of the system/process. The second step would be the collection of data. The quality of the collected information/data must also be useful to what was outlined in the goal definition and scope phase. Moreover, LCA practitioners should identify their data sources and types, and data quality indicators, in order to give the project credibility. Data quality indicators are benchmarks, to which the collected data can be analyzed, to determine if data quality requirements have been met (USEPA, 2001). The LCA practitioner usually gathers data through available sources (e.g. articles, online journals, government records, etc) or direct visits to locations were the LCA is being carried out (i.e. if the LCA is about a specific car manufacturing plant, visit the plant). Upon completion of the LCI, the data can be presented as a list containing the quantities of pollutants released to the environment and the amount of energy and materials consumed (USEPA, 2001).

The third phase of LCA, life cycle impact assessment (LCIA), aims to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO14044, 2006). An LCIA can be divided into both necessary and optional constituents. Mandatory elements include: selection and definition of the impact categories of interest (e.g. resource use, and human health and ecological consequences); classification, which is the assignment of inventory data (LCI) to the chosen impact categories (e.g. allocating SO_2 and NO_x emissions to acidification); and characterisation, which is the calculation of impact category indicators using characterisation factors (e.g. quantify potential impact of SO_2) (ISO14044, 2006; Pennington *et al*. 2004). Optional elements include the calculation of category indicator results relative to reference values (i.e. normalisation), and grouping and/or weighting the results (Pennington *et al*. 2004). To summarize, an LCIA allows for a better understanding of the impacts associated with certain manufacturing or industrial practices, and therefore can help in illuminating the differences between products, in terms of environmental impacts.

The last phase of an LCA is called life cycle interpretation. A life cycle interpretation is when "the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO14044, 2006). Similar to the other components of LCA, life cycle interpretation is broken down into smaller parts. These include identification of significant issues, evaluation of data, and conclusions with recommendations.

In order to identify significant issues one must first analyze the information that contributes most to the impacts. When this is achieved, LCA practitioners must determine if the goal and scope has been met. The evaluation step of the interpretation phase should establish confidence in and reliability of the results of the LCA (USEPA, 2001). This step examines the completeness of the study, the sensitivity of the results that influence the LCA the most, and the consistency of all the results of the LCA. The final step of life cycle interpretation is outlining conclusions made at the end of the study. Conclusions must be drawn by interpreting the results of the LCIA to determine which products/processes has the overall least impact to human health and the environment, address any limitations and recommendations based on the goal and scope of the study.

A benefit in conducting an LCA is the fact that it can help in choosing a production method, or a section of a production method, with the least amount of environmental impact. In addition, LCA can be coupled with economic and financial analyses to help further obtain and understand the benefits and detriments of a particular manufacturing process. LCA is unique in that it recognizes the transfer of environmental impacts from one process to another and from one life cycle stage to another (USEPA, 2001).

Although LCA is a comprehensive tool for environmental evaluation, it still has its limitations. A major detriment is that LCAs are usually very time and resource intensive. The availability and gathering of data might become an issue if the LCA is required to be very in depth. As a result, time and financial resources must be taken into consideration to complete a satisfactory LCA. Another important limitation is that certain methodological choices can potentially influence the results. Examples include allocation methods and choice of characterisation method for the impact Assessment (LCIA). Questions related to system boundaries and methodological choices are common for all systems analysis tools, and the lack of a right answer can sometimes create problems (Finnveden *et al*, 2009). Despite those issues, LCA continues to see use by authoritative bodies and industry. This is illustrated by Wal-Mart, for example, who set targets for reduced environmental impacts of products they are selling and require life-cycle information from their suppliers (Finnveden *et al*, 2009).

2.4.0. Application of LCA to Food Production and Agriculture

One of the main reasons for the application of LCA for agriculture is the realization that not only is the rate of the human population outstripping food production (i.e. population is expected to reach 9 billion by 2050), but also that food production uses a tremendous amount of energy and can cause environmental degradation (Gomiero *et al*. 2008). LCA can be used to help identify the issues related to energy use and negative environmental impacts, and to analyze the quantity and the type of pollutants entering the environment during agricultural production. To date, most of the life cycle studies carried out involve either agricultural production or industrial refining; several LCA studies on agricultural products have included agricultural production and industrial food processing, and the production of bio-ethanol and bio-diesel, (Roy *et al*. 2009).

2.5.0. LCA applied to Greenhouse Tomato Production

An early study in the Netherlands compared soil-grown crops, a substrate crop with free drainage, and a substrate crop with recirculation, for tomatoes and roses (Nienhuis and de Vreede, 1996). Using LCA, researchers determined that by reusing drainage water in substrate, there were lower emissions of nitrogen and phosphorus, which consequently reduced eutrophication and ecotoxicity impacts. Additionally, by avoiding leaching with the use of recirculation, less fertilizer would need to be purchased, thereby further reducing the environmental load because of avoided fertilizer manufacture/production (Nienhuis and de Vreede, 1996). Furthermore, it was determined that the energy/natural consumption required for heating, had a great share of the environmental burdens for many impact categories (e.g. 91% for Global Warming and 91% for Energy Depletion).

In Japan, Hayashi and Kawashima (2004) described the applicability of integrated evaluation methodologies for the impact assessment of management practices for greenhouse tomato production. The study compared two alternative greenhouse tomato production systems in order to study pesticide and fertilizer management: a conventional system, and a drip fertigation system. The results showed that the drip fertigation (i.e. the combination of fertilizer and irrigation) system reduced the direct environmental impacts on human health and ecosystem quality and highlighted the importance of the impacts of fertilizer production and pesticide application on ecosystem quality (Hayashi and Kawashima, 2004).

A Spanish study used LCA to look at the feasibility of using compost from municipal organic waste for the fertilization of tomato crops (Martinez-Blanco *et al*. 2009). Specifically, LCA was used to identify and compare the environmental impacts of using organic waste (from its collection, processing, etc) with impacts of using mineral fertilizer. The study determined that using municipal organic waste produced less environmental degradation and pollution than mineral fertilizer, and that agricultural production and quality were equal in both systems (Martinez-Blanco *et al*. 2009).

Medina *et al* (2006) used LCA methodology to give an overall picture for energy cost and burdens associated with tomato greenhouse production in Colombia in order to increase the sustainability of this crop. The most relevant result from this study was that improvements in tomato yields, water use efficiency, and enhancing the level of technology, were the key factors for reducing environmental impacts for greenhouse tomato production in high altitude tropics (Medina *et al*, 2006).

Russo and Scarascia-Mugnozza (2004) compared different technologies in Italian greenhouse cultivation: a pitched roof structure in zinc-coated steel with glass covering; a vaulted roof structure in zinc-coated steel with plastic film covering; and a pitched roof structure in wood with plastic film covering. It was determined that the presence of glass with aluminum in the steel structure was the reason for the higher emissions compared to other greenhouses, due to the quantity of metal and energy required to produce it. The authors suggested that plastic film would be more environmentally compatible than glass even if taking a 50% rate of recycling into consideration for new materials due to the quantity utilized and the material production process.

This result is similar to the findings of Torrellas *et al* (2008) who found that the simplest structures were better environmental options for greenhouses in the Canary Islands.

A Spanish LCA study, comparing greenhouse to open-field tomato production, found that the environmental burden per kg of tomato grown in open-field production was greater than that for tomatoes produced in greenhouses with respect to factors such as the use of water, fertilizers and pesticides (Munoz *et al*, 2008). The yields for greenhouse and open-field were 16.5 kg/m^2 and 8.6 kg/m^2 respectively. The open-field system resulted in 32% more acidification, 31% more depletion of non-renewable resources, 27% more energy consumption, 24% more eutrophication, and double the water use. These results are due in large part to the fact that the greenhouse system had substantively higher yields per area. The extraction of oil and natural gas were the main non-renewable resources affected by the consumption of energy, diesel, and electricity; and fertilizer production was the main factor that influenced the environmental burden associated with acidification and eutrophication.

Boulard *et al* (2011) was able to determine the environmental differences in producing greenhouse tomatoes (seasonal in plastic polytunnel) in southern versus northern France (heated, year-round production in plastic or glass). Results showed that, regardless of structure, heating of the greenhouse had the highest environmental impact (4.5 times greater than in polytunnels). However, pesticides had a 3- to 6-fold higher impact in polytunnel production in the categories of terrestrial or aquatic ecotoxicology, and human toxicology (Boulard *et al*, 2011).

In another study in southern Europe, a comparison of different waste management systems for biodegradable matter and plastic waste from the tomato horticultural sector was analyzed using LCA (Munoz *et al*, 2003). A key rationale for the study was the fact that for a single tomato crop, there could be as much as 20 000 kg of dry matter/ha/year of organic waste. This study compared three different methods of waste management: compost, landfill, and incineration. Results for the comparison between landfill and compost revealed that landfill disposal produced 60 times the amount of greenhouse gases, 6.5 times more acidification, and 3.7 times more eutrophication. Results for the comparison between incineration and compost revealed that incineration produced 7 times more greenhouse gases and acidification. The authors concluded that, compost of biodegradable matter was the most environmentally sustainable way of managing the waste (Munoz *et al*, 2003).

An Italian LCA project on greenhouse vegetable production compared the environmental impacts stemming from melon, pepper, zucchini, and tomato production. The study went beyond a cradle-to-farm gate and included the delivery of vegetables to local companies for their selection and packaging; and the delivery to the end-use and the production of wastes (biomass and packaging) after consumption (Cellura *et al*, 2012). The most significant environmental concerns regarding greenhouse tomato production in this case, related to the amount of waste produced (178.4 kg per 1000 kg tomato). However, the total environmental impacts were lower for tomatoes than for melons or zucchini's, primarily because of the lower impacts in the categories of global energy requirement (GJ), global warming potential (kg CO_2eq), acidification (kg SO_2eq) , and eutrophication (kg PO_4^{3-}eq) (Cellura *et al*, 2011).

Torrellas *et al* (2011) conducted a major LCA greenhouse tomato study comparing the cradle-to-farm gate environmental impacts among production scenarios in Hungary, the Netherlands, and Spain. The Hungarian scenario had the largest environmental impacts associated with the climate control system, fertilizers, and the greenhouse structure. In the Netherlands, the largest environmental burdens were associated with the climate control system and auxiliary equipment (i.e. rockwool substrate). In the Spanish scenario, the largest environmental loads came from the greenhouse structure and fertilizer manufacturing processes and emissions (Torrellas *et al*, 2011).

The functional unit used most often in LCA studies of tomato greenhouse production is mass of the specific product (i.e. kg of tomato). This functional unit makes sense over other types, including area, because the main function of horticulture/agriculture is crop production (marketable yield). It is possible that in the future more studies will turn to a "nutritional" type of functional unit, due to the increase in health consciousness among consumers (Roy *et al*, 2009).

Although there have been LCAs conducted for greenhouse tomato production scenarios around the world (and especially within Europe), there have been no similar studies conducted for greenhouse tomato production scenarios in North America, and specifically for Canada's largest production area, tomato greenhouse production scenarios in Leamington, Ontario area.

The European studies provide a good example of the ways to approach an LCA study for Ontario greenhouses, they provide examples of the investigation of a range of scenarios, issues, and production and structure specifications, and they also provide some baseline measures that are useful for comparison.

2.6.0. LCA in the context of issues for Greenhouse Tomato Production in southwestern Ontario

2.6.1 Relevance of LCA for southwestern Ontario Greenhouse Tomato Production

LCA can be utilized in a practical fashion in southwestern Ontario greenhouse tomato production in order to increase energy and water efficiency and lower pollution. For instance, agricultural contributions to CO_2 emissions come from the consumption of energy in the form of oil and natural gas, both directly (e.g. field work, machinery) and, concerning greenhouses, indirectly (e.g. production and transport of fertilizers and pesticides, manufacturing greenhouse structure, etc.) (Gomeiro *et al*, 2008). LCA can be used to measure the environmental impacts that stem from such activities and provide information on how to reduce negative environmental aspects of agricultural production.

In a broader context, the increase in agricultural intensification over the past 40 years has greatly increased the risk and incidence of soil, water, and air contamination by nutrients and pesticides globally, and this is true in Canada (Lynch, 2009). Agriculture and horticulture production are both promising and necessary for the economy of southwestern Ontario. Therefore, LCA can be used in the context of southwestern Ontario vegetable greenhouse production, to help inform policy makers of the ecological impacts of every stage of production and to suggest improvements.

Conducting an LCA on tomato greenhouse production will give useable results on the environmental effects of these systems. Therefore, if one could adjust an aspect of the products entire life cycle, one could alter (and perhaps reduce) the impact in terms of total environmental impact.

2.6.2 Previous studies on greenhouse vegetable production in Ontario

Agviro Inc. and AMEC Geomatrix Ltd. were commissioned by The Ontario Greenhouse Alliance (TOGA) to complete a Greenhouse Energy Survey in 2009. This was a large study that included 52 respondents from around Ontario, growing either flowers or vegetables. Some of the key findings in the study were that the average rate of energy consumption over all respondents was 1.8 GJ/m^2, with higher consumption rates observed in Leamington, and in larger facilities;

and 71% of the heat energy sourced was natural gas, 16% was biomass, 7% was coal, and 6% was oil (Agviro and AMEC Geomatrix, 2009). In addition, the primary concern from all the growers, including those in the financial sector, government, utilities and equipment suppliers, was the rising cost of heating. The other four important issues identified in this study, in order of declining importance were: labour costs, US-Canada exchange rate, cost of electricity, and overproduction (Agviro and AMEC Geomatrix, 2009).

TOGA also commissioned PPD Inc. to conduct a carbon footprint study for vegetable and floriculture greenhouses (TOGA, 2010). Unlike an LCA, which looks at a variety of impact categories (e.g. acidification, eutrophication, cumulative energy demand, etc), a carbon footprint study only considers greenhouse gases. The results from the PPD Inc. study showed that there are three primary sources for the carbon footprint in greenhouse production systems in Ontario in general: energy (53-85% of the total carbon footprint), growing media (2-22% of the total carbon footprint), and waste (1-15% of the total carbon footprint). It was also noted in this study that transport, packaging, and fertilizers were other areas offering opportunities to lower the carbon footprint of individual greenhouse operations (TOGA, 2010).

There were large variations in values within this carbon footprint study; because the study sample included floriculture greenhouses and different types of vegetable greenhouses, and the scope of the study varied among operations, (i.e. some operations packaged their own products, while others did not). Nevertheless, suggestions were made to the growers based on the results of this study including: use of higher efficiency boilers and lighting system, incorporation of combined heat and power (CHP); use of solar panels and biomass for energy, and expanding the use of reflective films to reduce heat loss.

The Ontario provincial government has been implementing policies to reduce the amounts of pollution, e.g. greenhouse gases (GHG), entering the environment. Ontario vegetable greenhouses growers were fortunate to have been exempted from the first round of cap and trade in 2012. However, under the Western Climate Initiative, Ontario is committed to implementing a form of cap and trade by 2015 for the economy more broadly (TOGA, 2010). The OGVG is aware of this issue, and is committed to an active research program focused on the development and implementation of environmentally sustainable practices in preparation for new environmental regulations (OGVG, 2012).

CHAPTER 3 – LCA OF GREENHOUSE TOMATO PRODUCTION IN SOUTHWESTERN ONTARIO

3.0.0. INTRODUCTION

In Canada, greenhouse tomato production in southwestern Ontario is the leader, yet there is little documentation on the environmental impacts of its production. This project will use Life Cycle Assessment (LCA) to help provide an understanding into the potential environmental impacts attributable to greenhouse tomato production and provide insight into the production systems as well as the challenges growers face in terms of production. The purpose of this project was (1) to evaluate the magnitude and significance of the potential environmental impacts for greenhouse tomato production in southwestern Ontario, (2) investigate which activity in the life cycle is responsible for the greatest environmental impact, and (3) represent different production scenarios that can aid in reducing the environmental burdens. It was hypothesized that the energy and the source of energy required for heating the greenhouse would cause the most environmental harm.

3.1.0. MATERIALS AND METHODS

3.1.1. Goal and Scope Definition

3.1.1.1. Goal

The goal of this LCA study is to quantify the environmental impacts associated with greenhouse tomato production systems typical of southwestern Ontario. For the purpose of this study, these are defined as non-glass tomato greenhouses, growing either beefsteak-type or cluster-type tomatoes (or both). In addition, the study was limited to commercial tomato-only production facilities of no less than 500 m^2 (0.05 hectares). Further, the goal of the study consisted of the following objectives: (1) establish an environmental reference (or benchmark), for further LCA studies of greenhouse tomato or vegetable production in the region, and (2) determine whether possibilities exist for reducing the environmental impact of greenhouse grown tomatoes from this region by modeling the environmental consequences of changing specific processes or elements within the life cycle.

This is a stand-alone LCA, which is used to describe a single product, often in an exploratory way in order to understand important environmental characteristics of a given product (Baumann and Tillman, 2004). It is often used to identify which activities cause the greatest environmental impact (i.e. “hot spots”). Stand-alone LCAs are the most common type and are conducted before any further detailed studies (Baumann and Tillman, 2004).

This LCA study followed ISO 14040/14044 standards and was an internal study, with the intended application of the results for use in product improvement, development, and research communication. The intended audiences were greenhouse vegetable scientists and/or LCA practitioners, the stakeholders of the Ontario Greenhouse Vegetable Growers (OGVG) association, and greenhouse tomato managers (or growers).

