

Comparative Life Cycle Assessment of Conventional and Guayule Automobile Tires

by

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ABSTRACT

Natural rubber and rubber products can be produced from the guayule plant (*Parthenium argentatum* Gray), which is a low input perennial shrub native to Mexico and the American Southwest. Guayule rubber has the potential to replace Hevea (*Hevea brasiliensis*) rubber, the most common natural rubber, and synthetic rubber, which is derived from petroleum, in a wide variety of products, including automobile tires. Rubbers make up approximately 47% of the analyzed conventional passenger tire's weight, with 31% from synthetic rubber and 16% from natural Hevea rubber. Replacing the current rubber sources used for the tire industry with guayule rubber could help reduce dependency on imported rubber in addition to reducing greenhouse gas emissions. Moreover, residues from guayule rubber are being researched as a bioenergy feedstock to further improve the environmental footprint of guayule rubber products.

This study used life cycle assessment (LCA), a useful tool to determine environmental impacts from a product or process, to quantify and compare environmental impacts of the raw material extraction, transportation and manufacturing of a conventional and a guayule rubber based passenger tire. The impact results of this comparative LCA identified the major environmental impacts and contributing process and informed how the impacts from the tire production can be reduced through utilization of natural rubber co-products as electricity off-sets and reducing guayule rubber's environmental impacts through agricultural and transportation modifications.

Results showed that tire raw material extraction contributed the majority of impacts in all categories, where the production of guayule rubber for guayule tires, and the production of synthetic rubber for conventional tires, were the main contributors. Guayule rubber impacts occurred mainly from electricity consumption for agricultural irrigation, while synthetic rubber is a petroleum-based material resulting in high impacts. Transportation impacts had little significance compared to other stages in the life cycle, except for smog impacts, which occurred mainly from truck transport for guayule tires, and transoceanic transport for conventional tires. Tire manufacturing impacts occurred mainly from electricity use in the facilities and were reduced with the use of guayule rubber in guayule tires.

DEDICATION

I dedicate this thesis to my Dad –

Tėveli,

Skiriu šį darbą tau už visus patarimus, skatinimus ir palaikymus, kuriuos suteikei nuo pirmųjų mokslo dienų. Tu dovanojai išskirtines galimybes pamatyti pasaulį ir užaugti Lietuvoj. Tu išmokei parodyti dėkingumą svarbiausiems gyvenimo žmonėms ir kasdien juos įvertinti. Ačiū, kad išmokei mane daugiau, nei visos universiteto programos!

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TABLE OF CONTENTS

	Page
LIST OF TABLES	vi
LIST OF FIGURES	vii
ACRONYMS.....	ix
PREFACE.....	x
CHAPTER	
1 INTRODUCTION	1
1.1 Project Introduction and Motivation	1
1.2. Goals and Objectives	3
1.3. Life Cycle Assessment	4
1.4. Natural Rubber and Tire Manufacturing Process Overview.....	10
2 BACKGROUND	13
2.1. Literature Review.....	13
2.1.1. Guayule Agriculture and Processing	14
2.1.2. Hevea Agriculture and Processing	19
2.1.3. Tire Studies and LCAs	21
2.2 Natural Rubber Background	24
2.2.1. Guayule and Hevea Agriculture	25
2.2.2. Guayule and Hevea Processing	35
2.3. Tire Manufacturing Background	43
2.3.1. Raw Materials	44
2.3.2. Tire Components and Manufacturing Process	49
3 COMPARATIVE LIFE CYCLE ASSESSMENT OF CONVENTIONAL AND GUAYULE AUTOMOBILE TIRES	55
3.1. Introduction.....	55
3.2. Materials and Methods	55
3.3. Results and Discussion	67

CHAPTER	Page
3.4. Conclusion	94
4 FUTURE WORK AND CONCLUSIONS	97
Future Work	97
Conclusions	99
REFERENCES	102
APPENDIX	
APPENDIX A	114
NATURAL RUBBER AGRICULTURAL MODELING INPUTS	1144
APPENDIX B	1166
NATURAL RUBBER AGRICULTURE AND PROCESSING MODELING	1166
APPENDIX C	1244
TIRE RAW MATERIAL AND TIRE MANUFACTURING MODELING	1244
APPENDIX D	1333
TRANSPORTATION MODELING	1333
APPENDIX E	1388
SUGARCANE SUBSTITUTION MODELING	1388
APPENDIX F	1411
NATURAL RUBBER CO-PRODUCT MODELING	1411
APPENDIX G	1488
IMPACT CATEGORIES	1488

LIST OF TABLES

Table	Page
Table 1. Energy Content of Guayule and Hevea Co-products.....	19
Table 2. Biomass and Rubber Yield, Irrigation rates and Fertilizer and Herbicide Applications for Guayule and Hevea.....	27
Table 3. Guayule Processing Steps patented by Cornish, McCoy et al. (2011).	36
Table 4. Raw Material Inventory Data Sources and Conversions.....	63
Table 5. Raw Material Transportation and Tire Manufacturing Inventory Data Source and Conversions.....	64
Table 6. Guayule and Hevea Co-product Energy Content.....	66
Table 7. Detailed Inputs for Natural Rubber Modeling in LCA Study.	115
Table 8. Natural Rubber Agriculture and Processing Inputs, Data Inventory, Substitutions from Databases.....	123
Table 9. Tire Raw Material Inputs, Data Inventory and Substitutions from Databases.....	130
Table 10. Tire Manufacturing Inputs, Data Inventory, Substitutions from Databases.....	132
Table 11. Transportation Data Inputs, Data Inventory, Substitutions from Databases.	137
Table 12. Natural Rubber Co-product Energy Content.	145

LIST OF FIGURES

Figure	Page
Figure 1. Life Cycle Assessment Phases	5
Figure 2. The Four Steps of an ISO LCA. Adapted from (ISO 14040 2006, ISO 14044 2006).	6
Figure 3. Rubber and Tire Process Overview.	10
Figure 4. Literature Review of Tire, Guayule and LCA Publications.	13
Figure 5. Guayule Plant (Rechenthin 2014)	24
Figure 6. Hevea Tree and Latex Tapping (Research.gov)	25
Figure 7. Guayule Processing adapted from Cornish 2011 Patent (Cornish, McCoy et al. 2011).39	39
Figure 8. Bridgestone/Firestone Processing Flow (van Beilen 2006).	40
Figure 9. Block Rubber Production Process, Using Dry Rubber, adapted from (Thailand Latex and Block Rubber Industry 2001).	43
Figure 10. Tire Composition by Mass.	46
Figure 11. Tire Components.	49
Figure 12. System Boundaries for LCA Study.	57
Figure 13. Tire Components.	61
Figure 14. Tire Composition by Mass of Raw Material.	61
Figure 15. Guayule and Hevea Natural Rubber Co-product Feedstock, Processing Methods and Products.	65
Figure 16. Guayule and Conventional Tire Comparison Displaying Normalized Impacts.	68
Figure 17. Comparison of Normalized Raw Material Extraction Impact Distribution Between the Rubber and other Raw Materials Relative to Total Tire Production Impacts.	69
Figure 18. Normalized Impact Comparison of Total Rubber in Guayule Tire (guayule) and Total Rubber in Conventional Tire (Hevea+synthetic) Relative to Total Tire Production Impacts.	71
Figure 19. Comparing Normalized Tire Grade Guayule Rubber and Hevea Rubber Impacts: Agriculture (AG), Processing (P) and Transportation (T).	74
Figure 20. Tire Raw Material Manufacturing and Transportation to Tire Manufacturing Facilities Normalized Impacts.	76

Figure	Page
Figure 21. Normalized Component Raw Material Impact Comparison for a Guayule and Conventional Tire.....	78
Figure 22. Normalized Guayule (green) and Hevea (orange) Tire Component Impact Comparison.	79
Figure 23. Normalized Comparison of Percentage of Electricity Use by Process in Tire Manufacturing Facilities.....	81
Figure 24. Energy Off-sets per Production of 1kg Natural Rubber.	82
Figure 25. Comparing Available Electricity Impact Off-sets per Production of 1 kg Natural Rubber.	83
Figure 26. Tire Manufacturing Impact Reduction with Utilization of 25% or 100% of Available Guayule Bagasse and Hevea Rubberwood.	85
Figure 27. Global Warming Impact Scenarios for Production of 1kg Rubber.	88
Figure 28. Eutrophication Impact Scenarios for Production of 1kg Rubber.	91
Figure 29. Area Needed to Grow Sufficient Guayule Rubber for Total U.S. Tire Supply.....	94
Figure 30. System Boundaries for Guayule Agriculture and Processing.	118
Figure 31. Schematic Overview of Hevea Latex and Primary Rubber Production.	120
Figure 32. Feedstock, Processing and Final Product of Energy-rich Hevea and Guayule Co-products.....	143
Figure 33. Inventory Inputs of Pyrolysis Oil Production from Woody Biomass Feedstock.	144
Figure 34. Energy Inputs and Energy Outputs in Palm Methyl Ester (PME) System.	145
Figure 35. Bio-oil Vs Biodiesel: Comparing Impacts from the Production of 1MJ Worth of Product.	146

ACRONYMS

ABS	Acrylonitrile-butadiene-styrene
BEGS	Belt Edge Gum Strip
BSW	Black Side Wall
CO ₂	Carbon Dioxide
DAP	Diammonium Phosphate
DRC	Dry Rubber Content
EIA	U.S. Energy Information Administration
EOL	End-of-life
ETRMA	European Tire and Rubber Manufacturers' Association
FFD	Fossil Fuel Depletion
GHG	Greenhouse gas
GW	Global Warming
ISO	International Organization for Standardization
K	Potassium
KOH	Potassium hydroxide
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPG	Liquefied Petroleum Gas
N	Nitrogen
NaHCO ₃	Sodium Bicarbonate
NH ₃	Ammonia
NO _x	Nitrogen Oxides
P	Phosphorus
RSS	Rubber Smoked Sheet
SBR	Styrene-butadiene Rubber
STR	Standard Thai Rubber
SWEEP	Southwest Energy Efficiency Project
TMTD	Tetra Methyl Thiuram Disulphide
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TSR	Technically Specified Rubber
ZnO	Zinc Oxide

PREFACE

This thesis reports the results of a comparative life cycle assessment of a conventional and guayule-based automobile tire. The objective of this study is to compare the environmental impacts of the raw material extraction, transportation and tire manufacturing process for each tire, highlight the processes with major impact contributions, present an additional scenario where natural rubber co-products are utilized as energy off-sets, and present a sensitivity analysis to assess the possibility of reducing guayule rubber impacts through changes in agricultural practices and transportation modes.

This thesis is organized in 4 chapters. The first chapter covers the project background, the goals of the research, and a summary of the LCA methodology. The second chapter provides a literature review on guayule, Hevea, tires and LCA studies on these topics; a background on tire manufacturing, and guayule and Hevea agriculture and processing. The third provides a succinct comparative LCA on conventional and guayule automobile tires. The fourth is recommendation for future work and a summary of the conclusions.

CHAPTER 1

INTRODUCTION

1.1 Project Introduction and Motivation

Increasing awareness of the negative effects of human activity on the environment has sparked interest in manufacturing sustainable products. One proposed approach to minimize environmental impacts is to alter commercial products by using renewable materials derived from biomass to replace synthetic components (Lynd, Wyman et al. 1999, Mohanty, Misra et al. 2002, Miller, Landis et al. 2007). Another approach for achieving reductions in environmental impacts focuses on minimizing transportation distances which can be achieved by using locally available materials (Bilec, Ries et al. 2006). This LCA proposes replacing the synthetic and imported rubber components of a passenger automobile tire with a domestic natural rubber, sourced from the guayule (*Parthenium argentatum*) plant.

Automobile tires are manufactured at a large scale and a bio-based material substitution could help reduce environmental impacts from tire production. Approximately 200 million passenger and commercial vehicle tires are produced in the US every year (RubberNews 2009) making the U.S. the second largest national consumer of tires. The demand for tires worldwide is expected to increase by 4.3 percent annually through 2017 (RubberNews 2014). The rubber used in a tire is a combination of synthetic rubber produced from petroleum, and natural rubber that is sourced from the Brazilian *Hevea* (*Hevea brasiliensis*) tree. It is essential to have a source of natural rubber for the tire industry, because synthetic rubber does not have sufficient heat dispersion, abrasion resistance, elasticity or resiliency for high performance requirements (Miyamoto and Bucks 1985, Herman 2004). The rubbers make up approximately 47% of a conventional U.S. produced passenger tire's weight, with 31% from synthetic rubber and 16% from natural Hevea rubber.

The conventional rubbers in automobile tires are associated with undesirable environmental, economic and social issues. The major component of a conventional tire,

synthetic rubber, is petroleum based and its production is accompanied by large environmental impacts. Unstable oil prices could lead to a major increase in the price of synthetic rubbers, which would increase the price of tires. Demand for natural rubber, the third largest component by mass of a conventional tire, is increasing worldwide, and production from Hevea plantations will not be able to keep pace (Ray, 2005). Hevea acreage has diminished in recent years as growers change to palm oil and other higher value crops (Wagner and Parma 1989, Cornish 1996, van Beilen and Poirier 2007b) and the strict climatic requirements of Hevea limit its cultivation to tropical regions (Herman 2004), which are a common landscape in Southeast Asia. Tropical forests are rich reservoirs of biodiversity and key ecosystem services (Foley 2007). A major concern is the dependence on natural rubber imports from Southeast Asia where over 90% of Hevea is currently grown (Mooibroek 2000); a reliable domestic source can reduce transportation impacts and benefit the local economy by creating jobs. Furthermore, Hevea cultivars have very little genetic variability and the lack of genetic diversity leaves the crop susceptible to pathogenic attack and failure (Herman 2004). Lowering our dependence on foreign natural rubber and finding a substitute for petroleum-based rubber has generated interest in an alternative source of rubber for the tire industry, one of which is the domestically grown guayule plant. This LCA study explores the potential of replacing the conventional rubbers in a tire with guayule natural rubber.

Guayule is a woody arid shrub native to Mexico and the American Southwest which can be used as a natural rubber source. It is classified as a low user of the major nutrients (Foster and Coffelt 2005) and requires little or no pesticide application (Herman 2004). Guayule has the benefit of being a low input crop (Rodríguez-García 2002), which could potentially qualify it as a sustainable substitute for Hevea natural rubber. It is comparable in quality to the Brazilian Hevea tree (Siler and Cornish 1994) and also produces tire-grade rubber. Several attempts have been made to commercialize guayule since the 1900s for rubber tire production, but failed due to economic and social factors (Foster and Coffelt 2005, Nakayama 2005, Ray, Coffelt et al. 2005). These attempts include the following: (1) During the early years of guayule interest, it was found that Hevea rubber was cheaper to produce than guayule, thus guayule research was discontinued; (2) during World War II, guayule production increased with the Emergency Rubber

Project (ERP) when the Hevea rubber supply from Southeastern Asia was cut off, but the effort was abandoned after the war ceased and the synthetic elastomer industry expanded (National Academy of Sciences 1977) (3) in the 1970s, the petroleum crisis sparked an interest in replacing synthetic rubber, but once oil sources and prices stabilized, guayule was no longer a necessity (Nakayama 2005). During the past few decades, there are two reasons why guayule has gained commercial interest. The first is the widespread occurrence of Type I latex allergy to the proteins in Hevea natural rubber (latex) products (Foster and Coffelt 2005). In the 1990s, guayule was shown to be a source of hypoallergenic latex that contained the necessary elasticity, which is not provided by synthetic materials (Siler, Cornish et al. 1996), and could easily act as a replacement for Hevea in medical and personal products (Nakayama 2005). The second reason is due to significant increases in guayule rubber yields with improved agronomic practices (Foster and Coffelt 2005). Conventional breeding and selection of guayule has been used to improve rubber yield by as much as 250% (Ray, Coffelt et al. 2005), and selections made since the 1980s have developed plants with improved biomass and rubber content (Estilai 1991b).

Although latex only makes up approximately 10% of the guayule plant (Nakayama 2005), the remaining materials, such as the bagasse and resin, have potential to become valuable co-products. After processing, 60-70% of the remaining plant is cellulosic residue, called bagasse (Estilai 1991a), which has a heating value similar to that of coal (Boateng, Mullen et al. 2009). This valuable co-product has potential to off-set the energy required to manufacture guayule tires and will be included into a scenario of the LCA.

1.2. Goals and Objectives

The purpose of this study was to conduct a comparative LCA for a conventional automobile tire and a guayule rubber-based automobile tire, and determine whether guayule is an environmentally sustainable substitute. Where available, primary data from a tire manufacturing company is used to evaluate and compare the different tires. Agricultural and processing data for

guayule and Hevea was collected from peer reviewed and scientific literature. Additional secondary data was collected from life cycle databases. Use phase and end-of-life phase are not incorporated in the LCA as the guayule tires are in the development stage and this data is currently unavailable. The performed study shows the impacts of rubber substitution, helps identify the inputs and processes with the highest environmental impacts and highlights where there may be opportunity for industry to reduce the environmental impacts of guayule tire production.

The research objectives of the study include:

- a. Compare environmental impacts of a conventional and guayule tire and identify areas for improvement to reduce global warming, photochemical smog formation, eutrophication, acidification and fossil fuel depletion impacts
- b. Evaluate the potential energy off-sets available from guayule and Hevea natural rubber co-products
- c. Present a sensitivity analysis to assess the possibility to reduce impacts by increasing rubber yields from the guayule plant, lowering electricity consumption for irrigation or using alternative methods of irrigation, and using different modes of transport for moving guayule rubber to tire production facilities

1.3. Life Cycle Assessment

Life cycle assessment (LCA) is a methodology used to assess the life cycle environmental impacts of products and services. LCA can be applied throughout the entire life cycle of the product, including raw material extraction, transportation, manufacturing, use and disposal (cradle-to-grave), through certain phases, such as raw material extraction through manufacturing (cradle-to-gate), or through one product's transformation to another product

(cradle-to-cradle). LCA methodology addresses the environmental aspects and impacts of a system, where economic and social aspects and impacts are not included.

LCA was used in this study to assess the production of conventional and guayule automobile tires. A cradle-to-gate LCA was conducted on the tires, which analyzes the early stages of the product's life, including raw material extraction, transportation and manufacturing (see Figure 1). Use phase and end-of-life phase are not incorporated in the LCA as the guayule tires are in the development stage and this data is currently unavailable.

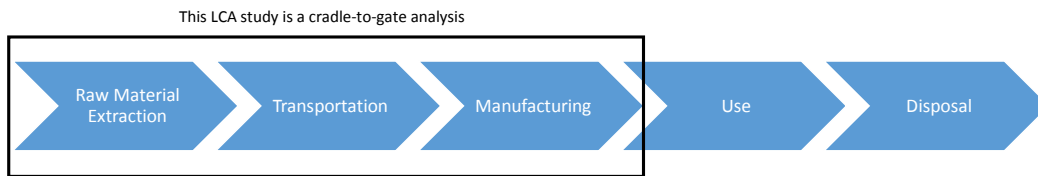


Figure 1. Life Cycle Assessment Phases.

