The Pennsylvania State University

The Graduate School

College of Agricultural Sciences

COMPARISON OF THE POTENTIAL ENVIRONMENTAL IMPACTS OF MICROWAVE PHYTOSANITARY TREATMENT OF WOODEN PALLETS TO CONVENTIONAL HEAT AND METHYL BROMIDE TREATMENTS

A Thesis in

Forest Resources

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2011

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ABSTRACT

In this thesis, a Life Cycle Analysis (LCA) of phytosanitary treatment of wooden pallets with microwave (MW) heating is presented. The focus of the LCA in this study is on the phytosanitary treatments of Grocery Manufacturers' Association (GMA) wooden pallets. Wooden pallets are used in most international deliveries and they are prone to pest infestation, serving as a pathway for the introduction and spread of pests to living trees. The current ISPM 15 guideline requires wood packaging materials to be either heat treated or fumigated with methyl bromide. These two currently approved methods have their advantages and disadvantages. Conventional heat treating is believed to have the highest impacts in some environmental categories and methyl bromide is being phased out due to its ozone depleting properties. There is a big debate about selecting a phytosanitary treatment method that has less environmental impacts and is less expensive. Temperature required to kill a particular pest and the amount of time needed are two important issues that needs to be considered since they control the amount of impacts a treatment method might have on the environment. The time required to reach the kill temperature depends on many factors including the type of energy source used to generate the heat.

The goal of this study is to compare the amount of carbon footprint and emissions released from potential microwave phytosanitary treatment of wooden pallets to conventional heat treatment and methyl bromide fumigation. This goal is achieved by using a life cycle assessment database, which analyzes data collected from pallet manufacturing, treatment companies, and published articles and journals and then quantifies the atmospheric emissions resulting from microwave treatment of 48" x 40" GMA wooden pallets as projected by pilot studies of potential microwave pallet treating technology.

The life cycle of wooden pallets was modeled in SimaPro Software 7.1 for carbon footprint and environmental impacts calculations. A model of the product life cycle with all the environmental inputs and outputs during phytosanitary treatments was developed. To accomplish this, we collected data for the Life Cycle Inventory (LCI) phase, evaluated the significance of potential impacts on the environment to meet Life Cycle Impact Assessment (LCIA) requirement, and finally, interpreted the results from the LCI and LCIA.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would first like to express my gratitude towards my thesis adviser, Dr. Charles D. Ray for his time, patience, mentorship and advice during the completion of this thesis. In addition, I would like to thank Dr. Kelli Hoover and Dr. John J. Janowiak for being on my committee.

This research was largely funded by the United States Department of Agriculture's Methyl Bromide Transition Program. I thank this program for the opportunity.

My parents, Minoo and Saeed, have always been there for me with their love and support. Thanks to them for always motivating me to think big and follow my heart. I would like to thank my brother Mohammad, and my sister-in-law, Beheshteh, for their constant support.

Tremendous thanks go to my sister, Shideh, and my brother-in-law, Mehdi, to whom I am indebted for their guidance and support in my perusal of a post-graduate degree. Without their encouragement none of this would have been possible.

Last but not least, I would like to thank my friends, especially Okhtay, for their unwavering support and positivity.

Chapter 1

Introduction

In an ongoing effort to minimize cost and carbon footprint, pallet manufacturers are looking for the most effective, environmentally clean and economically viable treatment method for eradicating pests within wood packaging materials (WPMs), and wood or wood products (excluding paper products) used in supporting, protecting or carrying a commodity (including dunnages) (ISPM 15 , 2002). Products made from untreated wood can be potential pathways for the introduction of invasive pests causing billions of dollars in economic losses (Allard et al. , 2003). Therefore, the International Plant Protection Convention (IPPC) and Animal and Plant Health Inspection Service (APHIS), adopted the International Standards for Phytosanitary Treatments guidelines (ISPM 15) to prevent the spread of pests, decrease the risk of the introduction of pests and to kill pest infestations in export wood packaging applications. Hence, the treatment of WPMs is now mandated by the Food and Agriculture Organization (FAO) of the United Nations according to the guidelines.

The focus of this study is on comparing three pest treatment methods of wooden pallets including conventional Heat Treatment (HT), Methyl Bromide chemical Fumigation (MeBr) and Microwave induced Heat Treatment (MW). Heat treatment and methyl bromide fumigation are the two currently approved methods used in pallet manufacturing companies and microwave heat treatment is proposed to be an alternative treatment method. The comparison process in this research is done by using Life Cycle Assessment (LCA) methods.

Life cycle assessment is the examination, identification, and evaluation of the relevant environmental implications of a material, process, product, or system through its life from raw material to disposal at the end of its life. It is an objective process to evaluate the environmental burdens associated with a product by identifying and quantifying energy and material inputs and environmental outputs to affect environmental improvements.

Solid Wood Packaging Materials (SWPM) such as pallets, crates and boxes are covered by the rules of ISPM 15. A pallet is a flat transport structure, made of wood, plastic, paper, metal, steel or sometimes aluminum (**Figure 1.1**). The purpose of pallet production is to transport goods with the help of lift trucks in a safe and easy way. Goods and containers are placed on pallets, strapped onto them and transported in bulk units called unit loads. Besides different materials used to produce a pallet, there are different types and sizes of pallets used in different industries and even in different countries and continents.

Figure 1-1-a Wood Pallet

Figure 1-1-b Plastic Pallet

Figure 1-1-c Paper Pallet

Figure 1-1-d Metal Pallet

Figure 1-1-e Steel Pallet

Figure 1-1-f Aluminum Pallet

Figure 1.1. Pallet Types Based on Construction Type of Material

1.1. Pallet Classification

The National Wooden Pallet and Container Association (NWPCA) classifies pallets on the basis of size, class, type, style, material and general use application. In a pallet measurement two numbers are provided to designate stringer length (also known as pallet length) and deckboard length (also known as pallet width), respectively (**Figure 1.2**). The International Organization for Standardization (ISO) approved six pallet dimensions which are listed in **Table 1.1**. The most commonly used pallet size in North America is 48" x 40" and it is known as the Grocery Manufacturer Association (GMA) pallet. This pallet size has the highest production of 26.9% of the market followed by 4.8% of the market for 42" x 42" pallets commonly used in telecommunications and paints industry (Remmey Pallets , 2011).

Figure 1.2. Designation of Pallet Length and Pallet Width

There are two pallet classes, stringer-class pallet and block-class pallet (**Figure 1.3**). Stringer-class pallets have rectangular stringers that run the full length of the pallet and the top deck is nailed to the top edge of the stringer to make a single-face pallet. Block pallets on the other hand, have rectangular blocks (or cylindrical posts) as components that separate the top and bottom deck. Pallet construction varieties depend on pallet class.

Table 1.1. Pallet Dimensions (Pallets Unlimited, 2011)

Dimensions (in)	Region most used in
48 x 40	North America
39.37 x 47.24	Europe, Asia
45.87 x 45.87	Australia
42 x 42	North America, Europe, Asia
43.30 x 43.30	Asia
31.50 x 47.29	Europe

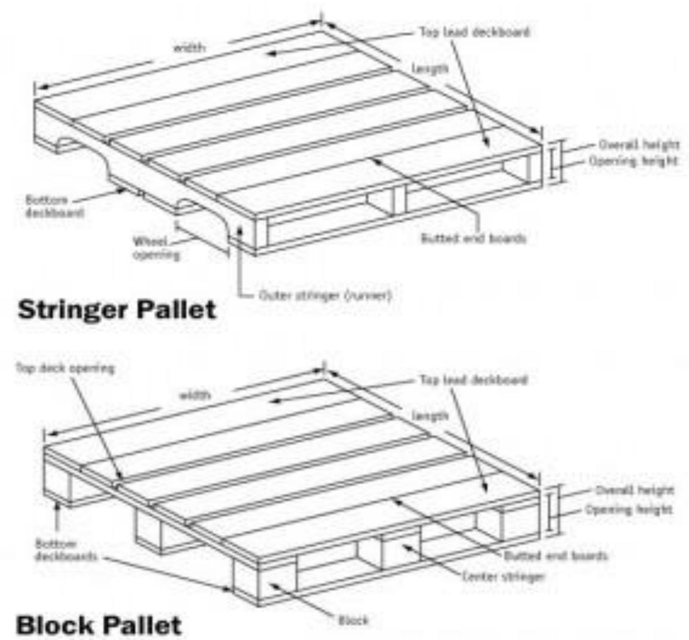

Figure 1.3. Illustration of Two Basic Pallet Classes

Pallet type defines the design of the pallet; it indicates how the pallet may be lifted by a lift truck or other equipment. Common types of pallets are two-way, partial four-way and full four-way pallets. Two-way and full four-way pallets are shown in **Figure 1.4**.

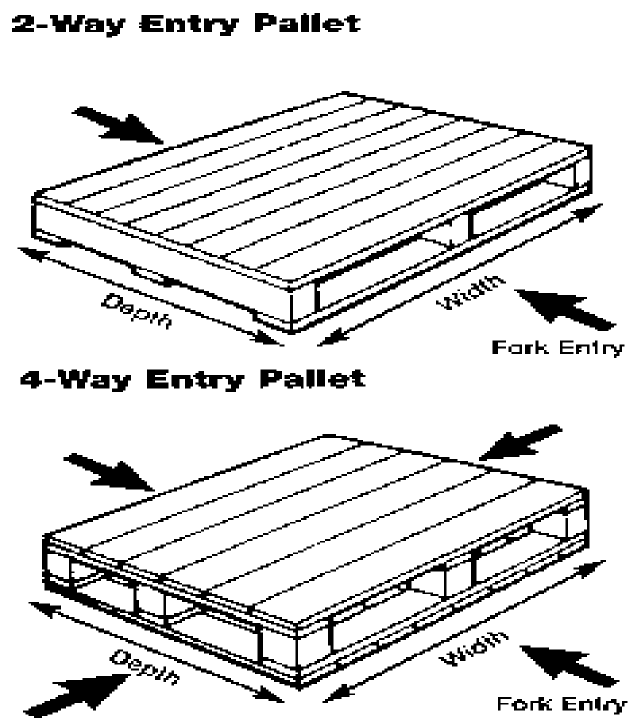

Figure 1.4. Two-way and Full Four-way Construction Pallet Types

Pallet style defines the basic construction style of an assembled pallet construction unit and it includes single-face, double-face non-reversible and double-face reversible pallets. Single-face pallets (also known as skids) have one deck, while double-face pallets have two decks.

Pallet use often delineated as limited-use and multiple-use. Limited-use pallets or single-use pallets are designed and used with a single unit load while multiple-use pallets are designed and used for repeated uses for more than one unit load. Multiple-use pallets typically have an extended life cycle, are designed for supply-chain recycling by pallet repair companies, and are used by pallet pool companies and independent pallet providers that supply durable pallets to the portion of the market that have higher unit-load requirements.

These classifications are mostly for wooden pallets which are the focus of this study.

1.2. Phytosanitary Treatment of Wooden Pallets

Most shipping pallets manufactured and used worldwide are made of hardwood and/or softwood lumber. Wooden pallets comprise roughly 90% of the world's current pool of pallets. Pallet stock is typically a low grade lumber by-product from a sawmill company, or it can be manufactured as the lumber from large re-sawn wooden cants produced at sawmill (Remmey Pallets , 2011; John Rock Inc. , 2011). If a used pallet cannot be repaired and reused, it must be recycled or sent to a landfill. The best option, of course, is pallet dismantling and recycling. The components of a used wood pallet at the end of its life are salvaged for reuse in other pallets or the wood is ground for use as landscape mulch, animal bedding, or wood stove pellets.

Fewer than 3% of the nearly 700 million pallets manufactured and repaired each year end up in landfills, the rest are either repaired or resold to pallet users according to a study by Virginia Polytechnic Institute and the USDA Forest Service (Bush et al. , 1997). Each year, 1.9 billion wooden pallets are in circulation in the United States, transporting a variety of goods (IFCO systems , 2011).

Wooden pallets can be impacted by forest pest infestation in their raw material. They are known to host Asian Longhorned Beetle (*Anoplophora glabripennis*), Pine Wood Nematode, and others. Therefore, they are required to be heat treated or fumigated with methyl bromide prior to international shipment to prevent pests from being transported internationally. Due to the international phasing out of methyl bromide use because of its significant contribution to ozone depletion, the development of alternative phytosanitary treatments for wooden pallets became imperative. One important factor in selecting a treatment method to replace methyl bromide fumigation is effectiveness of the treatment. As shown in **Figure 1.5**, phytosanitary treatment comprises a fairly small portion of the life cycle impact of the pallet products. However, finding alternatives to conventional heat treatment and methyl bromide fumigation can decrease the environmental damage caused by the air emissions from treatments and reduce heat release into the atmosphere.

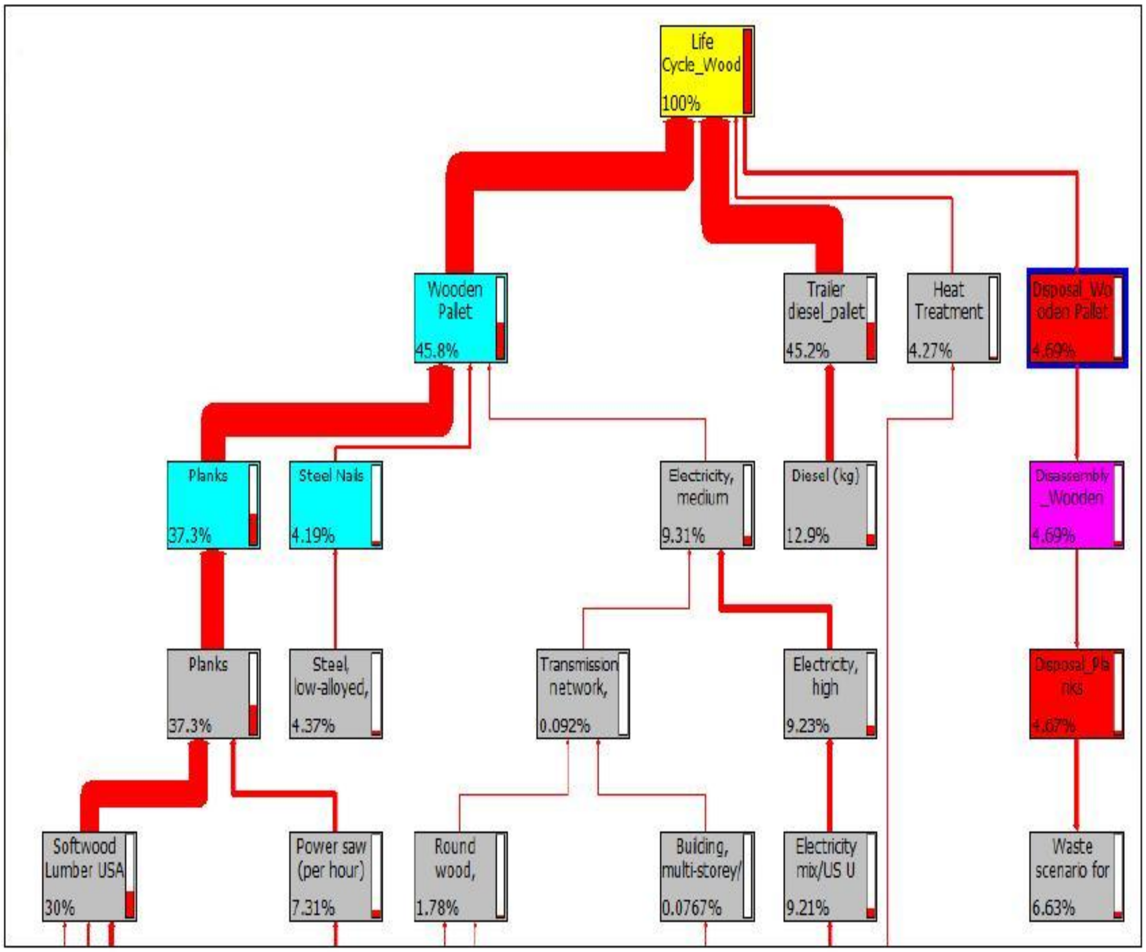

Figure 1.5. Network Flow of A Wooden Pallet Using Impact Assessment Method Eco-Indicator 99 In SimaPro (Anil , 2010)

Probit 9 mortality is a standard for treatment effectiveness that was adopted by the USDA for quarantine treatments. The Probit 9 mortality rate of the treated organisms or the efficacy of a treatment is as high as 99.9968329% which, if a confidence level of 95% is applied, would require no survivors in a minimum of 94,588 insects tested.