3.1.1.2. Scope

The scope of this study includes the methods or modelling required to achieve the goals of the study. These include the choice of functional unit, system boundaries, principles for allocation, selection of impact assessment method, data quality requirements, and descriptions of any assumptions or limitations.

3.1.1.2.1. Functional Unit

The functional unit (F.U.) describes “the primary function fulfilled by a product system, providing a reference to which the input and the output data can be standardized in a mathematical sense” (ISO14040, 2006). The functional unit allows for a reference to normalise all the inputs and outputs of the system. The primary function of a greenhouse, in the context of this study, is to produce tomatoes; therefore, the mass of tomatoes produced is the functional unit. Specifically, the functional unit is 1 kg of greenhouse tomatoes produced in a season (year). The average yield based on data provided by growers is 56.4 kg (SE 0.8) of tomatoes/m^2/year.

3.1.1.2.2. System Boundaries

The system boundary is a “set of criteria specifying which unit processes are part of a product system” (ISO14040, 2006). The system boundary was from raw material extraction to the farm gate. The greenhouse production area is the Leamington, Ontario region for the 2006-2011 growing seasons. The background processes considered were:

- extraction of raw materials (i.e. metals, fossil fuels, etc)
- fossil fuel production
- fertilizer manufacture
- electricity production
- water distribution
- steel production
- aluminum production
- plastics production
- rockwool manufacture
- transportation of materials (km)

The foreground (or greenhouse site) processes, included practices performed in the greenhouse such as: fertilizer application, water consumption, greenhouse heating, and electricity use. Waste treatment was considered as a downstream process. Excluded processes were compost and recycling processes. See section 3.1.1.2.9 for further explanations of reasons for inclusion or exclusion of processes.

3.1.1.2.3. Allocation

Allocation is defined as the “partitioning of the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO14044, 2006). However, with the tomato greenhouse systems studied in this project, only tomatoes are produced, therefore there is no need for allocation in this LCA project.

3.1.1.2.4. Impact Categories and Impact Assessment Method

Environmental impact categories are a class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO14044, 2006). This study assessed the impacts based on the following impact categories: Global Warming (kg CO_2 eq.), Acidification (H^+ moles eq.), Eutrophication (kg N eq.), Ozone Depletion (kg CFC-11 eq.), Smog (photochemical oxidation) (kg NO_x eq.), and Cumulative Energy Demand (MJ eq). These impact categories were chosen due to their relevance to agricultural studies. For instance, the large amounts of CO_2 eq emissions during agricultural production are an important concern for the industry (Pluimers *et al*, 2000). Furthermore, these categories were chosen due to their similarities to LCA studies on tomato greenhouse production done in other geographic regions including Spain and The Netherlands (Antón, *et al*, 2005; Martinez-Blanco *et al*. 2009; Muñoz *et al*, 2008; Muñoz *et al*, 2003; Nienhuis and de Vreede, 1996).

These impact categories stem from the Tool for Reduction and Assessment of Chemical and other environmental Impacts (TRACI) method. TRACI is a software program developed by the U.S. Environmental Protection Agency (USEPA) using scientific measurements of the effects of emissions on the North American environment. It was chosen as the method of choice for this project, as opposed to others that focus on other geographical regions (Bare *et al*, 2003).

3.1.1.2.5. Data Quality and Source

In order to initiate this project, a meeting was held with a group of greenhouse tomato growers from the Leamington, Ontario region in July 2011. The growers agreed to participate and provide data and subsequently a survey was developed and distributed (Appendix Table 6.1). Primary data (i.e. greenhouse management) for activity levels (e.g. amount of fertilizer used), was sourced directly from growers via the survey. Collection of data from the survey, involved acquiring knowledge about the tomato greenhouse industry and formulating questions to be answered by the growers. This process involved technical and confidential clarifications with the growers before proceeding. When necessary, data from the suppliers of goods and services to the greenhouses were also collected. Supplemental data used for calculation of greenhouse structural material, rockwool, rockwool plastic sleeve, packaging cardboard and plastics, are displayed in the Appendix.

The majority of the data retrieved from the surveys were filled in correctly; however, there were data gaps and issues with consumption levels that had to be addressed in some cases. For instance, a number of growers provided economic (i.e. Canadian dollar) values for the amount of electricity consumed; this data required obtaining information on the price per kWh for electricity in the region, and the transformation of the dollar value to a kWh value to get the appropriate activity level.

For any issues that arose in terms of interpretation of data by growers, they were contacted to provide further verification to ensure the highest possible consistency, accuracy, and quality of data.

Emission factors were primarily sourced from the US-EI and USLCI databases in SimaPro®, published scientific and engineering literature, government documents, and occasionally from personal communication with experts. Processes retrieved from SimaPro® were reviewed and selected for its adherence to the data quality requirements of the project using critical judgment. Secondary data included: extraction of raw materials, fertilizer production, rockwool production, water distribution, electricity generation and distribution, natural gas (or other forms of) heat production, aluminum and steel production, plastics production, and transportation of materials. The collected data were graded based on the data quality assessment method developed by Weidema and Wesnaes (1996) (Table 3.1). Each data quality indicator can be assessed by using a scale from 1-5, where the number 1 denotes the best quality. SimaPro® processes come with built-in data quality indicators based on Weidema and Wesnaes (1996).

The emissions to air, soil, and water of all upstream processes of raw material extraction, transportation, and manufacturing were obtained from the US-EI and USLCI databases. When available, Canadian versions of greenhouse gas (GHG) emissions (i.e. global warming kg CO_2 eq.) were determined for inputs of fertilizer production, natural gas and bunker oil heating, and aluminum and steel production. These GHG emissions were then inserted into the appropriate SimaPro® processes, replacing the GHG emissions for that particular process.

Table 3.1 Five Indicators Scores of Data Quality Index for LCA (Weidema and Wesnaes, 1996)

INDICATOR SCORE	1	2	3	4	5
RELIABILITY	Verified[a] data based on measurements[b]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
COMPLETENESS	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
TEMPORAL CORRELATION	Less than 3 years of difference to year of study	Less than six years difference	Less than ten years difference	Less than 15 years difference	Age of data unknown or more than 15 years difference
GEOGRAPHICAL CORRELATION	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
TECHNOLOGICAL CORRELATION	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data from processes and materials under study but from different technology

[a]Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources

[b]Includes calculated data (e.g. emissions calculated from inputs to a process) when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based partly on assumptions, the score should be 2 or 3

3.1.1.2.6. Temporal Boundaries

Data was collected from participating tomato greenhouse growers in 2011. These data were based on average data for the years 2006-2011 of production where possible (some growers did not have all data for all years). In terms of data on raw materials extraction, capital equipment manufacturing, fuel, electricity, etc. the databases from SimaPro® 7.3.3 (Product Ecology Consultants, 2010) LCA software were used. These data, along with literature sources and communication from experts, were primarily representative of the years 2000-2010.

3.1.1.2.7. Geographical Boundaries

In this study, the foreground activities occur in Canada, specifically Ontario. The extraction of raw materials, manufacturing of inputs, etc, however, can occur in different regions throughout the world. Data used for unit processes were derived from the US-EI and USLCI databases, and only greenhouse gas emissions (GHG) were retrieved from Canadian sources where available.

3.1.1.2.8. Technological Boundaries

This study aimed at representing the average technology used for the different greenhouse operations surveyed in this project. It corresponds to current (post-2000) technology for use in the production of greenhouse tomatoes in southwestern Ontario. In other words, similar heating systems, type of crop, and fertilization systems (this study preferred closed-loop), were chosen and used for the study as these were considered major technological aspects of production. If a greenhouse operation made changes in these processes, those years were omitted, so only years that shared similar technology were used. For instance, this project surveyed eight growers. However, for greenhouse 2, one year was not included because it grew a specialty crop as opposed to a beefsteak or TOV. One year was excluded from Greenhouse 3 because it had an open fertigation system. Lastly, four years from greenhouse 5 were omitted because it had an open fertigation system during that time.

3.1.1.2.9. Assumptions and Limitations

Large amounts of data are required to conduct an LCA. The quality of the data (i.e. sources) can often determine the level of credibility of an LCA. Moreover, if data is not found (i.e. data gaps), the assumptions made in their absence will also affect confidence in the results of an LCA study.

The following are the assumptions and omissions made in this LCA study either due to lack of data, unavailability, or similarities with other greenhouse tomato LCA projects.

- The production of seeds was not included, due to lack of available and reliable data
- It was assumed that, because growers are using a closed-looped fertilization system, that there is no leaching (or runoff) of nutrients occurring (Torrellas *et al*, 2012, Ruijs *et al*, 2012)
- The size of the trucks, and distances traveled, used in the study were based on assumptions achieved in discussions with a regional vegetable greenhouse production expert (S. Khosla, Ontario Ministry of Food, Agriculture, and Rural Affairs [OMAFRA] greenhouse vegetable specialist) and in relation to locations of suppliers
- There is no inclusion of thermal or shade screens in this project because of lack of available data
- All structural material (aluminum and steel) were assumed to have a life span of 25 years. The plastic covered greenhouses were assumed to have a life span of 4 years, and rockwool 1 year. These assumptions were based on personal communication with S. Khosla and provincial government documents (OMAFRA, 2010).
- Biological pest management, and bumblebee pollination were not included in this project because of lack of available data
- Specific lighting material is not identified (we used a typical lighting system) and the same was true for nutrient solution disinfection

- Transportation distances from areas of production (e.g. fertilizer production), were assumed to be 50 km which is reasonable in the Ontario context. The distance for the plastic material waste was assumed to be, the average distance from Canada to China, 4000 km by train and 9000 km by ship, because China is the typical final destination for this material

The results of this LCA study are limited to Ontario, specifically systems typical of and located in the Leamington region. Thus, it is not appropriate to assume that the results of this study represent other areas of Canada necessarily, nor other types of greenhouses (i.e. floriculture), or other tomato greenhouses throughout North America.

3.1.2. Life Cycle Inventory Analysis (LCI)

Life cycle inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system (ISO14040, 2006).

3.1.2.1. Flow Diagram

Figure 3.1 depicts the various processes considered in a tomato greenhouse production system typical of the Leamington, Ontario region. The processes included in the flow diagram must be consistent with the system boundaries set for the study within the goal and scope definition.

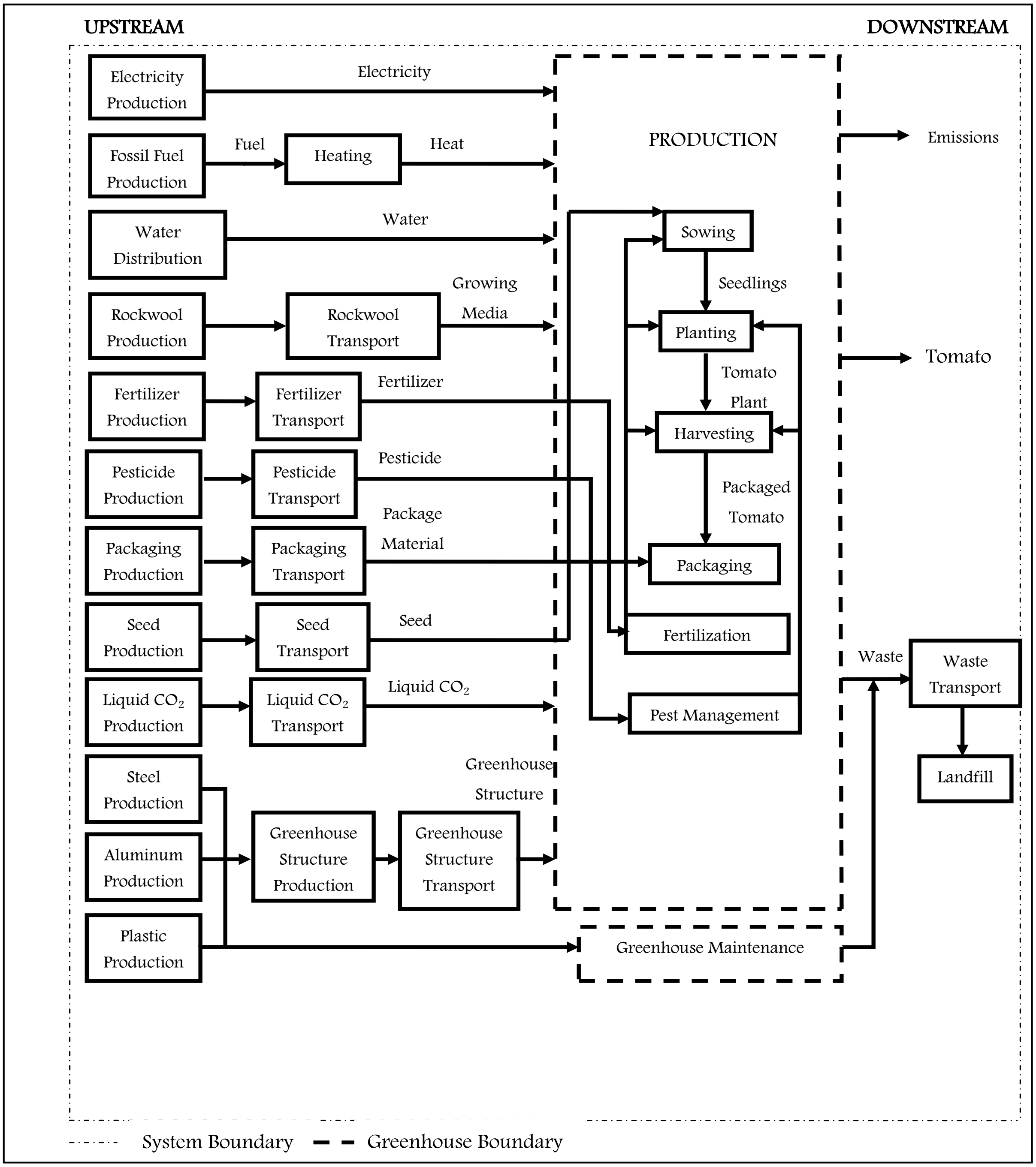

Figure 3.1 General Flow Diagram of Greenhouse Tomato Production System

The following processes and flows were modelled in this LCA project. Detailed descriptions are given here to complement and explain in more detail the flow diagram.

GREENHOUSE STRUCTURE

The structure of the greenhouse is made from steel, aluminum, and plastic (polyethylene). For this study, a leading greenhouse manufacturer for the region provided information concerning the quantity of materials used in a ‘typical’ southwestern Ontario tomato greenhouse (DeCloet Greenhouse Manufacturing, Delhi, ON). Specific dimensions of greenhouses used in this study, were provided in the survey via the growers. For this study, it was assumed that the metals used in the structure of the greenhouse were made from virgin materials. Data for aluminum and steel production emissions used Canadian GHG emission factors.

PRODUCTION – Electricity

This process includes total electricity consumption for the entire greenhouse activities. Emissions related to the production and transmission of electricity were based on the Ontario grid mix. The electricity grid mix for Ontario is: 22.3% Hydro; 49.1% Nuclear; 19.3% Coal; 7.9% Natural Gas; 0.8% Petroleum; 0.6% Wind (Environment Canada, 2008). These emission factors include extraction of raw materials, electricity losses, grid infrastructure and distribution via underground and overhead lines. Electricity consumption rates (kWh) were obtained from completed grower surveys.

PRODUCTION – Fertilization

This process includes building infrastructure, and electricity needed for production of fertilizers. Fertilizer consumption rates were taken from the results of the surveys. Emissions to air related to fertilization, were taken from Brentrup and Küsters (2000) and Pluimers *et al*, (2000). Data for the production of fertilizer (N, K_2O, P_2O_5), utilized Canadian GHG emission factors from Nagy (2000).

PRODUCTION – Heating

Greenhouses in southwestern Ontario commonly use a central heating system. Natural gas is the most popular source of energy, with some other growers using bunker oil. This system process includes infrastructure (boiler), and electricity needed for operation. Consumption levels (GJ) of energy for heating, were obtained from the completed surveys and averaged. Natural gas and bunker oil consumption emissions were based on Canadian GHG emission factors.

PRODUCTION – Rockwool

This process includes, material and energy inputs for the manufacturing of substrate (i.e. rockwool), and its packaging (plastic sleeve). The amount of rockwool used by the growers was determined via the survey.

PRODUCTION – Water Use

This process included the infrastructure and energy use for water treatment, distribution to the end user, and total water consumption by the greenhouse (L). The amount of water used was provided by growers via the survey.

WASTE

Various waste treatments were developed depending on the type of waste considered. Waste types were divided based on their source (Anton, 2011): greenhouse structure (steel, aluminum, and plastic); organic (plant debris); inorganic (rockwool); and rockwool plastic sleeve. In this LCA study, the greenhouse structure materials, excluding plastic, were assumed to have a lifespan of 25 years. For greenhouse structure composed of plastic, the lifespan considered was 4 years. Rockwool, and its plastic sleeve, is used for 1 year in this LCA model.