In the study, LCA will assist with:

- Identifying opportunities to improve the environmental performance of the product at various points in the life cycle; this will be used to identify hot-spots in tire raw material extraction, transportation and manufacturing
- Informing decision-makers; this study will inform tire manufacturers where changes can be made in their supply chain or production practices
- Compiling a detailed inventory of inputs and outputs; this can help the tire industry determine potential changes in environmental impacts associated with changes in production

According to the International Organization for Standardization (ISO) (ISO 14040 2006, ISO 14044 2006), there are four steps in an LCA study, also displayed in Figure 2:

- 1) The goal and scope definition
- 2) The life cycle inventory analysis (LCI)
- 3) The life cycle impact assessment (LCIA)
- 4) The interpretation

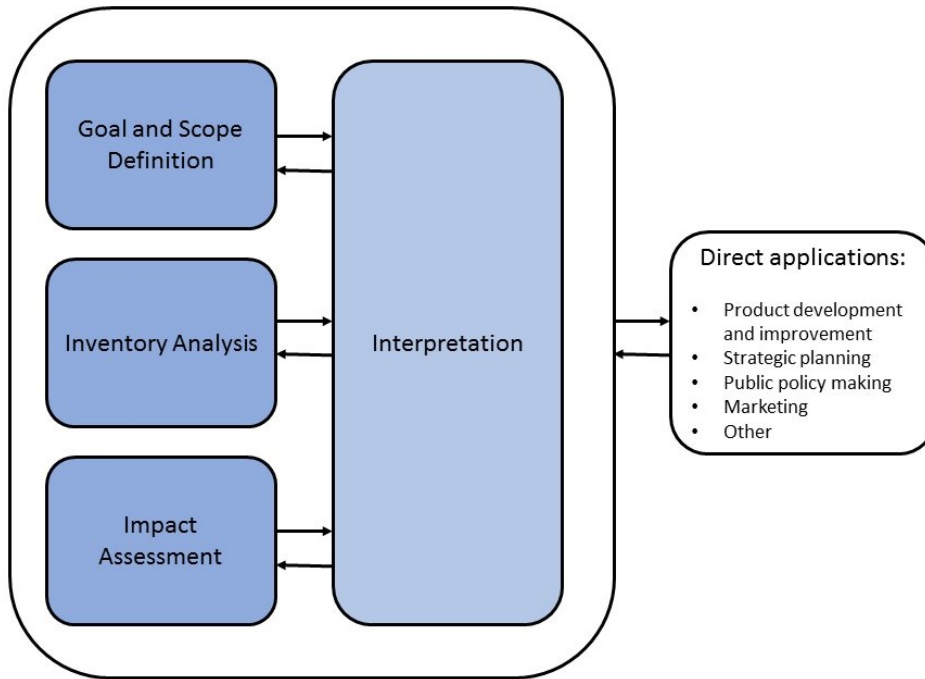


Figure 2. The Four Steps of an ISO LCA. Adapted from (ISO 14040 2006, ISO 14044 2006).

Goal and Scope Definition

The LCA goal includes introducing the intended application and audience of the study. The goal of this study is to compare a guayule-derived tire to a conventional tire. The scope identifies the system boundary and the level of details used for the LCA. The system boundary depends on the subject and the intended use of the LCA. The scope should be sufficiently defined to ensure the study is compatible and able to address the stated goal. The scope of this comparative LCA is cradle-to-gate, also referred to as including Scope 1 and Scope 2 activities. The system boundary defines the unit processes included in the system. The physical system elements chosen need to represent the goal and scope definition of the study and its intended application. There are many variations of the life cycle stages, unit processes and flows that can be taken into consideration when setting the system boundary. The system boundary can include acquisition of raw materials, inputs and outputs of manufacturing, transportation, use and maintenance of the product, disposal, recovery of used products for reuse, recycling and energy, and others.

LCA methodology is structured around a functional unit, which defines what is being studied and quantifies the identified functions. The analyses, inputs and outputs in the LCI and the LCIA are related to the functional unit. This reference is critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. In this study, the functional unit is considered to be a one tire. This provides a common unit to compare the conventional and guayule tire.

Inventory Analysis

The LCI step is the collection of inventory data related to the material and energy inputs and product and emission outputs related to the studied system. Reliable and carefully collected data is crucial for successful LCA results. Once the raw data is collected, it must be validated and related to the unit processes and functional unit. Data on guayule and Hevea agriculture and processing were collected from peer reviewed scientific literature. Where available, primary data was collected from a tire manufacturing company on the raw materials of a tire, the production process and the equipment energy use. Additional information was collected through life cycle databases, such as upstream data for the agricultural inputs, production of the raw materials comprising a tire, transportation modes and manufacturing inputs at the tire plant.

Most industrial processes yield more than one product or have waste or byproducts; as such consideration should be given to the need for allocation procedures to divide the environmental impacts from the process between the products. Allocation is commonly performed from an economic or mass point of view. For example, allocation is needed to assess the co-product beef from milk production since a significant amount of beef production is derived from co-products in the dairy sector (Cederberg and Stadig 2003). This could be performed by allocating impacts according to the cost of beef and milk, or by the mass of the produced beef and milk. In this tire LCA study, allocation was used to assign energy consumption for the production of each tire by collecting total manufacturing energy for the entire facilities, and dividing this value by the number of tires produced.

The goal and scope, LCI, LCIA, and interpretation are iterative processes that may require additional data collection as more is learned about the system.

Impact Assessment

The LCIA uses existing models of environmental fate, transport, and impact and translates LCI data into meaningful results. The LCIA provides a system-wide perspective of environmental impacts and resource depletion for the product system. There are numerous LCIA methodologies available, such as TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare 2011), Eco-indicator 99 (Eco-Indicator 2000, Goedkoop 2000) and ReCiPe (Goedkoop 2009, ReCiPe 2012). These methodologies assign impact categories to the LCI values and calculate the resultant environmental impacts. In this LCA study, United States impact-based TRACI was utilized as the LCIA methodology and results were presented in the categories of global warming, photochemical smog formation, eutrophication, acidification and fossil fuel depletion.

A major limitation of the LCIA is that it only includes environmental issues that are specified in the goal and scope, therefore it is not a complete assessment of all the environmental impacts of the product. Additionally, the lack of spatial and temporal dimensions introduces uncertainty in the LCIA. Normalization, weighting can be performed, where a weight is assigned to each impact based on relative importance. However, determining the importance of certain impacts introduces high uncertainty.

Interpretation

Life cycle interpretation is the step where the results of the LCI and/or LCIA are summarized and discussed as a basis for conclusion, recommendations and decision-making, with reference to the assigned goal and scope definition. Interpretation is an iterative procedure, which is repeated throughout the conduction of the LCA (as displayed in Figure 2).

The interpretation should show that the LCIA results are based on a relative approach and indicate potential environmental impacts, not actual impacts. The presentation of results should

be readily understandable, complete and in accordance with the goal and scope definition of the study.

The process of conducting an LCA is an iterative process where the goal and scope are consistently reviewed to determine if the study's objectives are met through the modeling process. Adjustments can be made by changing the system boundary or altering the functional unit. It is important to avoid incorporating subjectivity into the LCA to ensure that the results remain transparent. The assumptions should be clearly described and reported.

1.4. Natural Rubber and Tire Manufacturing Process Overview

Figure 3 displays the main processes in guayule and Hevea agriculture, guayule and Hevea processing and tire manufacturing.

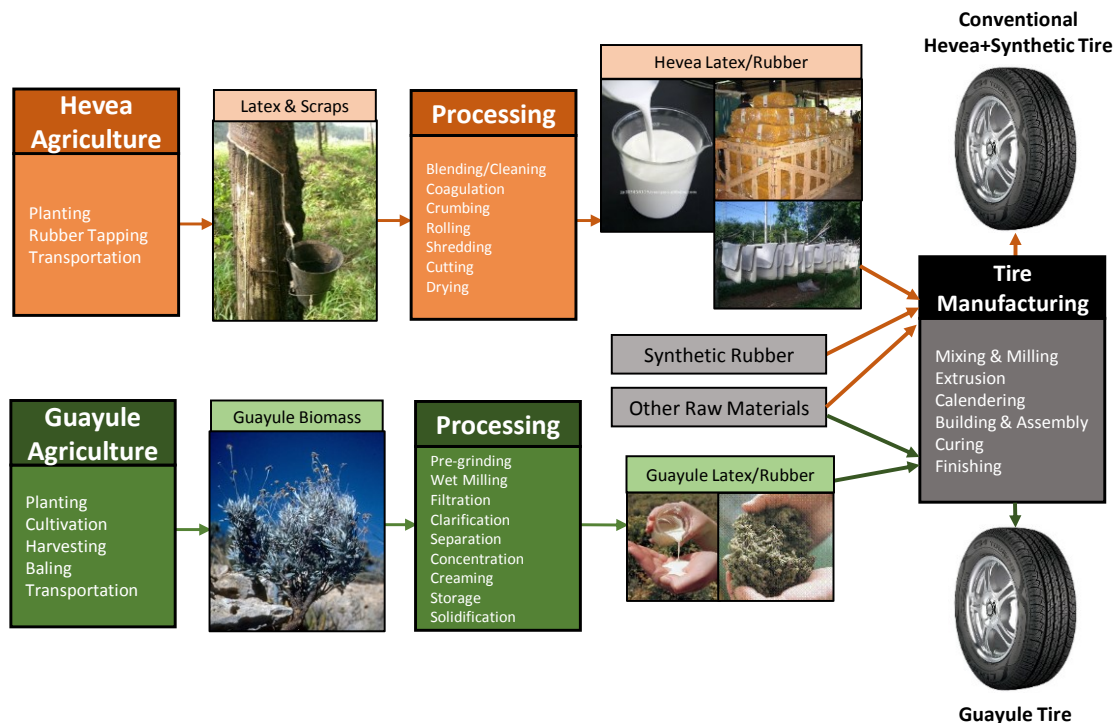


Figure 3. Rubber and Tire Process Overview.

Image references: Research.gov. "Using Fungi to Save Rubber Trees from Fungal Infection."; OSU (2010, December 6, 2010). "Faculty Spotlight - Dr. Katrina Cornish." Institute for Materials Research.; Viemeyer, N. (2008). "Underexploited Tropical Plants with Promising Economic Value: The Last 30 Years." *Trees for Life Journal* 3(1).; DIY Trade (2014). *Standard Vietnam Rubber. D. Trade.*; Regitex Co (2014). *MG-25: liquid latex rubber adhesive, MMA grafted natural rubber. Regitex Co. LTD.*; allbiz (2014). *Concentrated Natural Rubber Latex 20% HA, Hat Yai. Golden Tradecon Ltd.*; Sears (2014). *Cooper CS4 Touring - 225/60R17 99T BW - All Season Tire. Sears.*; Rechenthin, C. A. (2014). *Parthenium argentatum A. Gray - guayule PAAR5. Clarence A. Rechenthin @ USDA-NRCS PLANTS Database.*

The Hevea rubber tree predominantly grows in Southeast Asia, and can be tapped after approximately seven years of growth. The tapping process involves making incisions across the latex vessels and collecting the milky white latex in buckets. The tree can continued to be tapped for fresh latex for 13-18 years (Jawjit 2013). Other sources of Hevea rubber come from various Hevea tree scraps such as cup lump, bark scrap, earth scrap, also called coagula (Thailand Latex and Block Rubber Industry 2001). The raw rubber materials are transported to the processing facilities to manufacture various products. The primary rubber products include concentrated latex (for medical supplies), block rubber (used for tires), and ribbed smoked sheet rubber (for

industrial rubber parts). Concentrated latex is produced by centrifugation; block rubber for tires is produced by mixing the coagula with water, pressing to reduce moisture, shredding the rubber into small pieces, then drying and compacting into blocks; and ribbed smoked sheet rubber is made from liquid fresh latex that is transformed to solid rubber with chemical additions and a smoking process (Jawjit, Kroeze et al. 2010).

Guayule rubber is native to the American Southwest and is mature for harvest after approximately two years of growth. The plants are clipped above the crown, baled and transported to processing facilities. The latex in guayule is contained in the individual parenchyma cells, thus latex extraction requires the entire shrub to be processed (Wagner and Parma 1989). The product can be obtained in the form of latex or coagulated bulk rubber. For latex, the freshly harvested shrub is chopped into smaller pieces, milled in water or other aqueous medium, and separated from the bagasse through presses. The latex is clarified, concentrated and creamed to increase the concentration of the latex. The latex could then be solidified to create tire-grade rubber. For bulk rubber, the product is coagulated directly from ground shrub through solvent extraction. A common type of solvent extraction is simultaneous extraction, where ground shrub is washed with a rubber solvent to produce a dilute solution (Schloman Jr 2005) and a single stage separates both the resins and rubber from the fibrous tissue. The particulates are removed from the solution by methods of filtration and/or centrifugation (Wagner and Parma 1989). The rubber recovery and deresination are performed with the addition of a polar solvent which precipitates the rubber while the resins remain in the solution. Recent efforts in guayule commercialization have focused on producing a low-resin polymer to avoid rubber degradation polymer (Schloman Jr 2005).

Tire production begins with the mixing of the raw materials, such as various chemicals, carbon black, and rubber. Both Hevea and synthetic rubber are added to produce conventional tires, and only guayule rubber would be added to produce guayule tires assessed for this study. In commercial operations, the guayule would first be introduced as a replacement for the Hevea natural rubber. The mixed raw materials create rubber compounds that are extruded into pellets. The different types of pellets are placed on a drop mill to form the rubber into sheets and prepare

for the following steps. Some of the rubber compounds are extruded into certain shapes for specific tire parts, such as the tread, and some compounds are calendared. Calendaring is a process where additional materials, such as steel (e.g., for the belt) or textile (e.g., for the ply) are coated in a rubber compound. A tire consists of approximately 10 parts, and once the parts are manufactured, the tire is assembled and vulcanized in a mold using steam. This combines the parts into a solid final product. The finishing steps include visual inspections and uniformity tests to verify the tire quality.

CHAPTER 2

BACKGROUND

2.1. Literature Review

The objective of this literature review is to present the collection of publications on guayule, Hevea and automobile tires, and to highlight the lack of life cycle thinking in these publications. There has been extensive research performed on guayule and Hevea agriculture and processing, guayule co-products, and the end-of-life (EOL) of automobile tire (See Figure 4). To our knowledge, there are no publically available comprehensive LCAs on tire manufacturing and there are no existing LCAs on guayule rubber as a raw material for tires.

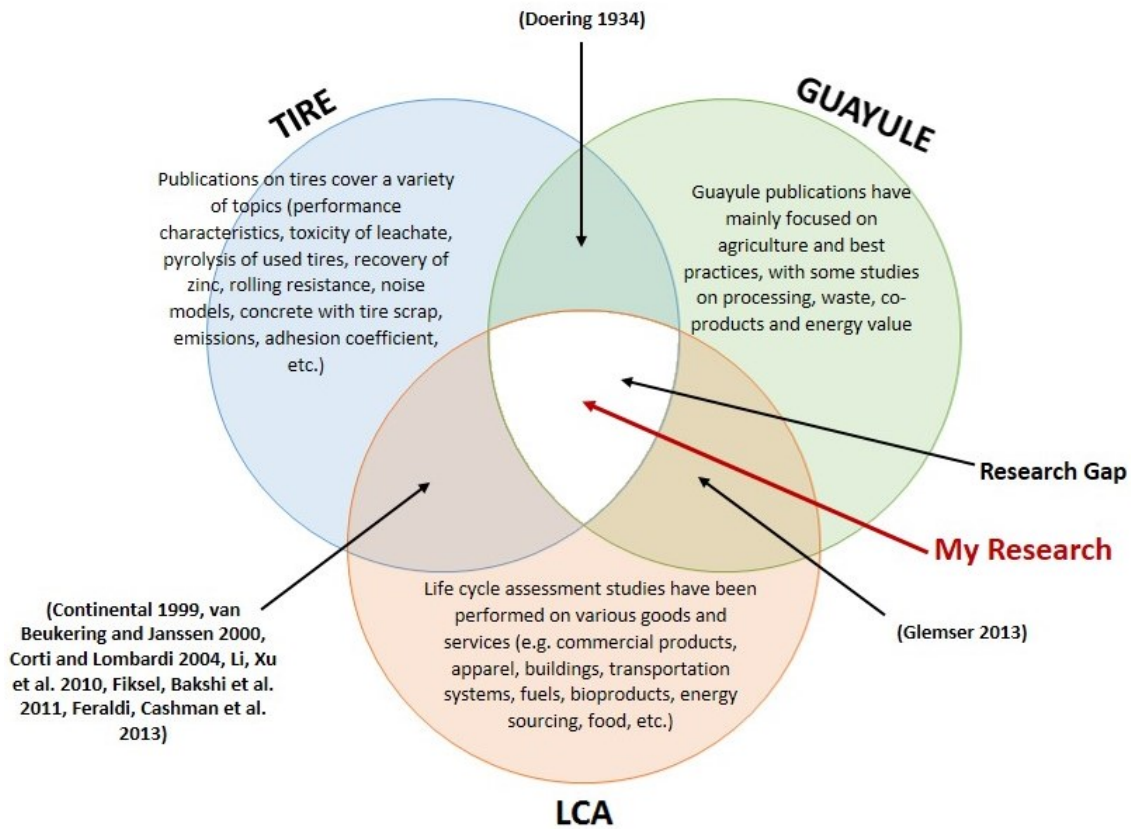


Figure 4. Literature Review of Tire, Guayule and LCA Publications. Extensive research has been performed on tires, guayule and LCA as unrelated topics. Data gaps exist with LCA on guayule rubber for tires.

Figure 4 shows that various studies have been published on tires, guayule and LCA as unrelated topics. Topics such as tire performance and material recovery, guayule agriculture and processing, and various LCA studies on products and processes are significantly covered in literature. There is a currently ongoing comparative study on guayule and Hevea rubbers and the utilization of co-products as energy off-sets (Glemser 2013). However, to my knowledge, there are no existing LCA studies on the use of guayule rubber in tires.

2.1.1. Guayule Agriculture and Processing

Agriculture

The guayule desert shrub is a member of the Compositae (or sunflower) family (Foster and Coffelt 2005) that reaches a height of 0.3-0.9m (11.8-35.4inches) (Correll 1979). Guayule naturally grows on the semi-arid limestone mountain slopes of the Big Bend region of Texas and Chihuahuan desert of north central Mexico (McGinnies 1980). Approximately 20,000km² can host the native guayule population within the states of California, Arizona, New Mexico and Texas (National Academy of Sciences 1977, Nakayama 1992). The regions native to the desert shrub range in temperature from -18°C and 49.5°C and receive 41cm (16 inches) or less of total annual precipitation (Foster and Karpiscak 1983).

Guayule is a difficult plant to breed because it is a perennial and requires relatively large amounts of land for breeding. It is physiologically immature for 2 years (van Beilen and Poirier 2007a), and the harvest time period has been shortened from 3-5 years to the currently implemented 2-3 years (Coffelt and Nakayama 2010). Guayule is commonly grown at densities up to approximately 54,000 plants/ha (Miyamoto and Bucks 1985, Coffelt, Nakayama et al. 2009) with the seeds planted approximately 1m (3.3 ft) apart (Foster, Fowler et al. 2002). One of the main issues with guayule cultivation is root disease, thus sandy-loam soils are most suitable (van Beilen 2006). The natural growth rates of guayule are too low for commercial harvesting and irrigation is necessary in most parts of the Southwestern US (Miyamoto and Bucks 1985, Foster

and Coffelt 2005). It is not an efficient user of water and requires high amounts of applied water to achieve maximum production (Foster and Coffelt 2005).