International Standards for Phytosanitary Measures No. 15 (ISPM 15), adopted by the IPPC, directly addresses the need to treat wood materials such as wooden pallets. According to this, every wood packaging material that has been heat treated or fumigated with methyl bromide using ISPM 15 standards must be stamped to indicate ISPM 15 compliance. The mark that is used to certify that the wood packaging material has been subjected to an approved treatment is shown in **Figure 1.6** where “XX” represents the ISO two-letter country code, “000” indicates the producer/treatment provider code which is assigned by the National Plant Protection Organization and “YY” represents the treatment code which is an International Plant Protection Convention abbreviation.

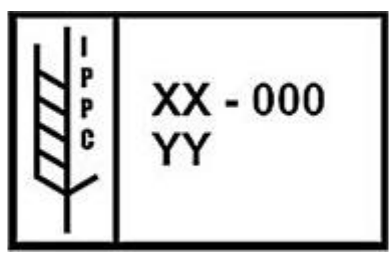

Figure 1.6. IPPC Stamp

1.2.1. Conventional Heat Treatment

The wood must be heated to achieve the core temperature of 56 °C (132.8 °F ~ 133 °F) and maintained for at least 30 minutes, based on ISPM 15 treating protocol. This process is carried out in a sterilization kiln, or heat treatment chamber. Various energy sources or processes may be suitable to achieve these parameters. For example, utilizing kiln-dried lumber, heat-enabled chemical pressure impregnation, microwave or other treatments may all be considered heat treatments provided that they meet the heat treatment parameters specified in this standard. Pallets treated with this method bear the initials HT in their IPPC stamp. The time to achieve the core temperature depends on the equipment used, size and design of the pallets, and wood material moisture content level. This process is costly due to the high capital investment requirement in large and expensive conventional ovens, and time consuming because it requires warm-up and cool-down periods in addition to the heating period requirement.

Another downside to this method is the way it heats the wood. The heating starts from the surface of the wood and penetrates the core by thermal conduction. This may lead to potential damage of the outer layer of the wood, in the form of checking or cracking. Also, in this process, heat is produced by a combustion source emits pollutants and greenhouse gases to the atmosphere. Also, slow rates of heating can result in the release of volatile organic compounds from the heated wood.

However, conventional heat treatment is considered a safer method to human health, in comparison with methyl bromide fumigation.

Figure 1.7 is a pallet kiln which carries out the conventional heat treatment of wooden pallets.

Figure 1.7. Pallet Kiln

1.2.2. Methyl Bromide Fumigation

If using a fumigant, the only fumigant permitted under the ISPM 15 standards is methyl bromide (**Figure 1.8**). Methyl bromide (CH_3Br) is a toxic material and a potent ozone depleting substance. Under the United Nation's Montreal Protocol and Clean Air Act, the U.S. Environmental Protection Agency (EPA) is strongly advocating that the chemical methyl bromide be phased out of use.

For methyl bromide treatment, the removal of bark must be carried out before treatment because the presence of bark on the wood affects the efficacy of the methyl bromide treatment (ISPM 15 , 2002). After bark removal, methyl bromide is sprayed on the surface of the wooden pallet. The minimum temperature of the wood and its surrounding atmosphere must be not less than 10 °C (50 °F) and the minimum exposure time must be not less than 24 hours. This process leads to the emission of methyl bromide gas, which is considered a Class I ozone depleting substance. Methyl bromide, also known as mono-bromo-methane, has effects on humans and other mammals, which appear to vary according to the intensity of exposure. At concentrations not immediately fatal, this chemical produces neurological symptoms (Environmental Protection Agency). High concentrations may bring about death through pulmonary injury and associated circulatory failure (MAF Biosecurity New Zealand , 2009). The onset of toxic symptoms is delayed, and the latent period may vary between 0.5 to 48 hours, according to the intensity of the exposure and the personal reaction of the patient (Von Oettingen 1955). Contact of the human skin with the liquid or strong concentrations of the MeBr gas may cause severe local blistering (Watrous , 1942).

Against insects, methyl bromide appears to exert its principal toxic effect on the nervous system. As in humans, the onset of poisoning symptoms may be delayed, and with many species of insects, definite conclusions as to the success of the treatment should be delayed for at least 24 hours. The comparative toxicity of this fumigant to successfully eradicate stored-product insects is given and discussed in (Hole , 1981) Chapter 14, Table 16.

Figure 1.8. Methyl Bromide Fumigation Application

Methyl bromide use in most phytosanitary treatment applications requires a relatively low capital investment, but the United States Department of Agriculture's Methyl Bromide Transitions Program supports the discovery and implementation of practical pest management alternatives to methyl bromide uses. The program seeks to ensure that economically viable and environmentally sound alternatives to methyl bromide are in place and available as soon as possible.

1.2.3. Microwave Heat Treatment

Dielectric heating methods are known to be faster and more energy efficient since they provide volumetric heating and the waves penetrate within the wood product causing the product to heat from inside to the outer layers. This may reduce potential damage due to checking and cracking as compared to conventional heat treatment. The use of microwave irradiation as a dielectric heating method to eradicate pests infested in wood products was described by Fleming et al. (2003, 2004, and 2005). The efficacy of microwaves were investigated by Fleming et al. (2005), using batch processing and continuous system to heat wood with microwaves. The continuous system consists of a roll conveyor which is an innovative microwave process modification that allows treating pallets in line by irradiating them while they pass on a roll conveyor or belt. The same thermal specification as in heat treatment can be achieved inserting the pallet inside a reverberation chamber operating at microwave frequencies. In particular the Industrial, Scientific, & Medical (ISM) radio frequency band assigned frequency of 2.45 GHz is used, because high power sources (magnetrons) are easily available for this frequency. **Figure 1.9** shows the industrial equipment used for this sterilization method. The stirrers shown in the picture reverberate the field in order to achieve a uniform power deposition on the pallet and the magnetron controls the delivered power.

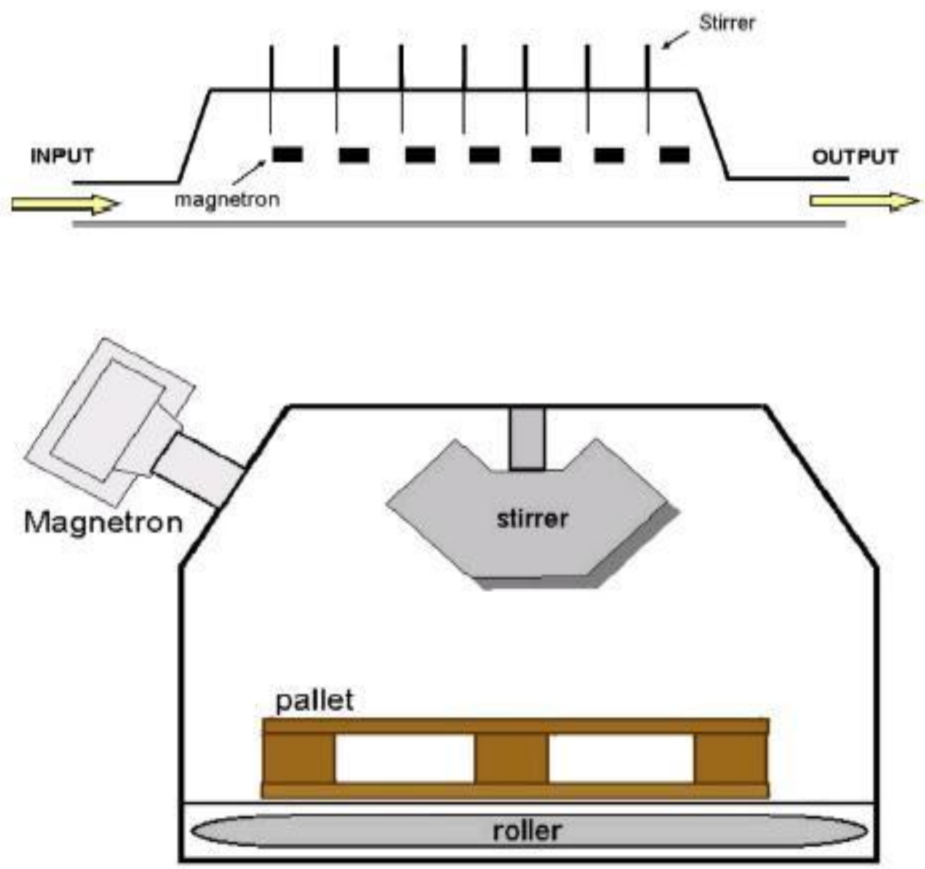

Figure 1.9. Reverberating Tunnel for Microwave Treatment of Wooden Pallets (De Leo et al. , 2006)

The studies and experiments showed that surface temperatures of 59.0-70.0 (estimated 62.2 °C) were lethal to specific pests under stationary microwave irradiation in a short time. **Figure 1.10** depicts the temperature pattern of a pallet after an exposure of 120 sec, using a delivered power of 2 kW.

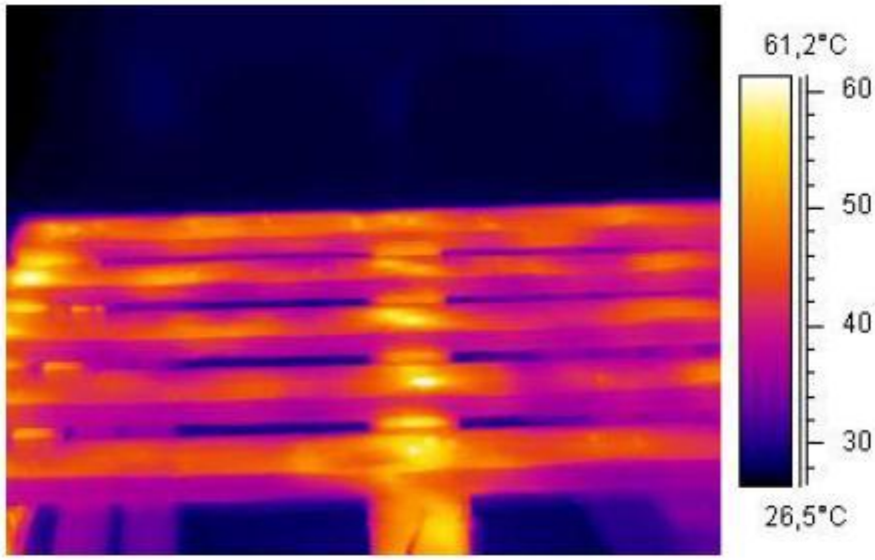

Figure 1.10. Infrared Temperature Pattern of a Pallet after Two Minutes of Exposure to MW Irradiation at 2kW Power (De Leo et al. , 2006)

In **Figure 1.11** the temperature-time history of a wooden pallet during microwave treatment with three different powers values is illustrated.

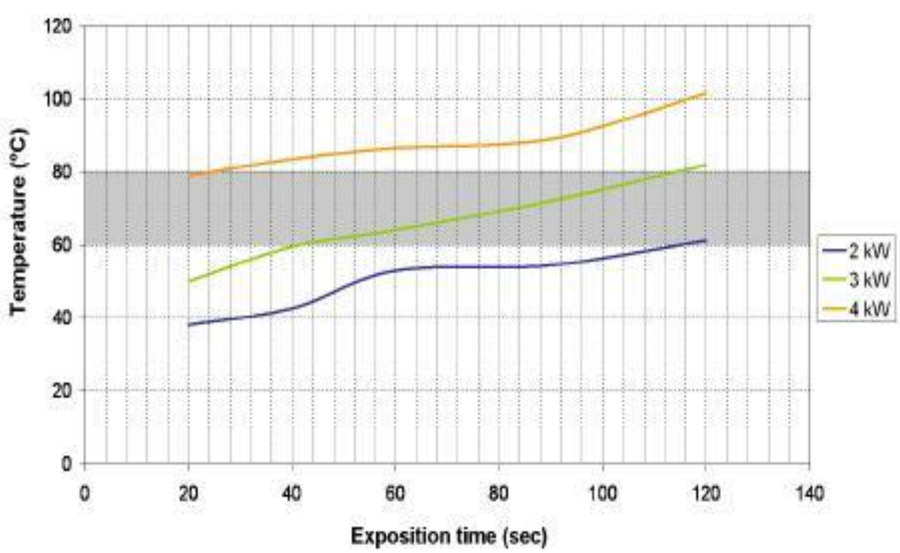

Figure 1.11. Temperature-Time History of a Wooden Pallet

The results also depicted that movement of the wood sample in the microwave field leads to higher efficacy of eradication which means lethal temperature was dropped to lower than 62 °C (Fleming et al. , 2005). Microwave heating can be the best environmentally viable alternative for treating pallets since it uses electrical energy, there is no combustion by-product, and it heats through the profile of the wood, and attains required temperature faster than conventional heat treatment. Because dielectric heating is volumetric, organisms infesting wood absorb MW energy at the same time that water in the wood does, so pests infesting wood are killed more quickly than by conventional heating (Nelson , 1996). It is also shown that microwave heating process has no pollution and electromagnetic safety because the irradiation is completely confined into the treatment chamber by the electromagnetic shielding (Bisceglia et al. , 2009).

1.3. Problem Description and Methodology

An environmental impact analysis is necessary to address the advantages and disadvantages of replacing currently used phytosanitary treatment methods with proposed treatment methods. Many pallet companies or treating companies in North America have already invested in a process; most are currently using conventional heat treatment. Replacing the treatment method may cost them at the beginning but will have less environmental impacts and may benefit them and their customers in the long run.

The methodology used in this study consisted of the following: defining the goal and scope of the project, which included the definition of functional unit, impact categories, system boundaries, and product system; and data collection for modeling the system according to a pallet production life cycle model was obtained from industry experts, academicians and published journals and papers to build a Life Cycle Inventory (LCI). Based on the results from LCI we evaluated the significance of potential environmental impacts of the above-mentioned stage to meet LCIA requirements. As the last step we interpreted the results from the LCI and LCIA.

Chapter 2

Review of Literature

A literature review was conducted to provide background information about phytosanitary treatments of wood packaging materials and to review the Life Cycle Analysis studies on wooden pallets. Previously published articles, journal papers, and other source materials with literature relevant to the topic, their findings and suggestions are reviewed here.

2.1. An overview of Phytosanitary Treatment of Wood Packaging Material

Solid wood packaging materials (pallets, boxes, packing blocks, crates, dunnage, load boards, etc.) are susceptible to pest infestation and it is necessary to treat them, to prevent the transportation and spread of diseases and insects. Major economic losses in agriculture were caused by the introduction of non-native species (Pimentel et al. , 2000). For instance, the introduction of Emerald Ash Borer (*Agrilus marcopoli or EAB*) into North America caused economic damage and loss (Kovacs et al. , 2010). Also, the USDA has predicted that Asian Longhorned Beetle could have severe economic, social, and ecological impacts on urban and natural forests of North American. The USDA estimated the potential national impact if ALB were to infest all urban centers of the United States to be a loss of 26.5% of the canopy cover and 30.7% of the urban trees equaling approximately 1.2 billion trees. This loss would carry a compensatory value of $522 billion (Nowak et al. , 2001). Therefore, all wood packaging materials (WPM's) should meet the International Standards for Phytosanitary Measurements (ISPM 15) and are to be treated before being used in global trade. ISPM recognizes solid wood packaging materials as an invasive species pathway and recommends sanitization through heat treatment or fumigation with methyl bromide (Schauwecker , 2007). In order to prevent further spread of pests, and the need for careful re-examination of the current heat treatment measures, the need to fully implement international standards on phytosanitary treatment of packaging wood is emphasized (Gu et al. , 2006).

Two approved processes that make wood products certified for this purpose are Heat Treatment and Methyl Bromide Fumigation. Radio Frequency (RF) heating and Microwave heating were proposed as two alternative heat treatments (Wang and Tang , 2001).

2.1.1. Conventional Heat Treatment

According to ISPM 15 (International Standards for Phytosanitary Measurements, Number 15), wood packaging material is required to be heated uniformly to a minimum wood core temperature of 56 °C (132.8 °F ~133 °F) for a minimum of 30 minutes. In the industry, a heat sterilization chamber (kiln) is used to heat lumber in pallets to achieve the temperature of 132.8 °F in the core for thirty minutes with the purpose of eradicating any living and environmentally significant pests (Remmey Pallets , 2011).

Bond (2005) has studied heat treatment of pallets following assembly. He found that a dry-heating schedule required a minimum of 80 minutes of heat-treating time for conventional stringer pallets and 165 minutes for block pallets. A steam-heating schedule required less time but still required a minimum of 65 minutes for conventional pallets and 100 minutes for block pallets.

Another study found that steam heating results in much faster heat treatment than dry heat. Heating times for dry heat were double or triple those for steam heating (Simpson 2001).

The heat treatment cost for wooden pallets including leasing costs, labor costs to operate the unit, and energy costs (the value added to the pallet for HT) is $0.90-$1.25/pallet (Kiln-Direct. , 2011).