LCAs on greenhouse tomato production typically included waste management (Boulard *et al*, 2011; Cellura *et al*, 2011; Torrellas *et al*, 2011; Russo and Mugnozza, 2005; Martinez-Blanco *et al*, 2011). Transportation distances, and emissions from the waste process (i.e. landfill, incineration, etc) are included. For compost and recycling processes, the most widely used method within greenhouse tomato/vegetable production LCAs, is the ‘cut-off’ method, (Ekvall and Tillman, 1997). In the cut-off method, only loads directly caused by a product are assigned to that product. Therefore, materials that were destined for composting or recycling were not considered as a part of the production system. As a result, only structural material and inorganic (rockwool) material emissions from landfills were considered and not plastics (recycle). Organic plant materials also were not considered as they were destined to be composted (Essex-Windsor Solid Waste Authority, 2012).

TRANSPORTATION

All processes required transportation from production sites to the greenhouse, and were calculated using the formula: kg x km. The average distance (Figure 3.1), was assumed and accepted for this project as 50 km by truck (3.5-16 ton) based on discussions with the OMAFRA vegetable greenhouse production expert (S. Khosla personal communication). Truck transportation included the operation of the truck; manufacture, maintenance and disposal of the truck; construction and maintenance and disposal of road. The transportation for waste plastics to China was estimated at 4000 km by train (freight, rail) and 9000 km by ship (barge). Ship transportation included operation of vessel; production of vessel; construction and land use of port; operation, maintenance and disposal of port. Train transportation included the operation of the train; manufacture, maintenance and disposal of the train; construction and maintenance and disposal of rails.

PRODUCTION – Liquid CO_2 Supplementation

This process contains material, infrastructure, and energy input and emissions for the production of liquid CO_2. Transportation from production site to the greenhouse was included and estimated at 50 km.

The estimation of liquid CO_2 use was made, as seven of eight growers did report using it despite not providing actual numbers. Data were not provided during the start of this project, because it was not part of the survey. A model was developed and analyzed to see the environmental effect of using liquid CO_2 supplementation (section 3.2.1.1.4).

PRODUCTION – Pest Management

This process includes the production of insecticides and fungicides including materials, energy use, and infrastructure. The quantity of pesticide used was retrieved from the surveys. Transportation from production site to the greenhouse was included and estimated at 50 km.

PRODUCTION – Packaging

This process includes the production of cardboard boxes and plastic packaging material. It contains the steps of cutting, extrusion, folding and printing. In addition to the input of cardboard and plastic, the electricity consumption and emissions from production are included as well. Transportation from production site to the greenhouse was included and estimated at 50 km.

During data collection a number of growers (three) detailed the amount of pesticide and material used for packaging, in their surveys. Because these data were not representative of all eight participants, it was not included in the main LCA. However, there was a separate analysis done on the impacts of pest management and packaging from those growers, and it is included in this study.

3.1.2.2. Life Cycle Inventory Data

Tables 3.2-3.4 show the average data from the eight growers for all the greenhouse processes. The average yield was 56.4 kg/m^2 (SE =0.8). The average size of the greenhouses surveyed was 60,954 m^2 (6.1 hectare or 15.1 acre). Data for pest management and packaging are provided in the Appendix.

Table 3.2 Average (AVG) input values for greenhouse structures from eight greenhouse operations surveyed in southwestern Ontario. Functional unit (F.U.) is 1 kg tomato. STD and SE represent standard deviation and standard error, respectively.

GREENHOUSE STRUCTURE	AVG/Greenhouse	AVG/F.U. ($x10^{-3}$)	STD/F.U. ($x10^{-3}$)	SE/F.U. ($x10^{-3}$)
Aluminum (kg)	20,496	6.1	0.58	0.205
Plastic (kg)	22,773	6.78	0.644	0.228
Steel (kg)	512,403	153	14.5	5.12

Note: The kg of materials per Greenhouse and F.U. value in this table, are not divided by 25 years (aluminum and steel) or 4 years (plastic) to represent the lifespan of these materials in this LCA (see section 3.1.3 Greenhouse Structure); these calculations were made in the LCA model.

Table 3.3 Average (AVG) yearly input values for production stage from eight greenhouse operations surveyed in southwestern Ontario. Functional unit (F.U.) is 1 kg tomato. STD and SE represent standard deviation and standard error, respectively.

PRODUCTION	AVG/Greenhouse	AVG/F.U. ($x10^{-4}$)	STD/F.U. ($x10^{-4}$)	SE/F.U. ($x10^{-4}$)
Heating– Natural Gas (GJ)	115,373	299	122	20.9
Heating– Bunker Oil (GJ)	13,496	69.6	138	23.6
Electricity (kWh)	1,107,100	2720	850	146
Rockwool Substrate (kg)	29,683	9.69	34.4	5.91
Water Use (L)	69,915,760	187000	51100	8760
Fertilization– Calcium Nitrate (kg)	46,091	117	91.9	15.8
Fertilization– Potassium Nitrate (kg)	44,030	119	26.2	4.49
Fertilization– Potassium Sulphate (kg)	3,480	15	12.4	2.13
Fertilization– Potassium Chloride (kg)	4,800	11.3	0.858	1.47
Fertilization– Magnesium Sulphate (kg)	12,128	31.8	30.1	5.15
Fertilization – Ammonium Nitrate (kg)	1,055	4.12	77	1.32

Table 3.4 Average (AVG) yearly input values for waste stage from eight greenhouse operations surveyed in southwestern Ontario. Functional unit (F.U.) is 1 kg tomato. STD and SE represent standard deviation and standard error, respectively.

Waste	AVG/Greenhouse	AVG/F.U. ($x10^{-7}$)	STD/F.U. ($x10^{-7}$)	SE/F.U. ($x10^{-7}$)
Plastic Film Roof (t)	7.98	17	7.37	1.26
Waste (inorganic, landfill) (t)	200	647	185	31.8
Waste (organic, landfill) (t)	299	790	564	96.7
Plastic Sleeve Rockwool (t)	2.14	9.66	1.37	2.34

To calculate average values we used only years from the surveys where the data was complete for all data categories within the year. In some cases, critical information was missing for a specific data set, and in these cases, we used data from the literature (OMAFRA, 2002) which was validated by the provincial expert on vegetable greenhouse production (S. Khosla, OMAFRA). When verified or reasonable data could be used to complete a data set for a given year at a given site, these data sets were then included when calculating averages.

3.1.2.2.1. Emission Calculations

Calculation procedures for process emissions (e.g. GHG emission from electricity production), requires knowledge of activity levels and emission factors. An emission factor is the ratio between the quantity of pollution generated and the amount of a raw material produced or processed. The equation is: Total Emissions = Activity Level x Emission Factor.

Activity level data (e.g. amount of fertilizer used) for the downstream processes in the greenhouse phase, were derived from the completed surveys. Emission factors for the calculation of GHG emissions were derived from government documents, and scientific literature. However, when Canadian or North American data were not available, emissions from the unit processes in the US-EI and USLCI database were used. Table 3.5 shows the GHG emission factors and nitrogen fertilizer application emissions used in this project.

Table 3.5 Emission factors and sources

Process Description	**Emission Factor**				**Units**	**Reference**
	CO_2	**CH_4**	**N_2O**			
Natural Gas	1879	0.037	0.035		g GHG/m^3	Environment Canada, 2011
Bunker Oil	2725	0.026	0.031		g GHG/L	Environment Canada, 2011
Aluminum	1650	0.8(CF_4)	0.13(C_2F_6)		kg GHG/ton	Environment Canada, 2010
Steel	2.484				t GHG/ton	Environment Canada, 2010
N Fertilizer Production	3.59				kg CO_2 /kg N	Nagy, 2000
P_2O_5 Fertilizer Production	0.5699				kg CO_2/kg P_2O_5	Nagy, 2000
K_2O Fertilizer Production	0.244				kg CO_2/kg K_2O	Nagy, 2000
N Fertilizer Emissions	0.025(NO_x)	0.030(NH_3)	0.0125(N_2O)	0.1(NO_3)	kg/kg N	Brentrup *et al*, 2000 Pluimers *et al*, 2000

3.1.3. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the phase of an LCA study during which the environmental impacts of the product are assessed and evaluated from the life cycle inventory (LCI) results. ISO 14044 (2006) defines obligatory elements (classification and characterization) and optional elements (normalization, grouping, and weighting) to be used in an LCIA (Figure 3.2).

Classification means the sorting of the inventory results according to the type of environmental impact they contribute to, e.g. CO_2 to global warming and NH_3 to acidification. Characterization uses science based factors (i.e. characterization factors) that are quantitative measures of environmental impacts (Baumann and Tillman, 2004). For example, on a time scale of 100 years the contribution of 1 kg CH_4 to global warming is 25 times higher than the emission of 1 kg CO_2. This means that if the characterisation factor of CO_2 is 1, the characterisation factor of CH_4 is 25. Therefore, the impact category indicator result for global warming would be calculated by multiplying the LCI result with the characterisation factor.

Normalization, in the context of environmental impact assessment, means that the impact of a studied product is associated with the total environmental impact in a geographical region so the relative contribution of the product can be identified (Baumann and Tillman, 2004). Weighting is a method that indicates the environmental harm of a pollutant or a resource relative to other pollutants or resources.

The elements used to present the results for this LCA project were the mandatory elements of classification and characterisation (ISO 14044, 2006). These elements were considered adequate to fulfill the purpose of the study, as normalization and weighting use a high degree of subjectivity.

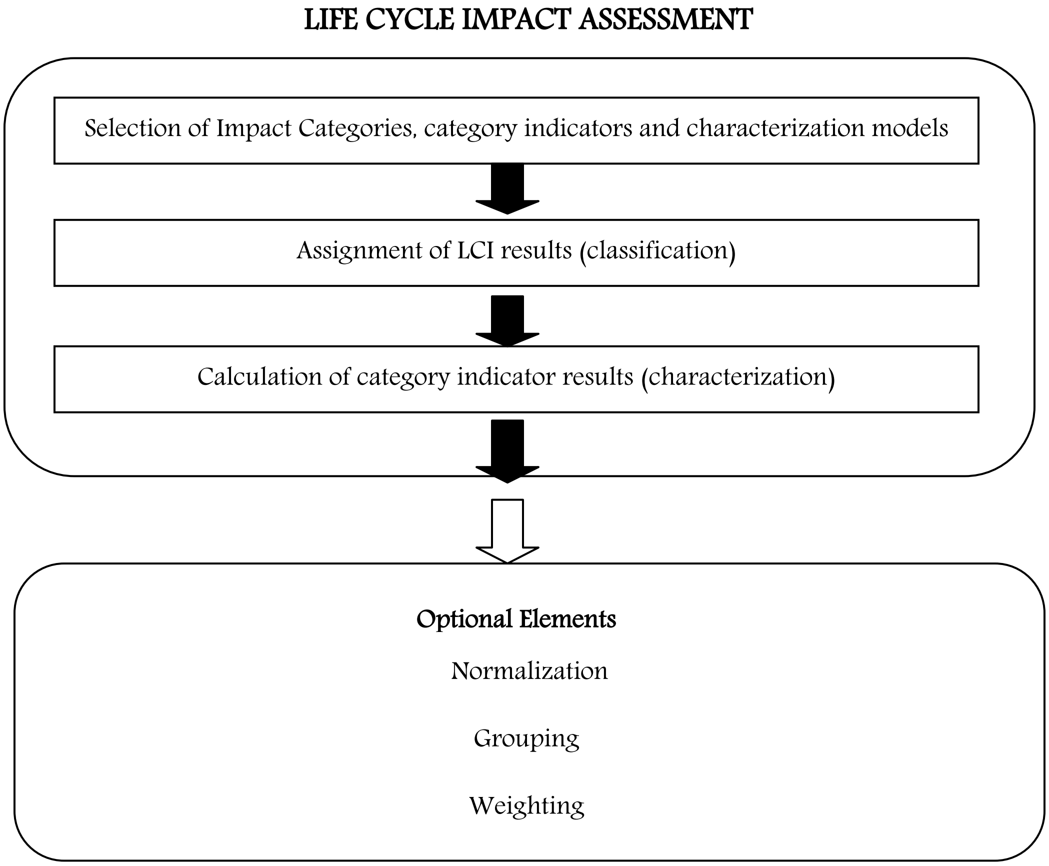

Figure 3.2 Steps in a typical Life Cycle Assessment Process

Table 3.6 provides a brief description of the TRACI impact categories used for this study.

Table 3.6 Description of Environmental Impact Categories for Life Cycle Assessments

IMPACT CATEGORY	CHARACTERIZATION FACTOR	DESCRIPTION
ACIDIFICATION	mol H^+ equivalent	Acidification comprises processes that increase the acidity (hydrogen ion concentration, [H^+]) of water and soil systems.
GLOBAL WARMING	kg CO_2 equivalent	The impact category of global climate change refers to the potential change in the earth's climate caused by the build up of chemicals (i.e., "greenhouse gases") that trap heat from the reflected sunlight that would have otherwise passed out of the earth's atmosphere

CUMULATIVE ENERGY DEMAND	MJ	A measure of the total amount of primary energy extracted from the earth
EUTROPHICATION	kg N equivalent	A measure of emissions that cause eutrophying effects to the environment. The eutrophication potential is a stoichiometric procedure, which identifies the equivalence between N and P for both terrestrial and aquatic systems.
OZONE DEPLETION	kg CFC-11 equivalent	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays.
SMOG (Photochemical Oxidation)	kg NO_x equivalent	A measure of emissions of precursors that contribute to low-level smog, produced by the reaction of nitrogen oxides and VOCs under the influence of UV light.

A sensitivity analysis is a "systematic procedure for estimating the effects of the choices made regarding methods and the data on the outcome of a study" (ISO 14044, 2006). Different types of analyses were evaluated to determine if benefits would result from changes in a particular process or material. These include reducing the amount of heating, fertilization, and electricity each by 10%, 20%, and 30%.

In addition, a scenario analysis was conducted to determine the effect of creating alternative scenarios of running the greenhouse (Baumann and Tillman, 2004). These include changing the original heating ratio of 80% natural gas and 20% bunker oil (80NG/20BO) to (a) 100% bunker oil (100BO); (b) 50% natural gas and 50% woodchips (50NG/50WC); (c) 100% woodchips (100WC); (d) 100% natural gas (100NG). Different scenarios were examined for the consumption of liquid CO_2. Finally, for greenhouse structure, a comparison was made between plastic and glass structures to determine which had the greater environmental impact.

3.2.0. RESULTS

The potential environmental impacts of greenhouse tomato production in southwestern Ontario are presented in this section.

3.2.1. Life Cycle Impact Assessment (LCIA)

3.2.1.1. Life Cycle of Greenhouse Tomatoes

Figure 3.3 displays the cradle-to-gate potential environmental impacts of producing greenhouse tomatoes in southwestern Ontario. The elements of production (i.e. electricity, fertilization, heating, rockwool, and water use) constitute the vast majority of the impacts in all the categories considered. Waste and greenhouse structure comprise minor environmental impacts in comparison.

Please note the acronyms used throughout this chapter: GW is global warming potential (kg CO_2 eq); SM is smog (g NO_x eq); OD is ozone depletion (kg CFC-11 eq); EU is eutrophication (kg N eq); AD is acidification (H^+ moles eq); CED is cumulative energy demand (MJ eq).

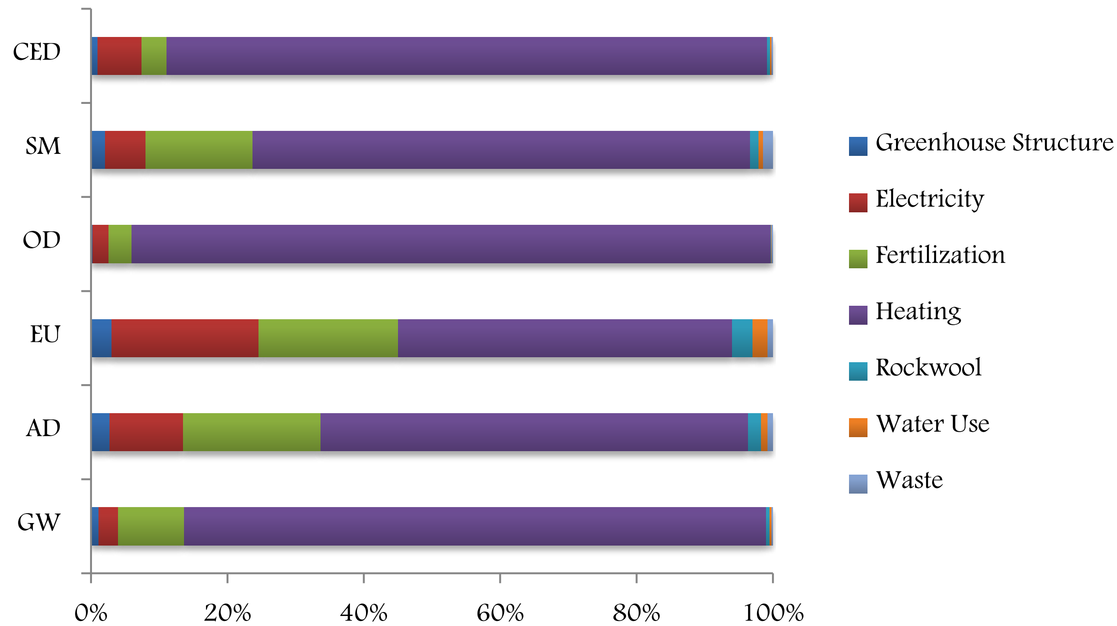

Figure 3.3 Environmental impacts of the greenhouse tomato system typical of systems in the Leamington, Ontario region based on Life Cycle Assessment using a base of data from eight grower operations in the region for the years 2006-2011. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Table 3.7 Impact assessment absolute and percentage values for greenhouse tomato production in southwestern Ontario per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment using base data from eight growers in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-3}$)	H^+ moles eq ($x10^{-3}$)	kg N eq ($x10^{-6}$)	kg CFC-11 eq ($x10^{-10}$)	g NO_x eq ($x10^{-5}$)	MJ eq ($x10^{-2}$)
Total	2881(100%)	273(100%)	1252(100%)	4205(100%)	270(100%)	5276(100%)
Greenhouse Structure	32(1%)	7(2%)	38(3%)	11(<1%)	6(2%)	51(<1%)
Electricity	83(3%)	30(11%)	270(22%)	98(2%)	16(6%)	340(6%)
Fertilization	279(10%)	55(20%)	256(20%)	141(3%)	42(16%)	196(4%)
Heating	2460(85%)	171(63%)	613(49%)	3940(94%)	197(73%)	4643(88%)
Rockwool	14(<1%)	5(2%)	38(3%)	5(<1%)	3(1%)	24(<1%)
Water Use	8(<1%)	3 (1%)	28(2%)	3(<1%)	2(<1%)	13(<1%)
Waste	5(<1%)	2 (<1%)	9(<1%)	7(<1%)	4(1%)	9(<1%)

For tomato greenhouse production systems typical of the Leamington region, heating was the major contributor to environmental impacts in all categories, followed by electricity and fertilization (Table 3.7). Heating was 85% of the total for GW; 63% of AD; 49% of EU; 94% of OD; 73% of SM; and 88% of CED. These findings clearly illustrate the dominance that the heating process plays in the life cycle of greenhouse tomato production in this region and it suggests that we can reject the null hypothesis of this study.