There has been a great increase in the number of publications on guayule agriculture since the 1980s. Agricultural papers focused on a variety of topics, such as the differences between transplanting and direct seeding and planting recommendations (Miyamoto and Bucks 1985, Foster, Fowler et al. 1999, Foster, Fowler et al. 2002, Foster and Coffelt 2005, Coffelt, Nakayama et al. 2009), soil's salinity effects on plants (Miyamoto and Bucks 1985), required water quantities and irrigation practices (Miyamoto and Bucks 1985, Bucks, Nakayama et al. 1985b, Bucks, Nakayama et al. 1985c, Bucks, Nakayama et al. 1985d, Nakayama, Bucks et al. 1991b, Foster and Coffelt 2005, Foster, Coffelt et al. 2011), selection of guayule species with high rubber yields and productivity (Estilai 1991a, Ray, Coffelt et al. 2005, Coffelt, Nakayama et al. 2009), defining the best time for harvesting (Coffelt, Nakayama et al. 2009, Coffelt and Nakayama 2010) and effects of cold temperature and water stress on growth and rubber/resin content (Bucks, Nakayama et al. 1985c, Foster, Coffelt et al. 2011). Papers on guayule have commonly been published in regions where the majority of guayule agricultural practices take place, mainly the Southwestern US and Mexico, but have also been published in Australia and Europe (Milthorpe, Sanderson et al. 1994, Dissanayake, George et al. 2004, van Beilen and Poirier 2007a, van Beilen and Poirier 2007b, Bedane, Gupta et al. 2011). However, no publications were found using LCA to evaluate guayule or its products.

Processing

Many methodologies have been used to process guayule since the early 1900s. The latex is produced by milling freshly harvested shrub in water or other aqueous medium followed by centrifugation (Jones 1948), and the bulk rubber is commonly produced through flotation (also called aqueous flotation) or solvent extraction, which includes sequential extraction or simultaneous extraction (also called simultaneous solvent extraction) (Wagner and Parma 1989, Schloman Jr 2005). The early methodologies used flotation, but this required large process water

requirements and energy intensive steps to recover rubber from the solution (Wagner and Parma 1989). Most guayule extraction processes include the use of solvents, such as hexane, acetone or pentane (Ray 1993).

Several patents have been published that discuss processing methods of guayule (Kay and Gutierrez 1984, Ji 1994, Cornish 1996, Cornish 2006, Cornish, McCoy et al. 2011). Firestone-Bridgestone has been known to use compounds such as hexane, pentane and acetone in solvent extraction (Kay and Gutierrez 1984, Kay and Gutierrez 1990, Schloman Jr 2005). In the processing method described by Cornish, McCoy et al. (2011), guayule goes through the processes of pre-grinding, wet milling, filtration, clarification, separation of liquid phases, purification, creaming, and concentration. This method incorporates a solution of water and a buffer instead of the typical solvents.

Waste and co-products

The main guayule co-products are the bagasse and resin, and the commercial applications are thoroughly discussed in a publication by Nakayama (2005). The co-products from guayule processing can be used to improve the overall economics of the guayule shrub and offset a substantial amount of the growing and processing costs (Wagner and Parma 1989). There have been numerous publications released on the potentials of the waste and co-products of guayule production. Studies have been performed on guayule wastewater concerning its reuse after guayule extraction and its substitution for irrigation water (Coffelt and Williams 2009) and the recovery of latex from the wastewater (Jones 1948). No studies have been performed on commercial uses for the processing wastewater (also called waste liquor) at this time (Nakayama 2005).

The bagasse is the remaining biomass after latex extraction, and the resin can be extracted from the bagasse or the whole plant. The latex also contains some of the guayule resin. Guayule bagasse and resin can be used, for example, in the pulp, paper and chemical industries (Chow, Nakayama et al. 2008), manufacturing of preservative-free termite resistant composite

boards (Nakayama, Vinyard et al. 2001, Nakayama 2005, Holt, Chow et al. 2012), as a soil amendment (Schloman 1991, Nakayama 2005), pesticide (Bultman, Gilbertson et al. 1991), as well as for fuel and energy sources (Kuester 1991, Wagner, Soderman et al. 1991, Nakayama 2003, Nakayama 2005, Boateng, Mullen et al. 2009).

Natural plant resins are used commercially in cosmetic, pharmaceuticals and as modifiers in synthetic rubber and plastics. They are insoluble in water, soluble in polar organic solvents, and viscous in consistency (Ray, Foster et al. 2010). The guayule resin can be used as a plastic binder, adhesive (Nakayama 2005) and wood treatment to resist pests (Bultman, Gilbertson et al. 1991, Nakayama, Vinyard et al. 2001, Nakayama 2005, Boateng, Mullen et al. 2009). It has also been converted directly into liquid hydrocarbons (Boateng, Mullen et al. 2009). The guayule resin can be used as a fuel and has energy values of 37.90 MJ/kg, which are comparable to the oil extracted from most oilseed crops (Nakayama 2003).

Bagasse is made up mostly of cellulose, hemicellulose, lignin and resin. It has been used for energy in the form of fireplace logs (Wagner, Soderman et al. 1991), pelletized fuel with a mixture of cotton gin trash (Nakayama 2005), gaseous and liquid fuels (Kuester 1991), and low yields of ethanol and bio-oil (Boateng, Mullen et al. 2009). The bagasse feedstock, depending on whether the entire shrub or just the twigs are included, contains an energy content between 21,000kJ/kg and 24,000kJ/kg (Boateng, Mullen et al. 2009) (See Table 1). Its high fuel (heating) value makes bagasse an acceptable fuel for direct combustion (Schloman Jr 1991). Kuester (1991) showed that gas yields of 0.9g/g plant matter with a heating value of 20.5kJ/l could be achieved, and diesel fuel produced by liquefaction of this gas yields 0.25l/kg of guayule feedstock.

Bio-oil, which is made by pyrolysis of bagasse, showed to have an energy content of ~30MJ/kg (Boateng, Mullen et al. 2009). This can be compared to the energy content of biodiesel (~42MJ/kg) and diesel (43MJ/kg) (Joshi and Pegg 2007). With the inclusion of the recovered bio-oil in the condensers and the system piping, the overall bio-oil yield is estimated at 64.1% for guayule bagasse (Boateng, Mullen et al. 2009). A study by Boateng, Mullen et al. (2010) found that the stem-derived, latex-extracted guayule bagasse (the leftover bagasse fraction following

commercial latex extraction) has the most thermochemical energy potential and represents an excellent feedstock for bioenergy. This was attributed to the resin component and the residual rubber still remaining in the bagasse. Co-products from the pyrolysis also have a high energy content. After bagasse pyrolysis, the charcoal averaged 24,438kJ/kg (Boateng, Mullen et al. 2009), and has potential to be a carbon-sequestering, soil-amending co-product of the pyrolysis process (Laird 2008).

Typical energy content of biomass materials such as wood and grasses range between 15 and 19MJ/kg (Boateng, Mullen et al. 2009). Nakayama (2003) conducted studies showing that the biomass of the whole plant has higher energy values (21.77MJ/kg) than any other biomass source, including corn (*Zea mays L.*) stalks, wheat (*Triticum aestivum L.*) straw, kenaf (*Hibiscus cannabinus L.*), and switchgrass (*Panicum virgatum L.*) (18.61MJ/kg) (Coffelt, Nakayama et al. 2009, Coffelt and Ray 2010). Even with the rubber (latex) and resin removed, the energy value (20.49MJ/kg) is still higher than other plant biomass sources (Nakayama 2003). In addition to being a high-energy feedstock, it is transportable and produced 12 months a year, thus there is potential for guayule to become commercially available as an energy source.

Table 1. Energy Content of Guayule and Hevea Co-products.

Co-product	Energy Content	Reference
GUAYULE		
Bagasse		
Whole shrub	21,770 kJ/kg	(Coffelt, Nakayama et al. 2009)
Whole shrub	21,018 kJ/kg	(Boateng, Mullen et al. 2009)
Bagasse feedstock (after latex extraction, with any remaining resin in the woody and bark fractions of the stem)	24,177 kJ/kg	(Boateng, Mullen et al. 2009)
Bagasse with resin	20,490 kJ/kg	(Nakayama 2005)
Bagasse without rubber and resin	20,490 kJ/kg	(Coffelt, Nakayama et al. 2009)
Bagasse without resin	18,300 kJ/kg	(Nakayama 2005)
Bio-oil after bagasse pyrolysis (smaller value for the whole shrub, larger value for the bagasse)	30,428-30,508 kJ/kg	(Boateng, Mullen et al. 2009)
Resin		
Resin that can be used as a fuel (no mention of treatment)	37,900 kJ/kg	(Coffelt, Nakayama et al. 2009)
Resin energy value	38,000 kJ/kg	(Nakayama 2003)
Heating values for resin	38,200 kJ/kg	(Schloman Jr, Carlson et al. 1988)
HEVEA		
Seed oil	32,600-39,700 kJ/kg	(Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011, Gimbun, Ali et al. 2013, Ahmad, Yusup et al. 2014)
Rubberwood	17,900 kJ/kg	(Krukanont and Prasertsan 2004)

2.1.2. Hevea Agriculture and Processing

There are numerous publications available on Hevea agriculture (Aweto 1987, Guardiola-Claramonte, Troch et al. 2010), processing (Tekasakul and Tekasakul 2006, Jawjit, Kroeze et al. 2010, Saidur and Mekhilef 2010, Jawjit 2013) and waste (Leong, Muttamara et al. 2003, Chairapat and Sdoodee 2007, Mitra Mohammadi 2010, Nguyen 2012). This study focused on

two particular papers that included standardized agricultural and processing data for Hevea rubber in Thailand. The first by Jawjit, Kroeze et al. (2010) incorporated industry data to evaluate greenhouse gas (GHG) emissions of the Hevea industry and the second by Jawjit (2013) used the data to conduct an LCA on Hevea rubber.

The Jawjit, Kroeze et al. (2010) publication presented emissions of greenhouse gases from the production of fresh latex and 3 types of primary rubber products, 2 of which used as raw materials for vehicle tires - block rubber (or Standard Thai Rubber (STR 20)) and ribbed smoked sheet rubber. Both the agricultural activities in rubber tree plantations (production of N and P fertilizer, production and use of diesel, land conversion, N fertilizer use) and industrial activities in the rubber mills (production of electricity, production and use of diesel, production and use of liquefied petroleum gas (LPG), production of ammonia, and wood use) are taken into consideration for the LCA. The study found that the CO₂ emissions are largely associated with energy use during processing and the use of synthetic fertilizers.

A paper by Jawjit (2013) entitled "Evaluating Environmental Performance of Concentrated Latex Production in Thailand" describes a partial LCA with a "gate-to-gate" analysis of 1 ton of concentrated latex. The system boundaries included production of chemicals, production of diesel and electricity, diesel combustion, and wastewater treatment for latex processing. The main environmental problems caused by Hevea latex production include water pollution (acidic wastewater), air quality problems (odor of rubber, and chemicals), and toxicity from the use of chemicals (such as sulfuric acid and ammonia) (Jawjit 2013). The results indicated that the most significant impacts were caused by electricity used for centrifugation, ammonia for latex preservation and the use of diammonium phosphate (DAP) used for the removal of magnesium from fresh latex (Jawjit 2013). The study used three impact assessment methods: ecoinvent 2.0, CML and Eco-indicator 99.

Papers have been published on the use of Hevea seed oil as biodiesel (Ikwuagwu, Ononogbu et al. 2000, Ramadhas, Jayaraj et al. 2005a, Melvin Jose, Edwin Raj et al. 2011, Morshed, Ferdous et al. 2011, Yang, Su et al. 2011, Gim bun, Ali et al. 2013, Ahmad, Yusup et al. 2014). These studies show that the energy content of the seed oil ranges from 32.6 to 39.7MJ/kg

(Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011, Gimbun, Ali et al. 2013, Ahmad, Yusup et al. 2014) (See Table 1). Although the use of this non-edible oil as a biodiesel is not currently commercialized, there is an interest to utilize the high yields of the seed by-product. It has been found that the productivity of rubber seed oil per hectare per year is 217kg (Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011) and the oil content in the rubber seed is approximately 40-60 wt.% (Ramadhas, Jayaraj et al. 2005b, Melvin Jose, Edwin Raj et al. 2011). The biodiesel extraction and production process involves steps such as breaking down the seed, screw pressing, acid esterification, and transesterification to mono-ester (Melvin Jose, Edwin Raj et al. 2011).

Hevea rubberwood can be used as an energy source for wood fired power plants (Krukanont and Prasertsan 2004), as a fuelwood and charcoal in rubber processing, steel industries, tobacco curing and brick manufacturing, and as a material for furniture, furniture parts and wood-based panels. Rubber trees are generally removed and replaced with new seedlings after 30 years (Balsiger 2000). The energy content for a wood fired plant is approximately 17,900kJ/kg, which is slightly lower than typical wood energy content (Krukanont and Prasertsan 2004).

2.1.3. Tire Studies and LCAs

Guayule Tires

To my knowledge, there is only one existing available publication on a guayule tire that was published by Doering (1934) of Firestone Tire and Rubber Company. In the study, tires and tubes were made using exclusively guayule rubber and tested over the period of 2 years. They failed between 8,500 and 10,500 miles due to tread wear (60% of the mileage obtained with Hevea tread), but the inner tubes performed well. The paper discusses changes in the composition and production of various rubber stocks when replacing Hevea with guayule rubber. The main difficulties in achieving high performance and mileage were the high resin content of guayule and the presence of bark and dirt (Doering 1934).

Studies on guayule rubber have focused on military application, such as in tank track pads, aircraft tires (Schloman Jr 1991), and in light truck tires (Herman 2004). These are published documents on guayule rubber tire performance that are not publically available, but their results are discussed in other publications. Tests performed on guayule rubber for a US Navy/USDA Guayule Program showed that new tires fabricated from 100% guayule rubber or a 50:50 blend of guayule and Hevea rubber did not pass all dynamic testing requirements (Herman 2004, Schloman Jr 2005). Other road tests performed by Firestone Tire and Rubber Company in the 1950s have shown that tires made from guayule rubber performed as well as the Hevea rubber tires (National Academy of Sciences 1977) Additionally, rebuilt aircraft tires built with guayule rubber was comparable to the performance of those containing Hevea (Herman 2004). Guayule rubber made under different specifications was used to fabricate light truck tires and the performance of these tires was comparable to that of controls containing Hevea rubber (Schloman Jr 2005).

Tire LCA

Continental AG conducted a publically available LCA on the complete life of a conventional European car tire which included processes of the raw material extraction, manufacturing of the tire's raw materials, production of the tire at the tire plant, use of the tire on the road, and utilization of the old tire as a raw material or energy provider (Continental 1999). One of the main goals of the LCA was to determine methods to reduce environmental impacts over the life of a tire. The LCA used data taken from 1990 to 1997 from a combination of raw material manufacturers, publications and personal communications. The study showed that the highest cumulative energy input, global warming potential, acidification potential and nitrification potential occurred during the use phase of the tire.

Authors van Beukering and Janssen (2000) evaluated tires from an industrial metabolism perspective through an LCA of truck tires in Western Europe. The main goal of the publication was to determine scenarios indicated by industrial and policy stakeholders to represent the most

important anticipated changes in the western European tire life cycle. Results showed that the emphasis in environmental policies related to tires should shift from the production and the waste stages to the consumption stage, since more than 95% of the overall environmental impact during the life of a tire occurs during the use of the tire, due to the impact of tires on automotive fuel efficiency.

Several LCA studies have been performed on tires, but the full reports are not publically available. PRé Consultants conducted an LCA in 2001 of a conventional European car tire (BLIC 2001b) with the help from numerous tire companies, including Bridgestone-Firestone, Continental, Cooper-Avon, Goodyear-Dunlop, Michelin, Nokian, Pirelli, Trelleborg and Vredestein. The study determined that the use phase has the highest contribution to environmental load in the life cycle of a car tire, and the most important aspect during the use phase is the fuel consumption that can be attributed to rolling resistance (the force resisting the motion when a tire rolls on a surface). The production phase of a car tire is mainly determined by the production of raw materials, and not the car tire manufacturing itself (BLIC 2001a).

Tire EOL

Most peer-reviewed LCAs of tires focus on EOL rather than the LCA of the production and use phases (Corti and Lombardi 2004, Li, Xu et al. 2010, Fiksel, Bakshi et al. 2011, Feraldi, Cashman et al. 2013). Studies on the EOL of tires discuss different scrap tire reuse methods and different processes for the end life treatment of exhausted tires. Other topics discussed in tire studies include life cycle energy accounting (Amari, Themelis et al. 1999), disposal for energy recovery with a focus on a safe environment (Sharma, Fortuna et al. 2000) and ways to reuse tires (Jang, Yoo et al. 1998, Rajan, Dierkes et al. 2006).

2.2 Natural Rubber Background

Guayule and Hevea are sources of natural rubber- both latex and solid rubber. The guayule plant is processed to extract liquid latex from the individual parenchyma cells, which is then solidified to produce the solid rubber as raw material for tire production. Natural rubber from the Hevea trees comes in two forms: liquid field latex and field coagula. Hevea trees can be tapped for the latex (a white sap) which can be dried to produce numerous products. Other useful parts of the Hevea trees are called coagula, such as cup lump, tree lace, and earth scrap. Cup lump is formed by the natural coagulation of latex which drips into the collection cup/bucket after collection. Tree lace refers to the thin skin of rubber that forms on the tapping cut which naturally forms to seal the latex vessel and stop the flow of latex (NIIR Board of Consultants and Engineers 2010). Earth scrap is the latex that has dripped on the ground. The coagula are additionally processed to make tire grade rubber.



Figure 5. Guayule Plant (Rechenthin 2014)



Figure 6. Hevea Tree and Latex Tapping (Research.gov)

2.2.1. Guayule and Hevea Agriculture

Guayule Agriculture

Guayule yields are reported as a range of values summarized in Table 2 in terms of both biomass yield and extractable latex and rubber. Guayule biomass yields are typically in the range of 13 tons/ha*year to 20 tons/ha*year (Estilai 1991a, George, Gupta et al. 2005, van Beilen and Poirier 2007a). The rubber yield also varies, and is commonly between 300 and 2,000 kg/ha*year (Kelley, Haise et al. 1946, Tingey 1952, Polhamus 1962, Swanson, Buchanan et al. 1979, Ray 1986, Thompson and Ray 1989, Estilai 1991a, Estilai 1991b, Mooibroek 2000, van Beilen 2006, van Beilen and Poirier 2007a). The time to reach maturity is approximately 2 years, after which the plant can be cut and regrown (Miyamoto and Bucks 1985, Estilai 1991a). Biomass yields often correlate with the rubber yield, but rubber concentration together with adequate biomass production are the ideal qualities for efficient latex extraction. A large plant size with a lower rubber concentration could be disadvantageous due to the additional transportation and handling and rubber processing required to extract the latex (Ray, Coffelt et al. 2005). Agricultural inputs such as irrigation rates, and fertilizer and herbicide applications are also summarized in Table 2.