The total carbon footprint generated from heat treatment of wooden pallets caused by the heat treatment of wood, the heat energy from LPG (Liquid Petroleum Gas) and due to the electricity (kWh) required for the operation of ovens is equal to 2.2 kg CO_2 per treated pallet (Anil , 2010).

2.1.2. Methyl Bromide Fumigation

Fumigation is a method of pest control and Methyl Bromide (CH_3Br) is one of the most widely known fumigants used to suffocate and/or poison targeted pests due to its penetrating ability, rapid efficacy, and high toxicity to invasive pests (Sai Pest Control Services , 2011). The wood packaging material should be fumigated with methyl bromide to the schedule that achieves the minimum concentration-time (CT) product for more than 24 hours, as shown in **Table 2.1**, prior to shipment. The treatment is indicated by the mark MB or MeBr.

As of 2009, ISPM 15 requires that the temperature be 52ºF or higher in order to fumigate wood packaging, and the minimum exposure time must be not less than 24 hours (International Plant Protection Convention (IPPC) , 2009).

Table 2.1. Minimum Standard for MB Fumigation (ISPM 15)

Temperature	CT ($g.h/m^3$) over 24 h	Minimum final concentration (g/m^3) after 24 h
21º C or above	650	24
16º C or above	800	28
11º C or above	900	32

The cost of methyl bromide fumigation of wooden pallets depends on the size and the number of pallets to be fumigated. It also depends on the location of the customer and whether stamping is required. The average price for the MeBr treatment has been stated as $1.69/pallet (Anil , 2010).

According to Anil's (2010) work, the total carbon footprint from the fumigation of a wooden pallet by methyl bromide is a 5.53 kg CO_2 equivalent per the treated pallet.

This pesticide is being phased out internationally under the Montreal Protocol due to concerns over its stratospheric ozone-depleting properties. It is proposed that developing countries will completely phase out its use in 2015 (UNEP. Methyl Bromide Technical Options Committee 2002), while it was 2005 for developed countries, except for allowable exemptions such as critical use exemptions agreed to by the Montreal Protocol Parties including the Quarantine and Pre-shipment (QPS) exemption, to eliminate quarantine pests and the Critical Use Exemption (CUE), for agricultural uses with no technically or economically feasible alternatives (UNEP , 2011)(UNEP. Methyl Bromide Technical Options Committee 2002)(UNEP , 2011). This scheduled phase out resulted in a significant U.S. Department of Agriculture (USDA) research program to find alternatives.

2.1.3. Dielectric Heating

High-frequency heating, also known as dielectric heating, is a technique in which radio wave or microwave electromagnetic radiation heats a dielectric material. Frequencies below 100 MHz (6-40 MHz) are considered radio frequencies (RF) and the properties above 500 MHz are known as microwaves (MW) (Resch 2009). The frequencies commonly used for microwave heat treatment of pallets are 915MHz and 2.45 GHz. The microwave irradiation generates a particular centrifugal heating that acts directly in the core of the materials and spreads outward ensuring a homogeneous heating of the object under treatment (Wilson , 2011).

Wilson et al. (2004) also determined the potential for phytosanitary treatment of green pallet parts with high-power radio frequency heating and they found RF heating a technically feasible method for phytosanitary treatment of pallet lumber without causing any damage to the lumber or degrading the quality of the lumber for pallet construction.

Dwinell et al. (1994) evaluated RF as a heat treatment for eradicating pinewood nematode (*Bursaphelenchus xylophilus*) in wood. Results showed that wood temperature and moisture content of wood are factors in mortality of the pest.

Zielonka and Gierlik (1999) presented a paper comparing conventional heat treatment and microwave wood heating. They pointed out that microwave heating increases the rate of evaporation because the energy is absorbed throughout the volume. On the other hand, conventional drying of wood is a slow conduction process. Also, they mentioned that heat in conventional drying methods penetrates through the material's surface while in microwave heating the energy directly transfers into the material and is absorbed by molecules and changes into heat.

The use of high frequency heating methods to kill pests in wood products was investigated using microwave by Fleming et al. (2003, 2004, and 2005). In 2003 they performed laboratory experiments on two different sizes of blocks of four native U.S. wood species and poplar which is the second most common wood used as WPM in China. The experiment results on the length of the irradiation periods showed that microwave heating is more efficacious than conventional heat treatment in eradicating Asian longhorned beetles (*Anoplophora glabripennis*) in solid WPMs. In 2004 they determined that among different microwave parameters, and under constant wood moisture content, energy density (total microwave power/wood volume) is the most acceptable parameter to predict mortality of Asian longhorned beetles larvae in laboratorysized wood samples exposed to 2.45 GHz microwave doses. Also, they mentioned that moisture content is a critical parameter to consider in scaling up from laboratory-scale experiments to commercial treatment processes. A year later, in 2005, this research group investigated the feasibility of using commercial 2.45 GHz microwave equipment to kill Asian longhorned beetle larvae and pinewood nematodes infesting lumber (Fleming et al. , 2005). In this study, a chamber unit for irradiation and a continuous conveying tunnel of microwave equipment were used. Results from this study showed that both methods achieved 100% mortality, but movement through a microwave field increased efficacy of eradication at lower wood temperatures.

Ambrogioni et al. (2005) found microwave irradiation thermal treatment to be very effective in producing temperatures lethal for pinewood nematode.

In 2008 a study was conducted to investigate the conventional and microwave heat treatment of wood for sanitary purposes of logs infested by emerald ash borers (*Agrilus planipennis or Agrilus marcopoli*) (Nzokou et al. , 2008). Antti and Perre (1999) suggested that this problem might be solved by the movement of lumber through a microwave field.

A study done by Henin et al. (2008) also proposed the tunnel oven for microwave treatment for eradication of pests. It also suggested that by measuring the wood's surface temperature, one might be able to control the treatment effectiveness of microwave irradiation.

The advantages of utilizing dielectric heating are fast and relatively uniform heat transfer, very high drying rates, and avoidance of various drying defects such as case hardening and discoloration of wood (Resch 2009). Electromagnetic energy has been studied to control insects in commodities for many years. Initial investigations using RF heating to control pests were conducted by Frings (1952), Thomas Jr et al. (1952) and Nelson (1996). (Hallman and Sharp , 1994) summarized RF and MW treatments that destroyed selected pests in post harvest food crops.

Table 2.2 shows RF and MW treatments of insects under different conditions and at different temperatures.

Table 2.2. Reported Radio Frequency and Microwave Heat Treatment for Different Products and Insects at Various Temperatures (Wang and Tang , 2001)

Frequency MHz	Temperature °C	Product (Insect)	Qualit Damage	References
27	56	Wheat (weevil)	No	(Anglade et al. , 1979)
	53	Walnut (codling moth)	Yes	(Wang et al. , 2001)
40	80	Pecan (weevil)	No	(Nelson and Payne , 1982)
915	55	Cherry (codling moth)	Yes	(Ikediala et al. , 1999)
915 & 2450	50-60	Cheese (microorganism)	Yes	(Herve et al. , 1998)
2450	45	Papaya (*D. dorsalis*)	No	(Hayes et al. , 1984)
	50	Fruit (Fruit fly)	Yes	(Sharp et al. , 1991)
	57	Wood (woodworm)	No	(Andreuccetti et al. , 1994)
	80	Cereal (weevil)	No	(Shayesteh and Barthakur , 1996)
12000-55000	43-61	Wheat (weevil)	No	(Halverson et al. , 1996)

For MW, because frequencies are much greater than for RF, fast heating can be achieved with lower field intensity (Nelson , 1996). However, dielectric heating seems to heat wood in an uneven manner (Fleming et al. , 2003).

Cost information is not available for RF heating because it is still in the experimental stages and not yet used in the industry. But according to Anil's (2010) work RF heating has a much lower estimated life-cycle cost than either conventional heat treatment or Methyl Bromide fumigation.

The carbon footprint of radio frequency treatment is relatively less than conventional heat treatment and any carbon footprint generated is because RF systems use electrical energy to heat wood. Therefore total carbon footprint from RF heating of a wooden pallet is 0.62 kg CO_2 equivalent per pallet (Anil , 2010).

2.2. Review of Previous Work Done on Life Cycle Analysis

Life cycle analysis (LCA) is a technique for assessing the potential environmental impacts and aspects associated with a product. It is about how much energy and material are used, and how much solid waste, liquid and gaseous waste is generated at each stage of the product's life cycle, which includes raw material extraction, energy acquisition, production and manufacturing, use, reuse, recycling, and ultimate disposal (Pennington et al. , 2004). It is important to also include all intervening transportation of the product. **Figure 2.1** illustrates the life cycle of a product.

Environmental impacts encompass all emissions into the environment throughout the consumption of resources, production of materials, manufacturing of the products, during use, and at the products' end-of-life. Global warming, climate change, stratospheric ozone depletion, acidification, eutrophication, toxicological stress on human health and ecosystems are some of the environmental impacts contributed by the emissions (Rebitzer et al. , 2004).

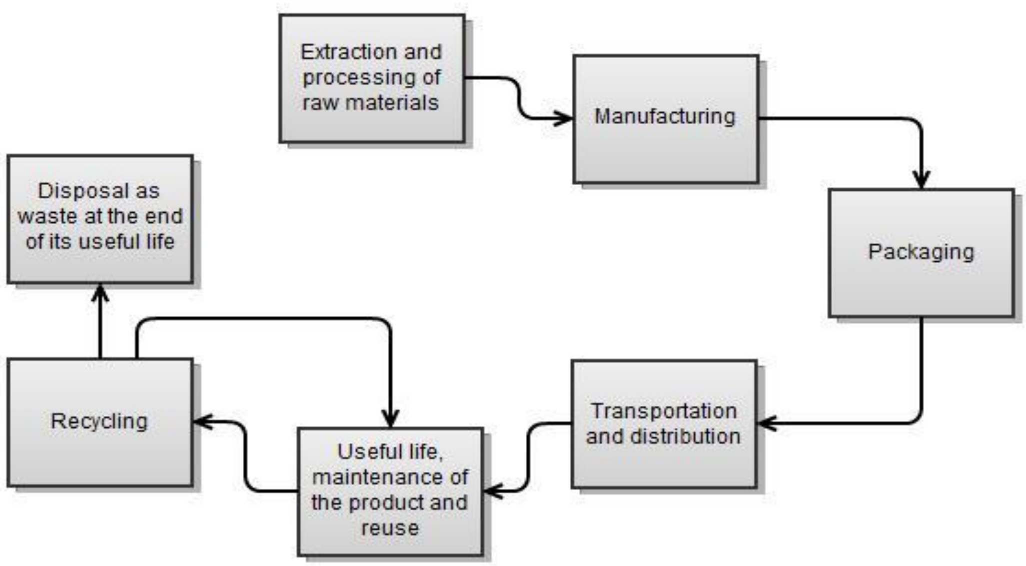

Figure 2.1. Life Cycle of a Product

The Life Cycle Assessment (LCA) process originally consisted of three sequential parts:

1. Life Cycle Inventory (LCI) quantifies the environmental inflows and outflows during the entire product life cycle.
2. Life Cycle Impact Assessment (LCIA) evaluates the significance of potential environmental impacts of the abovementioned stage.
3. Life Cycle improvement which focuses on reducing the environmental burden by using the results from the LCI and LCIA (Marano and Rogers , 1999).

Additional developments on LCA methodology are that the Goal and Scope Definition was added to the process. In this stage, the researcher outlines how to define and model a product's life cycle, and determine the system boundaries and the functional unit. It is also important to define the aim of the study and the potential use of the results. Other developments on LCA methodology are that life cycle improvement assessment is no longer considered as an independent stage in LCA methodology but as having influence on the whole analysis. Also, life cycle interpretation has been added which interacts with all other stages (Rebitzer et al. , 2004). **Figure 2.2** illustrates the life cycle assessment framework.

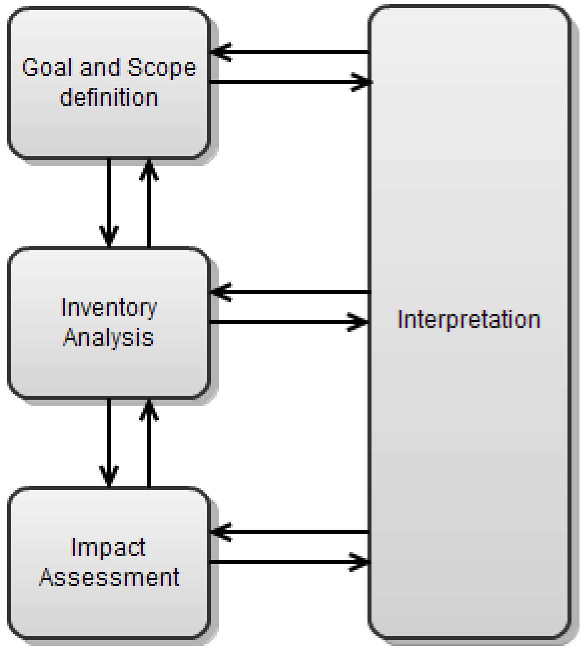

Figure 2.2. Life Cycle Assessment Framework

Different types of LCA are defined as follows:

- Cradle-to-grave: Life cycle analysis applied to the overall performance from manufacturing through the end-of-life (Jiménez-González et al. , 2004).
- Cradle-to-gate: Life cycle analysis applied to the overall efficiency of a product up to the point where it is delivered (Jiménez-González et al. , 2004).
- Cradle-to-cradle: Life cycle analysis applied for materials or products that are recycled into a new product at the end of its life. For products that are recycled and not disposed (Braungart et al. , 2007).
- Gate-to-gate: It only looks at one value-added process in the entire production chain. For example, in the production of softwood lumber, the gate-to-gate LCA system boundaries consider stages from the delivery of logs to the sawmill

complex to planed dry lumber and other co-products leaving the sawmill (Milota et al. , 2005).

2.3. Prior Life Cycle Analysis Studies on Wood Packaging Systems

Anil (2010) investigated and evaluated the environmental impacts incurred using a consequential life cycle analysis (LCA) to compare life cycle stages of wooden and plastic pallets. Significant emphasis of his study was placed on comparing heat treatment, methyl bromide fumigation and radio frequency (RF) heating to determine the most effective, environmentally clean, and economically viable treatment options. Anil found that plastic pallets incur large carbon footprints during the manufacturing phase, as opposed to wooden pallets that are relatively greener. It was also found that among the three treatment methods, methyl bromide fumigation incurred the maximum impact on global warming and ozone layer depletion. In all other impact assessment categories, heat treatment turned out to be the most impact-intensive method, and RF heating was seen to be an environmentally less intensive treatment method

Bergman and Bowe (2008) examined hardwood lumber manufacturing in sawmills of the northeastern United States using life cycle inventory. They standardized data to a per unit volume basis of 1.0 m^3 planed dry lumber.

Environmental Resources Management (2008) was retained by Intelligent Global Pooling Systems (iGPS) Company LLC to compare life cycle assessment of three types of GMA pallets commonly used in North America. The study approach was streamlined LCA with CML impact assessment method and the functional unit was 100,000 trips. The results of this study showed that the iGPS plastic pallet had lower environmental impacts in all impact categories compared to the typical pooled wooden pallet, and a substantially smaller environmental footprint than the single-use pallet. Incorporating a relatively small proportion (15% by weight) of recycled HDPE into the iGPS pallet further improved the environmental performance, while the 100% recycled HDPE pallet had a markedly smaller environmental footprint.

Barthel et al. (2007) analyzed and compared three different packaging materials (wooden boxes, foldable plastic boxes, and cardboard boxes) in Europe, using GaBi LCA-software, with respect to their environmental impacts. The results of this study are calculated for eight environmental indicators based on the CML 2001 method. The results of this study showed that the plastic crates and wooden boxes have almost similar impacts on the environment based on impact categories. They both have significant advantages compared to cardboard boxes.

A study conducted for CHEP (CHEP & Franklin Associates , 2007) compared and quantified resource and energy use, wastes and emissions associated with three different pallet systems (CHEP pooled wood pallet, GMA exchange wood pallet at six lifetime trips, GMA one-way wood pallet at 2 lifetime trips) through their whole life cycle. In this study, pallet systems were analyzed on the basis of 100,000 pallet loads of product delivered. The results showed that CHEP pallet systems produced much less production waste and recycling/disposal waste than exchange and one-way systems because of the high material efficiencies and controlled end-of-life management for CHEP pallets.

Ray et al. (2006) evaluated the financial components and relative advantages of rented and purchased GMA pallets. The results showed that rental pallets were more costly through the supply chain, with an average system cost of $5.56 per pallet trip compared to an average system cost for purchased pallets.