Electricity is a relatively large contributor to EU (22%) and AD (11%) and was a minor contributor to CED (6%), SM (6%), OD (2%) and GW (3%). At levels similar to electricity, fertilization was a factor in EU (20%) and AD (20%). The impacts from greenhouse structure, rockwool, and waste only had slight environmental impacts in comparison to the other categories (Table 3.7). Although water use was not a major issue in terms of overall impacts, still, a considerable amount of water (18.7 L, SE= 0.9) was used to produce 1 kg of tomato.

3.2.1.1.2 Production – Fertilization

This section presents the potential environmental impact of the fertilization system. The process that causes the largest impact across all categories within Fertilization is the production of potassium nitrate (Figure 3.4 and Table 3.8). It represents from 50% to 77% of the burdens in all categories. This was followed by the production of calcium nitrate, with percentages between 16% to 39% in all impact categories. Nitrogen emissions from crop application are a major factor in AD (20%), and a minor factor in EU (5%), and GW (5%). The production of the other fertilizers and transportation had negligible environmental impacts across all categories (Table 3.8).

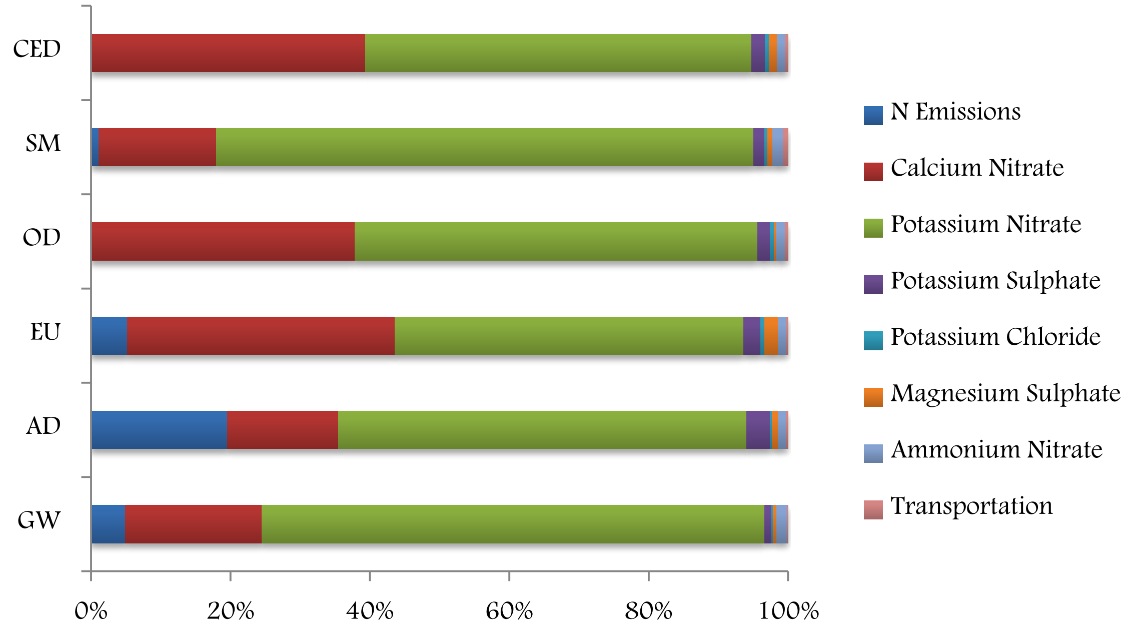

Figure 3.4 Environmental impacts from the fertilization process based on a Life Cycle Assessment of greenhouse tomato production systems typical of the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Table 3.8 Impact assessment absolute and percentage values for fertilization per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of greenhouse tomato production systems in the Leamington, Ontario region. F.U. is 1 kg tomato. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact Category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-4}$)	H^+ moles eq ($x10^{-4}$)	kg N eq ($x10^{-7}$)	kg CFC-11 eq ($x10^{-11}$)	g NO_x eq ($x10^{-6}$)	MJ eq ($x10^{-3}$)
Total	2791(100%)	547(100%)	2559(100%)	1408(100%)	425(100%)	1963(100%)
N Emissions	138(5%)	107(20%)	133(5%)	0(0%)	5(1%)	0(0%)
Calcium Nitrate	547(20%)	87(16%)	983(38%)	533(38%)	72(17%)	771(39%)
Potassium Nitrate	2010(72%)	322(59%)	1280(50%)	814(58%)	327(77%)	1090(56%)
Potassium Sulphate	28(1%)	18(3%)	61(2%)	25(2%)	7(2%)	38(2%)
Potassium Chloride	8(<1%)	1(<1%)	15(<1%)	8(<1%)	2(<1%)	10(<1%)
Magnesium Sulphate	14(<1%)	5(<1%)	51(2%)	4(<1%)	3(<1%)	22(1%)
Ammonium Nitrate	42(2%)	6(1%)	31(1%)	18(1%)	6(1%)	25(1%)
Transportation	4(<1%)	1(<1%)	5(<1%)	6(<1%)	3(<1%)	7(<1%)

3.2.1.1.3 Waste assessment

The environmental impacts stemming from waste management, were analyzed in this section. The transport from the greenhouse and emissions from waste treatment were considered. Only structural materials and rockwool went to landfill. Structure materials included aluminum and steel, with a life span of 25 years. Plastics included rockwool sleeves (life span 1 year) and plastic used for the greenhouse structure (life span 4 years). Transport distances were 50 km, except for plastics, which had a travel distance of 4000 km by train and 9000 km by ship.

Transport of the organic (i.e. tomato plant material), rockwool, and plastics were the major contributors in all impact categories (Figure 3.5 and Table 3.9). The landfill emissions from rockwool also had a large impact across the different categories.

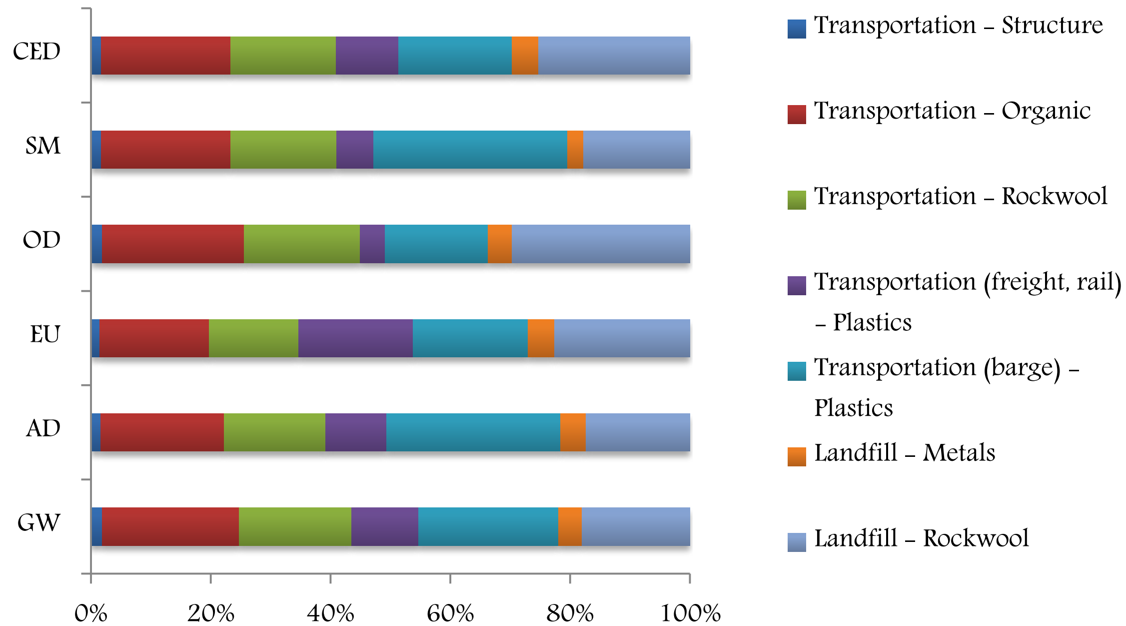

Figure 3.5 Environmental impacts from waste process based on a Life Cycle Assessment of greenhouse tomato production systems typical of the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Table 3.9 Impact assessment absolute and percentage values for Waste system per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-5}$)	H^+ moles eq ($x10^{-5}$)	kg N eq ($x10^{-5}$)	kg CFC-11 eq ($x10^{-5}$)	g NO_x eq ($x10^{-5}$)	MJ eq ($x10^{-5}$)
Total	501(100%)	208(100%)	93(100%)	68(100%)	384(100%)	85(100%)
Transportation – Structure	9(2%)	3(1%)	1(1%)	1(2%)	7(2%)	1(1%)
Transportation – Organic	115(23%)	43(21%)	17(18%)	16(24%)	83(22%)	18(21%)
Transportation – Rockwool	94(19%)	35(17%)	14(15%)	13(19%)	68(18%)	15(18%)
Transportation (freight, rail)- Plastics	56(11%)	21(10%)	18(19%)	3(4%)	24(6%)	9(10%)
Transportation (barge) – Plastics	117(23%)	61(29%)	18(19%)	12(18%)	124(31%)	16(19%)
Landfill – Metals	20(4%)	9(4%)	4(5%)	3(4%)	10(3%)	4(5%)
Landfill - Rockwool	90(18%)	36(17%)	21(23%)	20(29%)	68(18%)	22(26%)

3.2.1.1.4. Additional Analysis - Liquid CO_2

This section examined the complete life cycle of tomato greenhouses with liquid CO_2 supplementation. Seven of eight greenhouses reported using liquid CO_2; however, no data were provided from the greenhouses (in any production year) that use it. Furthermore, unlike the other processes involved within the system boundaries, the entire data set for liquid CO_2 consumption were taken from literature sources (Blom *et al*, 2002). This was why is was not included in the general analysis. The quantity of liquid CO_2 used was an estimate based on the potential yearly CO_2 use of a vegetable greenhouse, based on sunshine hours at Harrow, Ontario (approximately 30 km west of Leamington) (Blom *et al*, 2002). The amount of CO_2 considered was 65 kg CO_2/ha/hr (total of 2000 hours for the year) and applied to this project's production level (average yield) of 56.4 kg tomato/m^2. This process contains material and energy input and emissions for the production of liquid CO_2, with the inclusion of factory infrastructure.

Figure 3.6 and Table 3.10 indicates that the greatest change in environmental impacts from the inclusion of liquid CO_2, stem from EU (26%), with relatively modest impacts in other categories similar to those of fertilization and electricity. These results indicate that liquid CO_2 consumption is an important, but not the most important, contributor to the total environmental burdens caused by greenhouse tomato production in southwestern Ontario.

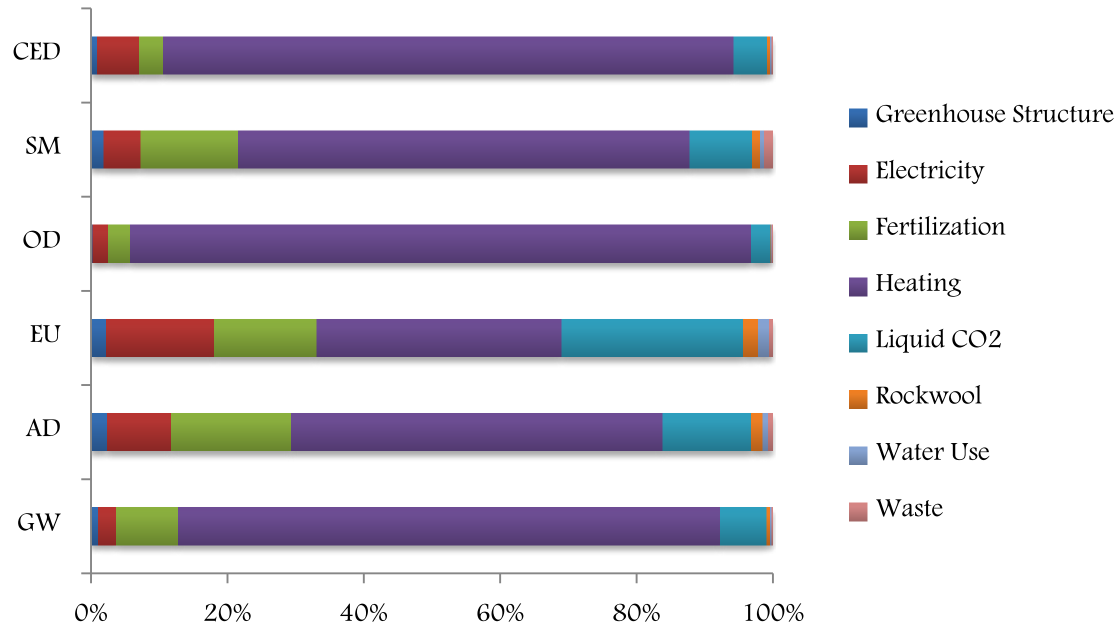

Figure 3.6 Environmental impacts of the greenhouse tomato system for greenhouses with liquid CO_2 (65 kg CO_2/ha/hr) per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Table 3.10 Impact assessment absolute and percent difference values for greenhouses with liquid CO_2 (65 kg CO_2/ha/hr) per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-3}$)	H^+ moles eq ($x10^{-3}$)	kg N eq ($x10^{-6}$)	kg CFC-11 eq ($x10^{-10}$)	g NO_x eq ($x10^{-5}$)	MJ eq ($x10^{-2}$)
Total	3093(100%)	314(100%)	1705(100%)	4327(100%)	297(100%)	5548(100%)
Greenhouse Structure	32(1%)	7(2%)	38(2%)	11(<1%)	6(2%)	51(1%)
Electricity	83(3%)	30(10%)	270(16%)	98(2%)	16(6%)	340(6%)
Fertilization	279(9%)	55(18%)	256(15%)	141(3%)	42(14%)	196(4%)
Heating	2460(80%)	171(55%)	613(36%)	3940(91%)	197(67%)	4643(84%)
Liquid CO_2	212(7%)	41(13%)	453(27%)	122(3%)	27(9%)	272(5%)
Rockwool	14(<1%)	5(2%)	38(2%)	5(<1%)	3(1%)	24(<1%)

Water Use	8(<1%)	3(<1%)	28(2%)	3(<1%)	2(<1%)	13(<1%)
Waste	5(<1%)	2(<1%)	9(<1%)	7(<1%)	4(1%)	9(<1%)

3.2.1.1.5. Additional analysis – Packaging and Pest Management

Packaging and pest management were not included in the main LCA on greenhouse tomatoes. For these two processes, we had data from only three greenhouse participants, compared to eight participants for the other processes. As a result, we included this analysis as separate from the general analysis (although both processes are within the system boundaries, Figure 3.1). The average size of the greenhouses surveyed for this separate analysis, was 92,076 m^2 (9.2 hectare or 22.7 acre), with an average yield of 54.7 kg/m^2 (SE= 1.4).

According to Table 3.11, when packaging was added to the LCA there is a slight noticeable increase in every environmental impact category. The largest increase comes from a +42% in EU, with the smallest increase, +2%, coming from OD. When pest management is added, there are no significant changes in any environmental impact category. The last row of Table 3.11 shows that the majority of changes that take place from every environmental impact category stem from packaging.