Irrigation rates to obtain high rubber content are comparable to alfalfa (Foster and Coffelt 2005). Irrigation in desert regions where guayule grows naturally include flood, sprinkler and drip methods. Flood irrigation (also called surface, furrow or level basin) water flows directly over the surface of the soil. Sprinkler involves water sprayed through the air from pressurized nozzles, and falls like rain on the crop. Drip (or trickle) irrigation supplies water directly onto or below the soil surface through pipes that control water flow (EPA 2012). The plants require minimal fertilization and chemical application.

Table 2. Biomass and Rubber Yield, Irrigation rates and Fertilizer and Herbicide Applications for Guayule and Hevea.

¹For guayule, it has been found that the productivity of latex and solid rubber are equivalent (Coffelt, Nakayama et al. 2009). For Hevea, literature does not always explicitly state whether the values are listed for latex or rubber, thus are assumed to be the yield for Hevea latex, not solid rubber. The ratio of Hevea latex to tire-grade rubber has been known to be 2:1 (Jawjit, Kroeze et al. 2010)

²Irrigation values found for guayule are assumed to be for flood irrigation.

	Guayule		Hevea	
	Value	References	Value	References
Biomass Yield (agricultural biomass harvested in field containing both plant material and latex)	Up to 13000 kg/ha*year	(George, Gupta et al. 2005)	2167-4333 kg/ha*year (rubberwood)	(Balsiger 2000)
	20000 kg/ha*year	(van Beilen and Poirier 2007a)		
	Up to 26000 kg/ha*year, average of 13000 kg/ha*year	(van Beilen and Poirier 2007a)		
	5623-15860 kg/ha*year	(Estilai 1991a)		
	5600-16800 kg/ha*year	(Personal communication with Bronson 2014)		
Rubber Yield¹	1500-1900 kg/ha*(3 years growth)	(Foster and Coffelt 2005)	1600 kg latex/ha*year	(OAE 2012)
	2000 kg/ha*year	(van Beilen and Poirier 2007a)	1614 kg /ha*year (non-irrigated)	Sopheaveasna 2008)
	300-1000 kg/ha*year	(Estilai 1991b)	1904 kg/ha*year (irrigated)	Sopheaveasna 2008)
	1100 kg/ha*year	(Thompson and Ray 1989)	2200 kg/ha*year	Sopheaveasna 2008)
Irrigation²	1000-1300 mm/year (irrigation only)	(Nakayama 1991a)	3515 mm/year (irrigation+rainfall)	(Vijayakumar, Dey et al. 1998)
	2850mm/(2 years) (irrigation only)	(Bucks 1985a)	3540 mm/year (rainfall only)	(Sopheaveasna 2008)
	280-640 mm/year (irrigation+rainfall)	(National Academy of Sciences 1977)	2000-5000 mm/year (rainfall only)	(Rao and Jessy 2007)
	1830-3824 mm/(21 months) (irrigation+rainfall)	(Bucks, Nakayama et al. 1985c)		
	713-1039 mm/year (irrigation+rainfall)	(Foster, Fowler et al. 2002)		
Fertilizer	210 kg N/ha*(2 years)	(Bucks 1985a)	70 kg N/ha*year	Jawjit, Kroeze et al. 2010)
	620 kg N/ha*(4 years)	(Nakayama, Bucks et al. 1991b)	35 kg P/ha*year	(Jawjit, Kroeze et al. 2010)
	130 kg N/ha (total application)	(Bucks, Nakayama et al. 1985c)		
Herbicides	DCPA: 4.5-11kg/ha	(Ray, Foster et al. 2010)		
	Bensulide: 2.2-4.5 kg/ha			
	Pendimethalin: 0.6-2.2 kg/ha			

Plant Establishment: Transplanting and Direct-seeding

Two methods have been used to establish guayule plants: transplanting and direct-seeding. Transplanting involves planting pre-grown plants (commonly in greenhouses) in agricultural fields, or replanting established plants from one location and moving them elsewhere. Direct-seeding is when seeds are directly planted on the ground in the field. Currently, the more common method is transplanting, but direct-seeding is a more economically feasible approach that is likely to be applied by commercialized industries.

The transplants are grown in nursery trays in a greenhouse for 7-15 weeks, range in height between 100 to 200mm, and have a shallow, fibrous root system (Foster, Fowler et al. 2002). During the first 4 weeks after transplanting, the transplants grow slowly by attaining a few centimeters of top growth and about 10 cm of root growth. They must be irrigated frequently, and are commonly planted in the spring when the total irrigation value ranges from about 10cm to 25cm with a 95% survival rate (Miyamoto and Bucks 1985). Summer transplanting survival rates has shown to be much lower (19%-80%). The transplants are commonly watered with furrow irrigation, but under drip irrigation the transplants could be established with lesser quantities of water. Transplants are found to be more expensive (US\$ 900-1200/ha for transplanting, versus US\$ 400/ha for direct seeding (Bucks 1986)) and require additional resources such as transportation from the transplant suppliers to the fields, greenhouse use and environmental control for the growing process, planting containers, tractors and labor to place the transplants into the soil.

Guayule can be established through direct seeding which holds an economic advantage, but it has been found that the survival rates are lower. However, the growth period until harvest could be shortened by nearly a year by seeding directly in the field (Foster and Coffelt 2005). Seedlings grow slowly with 10mm of top growth and 60mm of root growth during the first 2 weeks of emergence (Foster and Coffelt 2005). The irrigation amounts to establish the guayule by direct seeding have ranged between 20cm to 50cm during spring months (Miyamoto and Bucks 1985), but irrigation techniques must be carefully selected to avoid seedling diseases (Foster and Coffelt 2005). A 3-month seedling establishment through direct-seeding would require at least 300mm of

water, in addition to 56kg/ha of nitrogen (Bucks 1986). Studies have shown that there are no significant differences between the direct-seeded and transplanted shrubs and that direct seeding could be a viable system for commercially establishing guayule stands (Foster, Fowler et al. 2002).

Growing and Irrigation

Guayule produces higher yields on sandy or sandy-loam soils versus loamy soil due to better soil aeration. For maximum shrub production, the annual water use of guayule is high and comparative to alfalfa (Foster and Coffelt 2005). Additionally, guayule's water use efficiency is much less than other commercial crops. Its water use efficiency based on biomass production is approximately $0.8\text{kg}/\text{m}^3$, compared to $1.2\text{kg}/\text{m}^3$ for alfalfa or $2.8\text{kg}/\text{m}^3$ for corn (Nakayama 1992). Water quantity depends on the growing region and desired yield levels (Foster and Coffelt 2005). Irrigation recommendations vary amongst studies, with a range of 1000-1300mm/year in Arizona (Nakayama 1991a). However, the total water use requirement for guayule (irrigation and precipitation) will be on the order of 1500 to 2000mm during the first and second years, respectively (less water is needed for smaller plants) (Personal communication with Hunsaker 2014). Water requirements can increase up to almost 2200mm/year (See Table 2). Guayule plants are not typically watered during the winter months (December and January), and can be watered between 120mm-180mm monthly throughout the rest of the year (Bucks, Nakayama et al. 1985c). An advantage of the guayule plant is that it is drought tolerant, which can permit flexibility in irrigation scheduling. There are no critical periods, such as flowering or seed set, where drought can cause crop failure (Ray, Foster et al. 2010). An important factor to consider in addition to the environmental impacts of water use is the financial costs of water. Currently in the Maricopa-Stanfield area in AZ, Central Arizona Project, water costs are approximately \$50-\$60/acre-ft ($\sim\$0.04/\text{m}^3$). Thus, if guayule requires approximately 7ft/year (2100mm/year) or irrigation water, irrigation water costs would be on the order of $\sim\$400/\text{acre}/\text{year}$, or $\sim\$1000/\text{ha}/\text{year}$. Irrigation efficiency can be increased with land leveling and drip irrigation systems to minimize water use (Personal communication with Hunsaker 2014).

Literature values found on irrigation often report flood irrigation (Bucks, Nakayama et al. 1985c, Nakayama, Bucks et al. 1991b, Foster and Coffelt 2005, Bekaardt, Coffelt et al. 2010) or sprinkler irrigation values (Bucks 1985a). For this study, it is assumed that all values reflect flood irrigation application since this method is most common for guayule. Flood systems have been shown to operate at an efficiency of 65-85%, and drip operates at 90% (Howell 2003).

Guayule is a low user of major nutrients and fertilization is minimal compared to many other agricultural crops. Nitrogen (N) is an important nutrient for transplants and direct-seeding, and N application results in higher plant biomass (Foster and Coffelt 2005), especially when applied as nitrate rather than ammonium in transplants (Ray, Foster et al. 2010). N application amounts in publications are listed for a specific growth period of guayule, e.g. 210kg N/ha total applied during 2 years of growth (Bucks 1985a), 620kg N/ha total during 4 years of growth, or 130 kg N/ha as the total applied amount (Bucks, Nakayama et al. 1985c) (See Table 2). Per year, the average amount of N applied discussed in publications was averaged to approximately 120 kg N/ha*year. Potassium (K) levels are high in Arizona soil and no additional P is needed for guayule agriculture (Personal communication with Bronson 2014). Studies have shown that changing phosphorus (P) levels does not affect guayule plant dry weight (Ray, Foster et al. 2010).

Herbicides can be used during establishment in the pre-emergence phase to help compete against annual and perennial broadleaf and grass weeds, but are toxic to guayule transplants during periods of active growth (Foster and Coffelt 2005). Sprays for weed control can be applied to dormant guayule, or as spot treatment for localized weed infestations. Before the guayule plants reach full maturity, weeds can be removed with machinery. Machine weeding is usually performed on a monthly basis. Herbicides not toxic to guayule are summarized by Ray, Foster et al. (2010) and include glyphosate, oryzalin and oxyfluoren. Pre-emergence herbicides are required for optimal direct-seeding establishment, and herbicides such as DCPA, bensulide and pendimethalin treatments have been incorporated for direct-seeding (Ray, Foster et al. 2010) (See Table 2). Given the natural conditions in the Southwest US, insecticides are not needed for guayule. Overall, the optimum irrigation, herbicide, and fertilizer treatments vary in different soil and climatic conditions (Ray, Foster et al. 2010).

Harvesting and Transportation

There is no specific time of year during which guayule must be harvested and there seems to be enough differences among the guayule varieties that would allow growers to spread the optimum harvest time throughout the year (Coates 2001, Coffelt and Nakayama 2010). This would be beneficial in helping reduce production costs by having flexibility with harvest length and time of year. Studies have shown that harvesting from September to March produced more biomass, January was the best month to harvest for latex concentration, and July was consistently low for latex concentration (Coffelt and Nakayama 2010). The recommended method of harvesting involves cutting above ground plant material when plants reach 2 years of age then harvesting the regrowth after another 2 years (Foster and Coffelt 2005).

There are several methods used to harvest guayule. The plant can be clipped above the soil to remove only the branches and stem, or it can be undercut 15 to 20cm below the soil surface, leaving the top of the taproot intact (van Beilen 2006). The shrub can be harvested with a mowing system consisting of swath mowers or special mowers, cutters and saws at a speed of approximately 0.85-1 ha/hour (van Beilen 2006). Guayule can be baled in the field with balers with capacities of 0.42ha/hour (10.3tons/hour) that can process 0.17ha/hour (26.3tons/hour) (van Beilen 2006). Bales can be pressed up to a density of 280 kg/m³ (Coates 1991). Chopping the guayule in the fields has been suggested to reduce transport costs. Initially, this was only possible with nearby processing facilities, since longer transport distances and storage times cause latex degradation problems (Coates 1991). Unlike Hevea, guayule plants contain no antioxidant to retard oxidative degradation of the rubber once the cells are exposed to air (National Academy of Sciences 1977). Unprotected latex coagulates into solid rubber within the plant or harvested plant material which can only be extractable as solid rubber using organic solvents (Coffelt 2009). Methods of guayule biomass storage have been described in patents by Gutierrez, Kay et al. (1985) and Clark and Malani (1986). A method was recently developed to store freshly harvested shrub prior to processing for latex extraction and protect the latex concentration and yield (Coffelt 2009). This method requires keeping the harvested shrub moist

to protect the latex before the processing stages, which would allow more flexible harvesting and processing schedules for industry.

Early production and harvesting practices for guayule were focused on extracting bulk or solid rubber (Foster and Coffelt 2005) that could be used for tires. A practice described by Taylor (1952) involved curing the shrub in the field 10-45 days before processing, which dehydrates the shrub and reduces the weight of the shrub materials to be transported, and maximizes the amount of solid rubber that can be recovered during the milling process. This method leads to a rapid loss of water-soluble latex, thus is not acceptable when harvesting for latex (Coffelt 2009). For this study, it is assumed that guayule is transported from the fields to the processing facilities in a straight truck, which is the most conservative value. When fully loaded, these vehicles run at about 5mpg (Barnes 2003), and have a capacity of approximately 1,700 ft³.

A study by Coffelt, Nakayama et al. (2009) found that guayule latex concentration and yield were similar to those for guayule rubber concentration and yield. This indicates that results from studies only analyzing for rubber concentration and yield can probably be used interchangeably for the latex concentration and yield, and vice versa. It should be noted that latex is measured in percent solids, which would reduce the amount of rubber in relation to latex (i.e. 50% solids would indicate that half of the reported latex weight is rubber solids). Additionally, weather conditions could influence the quality and content of liquid latex available for extraction from guayule plants. For Hevea latex, studies have assumed that 2 tons of fresh latex are needed for the production of 1 ton of STR 20 (tire grade) rubber (Jawjit, Kroeze et al. 2010) and 2.5 tons of fresh latex are needed for the production of 1 ton of concentrated latex (dry rubber content) (Jawjit 2013).

Regrowth

Studies show that harvesting by clipping the top of the guayule shrub after a few years of growth, then again after approximately another 2 years of growth, increases the rubber yield (Miyamoto and Bucks 1985, Estilai 1991a, Cornish, McCoy et al. 2011), as opposed to harvesting

the whole plants after 4 years. If the guayule plants are capable of regrowth after each harvest, there would no longer be a need for retransplanting, thus making it an acceptable crop to be harvested regularly in 2-year cycles. This would avoid the additional transplanting cost and an additional harvesting cost (Estilai 1991a). It has also shown to increase rubber productivity per area, allow growers an early return on their investment, and delay the cost of stand reestablishment by permitting a stand to remain productive longer (Ray 1986).

Future of guayule agriculture and breeding

Over the years, Hevea trees have shown to provide higher production yields and higher rubber content. There is potential for guayule to greatly increase in output similarly to the progression that Hevea displayed over the years. In four decades, the Hevea rubber yield increased ten-fold from 300kg/ha*year to 3,000kg/ha*year (Estilai 1991a, van Beilen and Poirier 2007a). A goal for guayule producers is to increase the yield of the rubber product to one metric ton per acre per year (2,470kg/ha*year) by 2018-2019 (Lane 2013). PanAridus, the company leading in developing commercial processes to produce guayule for the tire industry, has cut the growing time before harvest in half and in 2012, reached a yield of 2,000 kg rubber/ha*year (PanAridus 2014). A guayule rubber yield over 1,000 kg/acre*year (2470 kg/ha*year) would be competitive with the rubber from the Hevea trees in Southeast Asia (Lane 2013). Ray et al. predicted that as guayule approached commercialization, breeding would become a priority and could greatly increase breeding efficiency (Ray, Coffelt et al. 2005). Companies and organizations such as PanAridus, Yulex, SGB, Versalis, Pantagonia, and the University of Arizona are working to increase plant yields under commercial conditions, broaden the geographical reach of the plant, and develop products to replace common materials with guayule (Lane 2013). Continuing research on breeding programs will develop higher yielding cultivars that are likely to equal or possibly even exceed Hevea rubber yields.

Hevea Agriculture

The top five Hevea rubber producing countries are Thailand, Indonesia, Malaysia, India and Vietnam. Thailand and Indonesia produce over 3 million tons of rubber yearly. In Indonesia, most of the rubber production (about 80%) is accounted for by smallholder farmers. About 85% of Indonesia's rubber is exported, and the US is the top Indonesian rubber importing country (Indonesia-Investments 2013).

A typical rubber plantation has a lifetime of about 20-25 years, the rubber tree can be tapped after approximately seven years of growth, and continue to be tapped for fresh latex for 13-18 years (Jawjit 2013). Hevea agriculture can be divided into two systems: rubber plantations and rubber mills. The plantations are where the rubber trees are tapped or coagula is collected, and rubber mills are where the raw rubber is processed to produce industry-suitable rubber.

Anti-coagulants such as ammonia (NH_3), sodium sulphite (Na_2SO_3), formalin (CH_2O) and tetra methyl thiurum disulphide (TMTD) or zinc oxide (ZnO) are added to the latex as soon as it is tapped and the amount depends on the season and the distance from the processing factory (Jawjit 2013). Information on Hevea agricultural inputs is listed in Table 2.

The rubber plantation provides two sources of rubber: fresh field latex and rubber coagula. Fresh field latex is the milky white sap that is collected in buckets after the Hevea tree bark is cut, and the coagula are latex remainders on and around the rubber tree that have solidified (cup lump, tree lace, and earth scraps). These raw materials are processed in different ways to produce 3 products: concentrated latex (used for medical gloves, condoms, etc.), block rubber (STR 20) (for tires, soles, etc.) or ribbed smoked sheet (RSS) (for tires, industrial rubber parts, etc.). The Jawjit, Kroeze et al. (2010) greenhouse gas emissions study presents the process, inputs and yields for each of these 3 products. For this LCA study, we focus on the STR production, which is commonly used in tire production. During the production of STR 20, chemical use is rare and can be considered negligible (most chemicals are used for the production of concentrated latex) (Jawjit, Kroeze et al. 2010).

The yields and inputs of guayule and Hevea for 1 kg of tire suitable rubber are compared in Chapter 3 Table 4 (or a more detailed version in Appendix A).

2.2.2. Guayule and Hevea Processing

Guayule Processing

The latex in guayule is contained in the individual parenchyma cells, thus latex extraction requires the entire shrub to be processed (Wagner and Parma 1989). Several patents have been published that discuss processing methods of guayule (Kay and Gutierrez 1984, Ji 1994, Cornish 1996, Cornish 2006, Cornish, McCoy et al. 2011). A common processing method is performed with the use of polar solvents to precipitate the rubber while resins remain in the solution (Wagner and Parma 1989). Solvents such as acetone and hexane are commonly used.

There are three types of processing methods for bulk guayule rubber: flotation, sequential extraction and simultaneous extraction. Flotation processing involves coagulation of latex in an aqueous base, and this methodology was used in the early years of guayule processing. Ground shrubs are placed in a dilution of sodium hydroxide until the woody tissue take up the water and sinks to the bottom. The resinous rubber floats to the top, and is deresinated with acetone. Sequential extraction is when resin is first extracted with acetone or another polar organic solvent and then the rubber is removed with hexane. This method has been experimental and does not appear to be economically viable (Ray 1993). Simultaneous extraction involve a mixture of solvents (usually acetone, hexane or pentane) where after the initial rubber extraction, more acetone is added to coagulate the high molecular rubber. The simultaneous extraction method is also known as the Bridgestone/Firestone method (Ray 1993, Schloman Jr 2005).