Milota et al. (2005) developed a study using gate-to-gate life cycle inventory of softwood lumber production. They standardized the data on the basis of 1.623 m^3 of planed, dry dimension lumber, which is equal to 1000 board feet (1 mbf) and is considered as the common unit in North America. The survey results were representative of the energy and material required to produce lumber. In the West and South, 53 and 41% of the log volume (3.05 and 3.92 m^3) leaves the mill as planed, dry dimension lumber, respectively. A much greater portion of the energy used for production in the South is produced on site from wood fuels. CO_2 emissions were greater in the South because of the wood fuel, 574 kg versus 419 kg per 1.623 m^3 produced.

Hischier et al. (2005) used the ecoinvent database to model the whole wood's life cycle/wood chain. This study gave an overview on how the wood and packaging material production is inventoried in ecoinvent. The conclusions of this study were that for wood, the database ecoinvent provides consistent datasets for the entire chain from forestry to intermediate products such as timber, different types of wood-based panels, chips, pellets, etc. For packaging materials, the number of datasets of basic materials has been extended. A modular concept for actual packaging container datasets allows the user an easy modeling of various types of packaging containers/boxes. In the area of paper and board, a comprehensive database for the production of various types of pulp, paper and panel is provided, which is representative of the average European production situation.

Lee and Xu (2004) conducted a simplified life cycle analysis to compare wooden pallets and recyclable plastic packaging system. The functional unit used in this study was environmental unit of the EPS 2000 default method, a unit of the plastic packaging system and a wooden pallet. Their LCA included raw materials extraction, manufacturing, transport, use, recycle and disposal phases of a single use wooden pallet and a plastic packaging system, Enviropak® T760. They concluded that in the case of the wooden pallet, truck transport, the corrugated cardboard boxes and the LDPE liner impacted the environment most, while for the plastic packaging system, truck transport and the LDPE liner were significant. Their results showed that the plastic packaging had a lower environmental impact than the wooden pallet for various reasons such as its weight which is lighter, having more re-usable parts and being able to transport more yogurt bottles per trip, its long service life and being virtually fully recyclable.

Scheerer et al. (1996) investigated alternatives in GMA pallet material substitution. The results illustrated that all companies responding to the questionnaire use wood pallets and some also use plastic pallets. The most common substitute for wood is plastic for cost savings. However, the majority of the companies at that time planned to continue using solid wood.

Singh and Walker (1995) conducted an LCA on different types of plastic and wooden pallets with the purpose of identifying the pallets that cost less, with longer lifetime trips without getting damaged, that are easily recyclable. The objectives of the study were to identify pallets that were less expensive, could survive a high number of trips without getting damaged, and that were lightweight and easily recyclable and lightweight. Twin sheet thermoformed HDPE plastic pallets were proven to have the highest performance, while press wood pallets had the lowest performance. Moreover, the plastic pallets were lightweight and nestable.

Bergman and Bowe (2008), Milota et al. (2005) and Wilson and Dancer (2005) used SimaPro to evaluate the life cycle inventory of different lumber productions. They used the software as the accounting program to track all the materials and to process the data and measure environmental impacts in terms of material use. They found the data useful as a benchmark for assessing process performance and for conducting life-cycle assessments of different assemblies.

Chapter 3

Research Question

After reviewing the existing literature on phytosanitary treatments and life cycle assessment of wood products and wooden pallets, it can be seen that no study has been done to evaluate or compare the environmental impacts of microwave phytosanitary treatments on wooden pallets using life cycle analysis.

In this research we conducted a life cycle analysis to compare environmental impacts of heat treatment, methyl bromide fumigation and microwave irradiation of wooden pallets to kill invasive organisms and pests. What we question here is whether microwave irradiation has less environmental impacts than conventional heat treatment and methyl bromide fumigation as two currently ISPM 15 approved processes. I hypothesize that MW will have a smaller carbon footprint. This hypothesis will be examined based on the material and energy input needed for these three different types of phytosanitary treatments and outputs produced during these processes, by using Life Cycle Assessment tools.

It must be noted that conventional heat treatment generates a large carbon footprint, while methyl bromide fumigation has an ozone-depleting potential and has been phased out from all its applications except for quarantine and pre-shipment purposes. Therefore, researchers have started to focus on dielectric heating as an alternative treatment method.

Lack of sufficient data on the environmental impacts and data to allow the International Plant Protection Commission (IPPC) to consider alternative technologies such as microwave treatment technologies were motivations for starting this study.

This research contributes to GMA pallet companies and United States Department of Agriculture by comparing conventional heating, methyl bromide fumigation, and MW heating, through a comprehensive evaluation of environmental impacts of treating wooden pallets with three optional methods, and by supporting the development of ISPM guideline to include dielectric heating as an alternative treatment option.

No statistical hypotheses or analyses will be utilized in the study, since microwave data to be used in the study are theoretical estimates based on exploratory prototype studies and resulting calculation, and only single data point estimates will be used. Future research should focus on analysis of data replicated for alternative microwave processing methods for wooden pallets, upon which statistical tests of significance can be conducted.

Chapter 4

Research Methodology

The methodology discussed is cradle-to-grave life cycle assessment, considering the treatment stage, to find information about the amount of environmental impacts created during treatment of wooden pallets.

The first step of the LCA involves defining the goal and scope of the study. Next, we build the LCA model by using data from the Life Cycle Inventory (LCI). Inventory analysis is followed by Impact Assessment (IA). Impact assessment methods are applied to determine the environmental effects of the data collected in the inventory. Results are then analyzed and interpreted.

4.1. Goals and scopes of the study

Our goal in this study is to determine and compare the environmental impacts of three different phytosanitary treatments applied to Grocery Manufacturers' Association wooden pallets, including heat treating, methyl bromide fumigation, and microwave heat treating; to support the development of ISPM guidelines to include dielectric heating as an alternative treatment option and to inform the industry about the environmental impact of potential microwave treatment technology relative to conventional heat treatment and use of methyl bromide.

The results of this research are proposed to help make a better decision on choosing the appropriate phytosanitary treatment, to evaluate the environmental impact of microwave energy for phytosanitary purposes, and to progress the process to the point of formal submission to

International Plant Protection Convention (IPPC). Results are also important to wood manufacturers, and their customers, who are considering reductions in carbon footprints and also to the countries that have agreed to follow ISPM 15 treatment control measures.

Our scope in this study is limited to the treatment stage of 48"x40" GMA wooden pallet. The idealized life cycle process map of wooden pallets is depicted in **Figure 4.1**. The expanded and more detailed process map is given in Appendix A.

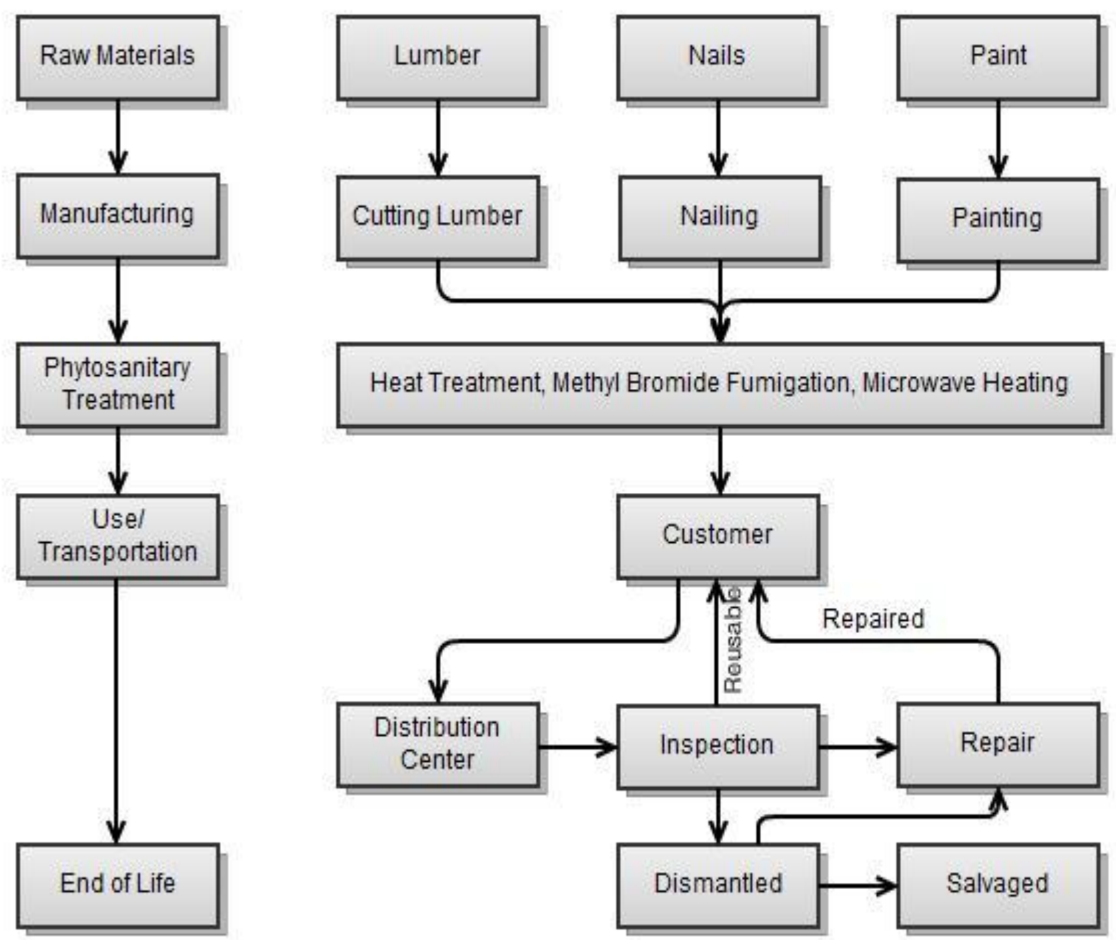

Figure 4.1. Idealized Process Map of Wooden Pallets Applied for the LCA study with focus on Phytosanitary Treatment for experimental investigation

As said, the focus of this research is specifically on the middle part of a pallet life cycle, which is the treatment of the wooden pallet. After pallets are manufactured, they are required to be treated to control significant pests and other potential pathogens from being transported in them. These treatment methods are called phytosanitary treatments shown to serve an adequate treatment to kill significant pest organisms e.g. Asian longhorned beetle *(Anoplophra glabripennis)*, pinewood nematode *(Bursaphelenchus xylophilus)* and bark beetles (Coleoptera: Curculionidae).

Heat treatment and methyl bromide fumigation are the only two currently approved processes under ISPM 15 for sterilizing wood packaging materials. Heat treatment is applied in heat chambers or conventional ovens until the core of wood material reaches a temperature of 56 °C (133 °F) and is kept at this temperature for at least 30 minutes. The energy for heat treatment is provided by fossil fuels and burning fossil fuels emits undesirable pollutants to the atmosphere. On the other hand, methyl bromide fumigation is applied by decontaminating a chamber full of wooden pallets in the fumigant for about 25 hours. Methyl bromide is a pesticide which will soon be phased out because it is one of the significant ozone depletion chemicals. These two methods both have environmental impacts; therefore alternative treatments such as dielectric heating, which have proved to be environmentally clean and effective in killing pests, are being considered.

The system boundary for this LCA study includes specifically and only the phytosanitary treatment process of the manufactured wooden pallet. We excluded all the processes and raw materials involved in the manufacture of pallet building components, transportation of raw materials to the pallet company, production of lumber, all manufacturing stages of the pallet such as lumber cutting, nailing and painting, manufacture and maintenance of phytosanitary treating equipment, transportation of treated pallets from the customer to the distribution centers and to the repair centers and all other transportations, and manufacture of vehicles involved in transportation and equipment for recycling. The logic of excluding these additional processes is that they do not differ relative to the process requirements of pallet treatment; this isolation of the difference in pallet treatment requires the assumption that pallets are identically produced and utilized.

Product system analyzed in this research is wooden pallets, treated with heat treatment, methyl bromide fumigation or microwave heating.

The functional unit used in this study to compare environmental impacts of different phytosanitary treatments is the experiment of one softwood pallet.

The impact categories represent environmental issues of concern to which life cycle inventory results may be assigned. The environmental issues related to global warming, climate change, toxic effects on humans and eco-systems, effects on natural resources and impacts of using fossil fuels were considered relevant to this study. The impact categories selected in each life cycle assessment have to describe the impacts caused by the products being considered or the product system being analyzed. In this study we selected the following impact categories and their characterization factors to evaluate the impacts during different treatment methods:

- Global Warming (Global Warming Potential)
- Stratospheric Ozone Depletion (Ozone Depleting Potential)
- Acidification (Acidification Potential)
- Eutrophication (Eutrophication Potential)

- Human Health (Lethal Concentration 50 – A standard measure of toxicity that will kill half of the population of a specific sample in a specific duration within a specific medium)
- Resource Depletion (Resource Depletion Potential)
- Terrestrial Toxicity (LC_{50})
- Aquatic Toxicity (LC_{50})
- Land Use (Land availability)
- Water Use (Water Shortage Potential)

Impact Assessment methods used in this study are Impact 2002+, Eco-Indicator 99 and CML 2001. These are Impact Assessment methods collection for conducting a Life Cycle Assessment project according to ISO standards. The Impact 2002+ impact assessment methodology combines midpoint and endpoint modeling approaches. It links all life cycle inventory exchanges to four endpoint categories using 14 midpoint categories. It involves new methodologies for comparative assessment of the human toxicity and eco-toxicity categories. Impact 2002+ includes some midpoint categories that are adapted from Eco-indicator 99 and CML 2001. Normalization is done at the midpoint or endpoint level. CML 2001 groups life cycle inventory results in so-called midpoint categories, according to themes and restricts quantitative modeling to relatively early stages in the cause-effect chain to limit uncertainties. The normalization data “CML 2001” have been calculated for the problem oriented life cycle assessment. CML 2001 also weights on the basis of individual chemical elements and not on the level of minerals (Guinee et al. , 1993). The impact categories defined in this method are: ozone layer depletion, human toxicity, fresh water aquatic eco-toxicity, marine aquatic eco-toxicity, terrestrial eco-toxicity, photochemical oxidation, global warming, acidification, abiotic depletion and eutrophication (PRé Consultants , 2009). Unlike CML 2001, Eco-Indicator 99 method uses a damage-oriented approach, which means this method does not weight the impact categories but the different types of damage that are caused by these impact categories. This model uses endpoint modeling and it is applied for the following impact categories: carcinogens, respiratory organics and respiratory inorganics, climate change, radiation, ozone layer depletion, eco-toxicity, acidification/eutrophication, land use, minerals and fossil fuels (PRé Consultants , 2009).

Figure 4.2. depicts a general structure of an impact assessment method with midpoints and endpoints. Endpoint environmental issues include human health, extinction of species, sea water level, dying forests, availability of resources in the future, etc. Eco-indicator 99 method uses endpoint modeling. Therefore, the impact categories selected in this study are linked to the endpoints selected.

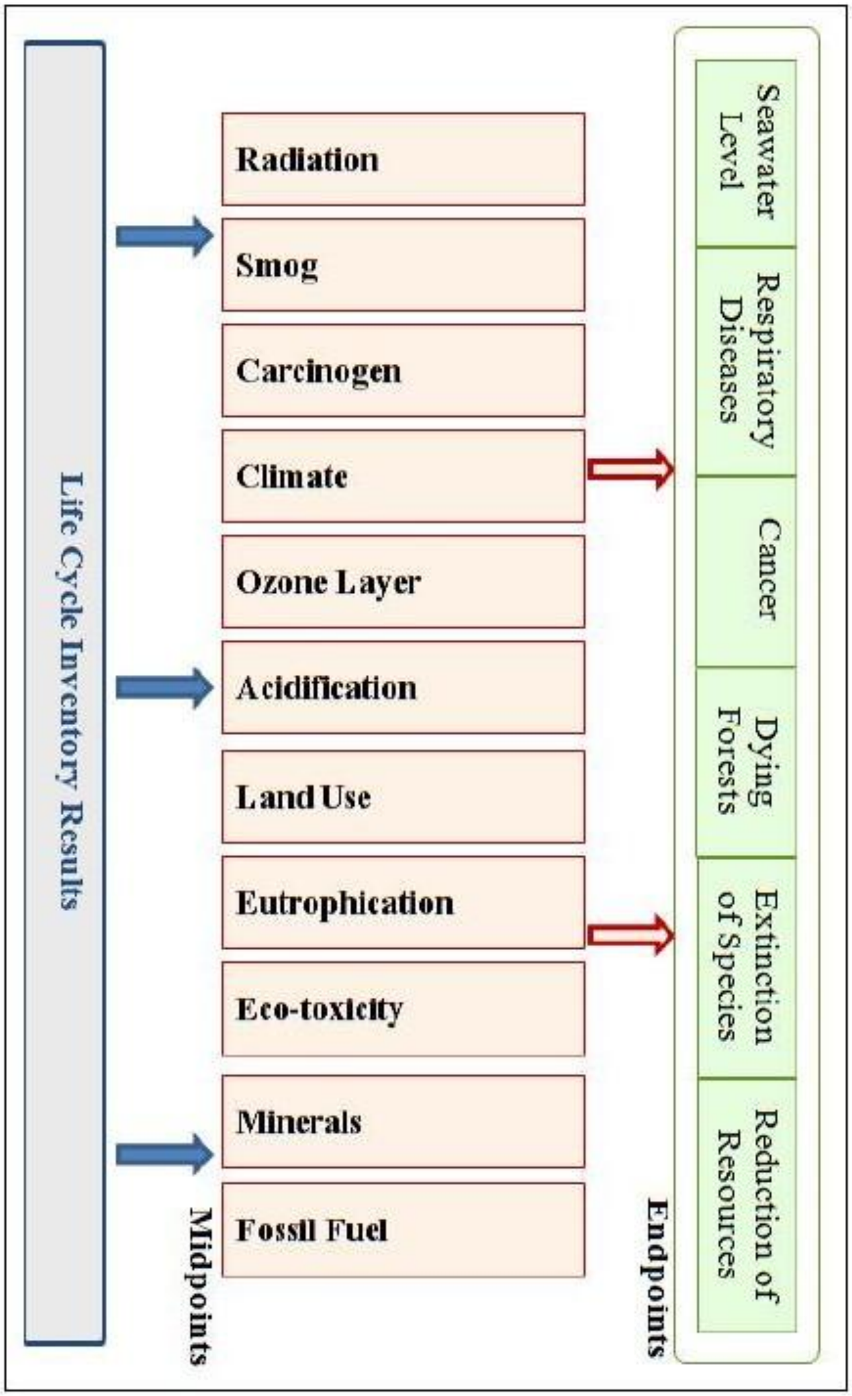

Figure 4.2. Overview of an Impact Assessment Method as Applied to the Experimental LCA Study

Data collecting utilized available wood pallet industry empirical data, from the time period of 1999 and later from industry experts, academic journals and LCA database. Sources of these data are North America, South and Central America and Europe to ensure that the results may be representatively applied for consideration of regulation around the world, since phytosanitary treatment of pallets is primarily applied to international shipment of products.