Table 3.11 Impact assessment absolute and percent difference values for greenhouses with or without packaging and pest management per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of three greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq ($x10^{-3}$)	kg N eq ($x10^{-6}$)	kg CFC-11 eq ($x10^{-7}$)	g NO_x eq ($x10^{-6}$)	MJ eq
LCA of Greenhouse Tomatoes	2.767	227	990	4.12	2442	53.8
LCA of Greenhouse Tomatoes with Packaging	2.898 (+5%)	258 (+14%)	1409 (+42%)	4.22 (+2%)	2779 (+14%)	57.1 (+6%)
LCA of Greenhouse Tomatoes with Pest Management	2.769 (+1%)	227 (0%)	1004 (+1%)	4.13 (+ <1%)	2446 (+ <1%)	53.8 (0%)
LCA of Greenhouse Tomatoes with Packaging and Pest Management	2.900 (+5%)	259 (+14%)	1423 (+44%)	4.23 (+2%)	2783 (+14%)	57.1 (+6%)

3.2.1.1.6. Packaging Analysis

Cardboard production was the major contributor across all impact categories by a wide margin (Table 3.12). It represented 84% of GW; 84% of AD; 95% of EU; 96% of OD; 86% of SM; and 79% of CED. Plastic packaging and transportation had a minor impact in comparison to cardboard.

Table 3.12 Impact assessment absolute and percentage values for packaging- independent of other processes per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of three greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-3}$)	H^+ moles eq ($x10^{-4}$)	kg N eq ($x10^{-6}$)	kg CFC-11 eq ($x10^{-10}$)	g NO_x eq ($x10^{-6}$)	MJ eq ($x10^{-2}$)
Total	131(100%)	313(100%)	420(100%)	100(100%)	337(100%)	329(100%)
Packaging – Cardboard	110(84%)	263(84%)	398(95%)	96(96%)	290(86%)	260(79%)
Packaging – Plastics	20(15%)	46(15%)	20(5%)	2(2%)	38(11%)	67(20%)
Transportation	1(<1%)	4(<1%)	2(<1%)	2(2%)	9(3%)	2(<1%)

3.2.1.1.7. Pest Management Analysis

The production of insecticides was the major contributor of environmental impacts across all categories with the exception of ozone depletion (OD), in which fungicides is the majority at 67% (Table 3.13). Transportation was not a major factor in any impact category.

Table 3.13 Impact assessment absolute and percentage values for pest management- independent of other processes per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of three greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-6}$)	H^+ moles eq ($x10^{-7}$)	kg N eq ($x10^{-9}$)	kg CFC-11 eq ($x10^{-13}$)	g NO_x eq ($x10^{-9}$)	MJ eq ($x10^{-5}$)
Total	2181(100%)	7746(100%)	14222(100%)	4823(100%)	443(100%)	3829(100%)
Insecticides	1496(69%)	5720(74%)	9990(70%)	1660(34%)	314(71%)	2650(69%)
Fungicides	683(31%)	2020(26%)	4230(30%)	3160(66%)	128(29%)	1176(31%)
Transportation	2(<1%)	6(<1%)	2(<1%)	3(<1%)	1(<1%)	3(<1%)

3.2.2. Life Cycle Interpretation

3.2.2.1. Identification of significant issues

The results from the LCIA indicate that the greatest environmental burden from producing greenhouse tomatoes in typical southwestern Ontario systems stem from the heating of the greenhouse. Other activities such as electricity and fertilization (and liquid CO_2 if included) were also substantive contributors, but still were largely surpassed by heating in all environmental impact categories (Figure 3.3 and Table 3.7).

Potassium nitrate and calcium nitrate were both dominant factors in all environmental impact categories when the fertilization process was examined separately. In regards to the waste process alone, all the activities within the waste process caused relatively similar impacts across all categories, but the transportation of the greenhouse structure metals (aluminum and steel) and the emissions from metals going to landfill, were only minor contributors across all impact categories.

The liquid CO_2 analysis showed that production with liquid CO_2 is an important contributor to the environmental impact categories. The largest increases in environmental impacts were from the EU impact category, in which liquid CO_2 comprised 27%. When packaging and pest management are taken into consideration, the cardboard production from packaging is a major contributor to all environmental impact categories. Although pest management does not create large impacts, insecticide production is the primary contributor.

3.2.2.2. Sensitivity Analysis

In the sensitivity analysis, we looked at (1) reducing the energy required for heating by 10%, 20%, and 30%; (2) reduced the fertilization required by 10%, 20%, and 30%; (3) reduced the electricity required by 10%, 20%, and 30%. These processes were chosen due to their relatively large impact across all impact categories in the LCA of greenhouse tomato production in southwestern Ontario, as was displayed in Figure 3.3 and Table 3.7.

Table 3.14, shows the different impact assessment values when the heating contribution is reduced by a certain percentage. A heating reduction of 10% causes a 2-3% reduction in environmental impact across all categories. When heating is reduced by 20%, there is more variation in reduced environmental impacts. For instance, the largest reduction, -19%, is for OD; the smallest reduction, -10%, is for EU. GW and CED also get significant reductions of -17% and -18%, respectively. A heating reduction of 30% also has variation in reduced environmental impacts. Similar to a 20% heating reduction, OD has the largest reduction (-28%) and EU has the smallest reduction at -14%. Of course this analysis is conducted in the context of the assumption that there is some ability to reduce the heating requirement without affecting yield.

Table 3.14 Impact assessment absolute values for sensitivity analysis of heating per functional unit (F.U. – 1 kg tomato) for greenhouse tomato production systems in southwestern Ontario. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq	kg N eq ($x10^{-3}$)	kg CFC-11 eq ($x10^{-7}$)	g NO_x eq ($x10^{-3}$)	MJ eq
LCA of Greenhouse Tomatoes	2.88	0.272	1.25	4.21	2.7	52.8
LCA of Greenhouse Tomatoes (-10% Heat)	2.8 (-3%)	0.264 (-3%)	1.21 (-3%)	4.09 (-3%)	2.62 (-3%)	51.5 (-2%)
LCA of Greenhouse Tomatoes (-20% Heat)	2.38 (-17%)	0.238 (-13%)	1.13 (-10%)	3.42 (-19%)	2.3 (-15%)	43.4 (-18%)
LCA of Greenhouse Tomatoes (-30% Heat)	2.14 (-26%)	0.221 (-19%)	1.07 (-14%)	3.02 (-28%)	2.11 (-22%)	38.8 (-27%)

Table 3.15, shows the different impact assessment values when the fertilization is reduced by 10%, 20%, and 30%. When fertilization is decreased by 10%, it causes very small reductions in environmental impact across all categories (- <1% to 2%). A fertilization decrease of 20% leads to slightly larger reductions across all impact categories (- <1% to 4%). For a fertilization reduction of 30%, OD and CED has the smallest reduction (-1%) and EU and AD has the largest reduction at -6%. Again, this analysis was conducted with an assumption that the fertilizer used reduction could be accomplished without reducing tomato yield. This may not be realistic given that tomato growers in this region are very particular about fertilizer use and have systems that are honed to maximize yield with given inputs, including fertilizer.

Table 3.15 Impact assessment absolute values for sensitivity analysis of fertilization per functional unit (F.U. – 1 kg tomato) for greenhouse tomato production systems in southwestern Ontario. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq	kg N eq ($x10^{-3}$)	kg CFC-11 eq ($x10^{-7}$)	g NO_x eq ($x10^{-3}$)	MJ eq
LCA of Greenhouse Tomatoes	2.88	0.272	1.25	4.21	2.7	52.8
LCA of Greenhouse Tomatoes (-10% Fertilization)	2.85 (-1%)	0.267 (-2%)	1.23 (-2%)	4.19 (- <1%)	2.66 (-2%)	52.6 (- <1%)
LCA of Greenhouse Tomatoes (-20% Fertilization)	2.82 (-2%)	0.262 (-4%)	1.2 (-4%)	4.18 (- <1%)	2.61 (-3%)	52.4 (- <1%)
LCA of Greenhouse Tomatoes (-30% Fertilization)	2.79 (-3%)	0.256 (-6%)	1.17 (-6%)	4.17 (-1%)	2.57 (-5%)	52.2 (-1%)

Table 3.16, displays the different environmental impact assessment values when the electricity is decreased by 10%, 20%, and 30%. When electricity is reduced by 10%, it causes miniscule reductions in environmental impact across all categories (- <1% to 2%). An electricity decrease of 20% leads to slightly larger reductions across all impact categories (- <1% to 4%). Finally, an electricity reduction of 30%, OD has the smallest reduction (- <1%) and EU has the largest reduction at -6%.

Table 3.16 Impact assessment absolute values for sensitivity analysis of electricity per functional unit (F.U. – 1 kg tomato) for greenhouse tomato production systems in southwestern Ontario. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq	kg N eq ($x10^{-3}$)	kg CFC-11 eq ($x10^{-7}$)	g NO_x eq ($x10^{-3}$)	MJ eq
LCA of Greenhouse Tomatoes	2.88	0.272	1.25	4.21	2.7	52.8
LCA of Greenhouse Tomatoes (-10% Electricity)	2.87 (- <1%)	0.27 (- <1%)	1.23 (-2%)	4.2 (- <1%)	2.68 (- <1%)	52.4 (- <1%)
LCA of Greenhouse Tomatoes (-20% Electricity)	2.86 (- <1%)	0.267 (-2%)	1.2 (-4%)	4.19 (- <1%)	2.67 (-1%)	52.1 (-1%)
LCA of Greenhouse Tomatoes (-30% Electricity)	2.85 (-1%)	0.264 (-3%)	1.17 (-6%)	4.18 (- <1%)	2.65 (-2%)	51.7 (-2%)

The results of the sensitivity analysis show, and confirm, that heat reduction has a much greater influence on the LCA of greenhouse tomatoes in southwestern Ontario than fertilization or electricity. For example, when both heat and fertilization are reduced by 20%, the range of percent decrease for the environmental impact categories is -10% to -19% for heat, and - <1% to 4% for fertilization and electricity. Although these analyses were conducted with an assumption of no impact on tomato yield, which may not be realistic, this sort of analysis can point to areas where impacts in environmental burden reduction could be best achieved and where best efforts could be made to gain efficiencies and reduce environmental burden without impacting tomato yield.

3.2.2.3. Scenario Analysis

3.2.2.3.1 Heating

Due to its significance in all impact categories of tomato greenhouse production, a scenario analysis was warranted to explore the change in impacts of heating for various heating energy sources. This type of analysis is important to growers for practical reasons and because they are always exploring options for improving their production systems, and increasingly this is in light of changes that could help them to make their systems more environmentally sustainable.

Figure 3.7 and Table 3.17 present the relative contribution to each impact category and the impact assessment values for each system (energy source) of heating. For global warming potential, heating with 100BO causes the greatest impact (3.22 kg CO_2 eq) for this category, while heating with 100WC, caused the least by a wide margin (0.267 kg CO_2 eq). 80NG/20BO (2.46 kg CO_2 eq), 100NG (2.28 kg CO_2 eq), 50NG/50WC (1.28 kg CO_2 eq), round out the middle positions. This category is particularly important, due to its importance as a carbon footprint indicator and most commonly there is public scrutiny of the carbon implications of energy source.

The results for acidification show that 100BO caused the most pollution in this category (0.393 H^+ moles eq). This was followed by 100WC (0.279 H^+ moles eq), 50NG/50WC (0.199 H^+ moles eq), 80NG/20BO (0.171 H^+ moles eq), and 100NG (0.119 H^+ moles eq).

The heating system of 100BO led to the greatest eutrophication impact (19 x 10^{-4} kg N eq). The second highest impact was 100WC (11 x 10^{-4} kg N eq), followed by 50NG/50WC (7.11 x 10^{-4} kg N eq) and 80NG/20BO (6.13 x 10^{-4} kg N eq). The heating system with the least eutrophication pollution potential was 100NG (3.15 x 10^{-4} kg N eq).

For ozone depletion, the heating system that created the largest impact was 100BO (477 x 10^{-9} kg CFC-11 eq). This was followed by 80NG/20BO (394 x 10^{-9} kg CFC-11 eq), 100NG (376 x 10^{-9} kg CFC-11 eq), 50NG/50WC (193 x 10^{-9} kg CFC-11 eq). 100WC (9.96 x 10^{-9} kg CFC-11 eq), potentially produced the least amount of environmental damage for this category.

The results for smog show that 100WC caused the most pollution in this category (5.25 x 10^{-3} g NO_x eq). This was followed by 50NG/50WC (3.47 x 10^{-3} g NO_x eq), 100BO (3.31 x 10^{-3} g NO_x eq), 80NG/20BO (1.97 x 10^{-3} g NO_x eq), and 100NG (1.66 x 10^{-3} g NO_x eq).

Lastly, the environmental impact category of cumulative energy demand revealed interesting results. The heating system of 100WC led to the largest potential impact (51.4 MJ eq). The systems with equal values were 100BO (48.8 MJ eq) and 50NG/50WC (48.8 MJ eq). These are followed by 80NG/20BO (46.4 MJ eq) and 100NG (46 MJ eq).

In summary, the heating system of 100BO had the largest potential environmental impact in four of six categories (GW, AD, EU, and OD). The 100NG had the lowest potential environmental impact in four of six categories (AD, EU, SM, and CED) (Figure 3.7). This information could be of value to growers but they would get most use from it if it was overlaid against cost estimates, and even more so, cost projections for various sources of energy. This is challenging given the uncertainty around energy costs and the interest of governments to implement energy policies which can impact the economics of using certain sources. In addition, Canada has not ratified any sort of cap and trade system for carbon, which could greatly impact the economics of energy sources, especially those with real offset potential such as wood.

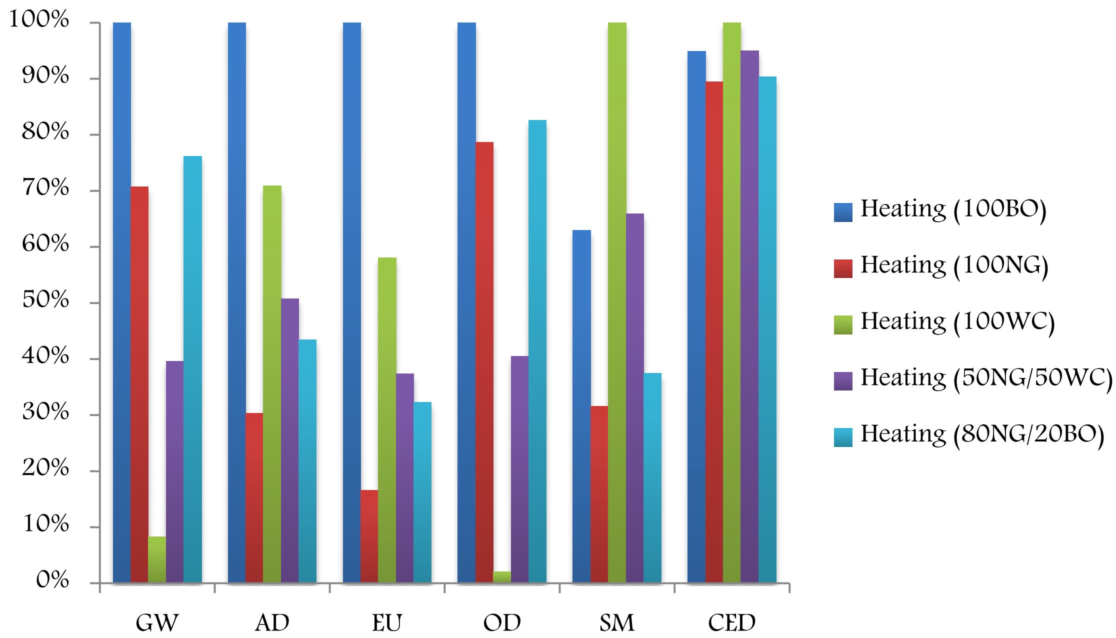

Figure 3.7 Comparison of potential environmental impact contributions from scenarios typical of southwestern Ontario greenhouse production systems for heating systems using a range of heat energy sources. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Table 3.17 Impact assessment absolute values for various heating systems-independent of other processes per functional unit (F.U. – 1 kg tomato) for greenhouse tomato production systems in southwestern Ontario. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq	kg N eq ($x10^{-4}$)	kg CFC-11 eq ($x10^{-9}$)	g NO_x eq ($x10^{-3}$)	MJ eq
Heating (100BO)	3.22	0.393	19	477	3.31	48.8
Heating (100NG)	2.28	0.119	3.15	376	1.66	46
Heating (100WC)	0.267	0.279	11	9.96	5.25	51.4
Heating (50NG/50WC)	1.28	0.199	7.11	193	3.47	48.8
Heating (80NG/20BO)	2.46	0.171	6.13	394	1.97	46.4

3.2.2.3.2. Liquid CO_2

Table 3.18, shows the different impact assessment values when the liquid CO_2 consumption is increased from 45 to 55 and 65 kg CO_2/ha/hr. At both 55 kg CO_2/ha/hr and 65 kg CO_2/ha/hr, the environmental impacts across all categories stays relatively constant, with the exception of EU which increase by +26%, +31%, and +37% for 45, 55, and 65 kg CO_2/ha/hr respectively. Whether the consumption of liquid CO_2 is at 45, 55, or 65 kg CO_2/ha/hr, the impacts for each environmental category remain relatively constant.