Guayule is commonly processed by simultaneous extraction, where a single stage separates both the resins and rubber from the fibrous tissue, which minimizes shrub handling. The particulates are removed from the solution by methods of filtration and/or centrifugation (Wagner and Parma 1989). The method patented by Cornish, McCoy et al. (2011) will be used as a reference to explain the processing methods of guayule, summarized in Table 3 and displayed in Figure 7. This method is similar to simultaneous extraction, but the chemical solution in which guayule is processed is a mixture of water and a buffer, such as ammonium hydroxide (NH₄OH),

potassium hydroxide (KOH), sodium hydroxide (NaOH), or sodium bicarbonate (NaHCO₃). No hexane, acetone, or pentane is used in this method.

Table 3. Guayule Processing Steps patented by Cornish, McCoy et al. (2011).

Steps		Processes	Inputs	Outputs	Products
I	Pre-grinding	1 Harvest process		harvested guayule shrub	
		2 Shrub chopper	harvested guayule shrub		
		3 Air density separator		leaves and small stems	
		4 Debarking system			
II	Wet milling	5 Milling system	chemical solution system	wet solids	
III	Filtration	6 First press		wet solids	latex rubber solution (aq)
		7 Washing	chemical solution system	wet solids	
IV	Clarification	8 Second press		wet solids/ bagasse	latex rubber solution (aq)
		9 Decanter	latex rubber solution (aq)	guayule solids	
V	Separation	10 First separator		aqueous waste	
VI	Concentration	11 First latex concentrator		aqueous waste	
		12 Second latex concentrator		aqueous waste	
VII	Creaming	13 <i>First cream settling system</i>	(recycle to cream mixing tank)	aqueous waste	
		14 Cream mixing tank	cream solution mix system		
		15 Second cream settling system		aqueous waste	Finished guayule latex product
VIII	Storage	16 Final product storage system			

Detail of processing steps from Table 3:

- I. Before processing, guayule leaves are removed in the field or at the processing facility (1 or 3). If performed at processing, the plants are first chopped into smaller uniform pieces (2), then separated with a gravity based conveyor belt system, washing steps, or air or water pressure to remove the leaves (3) (Cornish, McCoy et al. 2011). This step can be avoided if the guayule was already processed in the fields before packed into the truck that transports to the processing facilities (Coates 1991, Cornish, McCoy et al. 2011). Once the plant material is chopped into smaller pieces (2), the non-latex bearing leaves, flowers and small stems are removed with the use of a separator system (3), and the optional de-barking (4) is performed to remove the bark and assist in greater latex extraction during later processes. The materials are conveyed by augers, belt conveyors, hand bucket elevators or other handling equipment to the milling system.
- II. Wet milling (5) comprises grinding plant material to relatively uniform pieces in a chemical solution system. The processing method patented by Cornish, McCoy et al. (2011) uses a chemical solution containing water and a buffer, such as ammonium hydroxide (NH₄OH), potassium hydroxide (KOH), sodium hydroxide (NaOH), or sodium bicarbonate (NaHCO₃). This is an advantage of this method, since these chemicals may prove to be

less harmful than other commonly used solvents (i.e. acetone and hexane). The wet mill grinds chopped homogenous plant pieces into an emulsified slurry with a controlled amount of chemical solution, resulting in cell rupture, thus releasing the latex rubber into the aqueous phase for recovery and purification.

III. Filtration begins with the first press (6), where the wet solids (slurry) are added to remove a major portion of the latex rubber from the bagasse. The resulting latex rubber from the milling system is suspended in an aqueous solution as an emulsion and is removed from the biomass emulsion slurry by squeezing the liquids from the slurry in the first press.

There is a screen through which the liquid phase (also referred to as the latex homogenate liquid slurry) passes, and the solid phase (bagasse) does not pass. Washing (7) is an optional step that can remove additional latex particles trapped in the bagasse following the first press.

IV. Clarification involves the second press (8) and the optional decanter (9). Here, the latex homogenate is measured to determine the percentage of latex present (desirably about 0.01% to 1% after decanting). During the second press, certain steps may be taken to extract a greater latex yield from the bagasse (e.g. the use of a smaller screen or filter size). The liquid phase is pumped into a collection tank or decanter, while the solid phase bagasse is dropped into another collection area. The second press is comprised of a centrifuge, tank or other separator. Decanting is where the liquid latex homogenate slurry is collected from the first and second presses. This step removes the maximum amount of undesirable solids in the latex, while retaining the maximum amount of latex. Without the decanter, solids not removed from the latex may eventually shorten operating cycles and may cause undesirable down time and latex loss. Optional additives, such as stabilizers, anti-foaming agents, or de-foaming agents can be added to the clarified liquid latex homogenate during or after the decanter step in order to enhance specific chemical or physical properties using centrifugation.

V. The first separator (10) prevents clogging in the first latex concentrator (11) and second latex concentrator (12). These steps are optional to further remove fine solids from the

emulsion and remove particles that were not removed by the decanter (9). This step helps separate a light phase containing latex and heavy phase containing waste products. The resulting light phase containing latex may be further concentrated in one or more concentrator steps.

- VI. The concentration steps involve any physical or mechanical phase separating system used to remove water and concentrate the latex emulsion such as high speed centrifugation. A chemical solution may be added during this step to improve latex quality. If the latex is qualified after the first latex concentration (11) or the second latex concentration (12), it will be transferred to final product storage (16) for shipment to customers in various packages.
- VII. The creaming system serves a similar function to the concentration system, since both of these are additional concentration steps that increase the concentration of latex without affecting the concentration of soluble components in the aqueous phase of the latex. Both systems increase the volume of the latex while decreasing aqueous volume, and require several dilutions, which wash away solutes and re-concentrate latex. This step allows re-concentration by using normal gravity, if necessary after centrifugation becomes impractical. A cream solution mix comprised of a coagulant, several stabilizers, and an antioxidant are added to the cream mixing tank. First cream settling (13) comprises of one or more insulated non-agitated tanks where the cream settles until the bottom water phase (typically brown in color) separates from the top layer rubber phase (typically greenish in color). The aqueous layer is decanted. The cream mixing tank (14) further concentrates the latex, and the upper layer settled in the second cream settling tank (15) containing latex rubber phase is transferred to the latex product tank area for testing, and ultimately to the final product storage system (16).
- VIII. The final product storage system (16) consists of agitated tanks at 4°C, where the ASTM specification grade latex (ASTM D1076-02) can be stored for an indefinite period of time. Stabilizer or other agents may be added. Latex can be packaged in individual shipping containers or transported in bulk in refrigerated trucks, tankers, barges, railcars, etc.

The Cornish, McCoy et al. (2011) method describes a process to manufacture liquid latex that can be used for consumer goods such as medical devices and products, such as latex gloves. Solid rubber does not need to be kept under strict climatic control. Guayule is mainly used for medical applications and the industry might grow and develop starting with companies manufacturing liquid latex as their product, which would be dried for tire-rubber applications.

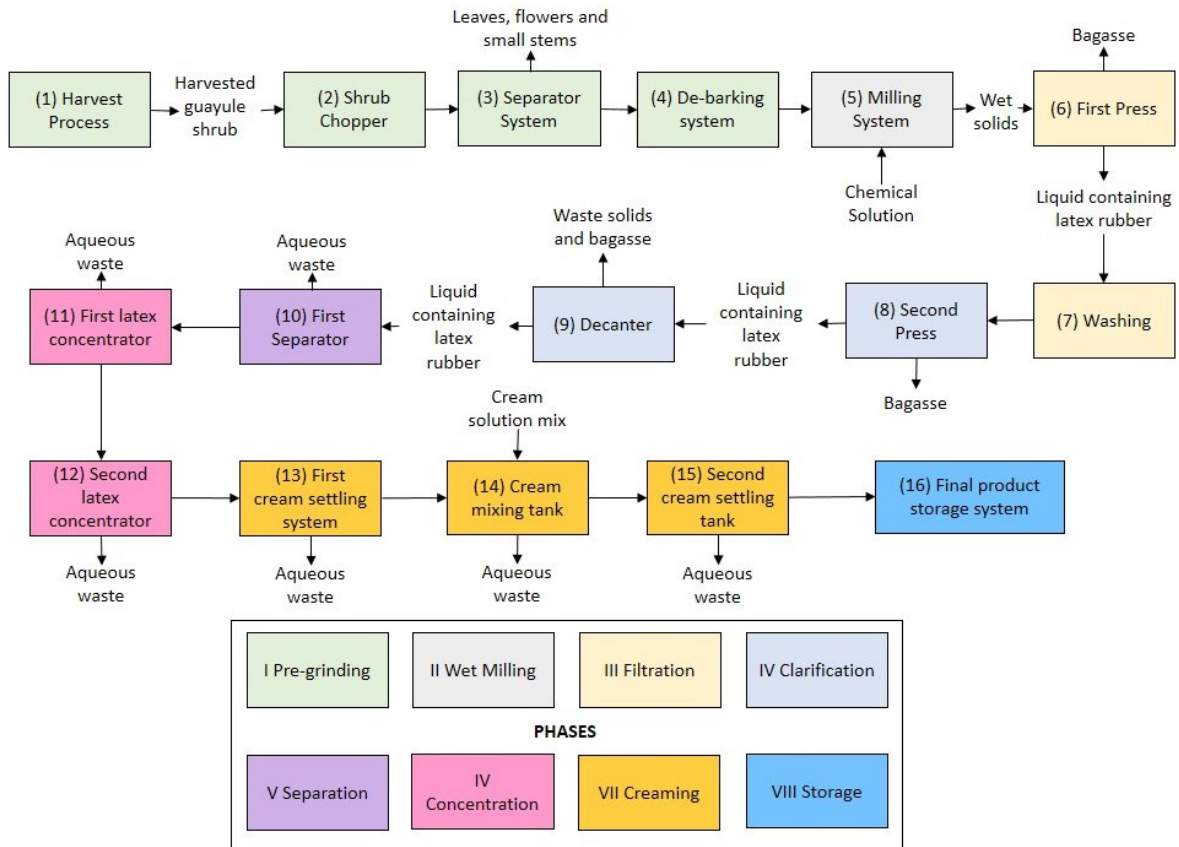


Figure 7. Guayule Processing adapted from Cornish 2011 Patent (Cornish, McCoy et al. 2011).

The processing method used for guayule processing known as the Bridgestone/Firestone method was used to produce tire-grade rubber called Grade 20 Technically Specified Rubber (TSR20). The Bridgestone/Firestone pilot facility in Sacaton, Arizona had a capacity of 152 tons of rubber product per year and a feed rate capacity of 990 kg/hour of fresh shrub (Schloman Jr 2005). In this method, incoming shrub was chopped into small pieces and then sheared in a flaker to rupture the rubber-bearing cells (See Figure 8). The flaked pieces were mixed with an

extraction solvent, such as a mixture of acetone and hexane, to form a slurry. The bagasse was separated by a centrifuge. The slurry solution was mixed with acetone to coagulate the rubber, which precipitated and settled to the bottom of the mixer. The lighter liquid phase, which contained most of the resin, was filtered out. The coagulated rubber then passed a few more steps with pentane, hexane and/or acetone to dissolve remaining resin and low-molecular weight rubber. The final swollen rubber passed through equipment to strip off the solvent, and then the extruded product was pressed into solid bales (Schloman Jr 2005).

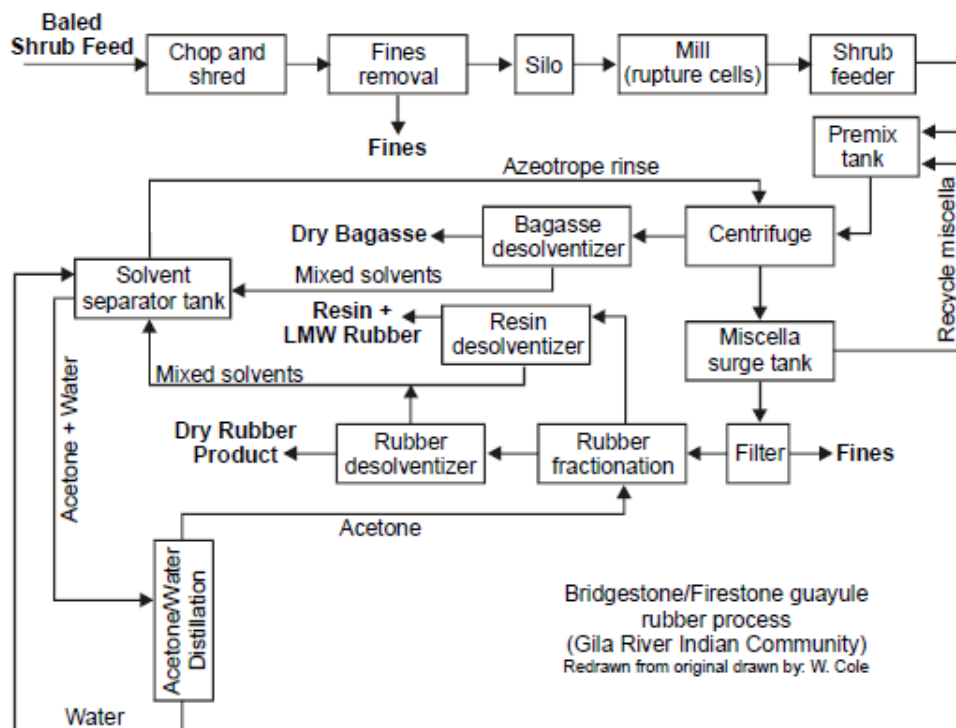


Figure 8. Bridgestone/Firestone Processing Flow (van Beilen 2006).

Hevea Processing

Two forms of raw rubber can arrive at the processing facilities: fresh field latex and rubber coagula. Fresh field latex is the milky white sap that is collected in buckets after the Hevea tree bark is cut, and the coagula are latex remainders on and around the rubber tree that have solidified (cup lump, tree lace, and earth scraps). The liquid latex is commonly processed into liquid concentrated latex for medical uses, or can also be made into block rubber for tires, or

ribbed smoked sheets for industrial rubber parts. The coagula is processed into block rubber as a raw material for tires.

When fresh latex is received from the farms to the processing facilities, it is transferred through a sieve into the reception tank, chemicals such as ammonia, TMTD/ZnO, and/or DAP (diammonium phosphate) are added, and the latex is transferred to a dilution tank to bring the latex to a standard dry rubber content (DRC). This aids in optimizing the separating efficiency in the centrifuge for the production of concentrated latex. After thorough mixing, the rubber and water is separated to produce concentrated latex. After this process, there is a remaining water layer (skim latex) that contains a lower content of dry rubber than the concentrated latex. This skim latex is further processed with added chemicals to produce skim block rubber (Jawjit 2013). Standard Thai Rubber (STR), also called block rubber, is the rubber used for tire manufacturing, where the production is mainly a mechanical process and relatively energy intensive. The raw materials to produce tire-grade rubber include various scraps such as cup lump, bark scrap, earth scrap, rubber cuttings (pieces of rubber trimmed off rubber sheets) and ribbed smoked sheets that have been kept a long time. Electricity is used for driving machines, including creepers, shredders, slab cutters, pre-breakers, rotary cutters, and packaging machines. Diesel and LPG are used in the drying process, with LPG being introduced recently in response to rising diesel prices (Jawjit, Kroeze et al. 2010). The main STR processes are cleaning, mixing rubber scraps with other rubbers, and drying the rubber (see Figure 9).

Before entering the production process, the raw materials (coagula) must be checked for dirt that is removed by hand or a separator. Water is added to the raw materials to soften the rubbers to help the cutting process. The scrap pieces are ground, shred and cut so that the rubber content can better come in contact with water, and dirt and unwanted materials can be washed away. The rubber is pressed, screened to separate the water from the rubber content, and passed through circulating tanks. It is then set aside to be mixed with shredded rubber of better quality.

After the cleaning stage, rubber is in the form of crepe sheets. These are mixed with rubber sheets at different proportions and passed through the creper, then the circulating tank to

achieve a homogenous content. A size reduction machine (shredder, pelletizer, etc.) forms the rubber into small pieces (crumb rubber) suitable and clean enough for drying.

Hot air running through the driers dries and dehumidifies the small pieces of rubber. It is important to adjust temperatures to avoid burning rubber. Drying is a major part of the production process. It removes humidity from the rubber content after the rubber has been cleaned and heats the rubber for adequate storage preparation to prevent biological deterioration. The natural rubber is usually dried using heat generated from combustion of fossil fuel (by rule of thumb, it consumes a tenth of the fossil fuel needed to produce synthetic rubbers), but can also be dried with solar heating (van Beilen 2006). Tire-grade rubber is dried with the use of diesel and liquefied petroleum gas (Jawjit, Kroeze et al. 2010)

After the drying processing, the rubber is pressed into blocks with a hydraulic presser to prepare for transport. The temperature of block rubber must be adjusted to below 60°C (140°F) before wrapping. Then, the blocks are wrapped in plastic (usually polyethylene) and marked for type and grade (Thailand Latex and Block Rubber Industry 2001).

For block rubber processing, approximately 23m³ water/tons of STR are used (23kg water/kg STR) (Thailand Latex and Block Rubber Industry 2001). The electricity for pumping is included in the reported processing electricity values (Jawjit 2014). Electricity in STR processing could be reduced with regular maintenance of machines, and proper design and management of the pre-cleaning system. It is estimated that 220 kWh of electricity are used to produce 1 ton (1,000 kg) of STR rubber (Jawjit, Kroeze et al. 2010).

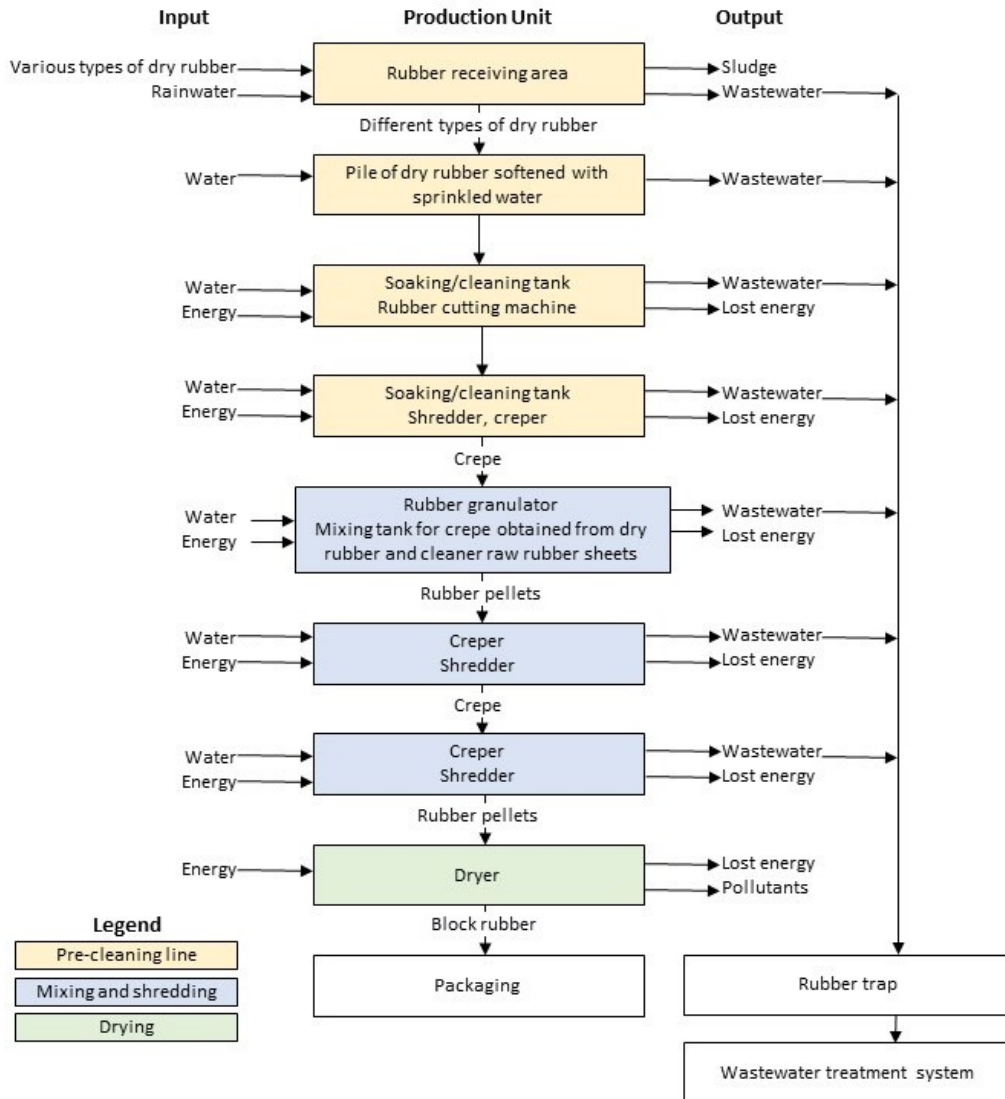


Figure 9. Block Rubber Production Process, Using Dry Rubber, adapted from (Thailand Latex and Block Rubber Industry 2001).