4.2. Life Cycle Inventory

An LCA model was built using data from energy and material consumptions and emissions to compile a life cycle inventory for this project. Data sources included SimaPro v7.2 software databases, data from pallet manufacturing companies, and published journal articles.

The goal of this study is to compare phytosanitary treatment methods. Therefore, the data collected was explicitly limited to the treatment stage of the life cycle of wooden pallets.

4.2.1. Heat Treatment of Pallets

Heat treatment of wooden pallets is done in specialized chambers. Required data are collected from pallet heat treating companies, which mostly use natural gas or propane for fuel. The heating system is capable of modulating heat from 50,000 Btu/hr to 2,000,000 Btu/hr (System model: Pest heat chamber Model # EC-300). The capacity of this chamber is 308 GMA pallets of 48”x42”. According to data received from a treating chamber manufacturer, one pallet requires fuel inputs of 1/20th of a gallon of Liquid Petroleum Gas. Each gallon of LPG fuel produces 95,475 Btu, thus each pallet requires 4775 Btu (Kiln-Direct. , 2011) equal to .

4.2.2. Methyl Bromide Fumigation

Methyl bromide (MeBr) fumigation is done by introducing the low vapor pressure methyl bromide into closed chambers with stacked pallets to allow gaseous chemical diffusion for up to 24 hours to kill pests. Typical MeBr application rates are 3-4 lbs/kft^3 for ISPM-15 standards. Most applications require fumigation at 3 lbs/kft^3. About 120 pallets (with average dimensions of 4 ft wide x 4 ft height x .5 ft height) would fit in each 1000 ft^3 of space. According to UNEP (1994), up to 88% of MeBr applied on durables such as timber is emitted into the atmosphere. MeBr has a global warming potential (GWP) of 5. Global warming potential is expressed as a factor of carbon dioxide (whose GWP is standardized to 1). The total carbon footprint of methyl bromide fumigation is 5.53 kg CO_2 equivalent per pallet (Anil , 2010).

4.2.3. Microwave Heat Treatment

The work on microwave treatment has been done largely in laboratory scale processes. The commercial microwave heat treatment can be delivered either by batch treatment or as a continuous process. Life cycle inventory for microwave heating was obtained from Remmey, the pallet company. Dielectric heating approaches wet wood in a different way than conventional heating. Microwaves heat the water in the wood and any organisms infesting the wood, which then heats the wood itself via conduction. The heated water molecules transfer heat through the profile of the material. For this discussion, the moisture content of wooden pallets is assumed to be 25%, 100% and 178%. Therefore, the amount of heat needed to heat a pallet would be as follows:

$$\text{Heat}_{wood} + \text{Heat}_{water}$$

Heat_{wood} = mass of wood * change in temperature * specific heat

$Heat_{water}$ = mass of water in sample * change in temperature * specific heat

Under these assumptions, the total amount of heat needed equals 76.72 Btu, 125.56 Btu and 148.22 Btu per pallet, correspondingly equal to 0.243, 0.397, 0.469 kWh of electrical energy (Wilson , 2011; Remmey Pallets , 2011; Anil , 2010).

Based on the literature, microwaves heat wood unevenly (Fleming et al. , 2003; Fleming et al. , 2005; Fleming et al. , 2004) and the penetration of microwave is lower in comparison with radio waves. On the other hand, microwaves can be effective and successful even in presence of metallic elements (nails, screws, etc.). Their overheating does not damage wood. Therefore, microwave heating is being considered as a reasonable alternative to conventional heat treatment and methyl bromide for large pallet manufacturers.

4.3. Life Cycle Impact Assessment

This life cycle analysis of wooden pallets has been conducted to calculate and compare the environmental impacts of the phytosanitary treatment methods. The calculations have been made using the Impact 2002+, Eco-Indicator 99 and CML 2001 optional environmental impact methods available in the SimaPro v7.2 LCA software. The environmental impact categories selected for the study were:

- Global warming: It is the increase of Earth’s average surface temperature due to effect of the emissions of greenhouse gases, such as carbon dioxide and water vapor, which trap heat that would otherwise escape from Earth.
- Ozone depletion: Deteriorating of the ozone layer due to the release of pollution containing the chemicals chlorine and bromine. This allows ultraviolet B rays to penetrate Earth’s atmosphere, which can cause skin cancer and cataracts in humans and also harm animals.

- Acidification: The decrease in the pH of water and soil due to the emission of acids and its compounds. This can cause the loss of essential plant nutrients and will affect aquatic life.
- Eutrophication: This category is defined as an increase in the rate of supply of organic matter in an eco-system. The nutrient enrichment will cause the growth of undesirable algae and aquatic weeds, which will cause a shortage in oxygen. This may occur naturally but can also be the result of human activity (from fertilizer runoff and sewage discharge) and is particularly evident in slow-moving rivers and shallow lakes. Increased sediment deposition can eventually raise the level of the lake or river bed, allowing land plants to colonize the edges, and eventually converting the area to dry land.
- Human health and toxicity: Human health refers to the effects of pollution on human body. Toxicity is used to describe how much exposure is needed to cause health effects.
- Resource depletion: This is a term referring to the exhaustion of raw materials within a region. Using raw materials beyond their rate of replacement is called resource depletion.

4.4. Carbon Footprint

Carbon footprint is a measure of the impact our activities have on the environment, and in particular climate change. It relates to the amount of greenhouse gases produced in our day-to-day lives through burning fossil fuels for electricity, heating and transportation etc. It is quantified using indicators such as Global Warming Potential (GWP), which is an indicator that reflects the relative effect of a greenhouse gas in terms of climate change considering a fixed time period, such as 100 years (GWP_{100}) (International Plant Protection Convention , 2002).

Wooden pallets are required to be heat treated to 56 °C (133 °F), and the temperature should be maintained for a minimum of 30 minutes. For this purpose, large conventional heat kilns are being used along with a combustion source that burns fossil fuel and emits pollutants. Total carbon footprint of conventionally heat treated wooden pallet is calculated based on carbon footprint calculations as follows:

- Amount of energy (Btu) contained in 1 gal. of LPG = 95,475 Btu
- Amount of Btu used by 1 pallet = $1/20^{th}$ of a gallon = 4774 Btu
- CO_2 emitted ($lb/10^6$ Btu) = 139 $lbs/10^6$ Btu = 0.000139 lbs/Btu
- Amount of emitted CO_2 for 1 pallet = 0.664 lbs CO_2 = 0.301 kg CO_2

Heat treatment of wooden pallets in heat treating chambers emits greenhouse gases such as carbon dioxide, carbon monoxide, oxides of nitrogen, methane and some other hydrocarbons. These emissions are then converted to CO_2 equivalents and indicated in the form of GWPs.

Based on SimaPro results, by using Eco-Indicator 99 impact assessment method, the total carbon footprint of heat treatment of a wooden pallet is 2.2 kg CO_2 equivalent, which is the sum of:

Carbon footprint from heat treatment of wood (0.609 kg CO_2) + Carbon footprint from the heat produced from LPG (0.657 kg CO_2) + Carbon footprint from electricity for operating ovens (0.942 kg CO_2) (Anil , 2010).

Methyl bromide fumigation of wooden pallets emits methyl bromide which is extremely toxic and is considered as a class I ozone-depleting substance. Depending on the amount of methyl bromide used for each fumigation job, the proportions of MeBr emitted to the atmosphere is estimated at approximately 70-80% of the applied chemical (Anil , 2010).

Based on SimaPro results, when using Eco-Indicator 99 method, the total carbon footprint caused by methyl bromide fumigation of 1 pallet is 5.53 kg CO_2 (Anil , 2010).

Microwave heat treatment of a wooden pallet uses electrical energy to heat the wood. It provides faster output processing, requires smaller heating equipment and uses less energy since it only heats the wood not the surrounding area so that all generated power is given to the pallets. Microwave heating is relatively clean, and any impact on the environment is due to the consumption and usage of electricity needed in the heating system (**Figure 4.3)**.

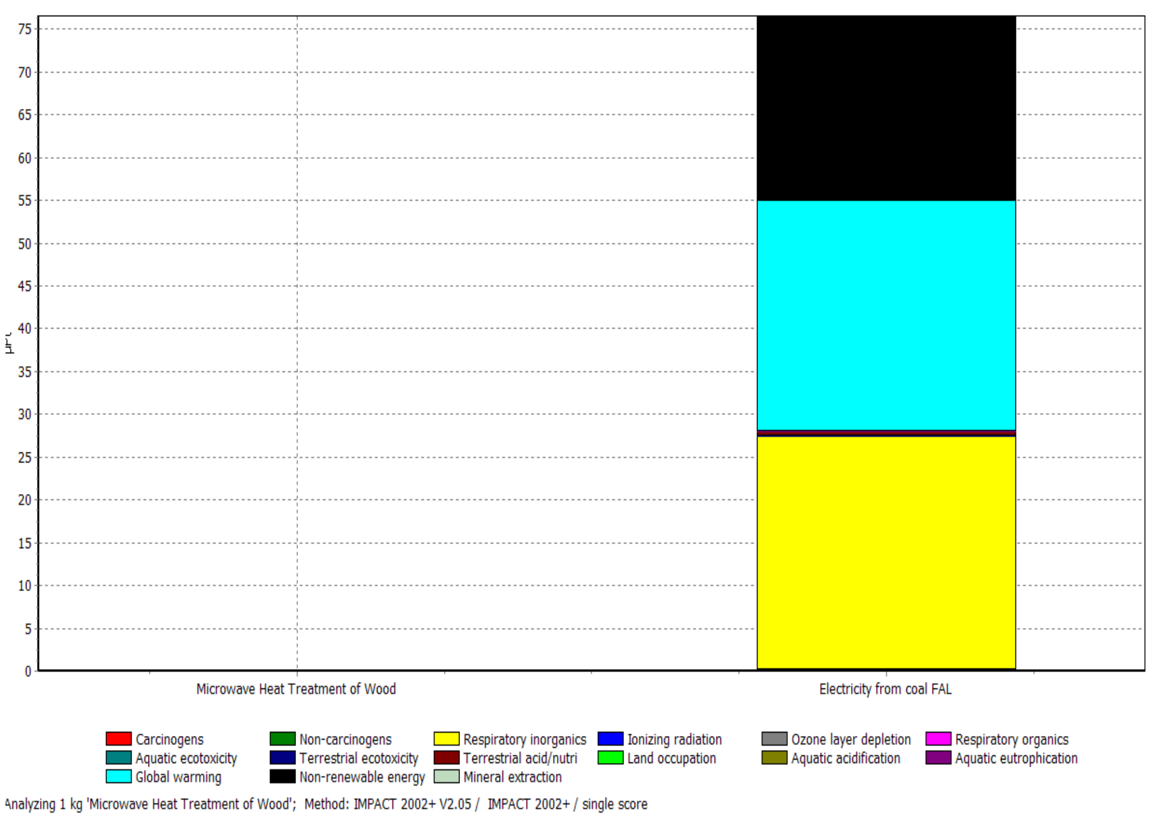

Figure 4.3. Impact Assessment of Microwave Heat Treatment of Wood (SimaPro)

The energy requirements for heating 1 kg of softwood with specific heat capacity of 1420 J/kg °K and 100% (25-178%) moisture from 70°F to 144°F can be calculated as follows. There are three different scenarios based on the moisture content of green wood. Other calculations can be found in Appendix F.

Total heat required to heat wood: Mass of dry wood x change in temperature x specific heat of wood

(1 Btu/lbs °F = 4186.8 J/kg °K)

1420 J/kg °K = 0.3391 Btu/lbs °F

Heat *wood* = 1.76 lbs x (144-70) °F x 0.3391 Btu/ lbs °F = 44.16 Btu

Scenario 1: Heat $water_{mc\ 25\%}$ = 0.44 lbs x (144-70) °F x 1 lbs^{-1}°F^{-1} = 32.56 Btu

Therefore, total heat needed to heat 1 kg of wood = 44.16 + 32.56 = **76.72 Btu**

1 Btu = 0.000293 kWh

Therefore, total equivalent electrical energy = 0.0225 kWh

Considering an efficiency of 60%,

Total electrical energy needed to heat 1 kg of wood = 0.0135 kWh

Total electrical energy needed to heat wooden pallet = **0.243 kWh**

Scenario 2: Heat $water_{mc\ 100\%}$ = 1.1 lbs x (144-70) °F x 1 lbs^{-1}°F^{-1} = 81.4 Btu

Therefore, total heat needed to heat 1 kg of wood = 44.16 + 81.4 = **125.56 Btu**

1 Btu = 0.000293 kWh

Therefore, total equivalent electrical energy = 0.037 kWh

Considering an efficiency of 60%,

Total electrical energy needed to heat 1 kg of wood = 0.022 kWh

Total electrical energy needed to heat wooden pallet = **0.397 kWh**

Scenario 3: Heat *water* $_{mc\ 178\%}$ = 1.41 lbs x (144-70) °F x 1 lbs^{-1}°F^{-1} = 104.06 Btu

Therefore, total heat needed to heat 1 kg of wood = 44.16 + 104.06 = **148.22 Btu**

1 Btu = 0.000293 kWh

Therefore, total equivalent electrical energy = 0.0434 kWh

Considering an efficiency of 60%,

Total electrical energy needed to heat 1 kg of wood = 0.0260 kWh

Total electrical energy needed to heat wooden pallet = **0.469 kWh**

The most common form of electricity used in North America is coal-based electricity, which was used in the model. It must be noted that the environmental impacts will be reduced if alternative energy sources such as hydro-electricity or nuclear-based energy are used. No emissions occur during the MW heating of wood and all environmental impacts happen during the extraction of electrical energy used in the process. The average weight of a 40" x 48" GMA pallet is 39.7 lbs (18 kg). Therefore, total carbon footprint or global warming impacts due to the MW heating of 1 green pallet with 100% moisture content is 0.608 kg CO_2 eq.

In the following chapter the total carbon footprint caused by microwave heat treatment in continuous systems is presented and is compared to the total carbon footprint produced by conventional heat treatment and methyl bromide fumigation.

Chapter 5

Research Findings

In this chapter the results of the life cycle analysis of phytosanitary treatments of wooden pallets are provided. The interpretation of impact assessment results is discussed as well. The aim of this chapter is to help manufacturers and treatment companies reduce the environmental impacts of their processes.

5.1. Life Cycle Assessment of Phytosanitary Treatment Methods

The life cycle analyses of three phytosanitary treatment methods of 48” x 40” GMA block type softwood pallets, including conventional thermal treatment, methyl bromide fumigation and microwave heat treatment were carried out using SimaPro LCA software. Data for all treatment methods were acquired from pallet companies, fumigators and heating equipment manufacturers. Data was modeled using the ecoinvent, Methods and Franklin USA databases in SimaPro but these databases did not contain information regarding MW heating and MeBr fumigation.