Table 3.18 Impact assessment absolute values for sensitivity analysis of liquid CO_2 per functional unit (F.U. – 1 kg tomato) for greenhouse tomato production systems in southwestern Ontario. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq ($x10^{-1}$)	kg N eq ($x10^{-3}$)	kg CFC-11 eq ($x10^{-7}$)	g NO_x eq ($x10^{-3}$)	MJ eq
Life Cycle of Greenhouse Tomatoes	2.88	2.72	1.25	4.21	2.7	52.8
Life Cycle of Greenhouse Tomatoes (45 kg CO_2/ha/hr)	3.02 (+5%)	3 (+10%)	1.57 (+26%)	4.29 (+2%)	2.89 (+7%)	54.6 (+3%)
Life Cycle of Greenhouse Tomatoes (55 kg CO_2/ha/hr)	3.06 (+6%)	3.07 (+13%)	1.64 (+31%)	4.31 (+2%)	2.93 (+9%)	55.1 (+4%)
Life Cycle of Greenhouse Tomatoes (65 kg CO_2/ha/hr)	3.09 (+7%)	3.13 (+15%)	1.71 (+37%)	4.33 (+3%)	2.97 (+10%)	55.5 (+5%)

3.2.2.3.3. Greenhouse Structure

This section examined the difference in environmental impact, caused by the production of glass or plastic greenhouse structures, independent of other processes or activities of the LCA. The calculations are based on a 4-year lifespan for plastic and a 25-year lifespan for glass. There was little difference in impact between the two structures (Table 3.19). The glass structure had a higher impact in GW, AD, EU, OD, and SM, but by only a narrow margin. Plastic had a slightly larger impact in CED of 0.511 MJ eq, compared to 0.422 MJ eq for glass.

Table 3.19 Impact assessment absolute values for glass and plastic greenhouse structure-independent of other processes per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of greenhouse tomato production systems in the Leamington, Ontario region. GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq ($x10^{-2}$)	H^+ moles eq ($x10^{-3}$)	kg N eq ($x10^{-5}$)	kg CFC-11 eq ($x10^{-9}$)	g NOx eq ($x10^{-5}$)	MJ eq
Greenhouse Structure (Glass)	3.22	8.54	3.9	1.48	6.62	0.422
Greenhouse Structure (Plastic)	3.18	7.38	3.79	1.12	5.6	0.511

3.2.2.4. Comparing environmental performance among individual greenhouse operations within this study

Within this LCA, we surveyed eight greenhouse tomato growers. Figure 3.8 and Table 3.20 present the differences and variability in environmental impacts for the life cycle of each operation.

For GW, greenhouse 8 had the largest impact and produces 3.96 kg CO_2 eq/kg tomato, which is considerably higher than the other greenhouses. The impact category of AD showed greenhouse 5 to have the lowest level at 0.197 H^+ moles eq/ kg tomato and greenhouse 8 with the largest score of 0.433 H^+ moles eq/ kg tomato. Greenhouse 5 caused the least amount of eutrophication (EU) with an impact of 8.15 x 10^{-4} kg N eq/ kg tomato; the most burdensome in this category was greenhouse 8 with a level of 20.5 x 10^{-4} kg N eq/ kg tomato. For OD, greenhouse 1 has the least impact at 3.07 x 10^{-7} kg CFC-11 eq/kg tomato, and greenhouse 8 had the greatest impact at 5.73 x 10^{-7} kg CFC-11 eq/kg tomato. In the SM environmental impact category, greenhouse 8 has the greatest impact (3.94 x 10^{-3} g NO_x eq/kg tomato) and greenhouse 1 has the least impact (2.01 x 10^{-3} g NO_x eq/kg tomato). Greenhouse 1 has the lowest level of cumulative energy demand (CED) at 39.7 MJ eq/kg tomato; while greenhouse 8 used the most energy per functional unit (66.1 MJ eq/kg tomato).

Greenhouse 8 has the largest environmental impact across all categories, while Greenhouse 1 has the lowest impacts in all categories except for AD and EU where, of which greenhouse 5 had a lower impact. Greenhouse 8 had the largest environmental impacts because it used the largest amount of bunker oil for heating. As Table 3.17 showed, bunker oil creates much more environmental burdens than does natural gas (growers only used natural gas and bunker oil in this study). Detailed comparative LCIA descriptions of each process for each greenhouse are found in the Appendix. However, information regarding the characteristics of each greenhouse operation and other input data (i.e. amount of electricity used) for this LCA, were not included in this thesis due to confidential agreements that were made prior to the start of this LCA project. See Chapter 4 for further explanations. However, what these results do show us is that there are substantive differences among greenhouse operations even within a discrete production region and for the same food product. This suggests that there is value in different approaches to production in terms of reducing environmental burden. Unfortunately, these superior production approaches can only be identified and exploited (and perhaps enhanced) if there is cooperation among growers within the region.

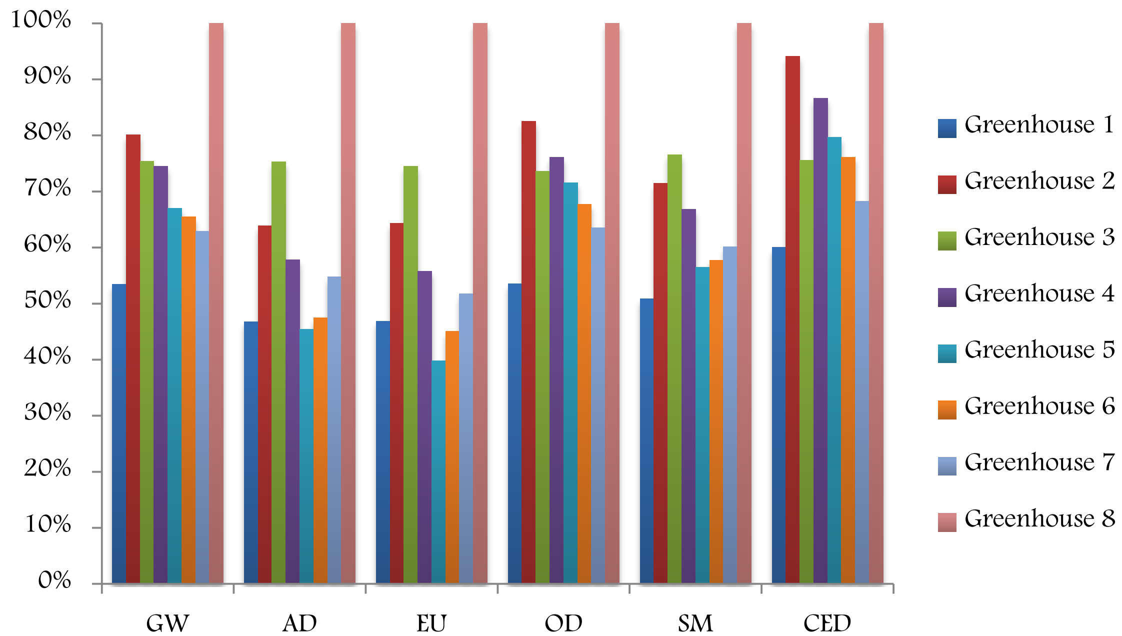

Figure 3.8 Comparison of environmental impacts from production between greenhouses per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of eight greenhouse tomato production systems in the Leamington, Ontario region. The average size of the greenhouses surveyed was 60,954 m^2 (6.1 hectare or 15.1 acre). GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Table 3.20 Comparison of environmental impacts from production between greenhouses per functional unit (F.U. – 1 kg tomato) based on a Life Cycle Assessment of greenhouse tomato production systems in the Leamington, Ontario region. The average size of the greenhouses surveyed was 60,954 m^2 (6.1 hectare or 15.1 acre). GW = Global Warming; AD = Acidification; EU = Eutrophication; OD = Ozone Depletion; SM = Smog; CED = Cumulative Energy Demand.

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H^+ moles eq	kg N eq ($x10^{-4}$)	kg CFC-11 eq ($x10^{-7}$)	g NO_x eq ($x10^{-3}$)	MJ eq
Greenhouse 1	2.12	0.202	9.61	3.07	2.01	39.7
Greenhouse 2	3.17	0.277	13.2	4.72	2.82	62.3
Greenhouse 3	2.99	0.326	15.3	4.21	3.02	50
Greenhouse 4	2.95	0.25	11.4	4.36	2.64	57.3
Greenhouse 5	2.65	0.197	8.15	4.1	2.23	52.7
Greenhouse 6	2.59	0.206	9.23	3.88	2.27	50.3
Greenhouse 7	2.49	0.237	10.6	3.64	2.37	45.2
Greenhouse 8	3.96	0.433	20.5	5.73	3.94	66.1

3.3.0. Discussion

3.3.1. Possible explanations and implications of the assessment results

The results of the life cycle impact assessment suggest that the heating of the tomato greenhouse created the largest potential environmental burden (Figure 3.3). This was true across all impact categories including, global warming potential, eutrophication, acidification, smog, ozone depletion, and cumulative energy demand. This result is relatively robust given the size of the dataset used in this analysis (the number of greenhouse production systems included). The heating systems for greenhouses in this region use a large quantity of fossil fuels in order to generate energy to heat the greenhouse during the production season (an average of 46.4 MJ eq/kg tomato). This result of 46.4 MJ eq/kg tomato, represents a cradle-to-farm gate LCA quantity derived from the arithmetic average of all eight greenhouses surveyed in this project. Otherwise, the non-LCA results, taken from the completed surveys, would amount to 36.9 MJ eq/kg tomato. This difference is substantive and it points to the value of LCA in terms of providing a more complete characterisation of the environmental burden of given systems.

After heating, fertilization was the next most important factor of production in terms of potential environmental impact across all categories. Potassium nitrate and calcium nitrate dominated the environmental impacts across all categories within this factor. The nitrogen air emissions stemming from crop application within the greenhouse played a significant role, especially in AD (0.0107 H^+ moles eq/kg tomato). Nitrogen is a vital plant nutrient and it enables high yields (OMAFRA, 2010). Its importance makes it a difficult nutritional requirement to reduce.

The transportation of plastics, organics (plant material), rockwool, and landfill emissions from rockwool (Figure 3.5 and Table 3.9), were the primary contributors to the environmental impacts from waste management. For the LCA model in this study, a train and ship was assumed to be used to transport the plastic waste (plastic sleeves and plastic roofing) a total of 13,000 km, the average distance from Canada to China, to be recycled. However, the “cut-off” model from Ekvall and Tillman (1997) was used, meaning the following process that will make use of the recycled plastic next, will absorb the plastic’s environmental burden; the same method was applied to plant material destined for compost.

There were important increases across all environmental impact categories when liquid CO_2 supplementation at 65 kg CO_2/ha/hr is used (Table 3.10). Heating was still the dominant process, as it represented 36% to 91% in every impact category. However, in the impact category of EU, the second largest impact stems from liquid CO_2 consumption. In fact, the environmental burdens for liquid CO_2 use in tomato greenhouses of southwestern Ontario are similar to those of electricity and fertilizer across all impact categories (Table 3.10). Liquid CO_2 can be a considerable burden for environmental impacts and for future analyses raw data from greenhouses will be extremely valuable, especially given that most (if not all) tomato greenhouse production systems in this region use some form of CO_2 supplementation.

Although not included in the main LCA, as it was not representative of the majority of growers included in this study, pest management and packaging are part of many tomato greenhouse systems and thus were analyzed separately within this study (Tables 3.11, 3.12 and 3.13). Packaging had a major impact on eutrophication (EU) with an impact value of 398 x 10^{-6} kg N eq/ kg tomato. In fact, packaging, primarily due to cardboard production, has a higher impact than any other process for the EU category (excluding heating) from Table 3.7. This result suggests that packaging can be a relatively significant consideration for environmental impacts and if part of a system, it should not be ignored or assumed to have no substantive impact. Pest management had only minor impacts across all environmental impact categories. This is primarily due to the small quantity applied in the greenhouses surveyed (see Appendix). This result possibly reflects a trend that greenhouse tomato production in southwestern Ontario has been successful in minimizing its use and therefore potential impact of pesticides.

The sensitivity analysis for heating showed interesting results. When reduced by -10% modest and similar decreases are seen across all environmental impact categories (between -2% and -3%). At -20% and -30% heat reductions, there are considerable decreases in every impact category (Table 3.14). If greenhouses in southwestern Ontario are able to achieve a 10-20% decrease in heating (without affecting tomato yield), the environmental burden from producing greenhouse tomatoes will decrease considerably. For fertilization and electricity, reductions in their consumption of 10, 20, or 30% are nowhere near as influential as heating. For instance, at a 30% reduction of either fertilization or electricity, no environmental impact category decreases by more than 6%. However, this does not mean that tomato greenhouses of southwestern Ontario should not take steps to reduce these inputs.

When we examined different heating sources and heating source ratios, we found that heating with 100BO caused the highest impacts in four of six categories (GW, AD, EU, and OD). This source of energy is usually used as a standby, but some growers do use it as their main source of energy occasionally (OMAFRA, 2010). Heating with 100NG had the lowest impact in four of six categories (AD, EU, SM, and CED). However, it cannot be considered the best heating option environmentally, because only six environmental impact categories were chosen for this study. Furthermore, GW is an important indicator in relation to climate change concerns and governments have begun to give tax relief to those who reduce their carbon footprint (TOGA, 2010; Schmidt, 2012). Based on that fact, heating with 100WC could also be a good option, socially and economically, given that it had the lowest impact in GW at 0.267 kg CO_2 eq/kg tomato. A number of the largest greenhouse operations in southwestern Ontario use woodchips or pelletized fuel composed of wood, as a primary source of energy, despite it not being the most environmentally sustainable option across all impact categories.

When liquid CO_2 was examined with scenario analysis, the results indicate that the different consumption rates of liquid CO_2 do not differ greatly; EU was the exception (Table 3.18). Liquid CO_2 is still an important activity in the LCA of greenhouse tomato production in southwestern Ontario, and due to this importance real data from growers would be instrumental in future analyses. Although the most common method of increasing CO_2 levels in vegetable greenhouses of Ontario, is by burning fuels such as natural gas, propane, or low-sulphur kerosene (OMAFRA, 2010), seven of eight participants in this survey reported using liquid CO_2 supplementation.

When comparing the environmental impacts between glass and plastic greenhouse structures, the results were similar across all impact categories (Table 3.19). These results suggest that both structures, with the appropriate lifespan (4 year for plastic and 25 years for glass), cause similar quantities of potential environmental impacts. Therefore, other factors need to be considered when constructing the greenhouse. Traditionally, vegetable greenhouses used glass. However, over the last 20 years, plastic greenhouse structures have become increasingly popular, combining energy conservation and low capital construction costs without loss of productivity (OMAFRA, 2010).

The functional unit for this LCA project was 1 kg tomato. The production average amongst the eight greenhouses was 56.4 kg tomato/m^2. Therefore, in order to determine the environmental burden of a particular impact category, we had to multiply the value by 56.4 to get the impact over a m^2. The average heat energy consumption for this LCA study, over a m^2, was 2.62 GJ eq/m^2 and electricity energy consumption was 0.192 GJ eq/m^2. Once again these results of 2.62 GJ eq/m^2 for heat and 0.192 GJ eq/m^2 for electricity, represents a cradle-to-farm gate LCA quantity derived from the arithmetic average of all eight greenhouses surveyed in this project. The non-LCA results would amount to 2.08 GJ eq/m^2 for heat and 0.055 GJ eq/m^2 for electricity. This level of energy consumption on a per area basis is similar to a recent greenhouse energy survey, which determined that in the Leamington area, the average vegetable greenhouse uses 2.18 GJ/m^2 for heat and 0.04 GJ/m^2 for electricity (Agviro and AMEC Geomatrix, 2009). The difference in the two results is reflection of the type of study (LCA vs. energy audit), product (tomatoes vs. all vegetables), and possibly the number of participants in the sample (8 for LCA and 14 for energy audit). It may also reflect differences in production systems given that the energy audit included other vegetable and flower production as well. Production systems can differ markedly depending on what is being grown. For instance, the fertilizer, climate, and water requirements for tomato production are different from cucumber, pepper, lettuce, and eggplants; and these differ from flower production. It is important in these types of studies to be comparing like products and it may not be reasonable to compare greenhouse to greenhouse based on structural systems alone.

3.3.2. Comparison with other tomato greenhouse LCAs

There have been a number of different LCA studies in agriculture and food production, and in particular, many complete and reliable LCA studies completed on tomato greenhouse production. Table 3.21 displays the global warming potential (kg CO_2 eq) and energy demand (MJ eq), for greenhouse tomatoes grown in different countries. The functional unit is for 1 kg of tomatoes.