2.3. Tire Manufacturing Background

The following section will discuss the raw materials that are used in a tire's production, the different components (or parts) of the tire, and the various manufacturing steps to make the final product.

Data Collection process

A tire manufacturing company provided information on the exact composition of the conventional tire, manufacturing parameters, and supply chain data, the latter with a focus on transportation. Additional secondary data was collected through databases (See Table 4 and Table 5 in Chapter 3). Multiple plant tours and meetings with the environmental team and tire engineers were arranged with the goal of collecting the most accurate, thorough and recent data as possible. The goal of the site visits was to understand the details and processes of tire production, the raw materials and other inputs, the energy consumption of the equipment, additional processes that are not directly involved with the production line, and the waste stream from tire production. Data to perform the study was collected from specialists on the supply chain, production line, Six Sigma activities, sustainability, environmental activities, waste management and laboratory procedures.

The LCA model was created by focusing on each tire component, beginning with the raw materials used for the part's manufacturing, through equipment used in its production. The tire-making process involves assembling these parts to form the green tire, which is then vulcanized to become a functioning tire. The LCA model includes the production of a conventional tire as well as the hypothetical production of a guayule tire. The LCA data for the models was derived from data collected directly from literature on guayule and Hevea rubber agriculture and processing; a tire manufacturing company on raw material quantities, tire composition, manufacturing energy consumption, other manufacturing inputs and the supply chain transportation; and life cycle databases (See Table 4 and Table 5 in Chapter 3).

2.3.1. Raw Materials

A tire is made from numerous raw materials; there are 12 major categories: synthetic rubber, natural rubber, carbon black, antioxidants, accelerators, other processing aids, zinc oxide, sulfur, stearic acid, silica, steel and textile. Guayule rubber is expected to replace all of the

synthetic rubber and the natural Hevea rubber at a 1:1 ratio for the concept tire assessed in this study.

The following summary discusses the purpose of each tire raw material. Details on the information and data collection process, databases and database substitutions are described in Chapter 3. Other than for Hevea and guayule, developing new raw material datasets was outside the scope of the study. Thus, some tire raw materials were substituted for similar materials available in databases. Table 4 in Chapter 3 shows the data sources for the raw materials in the tire. The details are further discussed in Appendix C.

Tire composition and Raw Materials

A high-level composition of a tire is shown in Figure 10. The figure displays the current composition of the tire materials and shows that all of the conventional rubber will be replaced with guayule rubber, resulting in approximately 47% of the tire comprising of guayule rubber. For commercial application, some parts, such as the tread and liner, would be made with epoxidized guayule rubber. For this study, it is assumed that the conventional rubbers are replaced with guayule natural rubber. No other alterations need to be made with the guayule replacement. The ratios of other materials remain the same.

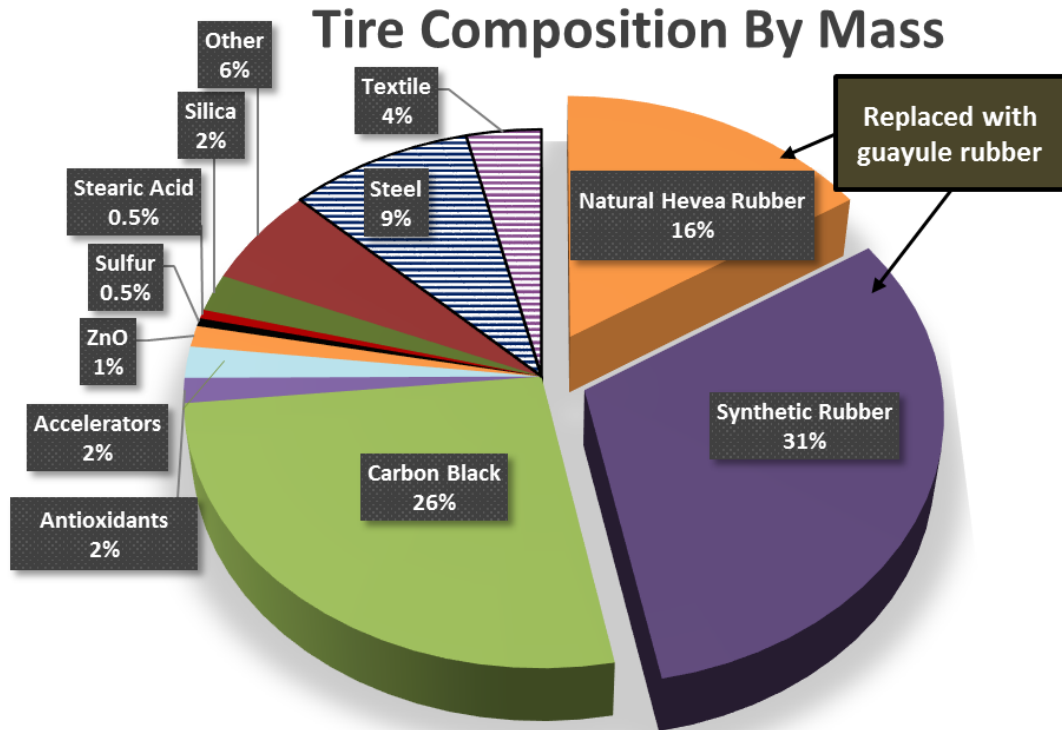


Figure 10. Tire Composition by Mass.
 The striped sections represent tire materials that are not mixed into the rubber compounds. Approximately 47% of the tire mass is comprised of the rubber, 9% is steel, 4% is textile.

Synthetic rubber

Synthetic rubbers are known to have chemical stability, high abrasion resistance, strength and good dimensional stability. Styrene-butadiene rubber (SBR) is the most widely used synthetic rubber, and its major use is for tire production (Matar 2000). Styrene-butadiene rubber, a petroleum based polymer, can be made by combining styrene, butadiene, soaps and a free radical initiation system (Colvin and Senyek 2002).

Natural rubber (Hevea and guayule)

Natural rubber's chemical configuration gives it outstanding properties of high resilience and strength. It is essential to have a source of natural rubber for the tire industry, because synthetic rubber does not have sufficient heat dispersion, abrasion resistance, elasticity or resiliency for high performance requirements (Miyamoto and Bucks 1985, Herman 2004).

Carbon black

Carbon black is a very fine powder that is extremely important in the synthetic rubber industry. Carbon black and sulfur are some of the few intermediates produced from natural gas, crude oils, and other fossil materials that are not hydrocarbon compounds. Adding carbon black to tires lengthens its lifetime by increasing the abrasion and resistance of rubber. Carbon black is produced by the partial combustion or the thermal decomposition of natural gas or petroleum distillates and residues (Matar 2000).

Antioxidants

Rubber compounds must have good aging properties to provide an extensive service life. They are susceptible to oxidation thermally or by reaction with ozone, thus antioxidants are needed to preserve the elastomers.

Accelerators

Accelerators are complex organic compounds used in the vulcanization system to react with the zinc oxide, stearic acid and sulfur (Rodgers 2006). Vulcanization is a chemical process involving heat to convert rubber and other polymers into more durable materials.

Zinc Oxide

Zinc oxide is necessary for the vulcanization process. It is part of the activation system in a tire compound, along with stearic acid (Rodgers 2006).

Sulfur

Sulfur acts as a vulcanizing agent (Rodgers 2006).

Stearic Acid

Stearic acid is necessary for the vulcanization process. It is part of the activation system in a tire compound, along with zinc oxide (Rodgers 2006).

Silica

Silica acts as a reinforcing agent, similar to carbon black.

Steel

The steel in tires is in the form of cords which are used to reinforce the rubber compounds. The cords can be used in the plies and/or the belt (Rodgers 2006). For typical tires, the steel cord is made up of brass-coated wire strands that are wrapped together to give cords with certain characteristics depending on the application. The tire cord is manufactured from high-carbon-steel rod that has been drawn to a diameter of approximately 1.2 mm. After the brass plating is added, the wire is drawn to 0.15-0.40 mm. The key mechanical properties of the steel cord include tensile strength, elongation and bending stiffness (Mark 2013).

Polyester

Polyester is used as the ply cord in car and light truck tires (Rodgers 2006).

Nylon

In commercial tires, nylon is used in the plies. For high-performance passenger and light truck tires, the nylon is used in the tire overwrap. The overwrap sits over the steel belts and holds the belts while the tire is operating at high speeds (Rodgers 2006).

Other

This subsection mainly includes processing aids and materials necessary for the manufacturing of the rubber compounds, such as compound extenders, tackifying resins, oils, coupling agents, wire adhesion promoters, vulcanization retarders and fillers.

2.3.2. Tire Components and Manufacturing Process

The tire making process was thoroughly analyzed with the goal of precisely quantifying the material inputs, outputs and energy consumption of the equipment in the manufacturing facilities. The processes can be organized by mixing and milling, extruding and calendaring, assembly and building, curing (or vulcanization) and finishing. Both the conventional and guayule tire use the same equipment for the manufacturing procedures. However, due to differences in rubber properties, time of operation for certain equipment may be reduced with guayule rubber.

Tire components

The tire can be divided into 10 major components: liner, ply, bead, chafer, black side wall (BSW), belt, belt edge gum strip (BEGS), overwrap (also called restrictor), cap and the base (see Figure 11).

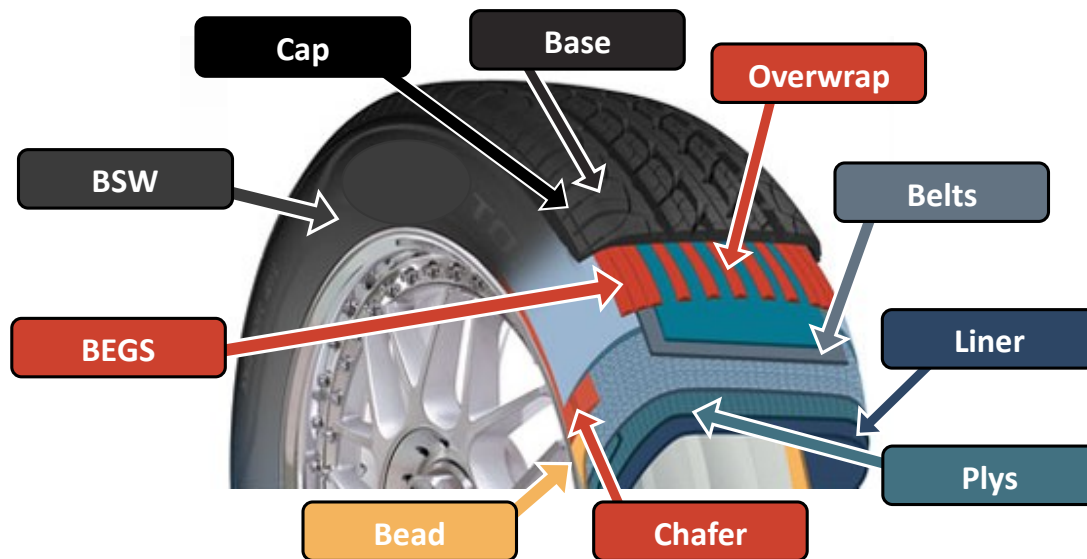


Figure 11. Tire Components.

1. The liner is a strip of rubber compound that covers the inner portion of the tire and assures that the tire will hold air pressure.
2. The plys are rubber/fabric composites distributed circumferentially around the tire which gives the tire structural strength.

3. The beads provide mechanical strength to fit the tire to the wheel and are comprised of steel wires coated in a rubber compound and then formed into a circular shape.
4. The black side wall (BSW) is a non-fabric reinforced component that gives the tire the ability to flex as it encounters objects in the road or during conventional running.
5. The chafer is the abrasion resistant rubber component that comes in contact with the rim. It is important that this component have good compression set so there is a good seal with the rim.
6. The belt package gives tire strength and assists in transmitting forces necessary for cornering, accelerating and braking. The belt is made up steel wires neatly lined up and compressed between two sheets of rubber compound and forms a hoop under the tread (explained in #9).
7. Belt edge gum strips are thin, narrow strips of rubber placed between the belts near the belt edges in order to provide a cushion between the steel belts.
8. The overwrap is comprised of a sheet of nylon compressed between two sheets of rubber compound. It is located between the belts and tread to resist centrifugal forces at very high speeds. It is strategically placed in a manner to improve ride quality and provide balanced, even tread wear for long life.
9. The cap and the base make up the tread of the tire, which is the component that makes contact with the road and influences the tire's wear resistance, rolling resistance and traction. The tread compound composition is designed according to the mission of the tire, i.e. in commercial truck tires that require good tread wear and fuel economy, high levels of natural rubber and high surface area carbon black are used (Rodgers 2006).

Mixing and Milling

The direct tire manufacturing process begins with the mixing of the rubber compounds. This is performed in Banbury mixers. The Banbury mixers have the highest energy consumption in the production line and their operation is key to making high quality rubber compounds. Mixing

is performed in two steps. During the first step, raw rubber, carbon black and other chemicals are combined to create a homogenous rubber mixture. Each tire component requires a certain rubber formulation, also called recipe, which differs by the rubber content and additional chemicals. This formulation is determined based on the purpose of the tire component. Each material is pre-weighed or placed on the conveyor belt which has a built-in scale, then is added to the Banbury mixer where the compound is heated and mixed for a specified amount of time. This mixture is then extruded into pellets and covered with an anti-tack agent to avoid the rubber from sticking to itself, and stored in bins until the second step of mixing. The rubber after this first step is called non-productive, or the master batch. In the second step of Banbury mixing, a recipe is followed to combine master batches with additional chemicals to make the productive, or final, batch of rubber. This is followed by the milling process, where the mixture is placed on a drop mill to form the rubber into sheets and prepare it for the further processing (calendering/extrusion).

Since commercial production of the guayule tire has not begun, the exact differences in manufacturing have not been determined. However, after literature review and discussion with the tire engineers at the tire manufacturing company, it is projected that the guayule rubber will require less energy during the mixing process. Mixing produces a more rapid reduction in the viscosity of guayule rubber than Hevea rubber, which reduces the optimum mixing time. It has been estimated that the energy consumed in mixing the guayule is about 65-70% that of mixing Hevea rubber (Schloman Jr 1991). However, this study was performed on a small lab-scale mixer and may not apply to industrial scale mixing. After discussion with tire engineers at the tire manufacturing company, it was decided that a conservative assumption for guayule mixing energy would equal 90% of the energy needed for Hevea mixing.

The current assumption is that mixing is the only step in tire manufacturing during which the guayule and Hevea tire will differ in energy use. The other manufacturing steps are assumed to be identical.

Extruding and Calendaring

The next step in tire manufacturing involves extruding and calendaring to make the components of the tire. As noted earlier, the tire can be divided into 10 major components: liner, ply, bead, chafer, sidewall (BSW), belt, belt edge gum strip (BEGS), an overwrap, cap (tread) and the base. Each one of these components is manufactured with different pieces of equipment and is constructed with a specific rubber compound. Some components include additional materials, such as steel or textile (polyester or nylon).

Extrusion is used on tire components with a definitive cross section, such as tread and sidewall. These components are extruded into the appropriate shape from the proper rubber compound. Different pieces of equipment are used to process each component, since the extrusion process varies for each component. Calendaring is a process during which treated textile fabric or steel cords are coated in rubber. In the case of fabric, treated material refer to the fabric which has been dipped in an adhesive, then dried. For steel, the coating consists of brass which assists in adhesion of the rubber to the belt. Once these materials are calendared at the tire manufacturing facilities (i.e. coated in rubber), they are considered to be final tire components. Calendaring is performed mainly on two pieces of equipment specified by configuration: the Z-calendar and Twin Two calendar. The belt, ply and overwrap components are prepared on the Z-calendar, and the liner component is made on the Twin Two calendar. The belt is made by covering steel wires in rubber, and the ply and overwrap are textiles (polyester and nylon) covered in rubber.

The tire bead contains several parts. Part of the bead requires extrusion of a rubber component to form the bead wedge (or bead filler), and the second part of the bead consists of steel wire coated with rubber in an extrusion process. These two parts are combined to form the final bead component. The final bead is circular shaped and forms the connection between the car tire and the rim. The tread consists of several layers of rubber and is applied to the outside of the tire and makes contact with the road.

Assembly and building

The first part of the building process produces a carcass, or a 1st stage tire. The inner liner, ply, BSW, chafer and beads are placed on a drum which contains an inflatable bladder to make a doughnut-shaped tire. The second part of tire building involves adding belts, cap, base, BEGS and overwrap to the carcass. This produces a “green tire” (uncured tire), or a 2nd stage tire.

Curing (Vulcanization)

The final manufacturing step is the tire curing. The molded green tire is placed in a mold which contains a tread pattern, side markings (size and government required information), and any other designs that are imprinted into the tire. The tire is inflated into the mold using a bladder pressurized with steam. Heat energy is transferred into the tire from this steam and through heating of the mold after a certain period the vulcanization is complete and the tire is removed from the mold.

Finishing

Before the tire is ready for distribution, it must be finished by visually inspecting for any non-standard conditions. Uniformity and balance machines tests tires for ride quality characteristics.

Supporting Process

There are many processes in the tire manufacturing facilities that are indirectly associated with production, but also consume energy and contribute to environmental impacts. Some examples of this include the heating of process oil used as a back-up energy source stored in large tanks that must be kept at a stable temperature, the receiving department which receives the raw material shipments, the carbon black unloading system where conveyor belts and scales weigh the carbon for the mixing process and water chillers for cooling equipment. This data was not collected in detail due to time constraints. However, the base electricity consumption was

available for lighting, air compressors, the boiler, chillers and fans, and additional information was collected on propane for the forklifts and cement use to help bond the tread ends, which were included in the LCA.

Tires are the only product produced in the plant, but many tire models are manufactured. Therefore, the supporting process emissions from manufacturing any tire type are not associated with a specific tire, but monitored only at the aggregate plant level. Specific information for manufacturing was not available, such as the waste and emissions released during production. Supporting processes that attribute to the general tire making process are allocated accordingly for a conventional or guayule-based tire. The conventional and guayule tire production modeling is based on the equipment used for the conventional tire, which is assumed to be identical.