Table 5.1 illustrates the impact assessment results of treatment methods of a wooden pallet for each impact category and provides a source for comparing environmental burdens of each treatment method. **Figure 5.1** depicts the impact assessment results using Impact 2002+. The functional unit used for comparison was treatment of one pallet constructed of softwood lumber which includes approximately18 kg wood. Global warming potentials of conventional heat treatment and methyl bromide fumigation are 2.2 kg CO_2 eq. and 5.53 kg CO_2 eq. per pallet, respectively. For microwave treatment the global warming potential is 0.265 kg CO_2 eq., 0.433

kg CO_2 eq. and 0.511 kg CO_2 eq. per pallets for wood with 25% moisture content (MC), 100% MC and 178% MC, respectively. In certain categories, MW heating on wooden pallet with 178% moisture content causes more environmental impacts compared with methyl bromide fumigation such as terrestrial acidity, aquatic acidification and aquatic eutrophication. In the non-renewable energy assessment, all three scenarios of microwave heat treatment have more impacts on the environment than methyl bromide fumigation. That is due to the high electricity demand, generated from coal, to produce microwave energy to heat wood. However, methyl bromide is being phased out and it had the highest ozone-depletion impact and the highest global warming impact among the three treatments. Therefore, it is a less preferred option than MW or conventional heating in relation to these criteria.

Table 5.1. Impact Assessment Results Applying Impact 2002+

Impact Category	**Unit**	**HT**	**MeBr**	**MW Electricity from Coal Scenario 1**	**MW Electricity from Coal Scenario 2**	**MW Electricity from Coal Scenario 3**
Carcinogens	kg C_2H_3Cl eq	0 062	0. 4	0.0000522	0.0000853	0.000101
Ozone Layer Depletion	kg CFC-11 eq	2.70E-08	3.40E-03	3.70E-09	5.51E-09	6.51E-09
Aquatic eco-toxicity	kg TEG water	81.962	5.588	0.0294	0.048	0.0567
Terrestrial eco-toxicity	kg TEG soil	14.395	0.935	0.0495	0.0809	0.0956
Terrestrial Acidity	kg SO_2 eq	0.019	0.0011	0.00704	0.0115	0.0136
Land occupation	m2org.arable	0.0023	0.00016	0	0	0
Aquatic Acidification	kg SO_2 eq	0.0073	0.00044	0.00237	0.00387	0.00457
Aquatic Eutrophication	kg PO_4 P-lim	7.70E-06	5.00E-07	1.34E-06	2.20E-06	2.59E-06
Global Warming	kg CO_2 eq	2.2	5.528	0.265	0.433	0.511
Non-renewable energy	MJ primary	20.323	1.057	3.25	5.32	6.28
Mineral Extraction	MJ surplus	0.0019	0.00013	0	0	0

Other results that compare heat treatment, methyl bromide fumigation, and radio frequency using other assessment methods and graphs depicting these results are shown in Appendices. Some of this information is taken from the literature to compare impacts of radio frequency treatment on the environment with microwave heat treatment impacts.

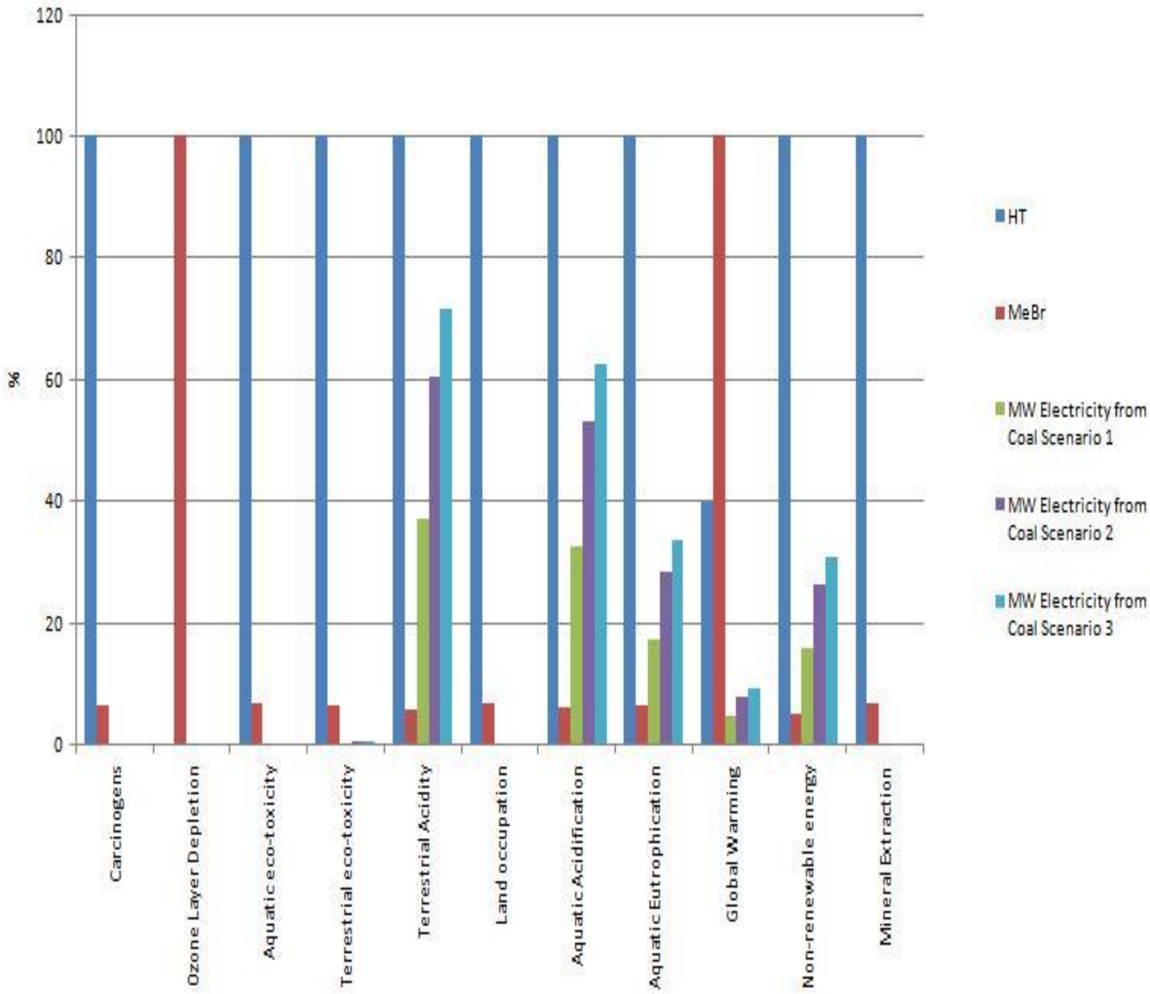

Figure 5.1. Impact Assessment Results using CML 2002+ Method (Normalized)

Figure 5.2 shows the global warming potential of each treatment method. It can be seen that fumigation incurs the maximum carbon footprint among other treatment methods.

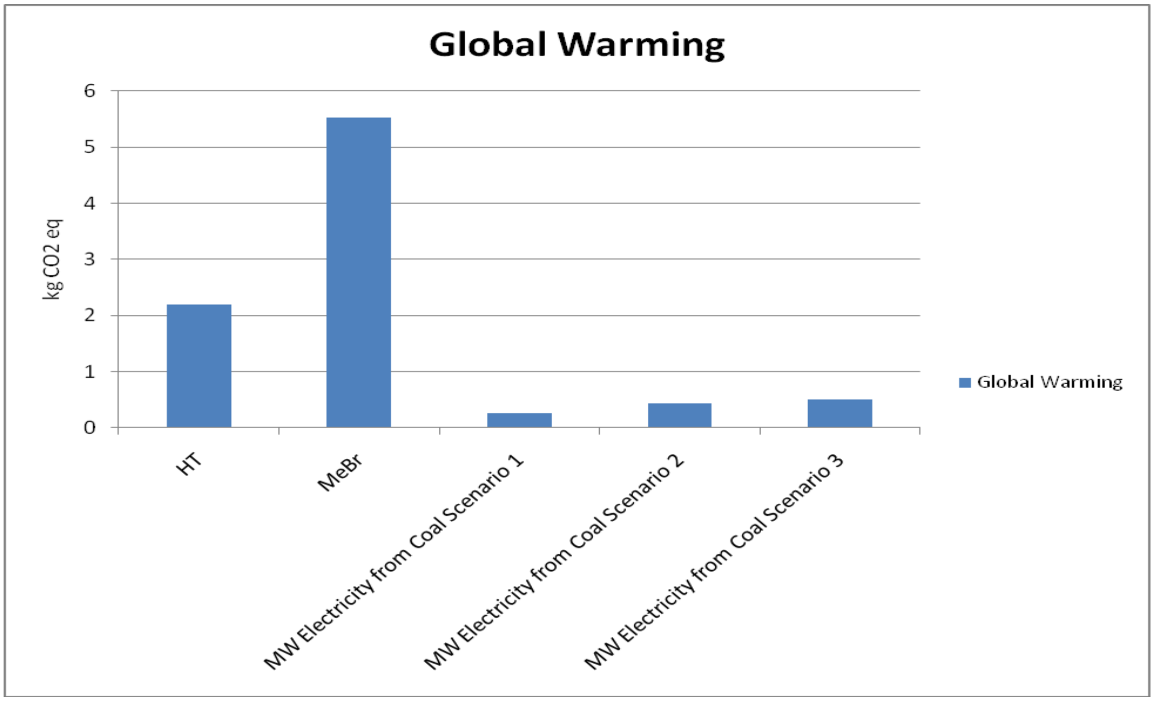

Figure 5.2. Global Warming Potential for Comparison of MW, Conventional HT and MeBr Phytosanitary Treatment

Figure 5.3 shows the ozone layer depleting potential of each treatment method. It can be seen that methyl bromide fumigation has the most contribution to depleting of the ozone layer. Conventional heat treatment, after methyl bromide fumigation, has the most impact on the ozone layer.

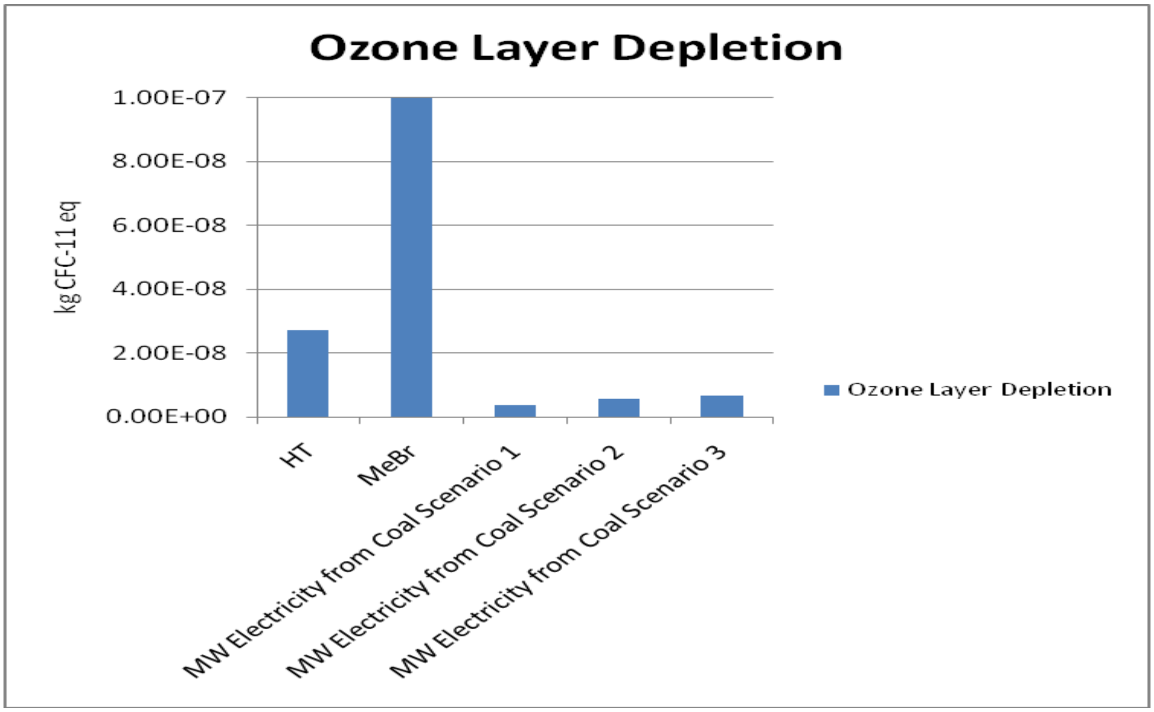

Figure 5.3. Ozone Layer Depletion for Comparison of MW, Conventional HT and MeBr Phytosanitary Treatment

Figure 5.4 and **Figure 5.5** illustrate the difference in impact assessment results from three different microwave heat treatment scenarios. As it is shown in the graphs, increases in the moisture content of wood lead to increases in the environmental impacts of microwave heat treatment of wooden pallets. This result is expected given that the greater moisture content, the longer it takes to heat the wood to lethal temperatures. However, the same pattern would hold for conventional heat treatment.

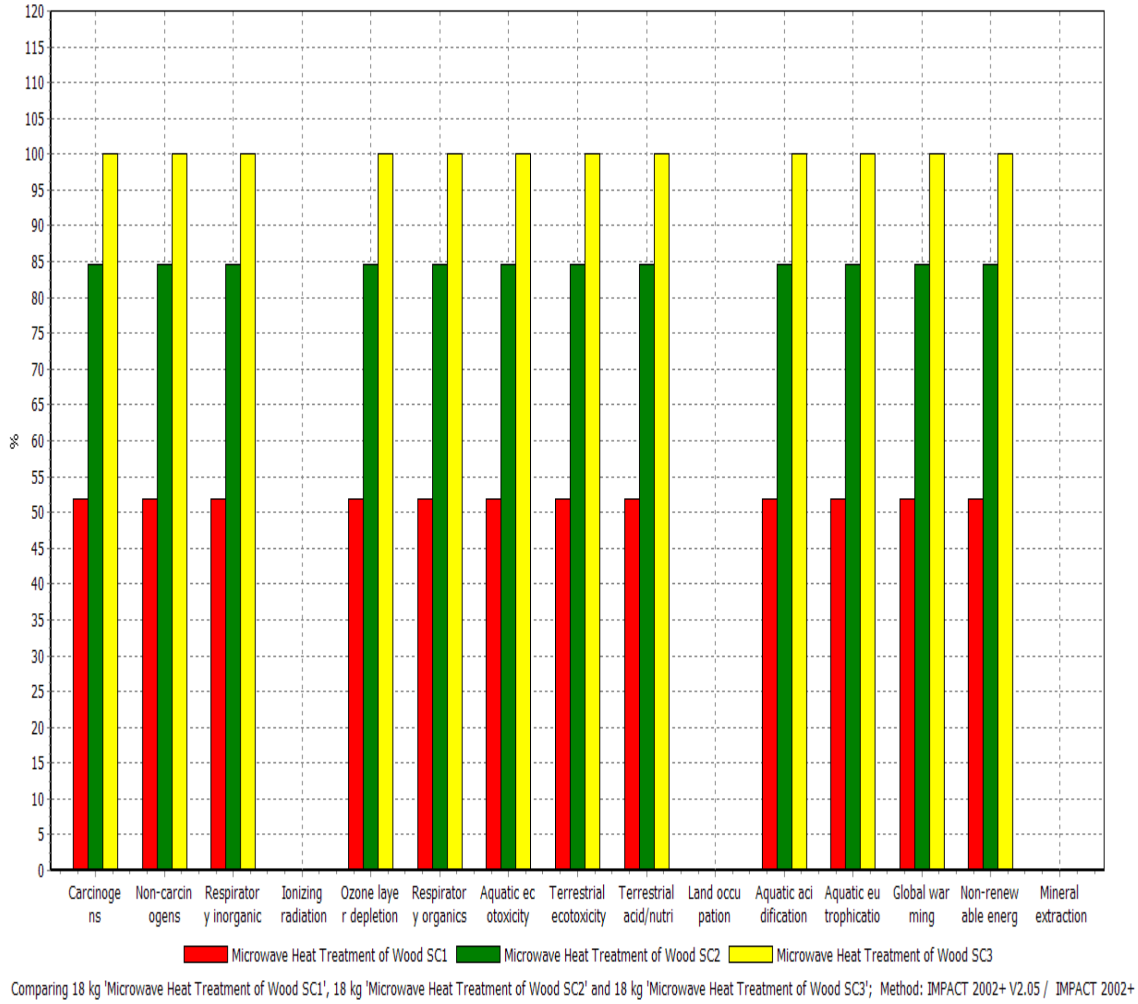

Figure 5.4. Impact Assessment Results Using Impact 2002+ for Microwave Heat Treatment Relative to the Three Wood MC Scenarios