Table 3.21 Comparison of MJ eq and CO2 eq required to produce 1 kg tomato from various LCA/energy studies

Country	System	Steps Included	Steps Excluded	Source	Result
Spain	Plastic, Unheated	Structure, Fertilizers, Pesticides, Electricity, Waste	Packaging, Commercialization	Torrellas *et al*, 2012	3.1 MJ eq 0.24 kg CO_2 eq
Hungary	Glass, Heated (Thermal Water^{x} or Natural Gas^{y})	Structure, Fertilizers, Pesticides, Electricity, Heat, Waste	Packaging, Commercialization	Torrellas *et al*, 2012	(7.2 MJ eq 0.53 CO_2 eq)^{x} (87 MJ eq 5.1 kg CO_2 eq)^{y}
Netherlands	Glass, Heated (CHP)	Structure, Fertilizers, Pesticides, Electricity, Heat, Waste	Packaging, Commercialization	Torrellas *et al*, 2012	31 MJ eq 2 kg CO_2 eq
France	(Glass and Plastic, Heated)^{x} (Plastic, Unheated)^{y}	Structure, Fertilizers, Pesticides, Electricity, Heat, Packaging, Waste	Commercialization	Boulard *et al*, 2011	(31.6 MJ eq 2.02 kg CO_2 eq)^{x} (5.2 MJ eq 0.51 CO_2 eq)^{y}
United Kingdom	Glass, Heated	Structure, Fertilizers, Pesticides, Electricity, Heat, Waste	Packaging, Commercialization	Williams *et al*, 2006	130 MJ eq 9.4 kg CO_2 eq
Turkey	Glass, Heated	Structure, Fertilizers, Pesticides, Electricity, Human Power	-	Canakci and Akinci, 2006	2.5 MJ eq
Italy	Plastic, Unheated	Structure, Fertilizers, Pesticides, Electricity, Packaging, Transport to Retailer, Waste	-	Cellura *et al*, 2011	16.2 MJ eq 0.74 kg CO_2 eq

Colombia	Plastic, Unheated	Structure, Fertilizers, Pesticides, Electricity, Human Power	Transport, Waste	Medina *et al*, 2006	1.1 MJ eq
Canada	Plastic, Heated	Structure, Fertilizers, Electricity, Heat, Waste	Commercialization, Packaging, Pesticides	This LCA	52.7 MJ eq 2.88 kg CO_2 eq
Canada	Plastic, Heated	Structure, Fertilizers, Electricity, Heat, Waste, Liquid CO_2, Packaging, Pesticides	Commercialization	This LCA	58.8 MJ eq 3.22 kg CO_2 eq

Note: Packaging and Pest Management data was taken from Table 3.11 and liquid CO_2 data was derived from Table 3.10 with a consumption of 65 kg CO_2/ha/hr.

There is considerable variation in results among the various studies conducted in countries around the world. This is in part because some of the studies were actual ISO defined LCAs, some included or excluded steps, and among the systems studied there was substantive variation in the levels of technology applied to tomato greenhouse production.

In southern Europe (Spain, Italy, and southern France) and Colombia there is no need for heating the greenhouse, therefore a large amount of energy and pollution is avoided. The Spanish systems (Torrellas *et al*, 2012) (3.1 MJ eq and 0.24 kg CO_2 eq) had less impact than the Italian LCA (Cellura *et al*, 2011) (16.2 MJ eq and 0.74 kg CO_2 eq), primarily due to the inclusion of packaging and transport to retailer in the Italian systems. While in southern France (Boulard *et al*, 2011), the impacts (5.2 MJ eq and 0.51 CO_2 eq) were slightly higher than for the Spanish systems due to the inclusion of packaging. Colombia had the lowest impacts (1.1 MJ eq) because the LCA excluded important contributors to energy use and GHG emissions in particular, transportation and waste management (Medina *et al*, 2006).

In colder regions, greenhouses use a tremendous amount of energy for heating, and the source is usually fossil fuels. The Hungarian LCA examined two systems, one using natural gas and the other geothermal energy (thermal water) for heating (Torrellas *et al*, 2012). The difference between the two systems was stark. The thermal water system (7.2 MJ eq and 0.53 kg CO_2 eq) had much less impact than the natural gas system (87 MJ eq and 5.1 CO_2 eq). However, the use of natural gas for heating is much more common in Hungary; the large capital investment required for thermal water makes this possible only for financially affluent operations and in the end, it may not be fiscally feasible on a functional unit basis. In France (31.6 MJ eq and 2.02

CO_2 eq), the LCA considered production under glass and plastic, which could explain the difference in results when compared to Hungary and in addition, the study in France included packaging.

The use, and possible use, of combined heat and power (CHP) was examined in a couple of published LCA tomato greenhouse studies. In the United Kingdom, tomato greenhouse production (130 MJ eq and 9.4 CO_2 eq) is very energy intensive, and the authors of this study hypothesized that the use of CHP could reduce energy demand by up to 70% (Williams *et al*, 2006). When compared to a Dutch study which incorporated CHP (31 MJ eq and 2 kg CO_2 eq) (Torrellas *et al*, 2012), one could definitely see the potential energy saving and environmental benefits of incorporating CHP into production systems.

In Turkey, an energy assessment was completed which revealed that a tomato greenhouse consumed 2.5 MJ eq/kg tomato (Canakci and Akinci, 2006). This is a relatively small number for a heated greenhouse (wooden blocks were used as the heating source). The impacts from Turkey were similar to Spain and Colombia and may reflect the low technology required to operate greenhouses in those environments.

The model used for this project (52.7 MJ eq and 2.88 kg CO_2 eq) did not include CHP because no CHP is used in the region for tomato greenhouse production. As such, a model with CHP could not be created because there was no reliable data available. Based on the results derived from LCA tomato greenhouse studies in European countries with cooler climates that might resemble the climate in the production region in Leamington, one could perhaps see the benefits of this type of system. It is peculiar that CHP systems have not been adopted yet in southwestern Ontario (the largest concentration of greenhouses in North America).

When liquid CO_2, packaging, and pest management are included in the LCA, energy consumption increases by 11%, from 52.8 MJ eq/kg tomato to 59.2 MJ eq/kg tomato. The majority of this increase comes from packaging, which adds approximately 3.3 MJ eq/kg tomato. In addition, CO_2 emissions also increased by 11% from 2.88 kg CO_2 eq/kg tomato to 3.22 kg CO_2 eq/kg tomato. It is important to reiterate that the data for packaging and pest management is representative of three of eight greenhouses. Liquid CO_2 is representative of seven of eight greenhouses with all data coming retrieved from literature sources.

In general, in comparison to other tomato production systems around the world, the typical system in the Leamington, Ontario region is relatively energy intensive. If one excludes heating, then the Leamington systems are only at levels of 6.4 MJ eq/kg tomato and 0.42 kg CO_2 eq/kg tomato, which is comparable to those results from Hungary (thermal energy) and southern France. When heating is included, the Leamington systems have greater impacts to those in cooler regions where heating is required. In fact, even if the heating scenarios were applied from section 3.2.2.3.1. (scenario analysis of different heating systems), the Canadian systems would still not fare well in the impact categories of GW and CED when compared to Hungary, France, or the Netherlands.

This comparison sheds light on the production systems of southwestern Ontario. It shows that there is room for environmental improvement in the Leamington area. Although thermal energy is not a feasible source of energy in southwestern Ontario, as in Hungary, CHP is a technology that has the potential to alleviate the large energy demand from greenhouse tomato production systems.

3.3.3. Conclusions and Recommendations

In this study we examined the environmental impacts stemming from greenhouse tomato production in southwestern Ontario. The method chosen for this project was a cradle-to-gate life cycle assessment. This project was initiated because a complete analysis of resource consumption and pollution emitted is scarce and poorly documented. Within this study we were able to determine that heating causes the most potential environmental impact across all the impact categories examined.

Although the average yield from this study was 56.4 kg tomato/m^2, the environmental impacts, especially from energy use, were quite large relative to other nations (Table 3.21). Southwestern Ontario has room for improvement, in terms of environmental sustainability and energy efficiency. The area of concern is the amount and source of heating required to control the climate of the greenhouse. We explored different alternatives for heating (i.e. 100NG and 100WC), which revealed that the decision of selecting the best source from an environmental perspective, is challenging and subjective.

This LCA project was able to achieve all its initial goals. We evaluated the magnitude and significance of the potential environmental impacts for greenhouse tomato production in southwestern Ontario, (2) investigated which activity in the life cycle is responsible for the greatest environmental impact, (3) represented different production scenarios that can possibly aide in reducing the environmental burdens. Furthermore, our hypothesis that the energy and source required for heating the greenhouse would cause the most environmental burden was correct.

When representing different heating scenarios, it was found that heating with 100WC gave the lowest impacts in only the GW impact category, and that across all impact categories chosen for this project, 100NG had the least environmental burdens. 100WC is being used for heating amongst larger greenhouse vegetable operations due to its low carbon footprint (i.e. CO_2 eq) score. Carbon footprint has become a more common environmental and, more importantly, social concern. The social significance (and economic benefits) from having a low carbon footprint is what compels larger operations to use 100WC. When looked at from a broader view via a life cycle assessment, it is can potentially be worse environmentally than even those operations that use 100NG. However, these conclusions are limited to the analysis approach (and dataset) used in this project, including the selection of environmental impact categories.

Although CHP was not included in this project due to lack of Canadian data, it is something that could be considered in greenhouse vegetable systems in this country. The results from the Netherlands, Table 3.21, showed benefit of including it in greenhouse tomato production. Ontario is the national leader in greenhouse tomato production, and the implementation of CHP could help to sustain this leadership role and position.

The results of this study show that LCA can be an effective tool for characterizing the environmental burdens of greenhouse production systems in Canada. Covering more environmental impacts than a carbon footprint or an energy audit, an LCA gives a more comprehensive view into the environmental performance of greenhouse production.

CHAPTER 4 - GENERAL DISCUSSION

This LCA project was able to represent in a broad fashion the state of environmental performance of greenhouse tomato production in southwestern Ontario. Results indicate that the largest potential environmental impacts across all categories, stemmed from heating. Electricity, fertilization, and liquid CO_2 also had contributions, but these were moderate relative to the potential environmental burden generated by heating the greenhouse.

The results gleaned from this study make a definite contribution to the greenhouse vegetable sector of southwestern Ontario and Canada. Environmental sustainability is an important aspect of any industry today, and this LCA can be considered as a step in this direction for the vegetable greenhouse industry. We now a have a better picture of where this industry is now from an environmental standpoint and the industry may be able to develop ways to mitigate not only its carbon footprint, but also its broader environmental burden.

The LCA results also revealed differences from other energy audit projects on Ontario's greenhouse industry (Agviro and AMEC Geomatrix, 2009). For instance, the energy audit reported that the average vegetable greenhouse uses 2.18 GJ/m^2 for heat and 0.04 GJ/m^2 for electricity. This LCA resulted in 2.62 GJ eq/m^2 for heat and 0.192 GJ eq/m^2 for electricity. As an LCA, this study incorporated all activities, both material inputs and emissions, from upstream processes (i.e. raw material extraction, processing, manufacture, etc) into the final results. Therefore, the environmental impacts are generally larger. When the LCA procedure is not used, these results become 2.08 GJ eq/m^2 for heat and 0.055 GJ eq/m^2 for electricity for the eight greenhouses surveyed in this study, which are more closely resembled to the energy audit results.

In terms of conducting the project itself, the greatest difficulty was getting and then confirming data. Data from growers often took considerable time to confirm whether the input data was correct or not. Further, when additional questions were raised about the data, in terms of technology, suppliers, etc, it also prolonged the project. Despite those issues, the raw data received from the growers is considered highly valuable. Nothing like this has ever been done in the greenhouse tomato or vegetable industry of southwestern Ontario. The fact that many growers participated really adds to the representativeness of this study for the region.

The participating growers had many differences among their systems and as a result, this was reflected in their respective LCIA results (Appendix Tables 6.5. – 6.16). Despite these sometimes very large variations, the common theme of large environmental burdens for heating for each operation is proof that sector needs to make an effort, in the future, to address these issues. Input data from the survey for each operation was not displayed in this thesis, due to confidentiality reasons that were agreed upon before the project began. Growers were assured that their personal data would not be revealed in this public document. OMAFRA greenhouse vegetable specialist, S. Khosla, validated and approved every input data from every greenhouse participant. Unfortunately, this takes away from the potential robustness of this project, as a detailed comparison of each greenhouse would only be useful if input data was available for the reader. It is possible, that in the near future the OGVG can become more transparent and allow production data to be available to the public. Nevertheless, the purpose of this project was to represent the "typical" or "average" tomato greenhouse in the region, and not to do a detailed comparison of the participants.

There are a number of limitations to this project that deserve to be mentioned. Secondary data sources were used from life cycle inventories when primary data could not be retrieved or were not available. The secondary data from these inventories were obtained from peer-reviewed scientific research articles; however, they are usually conducted in specific countries or regions. For instance, the primary database used for this study was from Ecoinvent, which collects data from operations and manufacturers primarily from European nations. Therefore, there are uncertainties present when making use of these data due to regional, and perhaps technological, differences in production. Another limitation was the exclusion of certain processes from the LCA project due to the lack of large enough data sets. For example, pest management and packaging were omitted because only three of the greenhouses surveyed had available data. This LCA project strived to maximize the data set obtained from all the eight participants in order to complete an even project that is able to represent all the participants.

This project was a baseline (or benchmark) study, conducted in order to determine where the industry is in terms of its ecological-footprint. Many growers and operations provided extensive data for this project, and the project included five seasons of data which is rare in LCAs as most vegetable greenhouse studies focus on one operation for one season.

The results from this research could be used for further studies in greenhouse vegetable production. Future research could include a cost-benefit analysis (CBA) or a life cycle costing (LCC), to determine how the industry needs to function to be economically sustainable. Other crops (peppers, cucumbers, lettuce, and eggplant) also could be analyzed with LCA to compare their environmental performances.

All the data and documentation from this LCA project can now be used for further modelling of greenhouse systems in southwestern Ontario.

5.0. LITERATURE CITED

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6.0. APPENDIX

Table 6.1 Copy of survey used for this LCA project

Questionnaire	**Quantity Year 1**	**Quantity Year 2**	**Quantity Year 3**	**Quantity Year 4**	**Quantity Year 5**	**Comments (e.g. supplier, fertilizer formulation (NPK content), etc.)**
Company Name						
Growing Area						
Type of tomato grown						
Yield of tomato (kg/m^2)						
Size of Greenhouse (acres, ft^2 or m^2)						
Height of Greenhouse (ft or m)						
Greenhouse Structure (glass or plastic)						
Heating / Fuel						
Natural gas (GJ, m^3or $)						
Wood chips (waste wood) (kg)						
Bunker oil or #2 oil (L)						
Propane (m^3)						
Coal (kg)						
Electricity consumption (kWh or $)						
Fertilizers						
Calcium Nitrate - $Ca(NO_3)_2$ (kg)						
Potassium Nitrate - KNO_3 (kg)						
Monopotassium Phosphate - KH_2PO_4 (kg)						
Potassium Sulphate - K_2SO_4 (kg)						
Potassium Chloride - KCl (kg)						
Magnesium Sulphate - $MgSO_4$ (kg)						
Ammonium Nitrate - $(NH_4)(NO_3)$ (kg)						
Micronutrients (g)						
Water						
Irrigation water consumption (L)						
Growing Media						
Rockwool (kg)						
Coir or Coco Peat (kg)						
Other (kg)						
Packaging Material						

Corrugated cardboard (# or kg)						
Plastic (baskets, crates, clips, strings) (# or kg)						
Cultivation						
Plastic Film (LDPE) (t)						
Waste (organic, inorganic, landfill) (t)						
Compost (t)						
Pesticides						
Insecticides (insect and mite pests) (kg or L)						
Fungicide (diseases) (kg or L)						

Table 6.2 Upstream processes and data sources

Inventory Energy/Material	Database	Period	Geographic Region
	GREENHOUSE STRUCTURE		
Steel	US LCI/ US-EI v 2.2	2007	United States/ Europe, average
Aluminum	US LCI/ US-EI v 2.2	2007	North America, average/ Europe, average
Plastic	US-EI v 2.2	2000	Europe, average
Glass	US-EI v 2.2	2000	Europe, average
	ELECTRICITY		
Electricity Production/Distribution	US-EI v 2.2	2007	Europe, average
	FERTILIZATION		
Calcium Nitrate	US-EI v 2.2	2003	Europe, average
Potassium Nitrate	US-EI v 2.2	2004	Europe, average
Potassium Sulphate	US-EI v 2.2	2003	Europe, average
Potassium Chloride	US-EI v 2.2	2003	Europe, average
Magnesium Sulphate	US-EI v 2.2	2007	Europe, average
Ammonium Nitrate	US-EI v 2.2	2003	Europe, average
	HEATING		
Natural Gas	US-EI v 2.2	2000	Europe, average
Bunker Oil	US-EI v 2.2	2000	Switzerland
Wood Chips	US-EI v 2.2	N/A	Europe, average
	PACKAGING		
Cardboard	US-EI v 2.2	N/A	Europe, average
Plastic	US-EI v 2.2	2000	Europe, average
	PEST MANAGEMENT		
Insecticide	US-EI v 2.2	2010	Europe, average
Fungicide	US-EI v 2.2	2010	Europe, average
	SUBSTRATE		
Rockwool	US-EI v 2.2		Switzerland
Plastic Sleeve	US-EI v 2.2	2005	Europe, average
	WASTE		
Metals Landfill	US-EI v 2.2	2003	Switzerland
Rockwool Landfill	US-EI v 2.2	2003	Switzerland
	WATER USE		
Water Distribution	US-EI v 2.2	2005	Switzerland/Denmark
	TRANSPORTATION		
3.5-16 ton Truck	US-EI v 2.2	2007	Europe, average
Freight, rail Train	US-EI v 2.2	2003	Europe, average
Barge, Ship	US-EI v 2.2	2003	Netherlands/Germany