Data for supplier processes is included in the LCA using existing databases described in more detail in Chapter 3. However, some supplier processes that are performed before the materials are received at the tire manufacturing facilities are not included in the LCA. Examples of processes not included in the LCA are adhesives in which fabric is dipped, or the brass coating on wires.

CHAPTER 3

COMPARATIVE LIFE CYCLE ASSESSMENT OF CONVENTIONAL AND GUAYULE AUTOMOBILE TIRES

The following chapter is intended to be written as a journal publication and may contain repetitive information on the background, goals, and methods of the LCA study. However, the introduction for the publishable paper has been omitted, and will later be added as a summary of Chapters 1 and 2.

3.1. Introduction

The goal of this study was to conduct a comparative LCA for a conventional passenger automobile tire and a guayule (*Parthenium argentatum*) rubber-based passenger automobile tire, and determine whether guayule is an environmentally sustainable substitute. Guayule rubber is a renewable material that can be grown in the U.S. and has the potential to reduce environmental impacts by replacing the synthetic petroleum-based rubber and Hevea rubber in a conventional tire. Guayule rubber tires also have the potential to minimize transportation impacts compared to Hevea (*Hevea brasiliensis*) rubber, which is imported from Southeast Asia. The results of this study can help inform tire manufacturing companies, as well as other rubber industries, on the trade-offs with guayule as an alternative source of rubber.

3.2. Materials and Methods

This study presents a comparative LCA based on the ISO framework from cradle-to-gate, including the raw material extraction, transportation, and tire manufacturing. The inventory includes data from scientific literature and patents for guayule and Hevea agriculture, primary data from a tire manufacturing company, and additional data from existing LCA databases. The LCA was conducted using TRACI v2.0 (Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts) and presented environmental results from global warming, smog,

acidification, eutrophication and fossil fuel depletion impact categories. The study included an analysis of potential energy off-sets with the utilization of natural rubber co-products, and a sensitivity analysis to evaluate potential impact reductions with implemented agricultural and transportation changes.

Goal and Scope Definition

The goal of this study was to conduct a comparative LCA for a conventional automobile tire, made from natural Hevea rubber and petroleum-based synthetic rubber, and a guayule natural rubber-based automobile tire.

The boundaries of the system used in the comparative LCA are presented in Figure 12. LCA can compare products on the basis of a functional unit, which is chosen to appropriately compare the performance of the products. In this study, the functional unit was one tire. Details on the use and end of life of the guayule tire are currently unknown, therefore the scope of the study included the raw material extraction through tire production phases (cradle-to-gate), without the use and end-of-life phases. The cradle-to-gate process flow diagram shown in Figure 12 includes primary and secondary inputs and excludes the manufacturing of capital equipment. There were valuable energy-rich co-products associated with the production of both guayule and Hevea rubber, and an additional analysis was performed to evaluate the potential energy-offsets if these co-products were to be utilized. The emissions and runoff from guayule and Hevea agriculture were not included in the assessment due to lack of data. Natural rubber processing waste and emissions were also not included. Carbon capture sequestration in soils was not accounted for. Emissions associated with the processes leading up to tire manufacturing were included in the system boundary, but emissions from manufacturing processes in the facilities were not.

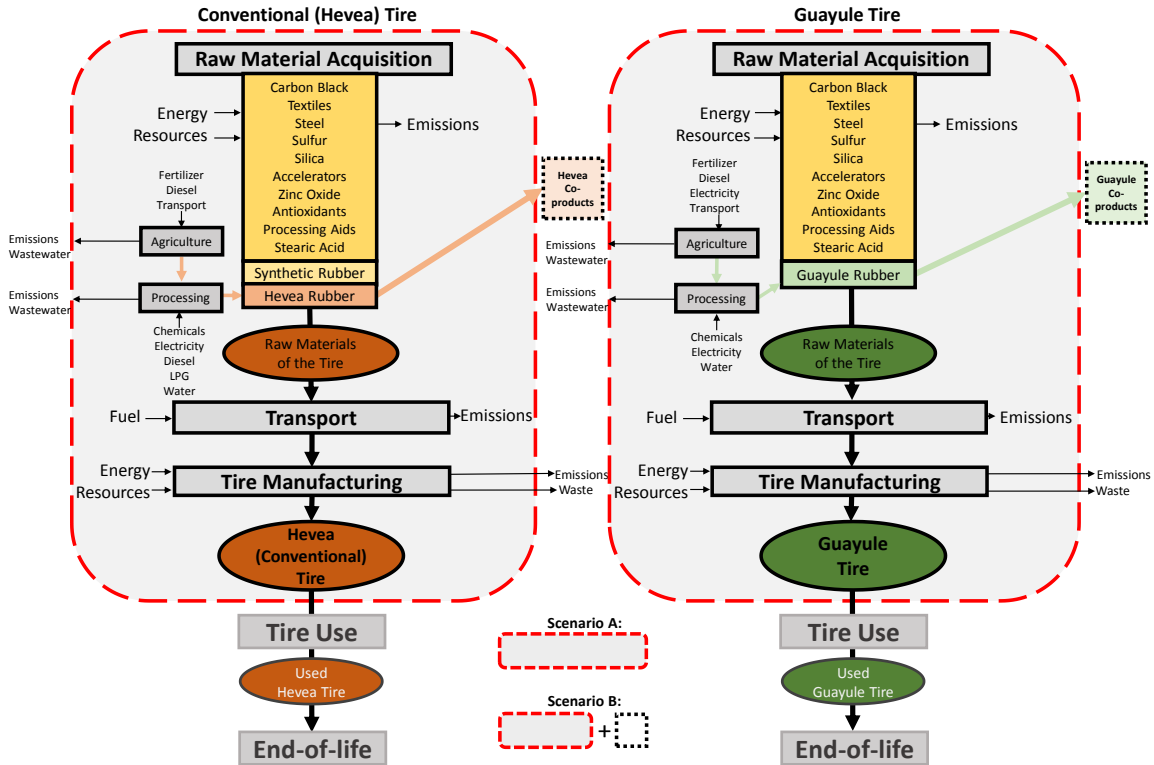


Figure 12. System Boundaries for LCA Study.

Some supplier processes that are performed before the materials are received at the tire manufacturing facilities are not included in the LCA. For example, qualities such as the adhesives in which fabric is dipped, or the brass coating on wires were not included in the assessment. Due to time constraints, comprehensive waste data was not collected and was not included in the LCA. There are various waste products from the tire manufacturing process that have an energy content and could be utilized as waste-to-energy to off-set tire manufacturing impacts, but these were not considered in this analysis.

The specific equipment used in the tire manufacturing process will not change when replacing Hevea and synthetic rubber with guayule natural rubber; however, the rate of processing and energy consumed in the production may change, and the sensitivity of these parameters will be discussed in following sections.

Inventory Analysis

Data on the agricultural processes of the guayule and Hevea plant, and the processing of each plant into industrial rubber was collected from scientific literature, summarized in Table 4. The original data was converted to reflect rubber yields and inputs for the production of 1 kg of both guayule and Hevea tire-grade rubber (see Table 4, or a more detailed version in Appendix A). Primary data for tire manufacturing was collected from a tire manufacturing company which provided information on the exact composition of a conventional tire (Table 4), supply chain transportation distances and modes (Table 5), tire manufacturing inputs and energy requirements (Table 5), and potential changes in production with the substitution of guayule rubber. Raw data from tire manufacturing is proprietary and was not reported in the study; however aggregated data and results are presented. Data related to upstream production of supplies and raw materials (e.g. agricultural inputs, raw material production, and tire manufacturing inputs) was collected through databases and peer-reviewed journal articles; the upstream LCI data was obtained from the USLCI and ecoinvent databases, listed in Table 4 and Table 5 and described in detail in Appendix B, C and D.

Guayule Agriculture and Processing

Agricultural data for guayule was collected from peer-reviewed scientific literature and the inputs were converted from their original units to represent inputs for 1 kg of tire-grade rubber (Table 4). Published literature data for guayule rubber yields (Thompson and Ray 1989, Estilai 1991b, Foster and Coffelt 2005, van Beilen and Poirier 2007a) were averaged to find a value of 1,183 kg rubber/ha*year, which was used for the LCA study. Agricultural input data on irrigation, fertilizer and herbicide application was collected from literature, and was commonly reported per ha-year (mm/year for irrigation, kg/ha*year for fertilizer and herbicides; sources are listed in Table 4). Using the average rubber yield (1,183 kg/ha*year), the collected agricultural input data was averaged and converted to represent inputs needed per kg tire-grade rubber. The conversions

were used to calculate energy for pumping and diesel use in fields per kg of tire-grade rubber (listed in Table 4).

Transportation distances were assumed to represent possible harvesting and processing locations. The round-trip travel distance used for the study was 96 km (60 miles) as an estimate of the distance between agricultural areas and possible processing locations in Maricopa County in Arizona.

The electricity used in guayule agriculture and processing was modeled according to Southwest Energy Efficiency Project's Arizona Electricity Mix (36% coal, 29% nuclear, 27% natural gas, 8% renewable) (SWEET 2014). Arizona electricity was used for pumping agricultural water and guayule rubber processing. Diesel use for agricultural equipment was estimated from agricultural averages (Table 4; details listed in Appendix A). Guayule processing energy was unavailable, and the processing of sugarcane, an agricultural feedstock that produces a similar fraction of valuable product (sucrose) and co-products (bagasse), was used as a substitute (Table 4; calculations and references are presented in Appendix E). The processing steps for sugarcane and guayule have similarities, such as shredding, milling, filtration, clarification and drying, thus it was assumed to be an adequate substitute for the LCA. The electricity consumption value assumed for processing was 0.09 kWh/kg guayule rubber, which was the average value for the processing of 1kg of sugarcane. It is unclear how close this energy estimation is, since guayule rubber processing times and equipment may differ; industry data should be collected for future studies for more accurate values of guayule processing energy.

Hevea Agriculture and Processing

Hevea agricultural and processing data was collected from a study performed by Jawjit, Kroeze et al. (2010) on GHG emissions of Hevea rubber production (listed in Table 4). Agricultural, electricity, energy and chemical inputs, and processing yields were specific for block rubber (tire-grade rubber). The Hevea rubber used for this study was sourced from Indonesia,

therefore an Indonesian electricity mix was used to model Hevea processing electricity (EIA 2014) (44% coal, 31% natural gas, 13% oil, 7% hydropower, 5% geothermal, 1% renewables).

Tire Raw Materials and Transportation

A tire consists of multiple parts, or components, shown in Figure 13, each of which is made up of many different types of raw materials. The LCA model was created by focusing on each tire component, beginning with the raw materials used for the part's manufacturing upstream of the tire manufacturing facility and including inputs required to operate equipment used in its production at the tire manufacturing facility. Tire composition and equipment energy consumption was collected during multiple visits to the tire manufacturing facilities. Manufacturing energy consumed at a facility was allocated to the functional unit (i.e. a single tire) by dividing total annual energy consumed in the tire manufacturing facilities by the total annual tires production. A state-specific electricity mix was modeled for the assessment (EIA 2012) (54.4% natural gas, 25% coal, 17.8% nuclear, 2.8% biomass, 0.2% other renewables). Data for the upstream production of some of the raw materials in a tire were not available. Of over 40 materials in a tire that are generalized by 12 categories (Figure 14), only a few raw materials were found in existing LCA databases (i.e. carbon black, zinc oxide, steel). The remaining materials (e.g. stearic acid, various accelerators, antioxidants, other processing aids) were assigned a reasonable proxy unit process in existing LCA databases with the aid of tire engineers and experts (e.g. petroleum refining co-products, organic chemicals, phenolic resin, phenol formaldehyde); these assumptions are listed in Table 4, and described in detail in Appendix C. The proxies were applied to materials comprising approximately 11% of the tire's weight. Detailed information on this raw material data is proprietary, therefore was reported as normalized values in the results.

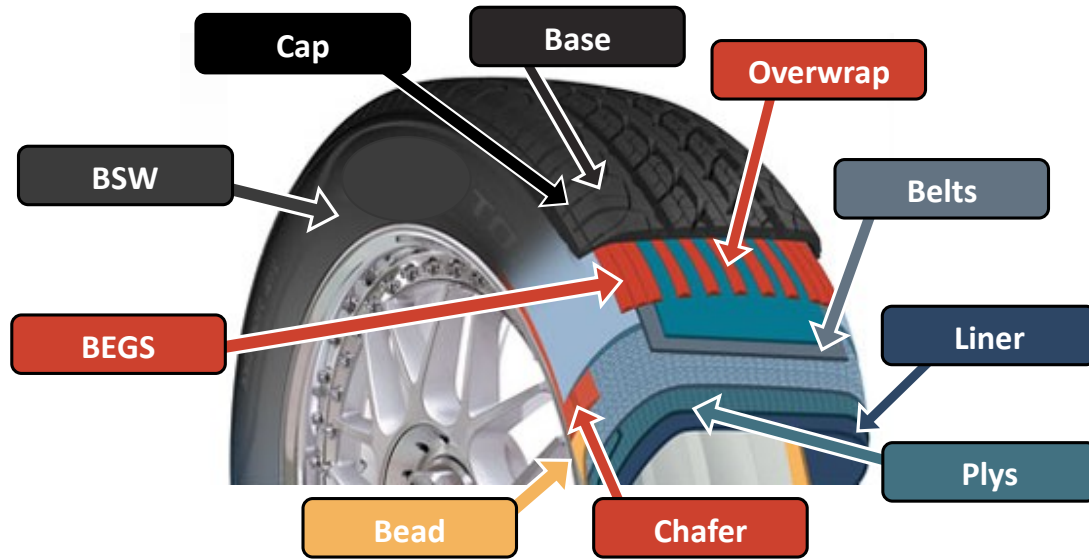


Figure 13. Tire Components.
BSW – Black side wall; BEGS – Belt edge gum strip.

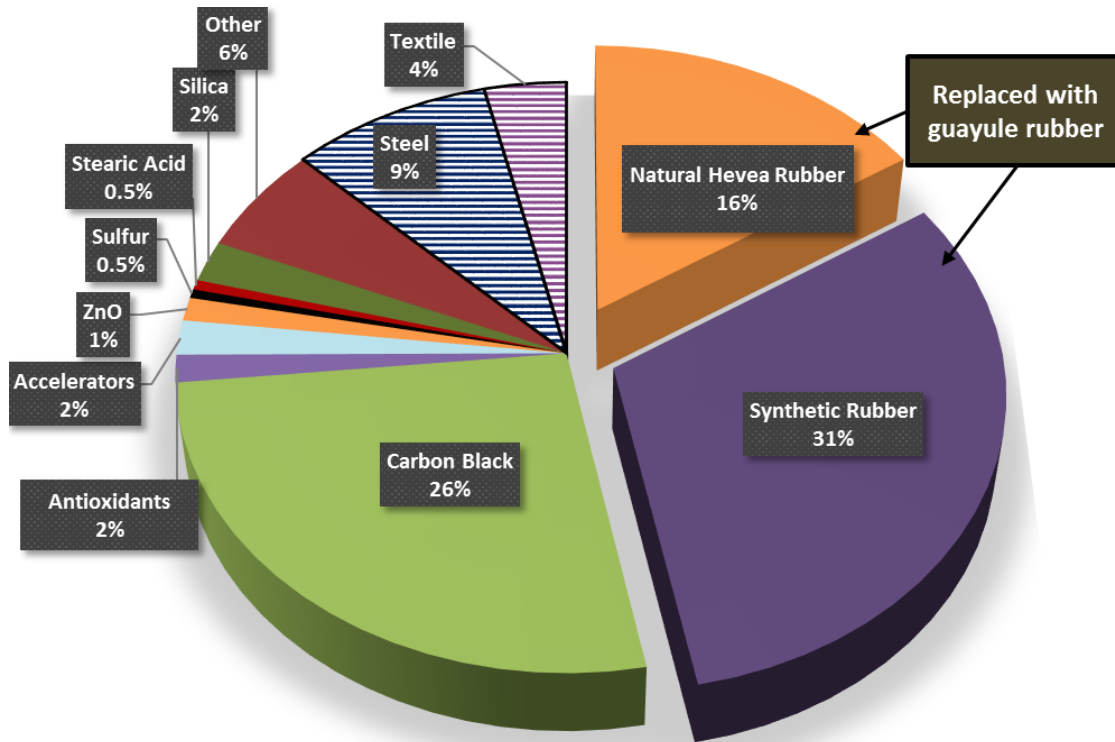


Figure 14. Tire Composition by Mass of Raw Material.

Supplier transportation information and packaging specifics for the most prominent materials (i.e. Hevea rubber, synthetic rubber, carbon black, textiles and steel) was collected through the tire manufacturing company and modeled with the use of typical distances for transoceanic shipping, road shipping via diesel truck, and rail via diesel powered trains. For other materials (i.e. silica, stearic acid, sulfur, zinc oxide, accelerators, antioxidants and other processing aids), actual locations for suppliers were not available; transportation distances were assumed to be for materials locally produced in the U.S. The shipping distance used for these other materials in the LCA was assumed to be an average of the truck distance traveled by the local U.S. suppliers for synthetic rubber, carbon black, textiles and steel; it was assumed that the tire manufacturing company receives all materials from the same general part of the U.S. The raw material shipping distances used for the LCA study are listed in Table 5 and discussed in more detail in Appendix D. Data on the specifics of packaging was provided for several of the materials (Hevea rubber, synthetic rubber, steel, polyester, nylon) and return of the packaging back to suppliers was accounted for in the transportation impacts. This is explained in more detail in Appendix D.

Table 4. Raw Material Inventory Data Sources and Conversions.

DB-database; e -ecoinvent; U - USLCI

The note [calculation] refers to values that were found through collection and combination of literature data and agricultural assumptions, i.e. rubber yield, irrigation efficiency, irrigation application and rainfall data, and combined with an assumption that the assumptions represent the inputs and performance of guayule agriculture in Arizona. The note [assumption] refers to simple inputs that have been chosen at the best of my knowledge, i.e. possible agricultural locations and equipment used in agriculture.