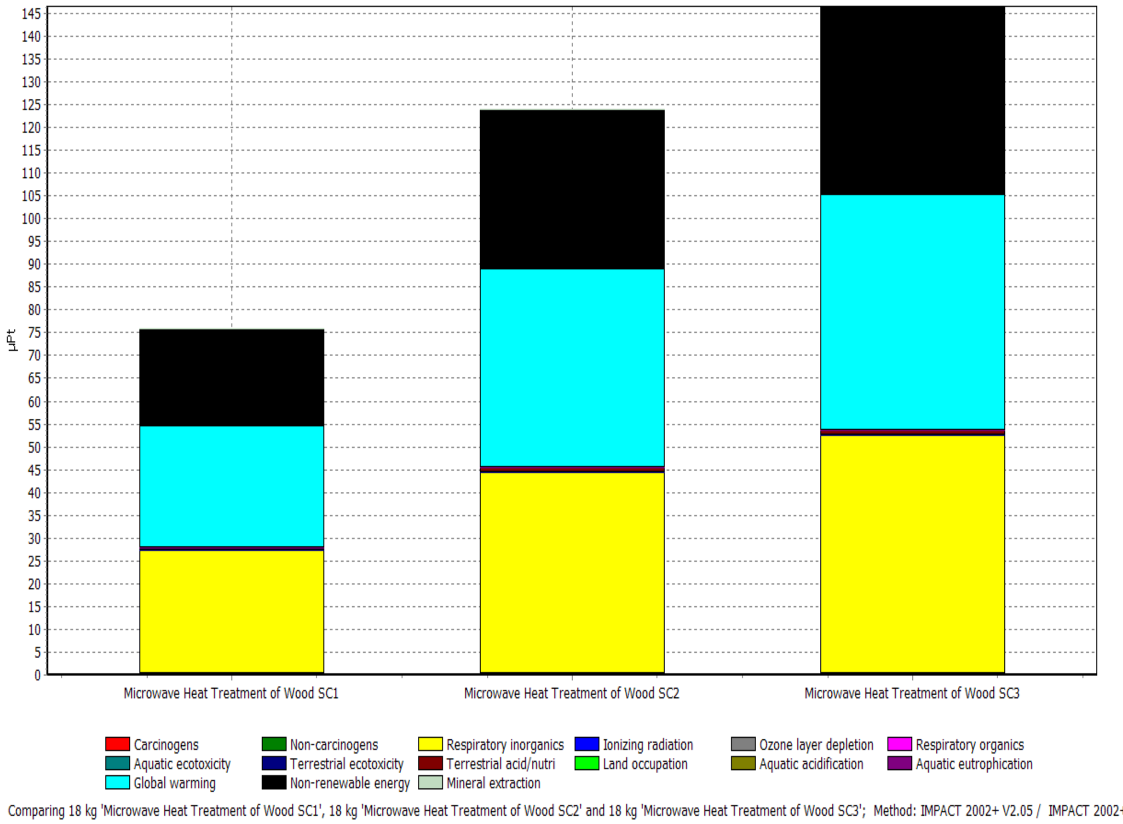

Figure 5.5. Single Score Impact Assessment Results Using Impact 2002+ for Microwave Heat Treatment Relative to Three Wood MC Scenarios

Figures 5.6, **5.7** and **5.8** show the impact assessments of each microwave heat treatment scenario individually. These graphs are results from using Impact 2002+ impact assessment methods in SimaPro 7.1 LCA software.

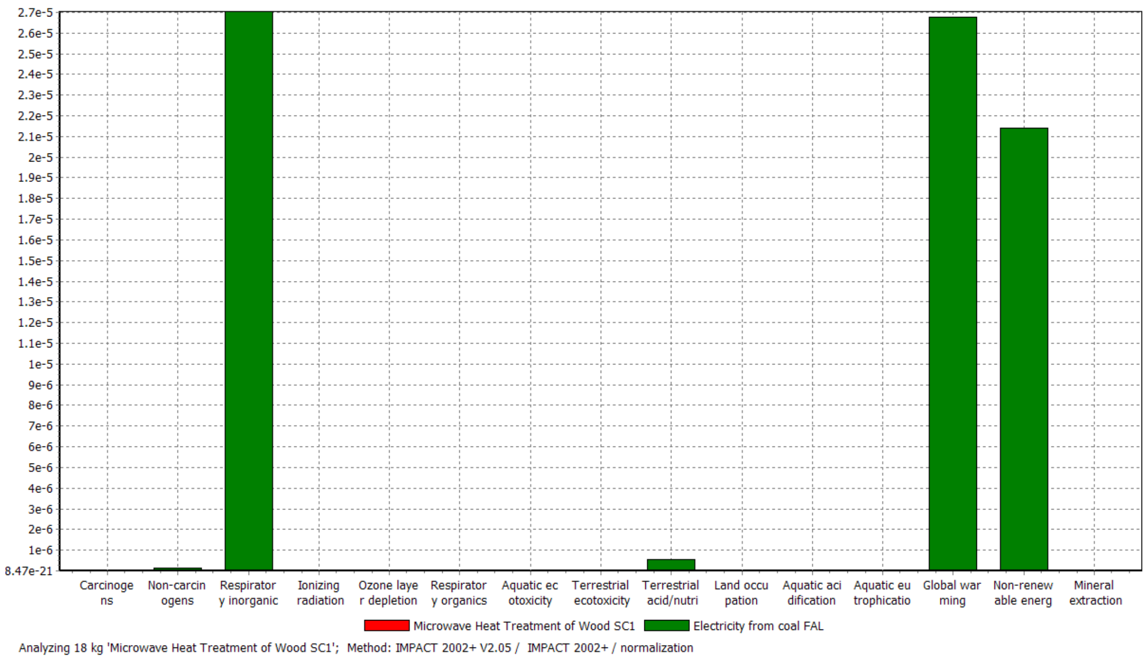

Figure 5.6. Impact Assessment – MW Treatment of Wooden Pallet with 25% Moisture Content

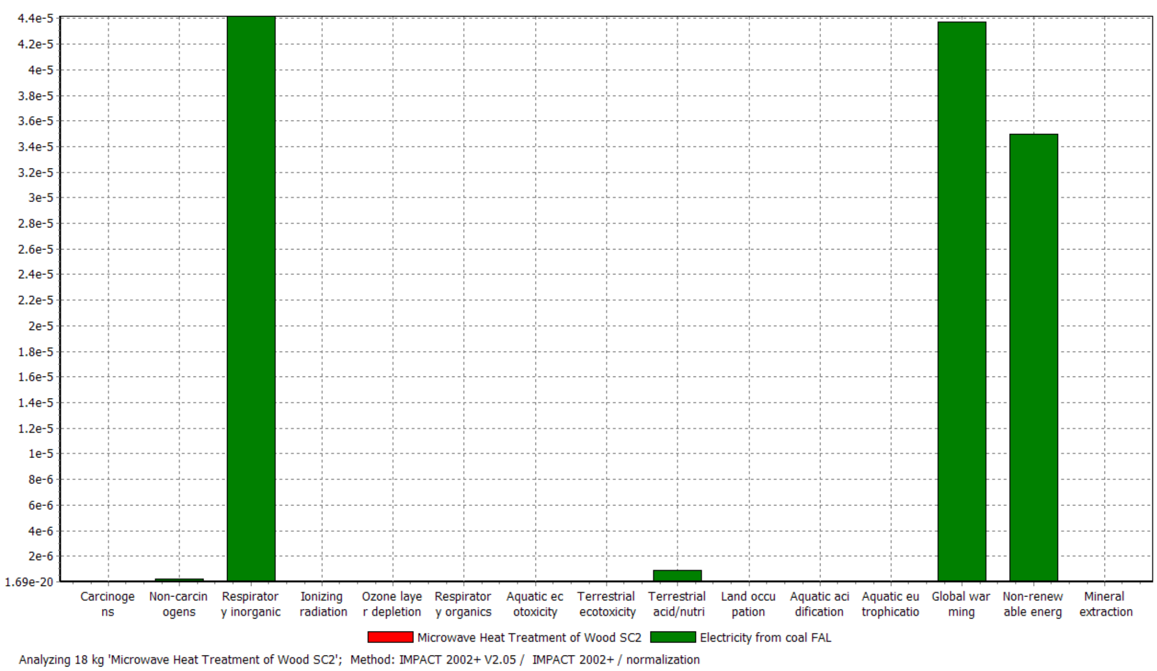

Figure 5.7. Impact Assessment – MW Treatment of Wooden Pallet with 100% Moisture Content

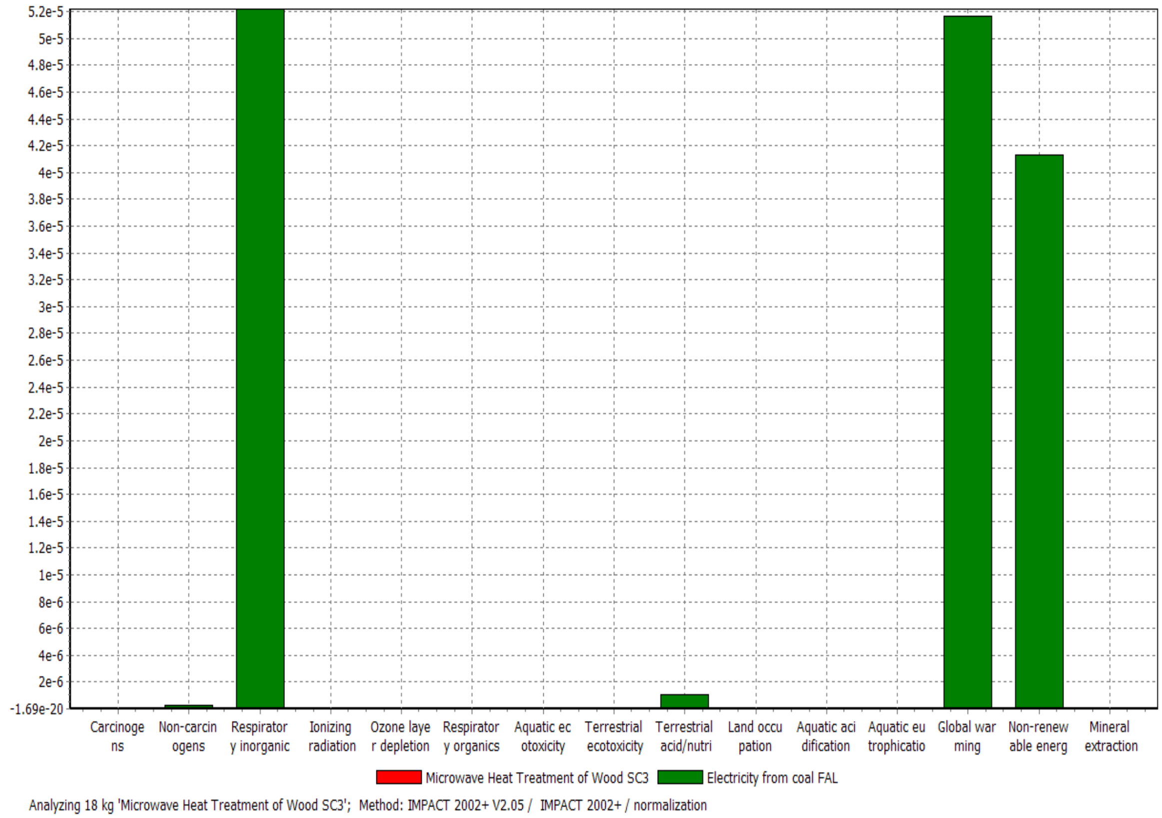

Figure 5.8. Impact Assessment – MW Treatment of Wooden Pallet with 178% Moisture Content

In **Figure 5.9** normalized impact assessment results from three different microwave heat treatment scenarios using CML 2001+ are shown.

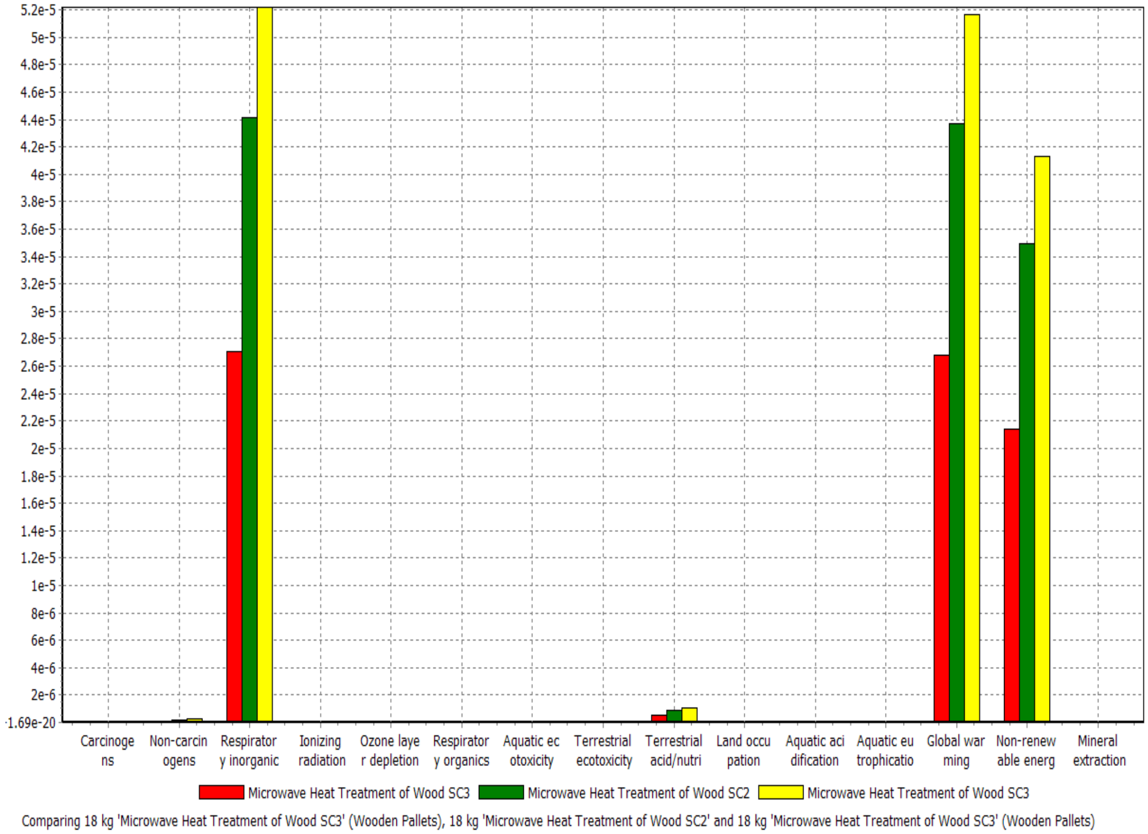

Figure 5.9. Impact Assessment – MW Treatment Scenarios (Normalized)

Chapter 6

Conclusion and Future Works

A detailed review of the existing literature on the Life Cycle Assessment of wood packaging materials reveals that these analyses have been used by companies to calculate and establish the environmental advantages of their own products or as product improvement tools to quantify and minimize their carbon footprint at different life cycle stages. The various advantages and disadvantages of heat treatment and methyl bromide have been purported by pallet companies and treatment companies in the past, e.g., an LCI analysis conducted by CHEP (2007).

A life cycle analysis study consists of a comprehensive assessment of the environmental impacts of the entire product life cycle that consists of raw material sourcing and acquisition, manufacturing processes, energy use, emissions into air, water and land, and its disposal pattern. In this study we focused on the phytosanitary treatment stage of processing wooden pallets. Wooden pallets require treatment to significantly reduce the risk of spread of pests that infest wood, since international movement of wood products is the most common pathway for introduction of exotic pests to new areas. Treatment methods such as heat treatment and methyl bromide fumigation are carbon footprint intensive, thus studying and evaluating environmental impacts produced by phytosanitary treatments are of great interest nowadays.

The research methodology used in this LCA study consisted of an environmental impact assessment applied to phytosanitary treatment methods of 48” x 40” GMA wooden pallets. It was found that among the three treatment methods, methyl bromide fumigation incurred the maximum impact on global warming and ozone layer depletion. In all other categories, heat treatment turned out to be the most impact-intensive method, and MW heating was seen to be an environmentally less intensive treatment method and to have less impact on the environment. The results show that microwave treatment is a feasible alternative to conventional heat treatment or methyl bromide fumigation for eradication of wood-inhabiting pests. Also, the literature shows that the sterilization of wooden pallets can be efficiently carried out using MW. Although the lethal temperature using microwave and conventional heat treatment were the same, the time required for each process to reach the Probit 9 mortality level is different. Dielectric methods such as microwaves heat through the profile of the wood, therefore requiring less time to reach lethal temperature and only needs to be determined for one minute to be effective. On the other hand, conventional heat treatment requires a long heat-up period to achieve the required core temperature of 56 °C followed by a 30 minute-hold time, since it relies on the conduction of thermal energy from the surface to the core.