Table 6.3a Aggregated data collection sheet of all greenhouse participants

Process	Material/Energy Flow	Unit	AVG	STDEV	COV	STERR
Fertilizers	Calcium Nitrate - $Ca(NO_3)_2$	kg	46,091	68,339	148	11,720
	Potassium Nitrate - KNO_3	kg	44,030	47,004	107	8,061
	Potassium Sulphate - K_2SO_4	kg	3,480	3,959	114	679
	Potassium Chloride - KCl	kg	4,800	8,326	173	1,428
	Magnesium Sulphate - $MgSO_4$	kg	12,128	21,509	177	3,689
	Ammonium Nitrate - $(NH_4)(NO_3)$	kg	1,055	2,560	243	439
	Total	kg	117,483	151,412	129	25,967
	Micronutrients	g	1,326,055	2,730,324	206	468,247
Cultivation	Rockwool	kg	29,683	28,700	97	4,922
	Water Used	L	69,915,760	77,257,119	111	13,249,487
Pest Management	Insecticide Rate	kg	299.0	454	152	131
	Fungicide Rate	kg	266.3	413	155	119
Packaging	Cardboard Used	kg	456,611	358,111	78	107,975
	Packaging Plastics Used	kg	56,548	88,169	156	26,584
Waste	Plastic Film Roof (LDPE)	t	7.98	9.117	114	1.564
	Waste (inorganic, landfill)	t	200	197.4	99	33.86
	Waste (organic, landfill)	t	299	296.7	99	50.89
	Compost	t	212	222.9	105	70.50
	Plastic Sleeve Rockwool (LDPE)	t	2.14	2.149	100	0.369
Greenhouse Structure	Steel Used	kg	512,403	545,711	107	192,938
	Aluminum Used	kg	20,496	21,828	107	7,718
	Glass Used	kg	273281	291046	107	102900
	Plastic Used	kg	22773	24254	107	8575
	Size of Greenhouse	m2	60,954	64,916	107	22,951

Climate System	Natural gas	GJ	115,373	137,654	119	23,608
	Wood chips (waste wood)	kg				
	Bunker oil or #2 oil	GJ	13496	21326	158	3657
	Propane	m3				
	Coal	kg				
	Total	GJ	128,869	132514	103	22726
	Electricity consumption	kWh	1,107,100	1,336,524	121	229,212
Tomato Yield		kg	3,330,945	3,463,999	104	1,224,708

Table 6.3b Aggregated F.U. data collection sheet of all greenhouse participants

Process	Material/Energy Flow	Unit	FU (1kg)	STDEV	COV(%)	STERR
Fertilizers	Calcium Nitrate - $Ca(NO_3)_2$	kg	0.0117	9.19E-3	78	1.58E-3
	Potassium Nitrate - KNO_3	kg	0.0119	2.62E-3	22	4.49E-4
	Potassium Sulphate - K_2SO_4	kg	1.5E-3	1.24E-3	83	2.13E-4
	Potassium Chloride - KCl	kg	1.13E-3	8.58E-4	76	1.47E-4
	Magnesium Sulphate - $MgSO_4$	kg	3.18E-3	3.01E-3	95	5.15E-4
	Ammonium Nitrate - $(NH_4)(NO_3)$	kg	4.12E-4	7.70E-4	187	1.32E-4
	Total	kg	0.031	0.0134	44	0.002
	Micronutrients	g	0.258631	0.273	105	0.047
Cultivation	Rockwool	kg	9.69E-3	3.44E-3	36	5.91E-04
	Water Used	L	18.7	5.11	27	0.876
Pest Management	Insecticide Rate	kg	5E-5	3.80E-5	70	1E-5
	Fungicide Rate	kg	4E-5	4.04E-5	95	1E-5
Packaging	Cardboard Used	kg	0.084	6.53E-3	8	0.002
	Packaging Plastics Used	kg	0.006	8.09E-3	141	0.002

Waste	Plastic Film Roof (LDPE)	t	1.7E-6	7.37E-7	43	1.26E-7
	Waste (inorganic, landfill)	t	6.47E-5	1.85E-5	29	3.18E-6
	Waste (organic, landfill)	t	7.9E-5	5.64E-5	71	9.67E-6
	Compost	t	2.37E-5	1.91E-5	80	6.74E-6
	Plastic Sleeve Rockwool (LDPE)	t	9.66E-7	1.37E-6	142	2.34E-7
Greenhouse Structure	Steel Used	kg	0.153	0.0145	9.50	5.12E-3
	Aluminum Used	kg	6.1E-3	5.8E-4	9.50	2.05E-4
	Glass Used	kg	0.081	7.73E-3	9.50	2.73E-3
	Plastic Used	kg	6.78E-3	6.44E-4	9.50	2.28E-4
	Size of Greenhouse	m2				
Climate System	Natural gas	GJ	0.0299	0.0122	41	2.09E-3
	Wood chips (waste wood)	kg				
	Bunker oil or #2 oil	GJ	6.96E-3	0.0138	198	2.36E-3
	Propane	m3				
	Coal	kg				
	Total	GJ	0.0369	7.82E-3	21	1.34E-3
	Electricity consumption	kWh	0.272	0.085	31	0.0146

Table 6.4 Supplemental Data for LCA of greenhouse tomatoes in southwestern Ontario – with validation by Shalin Khosla OMAFARA greenhouse vegetable specialist.

Type of Data	Units	Source
STRUCTURE		
Steel	75,000 lbs/acre	DeCloet Greenhouses
Aluminum	3,000 lbs/acre	DeCloet Greenhouses
Plastic	100,000 ft^2/acre 1 lbs/30ft^2	DeCloet Greenhouses
Glass	50,000 ft^2/acre 0.8 lbs/ft^2	DeCloet Greenhouses

PACKAGING		
Plastic Clips	100 = 0.23 lbs	Hydro-gardens.com/growsup1.htm
String	10,000 ft = 11 lbs	Hydro-gardens.com/growsup1.htm
Accordions or Arch Support	500 = 6 lbs	Hydro-gardens.com/growsup1.htm
Cardboard Boxes (60 x 40 x 15 cm)	0.6 kg	Hydro-gardens.com/growsup1.htm
ROCKWOOL		
90-100 x 20 cm slab	0.955 kg	Grodan.com
Plastic Sleeve	0.045 kg	Grodan.com
WASTE		
Plastic Roof	1.33 t/ha/year	OMAFRA, 2002a
Plant Debris	40 t/ha/year	OMAFRA, 2002a

Table 6.5 Comparison of environmental impacts for electricity between greenhouses per F.U. (kg)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	0.0842	0.0300	2.74E-04	9.92E-09	1.63E-04	3.45
Greenhouse 2	0.125	0.0446	4.06E-04	1.47E-08	2.42E-04	5.12
Greenhouse 3	0.0525	0.0187	1.70E-04	6.18E-09	1.01E-04	2.15
Greenhouse 4	0.114	0.0408	3.72E-04	1.35E-08	2.21E-04	4.69
Greenhouse 5	0.0616	0.0220	2.00E-04	7.26E-09	1.19E-04	2.52
Greenhouse 6	0.0806	0.0287	2.62E-04	9.49E-09	1.56E-04	3.30
Greenhouse 7	0.0659	0.0235	2.14E-04	7.77E-09	1.27E-04	2.70
Greenhouse 8	0.0647	0.0230	2.10E-04	7.62E-09	1.25E-04	2.65

Table 6.6 Comparison of environmental impacts for fertilization between greenhouses per F.U. (kg)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	0.235	0.0456	2.16E-04	1.2E-08	3.57E-04	1.66
Greenhouse 2	0.357	0.0762	4.27E-04	2.23E-08	5.17E-04	3.18
Greenhouse 3	0.331	0.0645	2.88E-04	1.58E-08	5.11E-04	2.19
Greenhouse 4	0.338	0.0664	3.32E-04	1.81E-08	5.05E-04	2.53
Greenhouse 5	0.150	0.0310	1.59E-04	8.61E-09	2.25E-04	1.20
Greenhouse 6	0.241	0.0452	1.81E-04	1.05E-08	3.80E-04	1.43
Greenhouse 7	0.205	0.0380	1.44E-04	8.42E-09	3.19E-04	1.13
Greenhouse 8	0.294	0.0570	2.62E-04	1.46E-08	4.48E-04	2.02

Table 6.7 Comparison of environmental impacts for heating between greenhouses per F.U. (kg)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	1.74	0.111	3.69E-04	2.82E-07	1.35E-03	33.7
Greenhouse 2	2.63	0.137	3.63E-04	4.33E-07	1.91E-03	52.9
Greenhouse 3	2.54	0.224	9.42E-04	3.97E-07	2.24E-03	44.6
Greenhouse 4	2.44	0.128	3.37E-04	4.02E-07	1.78E-03	49.2
Greenhouse 5	2.37	0.124	3.28E-04	3.91E-07	1.73E-03	47.8
Greenhouse 6	2.22	0.116	3.06E-04	3.65E-07	1.61E-03	44.7
Greenhouse 7	2.15	0.156	5.81E-04	3.45E-07	1.76E-03	40.3
Greenhouse 8	3.54	0.336	1.47E-03	5.48E-07	3.23E-03	60.5

Table 6.8 Comparison of environmental impacts for substrate between greenhouses per F.U. (kg)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	0.0143	5.30E-03	3.86E-05	5.38E-10	3.45E-05	0.249
Greenhouse 2	0.0169	6.27E-03	4.56E-05	6.36E-10	4.08E-05	0.295
Greenhouse 3	0.0142	5.26E-03	3.83E-05	5.35E-10	3.43E-05	0.247
Greenhouse 4	0.0075	2.77E-03	2.02E-05	2.82E-10	1.81E-05	0.130
Greenhouse 5	0.0182	6.75E-03	4.91E-05	6.85E-10	4.4E-05	0.317
Greenhouse 6	0.0154	5.73E-03	4.17E-05	5.82E-10	3.73E-05	0.269
Greenhouse 7	0.0157	5.84E-03	4.25E-05	5.93E-10	3.8E-05	0.274
Greenhouse 8	0.0136	5.06E-03	3.68E-05	5.14E-10	3.3E-05	0.238

Table 6.9 Comparison of environmental impacts for water use between greenhouses per F.U. (kg)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	6.03E-03	1.98E-03	2.05E-05	1.88E-10	1.32E-05	0.0951
Greenhouse 2	8.51E-03	2.79E-03	2.89E-05	2.65E-10	1.85E-05	0.134
Greenhouse 3	0.0120	3.93E-03	4.08E-05	3.73E-10	2.61E-05	0.189
Greenhouse 4	9.94E-03	3.26E-03	3.38E-05	3.1E-10	2.17E-05	0.157
Greenhouse 5	8.16E-03	2.68E-03	2.78E-05	2.54E-10	1.78E-05	0.129
Greenhouse 6	5.38E-03	1.76E-03	1.83E-05	1.68E-10	1.17E-05	0.0849
Greenhouse 7	7.25E-03	2.38E-03	2.47E-05	2.26E-10	1.58E-05	0.114
Greenhouse 8	8.77E-03	2.87E-03	2.98E-05	2.73E-10	1.91E-05	0.138

Table 6.10 Comparison of environmental impacts for waste between greenhouses per F.U. (kg)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	4.62E-03	1.93E-03	8.58E-06	6.19E-10	3.53E-05	0.0780
Greenhouse 2	4.63E-03	1.89E-03	8.51E-06	6.76E-10	3.47E-05	0.0815
Greenhouse 3	6.89E-03	3.01E-03	1.32E-05	8.07E-10	5.47E-05	0.111
Greenhouse 4	4.54E-03	1.94E-03	8.51E-06	5.6E-10	3.52E-05	0.0741
Greenhouse 5	3.98E-03	1.62E-03	7.42E-06	6.01E-10	2.96E-05	0.0716
Greenhouse 6	3.19E-03	1.32E-03	6.11E-06	4.8E-10	2.4E-05	0.0578
Greenhouse 7	7.49E-03	3.08E-03	1.33E-05	9.92E-10	5.68E-05	0.124
Greenhouse 8	5.28E-03	2.17E-03	9.63E-06	7.25E-10	4E-05	0.0897

Table 6.11 Comparison of environmental impacts for electricity between greenhouses per F.U. (m^2)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	5.10	1.81	0.0166	6E-07	9.84E-03	209
Greenhouse 2	6.77	2.41	0.0220	7.98E-07	0.0131	277
Greenhouse 3	3.14	1.12	0.0102	3.7E-07	6.07E-03	129
Greenhouse 4	5.98	2.13	0.0194	7.05E-07	0.0115	245
Greenhouse 5	2.87	1.02	9.32E-03	3.38E-07	5.54E-03	117
Greenhouse 6	4.70	1.67	0.0153	5.54E-07	9.07E-03	192
Greenhouse 7	3.39	1.21	0.0110	3.99E-07	6.54E-03	139
Greenhouse 8	3.88	1.38	0.0126	4.57E-07	7.48E-03	159

Table 6.12 Comparison of environmental impacts for fertilization between greenhouses per F.U. (m^2)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	14.2	2.76	0.0131	7.24E-07	0.0216	101
Greenhouse 2	19.4	4.15	0.0233	1.21E-06	0.0281	173
Greenhouse 3	19.9	3.87	0.0172	9.44E-07	0.0307	132
Greenhouse 4	17.7	3.48	0.0174	9.47E-07	0.0265	133
Greenhouse 5	6.76	1.41	7.24E-03	3.92E-07	0.0101	54.8
Greenhouse 6	14.1	2.64	0.0106	6.15E-07	0.0222	83.4
Greenhouse 7	10.6	1.96	7.42E-03	4.35E-07	0.0165	58.4
Greenhouse 8	17.6	3.41	0.0157	8.74E-07	0.0268	121

Table 6.13 Comparison of environmental impacts for heating between greenhouses per F.U. (m^2)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	104	6.62	0.0221	1.68E-05	0.0806	2004
Greenhouse 2	142	7.43	0.0196	2.34E-05	0.103	2864
Greenhouse 3	152	13.4	0.0565	2.38E-05	0.134	2671
Greenhouse 4	130	6.78	0.0179	2.14E-05	0.0944	2615
Greenhouse 5	111	5.81	0.0154	1.83E-05	0.0809	2242
Greenhouse 6	130	6.78	0.0179	2.14E-05	0.0944	2615
Greenhouse 7	113	8.16	0.0302	1.8E-05	0.0918	2110
Greenhouse 8	211	20.2	0.0883	3.26E-05	0.193	3601

Table 6.14 Comparison of environmental impacts for substrate between greenhouses per F.U. (m^2)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	0.865	0.321	2.33E-03	3.26E-08	2.09E-03	15.1
Greenhouse 2	0.919	0.341	2.48E-03	3.46E-08	2.22E-03	16.0
Greenhouse 3	0.852	0.316	2.30E-03	3.21E-08	2.06E-03	14.9
Greenhouse 4	0.391	0.145	1.06E-03	1.47E-08	9.46E-04	6.82
Greenhouse 5	0.852	0.316	2.30E-03	3.21E-08	2.06E-03	14.9
Greenhouse 6	0.908	0.337	2.45E-03	3.42E-08	2.19E-03	15.8
Greenhouse 7	0.808	0.300	2.18E-03	3.05E-08	1.95E-03	14.1
Greenhouse 8	0.818	0.304	2.21E-03	3.08E-08	1.98E-03	14.3

Table 6.15 Comparison of environmental impacts for water use between greenhouses per F.U. (m^2)

Impact category	GW	AD	EU	OD	SM	CED
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	0.364	0.119	1.24E-03	1.13E-08	7.93E-04	5.74
Greenhouse 2	0.460	0.151	1.57E-03	1.43E-08	1.00E-03	7.26
Greenhouse 3	0.720	0.236	2.45E-03	2.24E-08	1.57E-03	11.3
Greenhouse 4	0.520	0.170	1.77E-03	1.62E-08	1.13E-03	8.20
Greenhouse 5	0.383	0.126	1.30E-03	1.19E-08	8.36E-04	6.04
Greenhouse 6	0.315	0.103	1.07E-03	9.8E-09	6.86E-04	4.96
Greenhouse 7	0.373	0.122	1.27E-03	1.16E-08	8.14E-04	5.89
Greenhouse 8	0.526	0.172	1.79E-03	1.64E-08	1.15E-03	8.29

Table 6.16 Comparison of environmental impacts for waste between greenhouses per F.U. (m^2)

Impact category	**GW**	**AD**	**EU**	**OD**	**SM**	**CED**
Unit	kg CO_2 eq	H+ moles eq	kg N eq	kg CFC-11 eq	g NO_x eq	MJ eq
Greenhouse 1	0.273	0.113	5.05E-04	3.77E-08	2.07E-03	4.68
Greenhouse 2	0.240	0.0976	4.39E-04	3.5E-08	1.79E-03	4.21
Greenhouse 3	0.443	0.194	8.54E-04	5.18E-08	3.51E-03	7.12
Greenhouse 4	0.203	0.0847	3.71E-04	2.64E-08	1.54E-03	3.36
Greenhouse 5	0.198	0.0805	3.69E-04	2.99E-08	1.47E-03	3.56
Greenhouse 6	0.197	0.0812	3.74E-04	2.9E-08	1.48E-03	3.52
Greenhouse 7	0.360	0.146	6.34E-04	4.98E-08	2.70E-03	6.07
Greenhouse 8	0.273	0.113	5.05E-04	3.77E-08	2.07E-03	4.68