Proposed future research related to this study includes comparing the economic impacts of different phytosanitary treatments and evaluating cost/benefit of each treatment method. They are also aimed at broadening the scope of this project to include more than just GMA pallets and pallets made from materials other than wood, which could be beneficial to other industries such as pharmaceuticals, chemicals, beverages, etc. The increase in the use of conventional heat treatment due to methyl bromide phase-out increases the cost of this process. Therefore, a study to specify the economic viability of each treatment method would be of great benefit to pallet manufacturers and pallet treating companies. An analysis of the environmental impacts of pallets moving across a global supply chain might also be considered. From a practical standpoint the impacts of energy requirements, capital costs and wood moisture content are four elements that should be considered in the comparison of life cycle stages and treatment methods.

Appendices

Appendix A - Defining the Scope of LCA

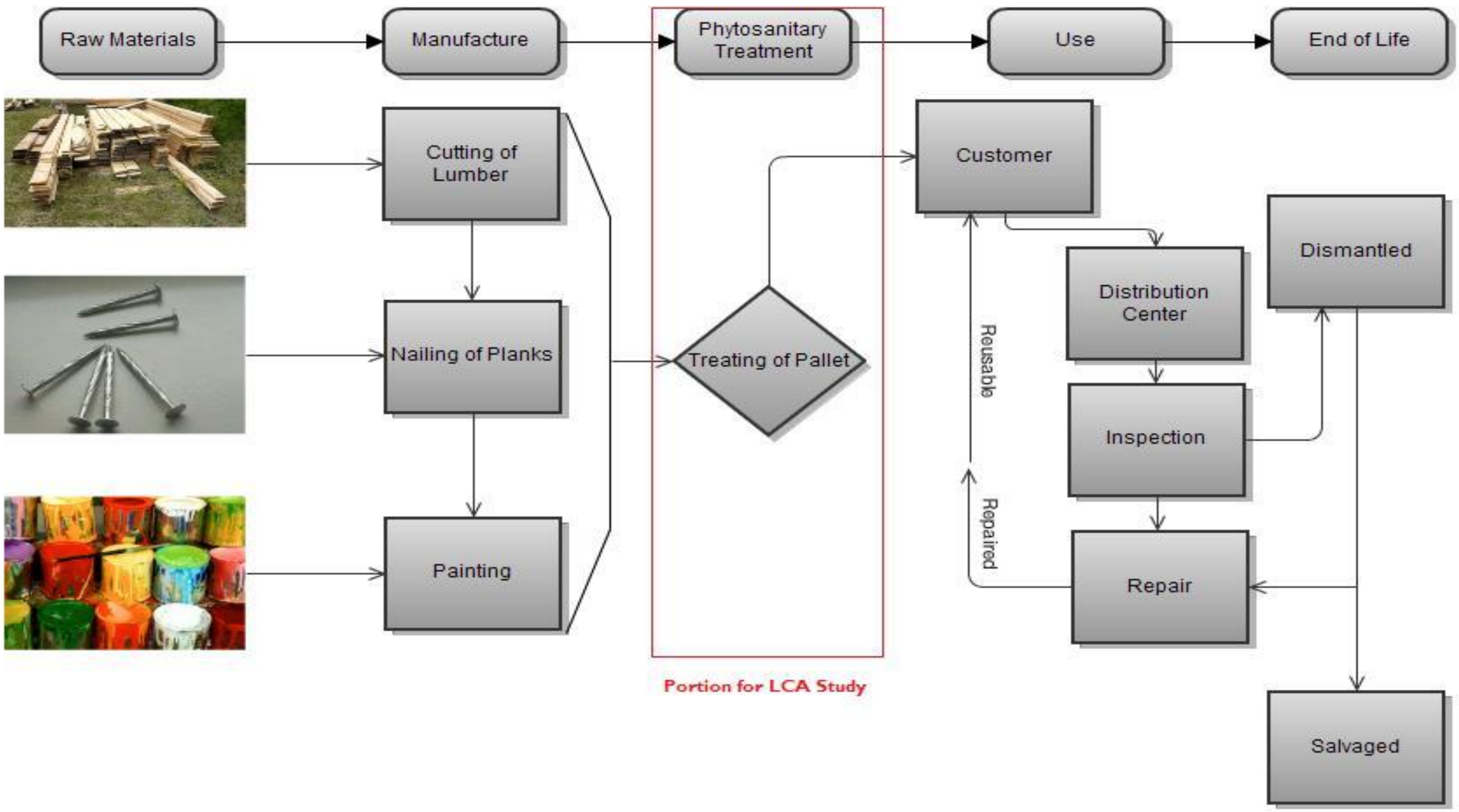

Figure A.1. Process Map of Wooden Pallets and Experimental Portion for LCA study Analysis

Appendix B - Network Diagrams using CML 2002+

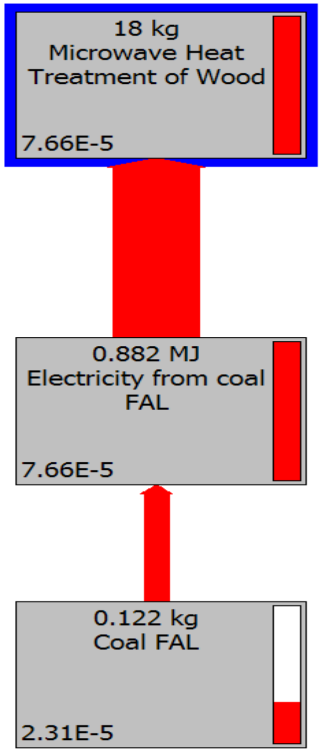

Figure B.1. Network Flow Diagram – MW Treatment of Wooden Pallet with 25% Moisture Content

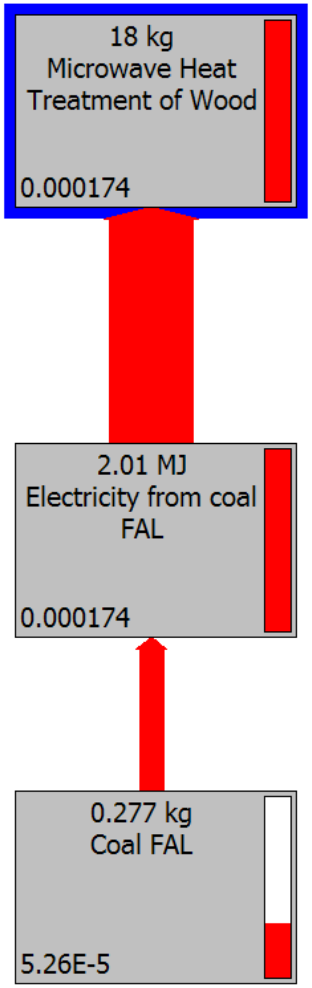

Figure B.2. Network Flow Diagram – MW Treatment of Wooden Pallet with 100% Moisture Content

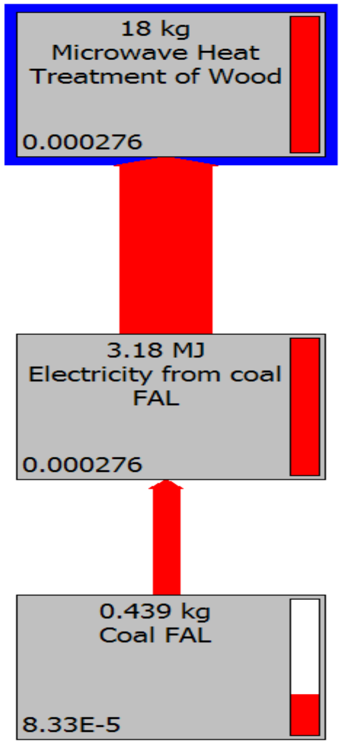

Figure B.3. Network Flow Diagram – MW Treatment of Wooden Pallet with 178% Moisture Content

Appendix C - Impact Assessments Using Eco-Indicator 99

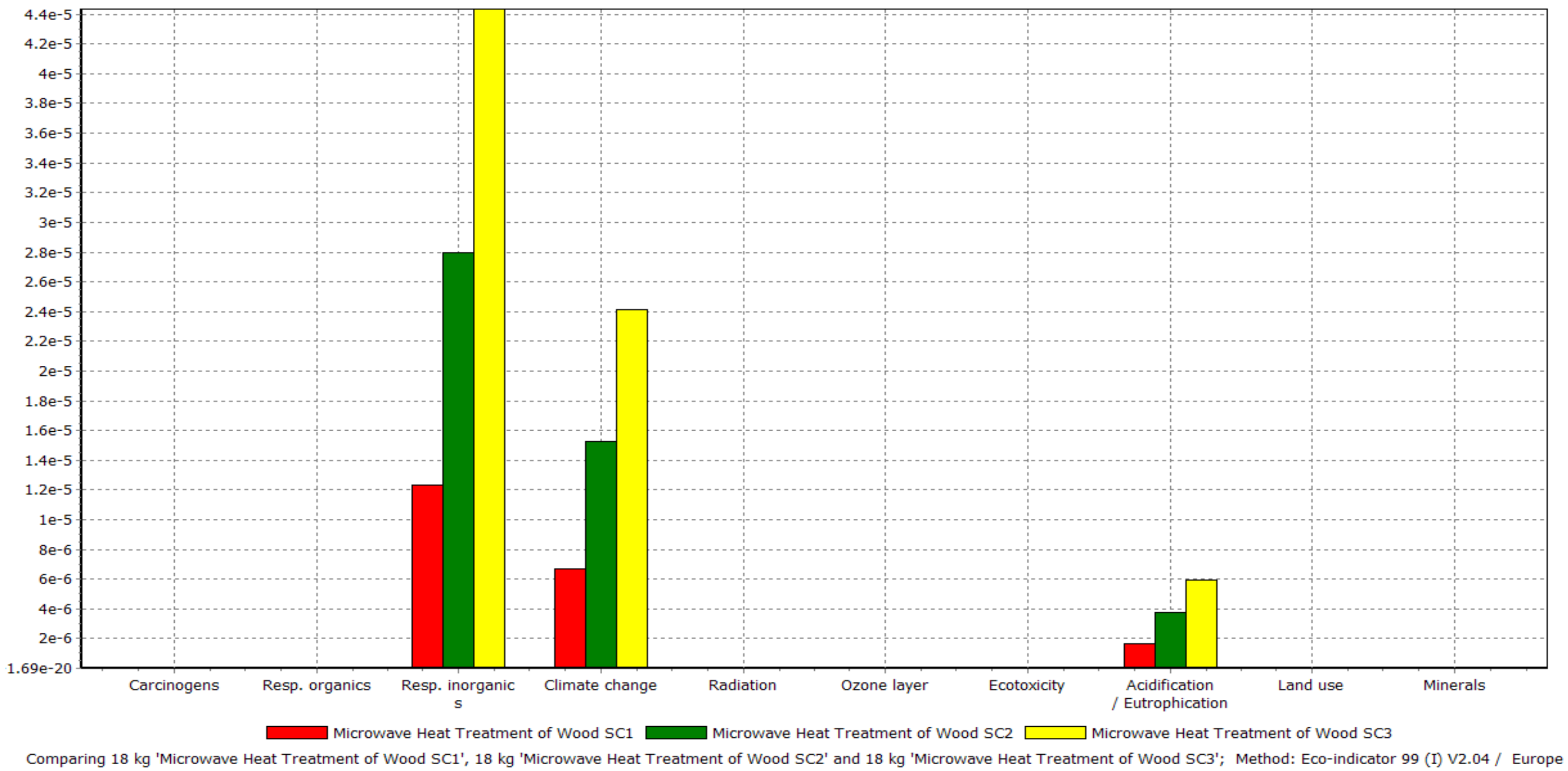

Figure C.1. Comparison of Impact Assessments Caused by Three Different Microwave Treatment Scenarios Using Eco-Indicator 99

Impact Category	**Unit**	**Microwave Heat Treatment of Wooden Pallet (MC = 25%)**	**Microwave Heat Treatment of Wooden Pallet (MC = 100%)**	**Microwave Heat Treatment of Wooden Pallet (MC = 178%)**
Carcinogens	kg C2H3Cl eq	4.30E-09	9.79E-09	1.55E-08
Respiratory organics	kg C2H4 eq	3.00E-09	6.83E-09	1.08E-08
Respiratory inorganics	kg PM2.5 eq	1.23E-05	2.80E-05	4.43E-05
Global Warming	kg CO2 eq	6.68E-06	1.52E-05	2.41E-05
Ozone Layer Depletion	kg CFC-11 eq	5.75E-10	1.31E-09	2.07E-09
Eco-toxicity	kg TEG	3.74E-09	8.52E-09	1.35E-08
Acidification/Eutrophication	kg SO2 eq	1.64E-06	3.73E-06	5.91E-06
land use	m2org.arable	0	0	0
Minerals	MJ surplus	0	0	0

Table C.1. Impact Assessment of Three MW Treatment Scenarios Using Eco-Indicator 99

Appendix D - LCA of HT, MeBr Fumigation and RF (19% Moisture Content)

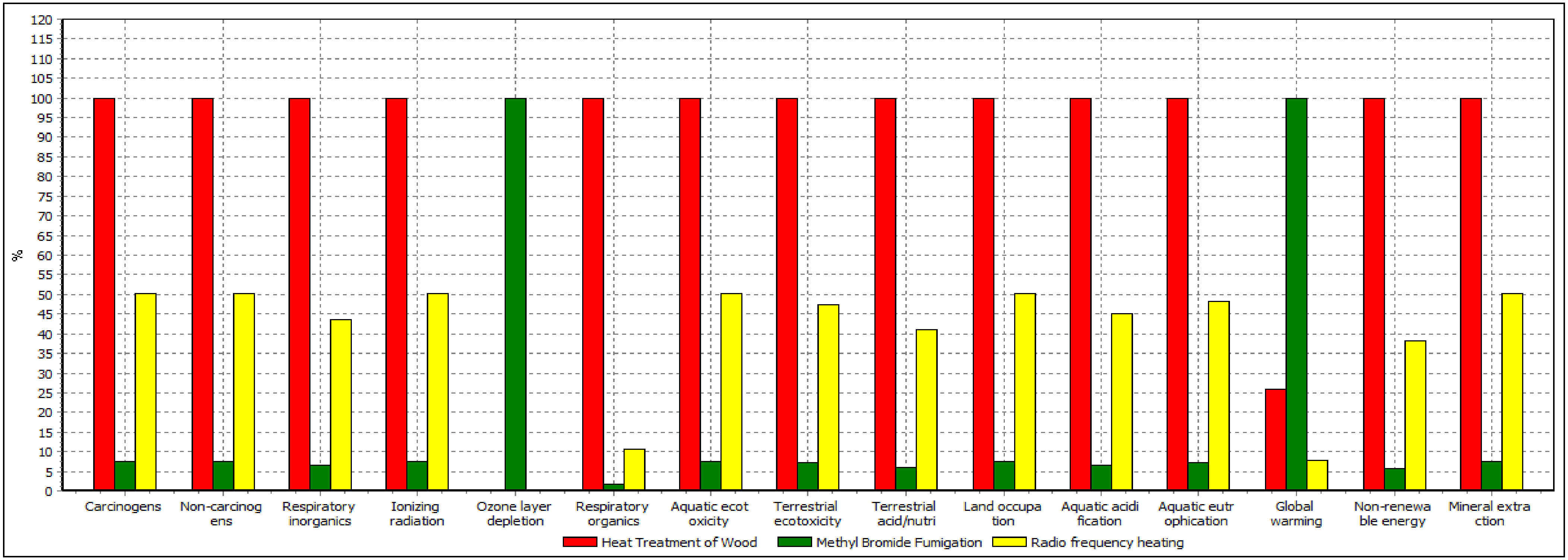

Figure D.1. LCA from the Literature Using Eco-Indicator 99 (Graph from SimaPro)

Appendix E – Calculations Regarding Carbon Footprint of Microwave

1 kg = 2.2 lbs

1 kg of wood at 25% moisture content has the following amount of dry wood:

(2.2 lbs – x) / x = 0.25, x = 1.76 lbs

, and the following amount of water:

2.2 lbs – 1.76 lbs = 0.44 lbs

1 kg of wood at 100% moisture content has the following amount of dry wood:

(2.2 lbs – x) / x = 1, x = 1.1 lbs

, and the following amount of water:

2.2 lbs – 1.1 lbs = 1.1 lbs

1 kg of wood at 178% moisture content has the following amount of dry wood:

(2.2 lbs – x) / x = 1.78, x = 0.79 lbs

, and the following amount of water:

2.2 lbs – 0.79 lbs = 1.41 lbs

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