	Input process	Inputs for 1kg of guayule tire rubber		Source	DB		
	Raw materials: Natural rubber inputs	Agriculture					
Irrigation		Drip irrigation water application	10.376	m ³ /kg guayule rubber	[calculation]	—	
		Max irrigation for guayule (averaged flood from literature)	12.451	m ³ /kg guayule rubber	Nakayama 1991a, Bucks 1985a, Bucks 1985c, Foster 2002, Hunsaker 2014	—	
		Electricity used for irrigation (flood)	3.289	kWh/kg guayule rubber	[calculation]	e	
Fertilizer		Max N application for guayule (averaged)	0.075	kg N/kg guayule rubber	Bucks 1985a, Nakayama 1991b, Bucks 1985c, Brunson 2014	U	
Herbicides		Max herbicide application (DCPA, bensulide and pendimethalin)	0.015	kg total/kg guayule rubber	Ray 2010	e	
Field activities (diesel)		Cultivator, Planter, Forage harvester, Baler	0.036	liters/kg guayule rubber	Downs 1998	U	
Transport from fields to processing		Diesel use	0.045	liters/kg guayule rubber	[assumption]	U	
Processing							
Electricity		Electricity (assumed to equal average sugarcane processing electricity)	0.090	kWh/kg guayule rubber	Renouf 2007, Seabra 2011, Renouf 2008	e	
Water		Water (Ratio of liquid:bagasse)	5	:1	Schuman Jr 2005	e	
Chemicals		Chemical (KOH) dilution in water	0.2%	dilution in water	McIntyre 2000	e	
		Input Process	Inputs for 1kg Hevea tire rubber		Source	DB	
Raw Materials: Other		Agriculture	N fertilizer use	0.088	kg N/kg Hevea rubber	Jawjit 2010	e
	P fertilizer use		0.044	kg P/kg Hevea rubber	Jawjit 2010	e	
	Diesel use in tillage		0.001	liters/kg Hevea rubber	Jawjit 2010	U	
	Diesel use for transport		0.005	liters/kg Hevea rubber	Jawjit 2013	U	
	Processing	Ammonia Use	0.017	kg ammonia/kg Hevea rubber	Jawjit 2010	e	
		Electricity	0.220	kWh/kg Hevea rubber	Jawjit 2010	e	
		LPG Use	1.252	MJ/kg Hevea rubber	Jawjit 2010	U	
		Diesel use in block rubber (STR) mills	1	MJ/kg Hevea rubber	Jawjit 2010	U	
		Raw material					
		Database proxy					
Source							
DB							
Synthetic Rubber	Acrylonitrile-butadiene-styrene copolymer resin			Industry Data	U		
Carbon Black	Carbon black			Industry Data	e		
Antioxidants	Chemicals organic			Industry Data	U		
	Petroleum refining co-product			Industry Data	U		
Accelerators	Chemicals organic, at plant			Industry Data	e		
	Petroleum refining co-product			Industry Data	U		
	Phenolic resin			Industry Data	e		
	Phenol formaldehyde			Industry Data	U		
Zinc Oxide	Zinc oxide			Industry Data	e		
Sulfur	Secondary sulphur			Industry Data	e		
Stearic Acid	Fatty acids, from vegetarian oil			Industry data	e		
Other and Processing Aids	Silica	Sodium silicate, spray powder 80%			Industry data	e	
		Chemicals organic			Industry data	e	
	Other and Processing Aids	Petroleum refining co-product			Industry data	U	
		Phenolic resin			Industry data	e	
		Phenol formaldehyde			Industry data	U	
		Cobalt			Industry data	e	
	Textile (polyester & nylon)	Weaving, bast fibres	Yarn production, cotton fibres			Industry data	e
			Steel, low-alloyed			Industry data	e
Steel	Wire drawing, steel	Kaolin			Industry data	e	
					Industry data	e	

Table 5. Raw Material Transportation and Tire Manufacturing Inventory Data Source and Conversions. DB-database; e -ecoinvent; U – USLCI.

The transport modes were assumed to be fully loaded.

* These raw materials are shipped from several suppliers, and they do not all require transoceanic freight. The LCA study accounted for the portion of materials received from particular suppliers and their respective shipping mode and distances. This table only presents the materials shipped from suppliers that include transoceanic freight; these are the furthest distances traveled by the listed raw material.

Raw material	Transportation Type and Distance Traveled			Source	DB
Guayule Natural Rubber	Truck (processing->tire manufacturing)	2538	km	[assumption]	U
	Rail (processing->tire manufacturing)	2317	km	[assumption]	U
Hevea Natural Rubber	Truck (processing->port)	400	km	[assumption]	U
	Ship (port->port)	27412	km	Industry data	e
	Truck (port->tire manufacturing)	696	km	Industry data	U
Synthetic Rubber	Truck	870	km	Industry data	U
Carbon Black	Truck	708	km	Industry data	U
	Rail	840	km	Industry data	U
Antioxidants	Truck	908	km	[assumption]	U
Accelerators	Truck	908	km	[assumption]	U
Zinc Oxide	Truck	908	km	[assumption]	U
Sulfur	Truck	908	km	[assumption]	U
Stearic Acid	Truck	908	km	[assumption]	U
Silica	Truck	908	km	[assumption]	U
Other and Processing Aids	Truck	908	km	[assumption]	U
Textile (polyester)*	Transoceanic freight	22313	km	Industry data	e
	Truck	922	km	Industry data	U
Textile (nylon)*	Transoceanic freight	19713	km	Industry data	e
	Truck	782	km	Industry data	U
Steel*	Transoceanic freight	18623	km	Industry data	e
	Truck	2343	km	Industry data	U
Process	Application in manufacturing plant facilities			Source	DB
Electricity consumption	Electricity to run equipment and basic plant requirements (lighting, fans, etc.)			Industry data	e
Natural gas consumption	Natural gas to heat steam			Industry data	U
Cement	Cement to bond tread ends			Industry data	e
Propane	Propane to operate forklifts			Industry data	e
Diesel	Diesel to operate forklifts and transport equipment			Industry data	U

Impact Assessment

This LCA was conducted using TRACI 2.1 (v1.01) (Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts) developed by the U.S. EPA (Bare 2011). This study presents TRACI environmental results from global warming, smog, acidification, eutrophication and fossil fuel depletion impact categories.

Co-products

Both guayule and Hevea rubber agriculture produces co-products that can be processed into an energy source (See Figure 15). Guayule bagasse can be pyrolyzed to make bio-oil (Boateng, Mullen et al. 2009), and the bagasse itself can be compressed into fireplace logs (Wagner, Soderman et al. 1991) or pellets, including 25% processed cotton gin byproducts

(Nakayama 2005) and used as an energy source. Hevea seeds can be transformed into biodiesel through transesterification (Melvin Jose, Edwin Raj et al. 2011), and the rubberwood can be used for wood fired power plants (Krukanont and Prasertsan 2004).

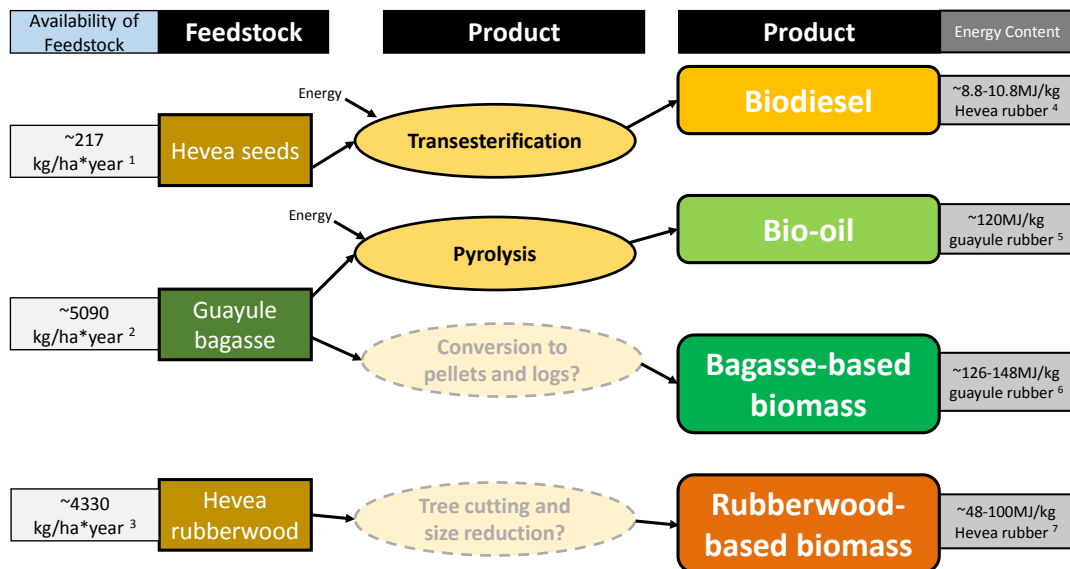


Figure 15. Guayule and Hevea Natural Rubber Co-product Feedstock, Processing Methods and Products. ¹ (Morshed, Ferdous et al. 2011); ² Calculations; ³ (Balsiger 2000); ⁴⁻⁷ Calculations

The energy content range available from utilizing these co-products is listed in Table 6. Data on the energy content of co-products was collected from literature. The productivity of each feedstock was converted to energy availability per production of kg of tire-grade rubber. Guayule bagasse is known to be available every 2 years (Miyamoto and Bucks 1985, Estilai 1991a, Cornish, McCoy et al. 2011), the Hevea seed oil is reported as an annual value (Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011), and rubberwood is known to be available every 30 years when rubber plantations are replanted (Balsiger 2000).

The energy inputs for pyrolysis (Fan, Kalnes et al. 2011) and transesterification (Pleanjai and Gheewala 2009) were estimated from values found in literature. The processing of bagasse and rubberwood feedstocks into sources of energy was unknown, and not included in the LCA. Details on the co-product and energy off-set modeling is discussed in Appendix F.

Table 6. *Guayule and Hevea Co-product Energy Content.*

Data Collection from Literature		Energy Value Modelling						
Co-product	Energy content range (kJ/kg of co-product)	Availability (kg of feedstock/ha*yr)	Oil Yield	Potential energy value range (MJ/ha*yr)	Energy content (MJ/kg of natural rubber production)	kg of rubber to produce 1MJ	References	
GUAYULE								
Bagasse feedstock (after latex extraction, with any remaining resin in the woody and bark fractions of the stem)	20490-24177	5092	-	104336-123110	88-104	0.010	Estilai 1991a, Boateng 2009, Nakayama 2005	
Bio-oil after bagasse pyrolysis (smaller value for the whole shrub, larger value for the bagasse)	30428-30508	5092	64%	99317-99578	84	0.012	Estilai 1991a, Boateng 2009	
HEVEA								
Rubberwood	17900	4333	-	38783-77567	48-97	0.010	Krukanont 2004, Balsiger 2000	
Seed oil	32600-39700	217	40%-60%	7074-8615	9-11	0.093	Ahmad 2014, Gimbin 2013, Morshed 2011, Ramadhas 2005a	

Sensitivity Analysis

A sensitivity analysis was conducted on four variables: yield and irrigation for the guayule plant, transportation mode for the guayule rubber, and tire manufacturing electricity in the production plant. Variables that may vary considerably as guayule cultivation becomes more efficient include yield and irrigation. Rubber yields from the guayule plant were modeled in the LCA as an average yield of 1,183 kg/ha; the sensitivity analysis increased the yield to 2,000 kg/ha (this is a rubber yield that has been reached in industry (PanAridus 2014)). Irrigation was modeled in the LCA as flood irrigation (operating at 75% efficiency) (Howell 2003), and the sensitivity analysis evaluated alternative efficiencies from drip irrigation, which operates at 90% efficiency. A higher pumping efficiency was added as a scenario where the electricity was reduced by 30%. The sensitivity analysis also incorporated a transportation modification; the LCA was modeled with truck transport for the guayule rubber, and rail transport was used as a substitute for the sensitivity analysis. The distance traveled by truck used in the modeling was 2,538 km, and rail distance was assumed to be 2,317 km. The impact categories chosen for the

sensitivity analysis include the categories where the replacement of Hevea and synthetic rubber with guayule resulted in higher impacts of the tire manufacturing life cycle.

A sensitivity analysis was also conducted on the electricity of the mixing and milling process of tire manufacturing, where guayule tires have potential to consume less energy. The changes in environmental impacts with the additions of these improvements as various scenarios are discussed in following sections.

3.3. Results and Discussion

This study compares a conventional passenger automobile tire and a guayule rubber-based passenger automobile tire from cradle to gate. The results explore the different raw materials of the tires, the components that comprise a tire, the transportation of the raw materials and electricity use in the manufacturing process. The potential for energy off-sets by utilizing natural rubber co-products is also analyzed. Finally, a sensitivity analysis was performed to evaluate potential impact reductions with implemented agricultural and transportation changes.

3.3.1. Guayule rubber tire compared to a Conventional passenger tire

A comparison of the impacts from the raw material extraction, their transportation, and the tire manufacturing process for a conventional and guayule tire shows that the impacts in global warming (GW) and smog are comparable between the two tire types; guayule tires have lower acidification and fossil fuel depletion (FFD) impacts, and conventional tires have lower eutrophication potential impacts (Figure 16).

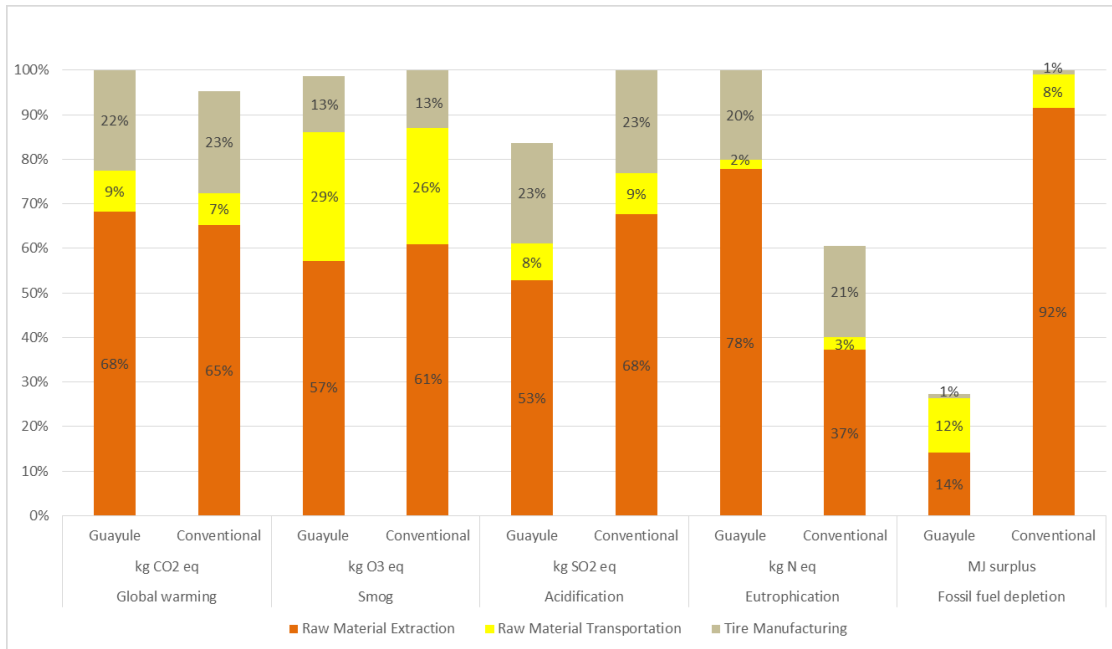


Figure 16. Guayule and Conventional Tire Comparison Displaying Normalized Impacts. These results represent calculations performed as the “Scenario A”, as discussed in the system boundaries: the results report impacts from the raw material extraction, transportation and tire manufacturing and do not include energy off-sets from the natural rubbers.

Tire manufacturing impacts between the two tire types do not show significant differences. Impacts from the manufacturing for both tires are high in global warming, acidification and eutrophication due to the electricity consumed during the manufacturing process. The electricity mix for the tire manufacturing facilities is comprised of 54% natural gas and 25% coal. Natural gas-based and coal electricity emit high CO₂ and methane, which significantly contribute to the GW potential. Sulfur dioxide released during both natural gas and coal electricity production contributes to acidification. Eutrophication impacts from natural gas electricity occur mainly due to emitted nitrogen oxides, and from coal due to emitted phosphate. Other activities during tire manufacturing, such as propane, diesel, steam heating, and cement use are insignificant contributors to all impact categories compared to electricity consumption.

Transportation impacts contribute most significantly in the smog and FFD categories. The fuel source used in the modeling was diesel, and its production is the main contributor for truck transport in FFD due to crude oil production, and a significant contributor in smog. For

transoceanic transport, the main contributors are operation maintenance for the ships that requires electricity inputs, and diesel use, which significantly contributes to the freight's smog. Raw material extraction is clearly the largest contributor to GW, smog, and acidification for both types of tires, the major contributor in eutrophication for guayule tires, and is the source of over 90% of the impacts for FFD for a conventional tire. The raw materials are further analyzed in the following sections.

Figure 17 displays how the raw material extraction impacts from Figure 16 are distributed between the non-rubber raw materials (“Other raw materials”), guayule rubber, Hevea rubber, and synthetic rubber. “Other raw materials” includes all materials that are not rubber (carbon black, steel, textile, antioxidants, antidegradents, etc.) (see Figure 14). Guayule rubber contributes between 31% and 60% of impacts for the various impact categories, and the Hevea and synthetic rubber in a conventional tire are responsible for 15% to 89% of the total raw material impacts. In the conventional tire, synthetic rubber contributes the majority of impacts.

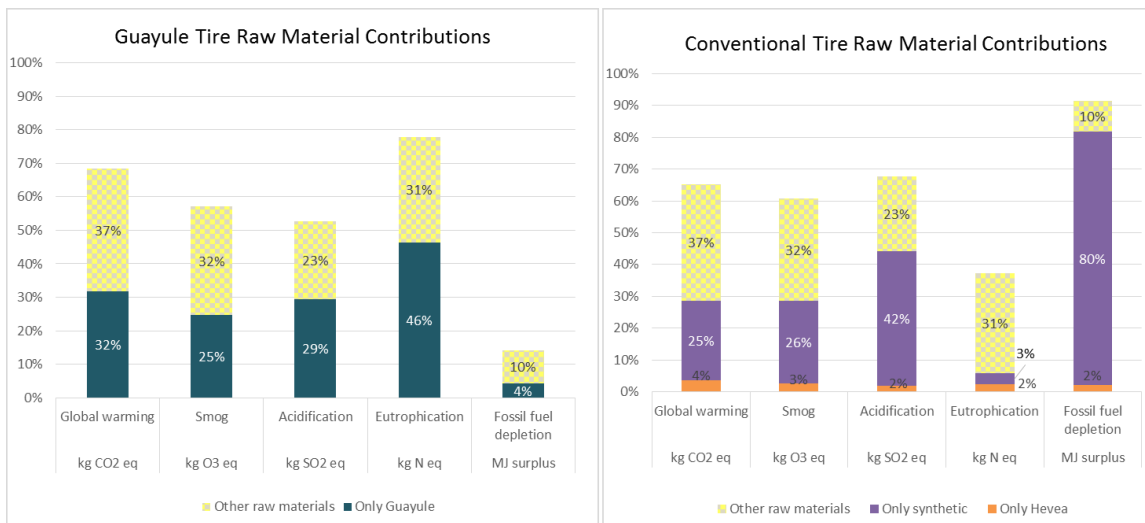


Figure 17. Comparison of Normalized Raw Material Extraction Impact Distribution Between the Rubber and other Raw Materials Relative to Total Tire Production Impacts. The raw material impacts first displayed in Figure 16 are broken down into more specific categories.

3.3.2. Comparison of Rubbers used in Guayule Tires and Conventional Hevea+Synthetic Tires

A comparison of exclusively the rubber needed to produce a guayule tire –which is all guayule rubber– and the rubber used for a conventional tire –which is a mix of Hevea and synthetic rubbers– shows that there are tradeoffs in the production of each type of tire rubber. Figure 18 presents tradeoffs within the agricultural, transportation, and processing steps. Guayule tire rubber produces lower impacts in the categories of smog, acidification and FFD. Guayule tire rubber is slightly higher in GW impacts than conventional tire rubber, but is considerably higher in eutrophication impacts. It is evident that the major impact contributions in almost all categories for guayule tire rubber come from guayule agriculture. For conventional tires, the major impacts result from synthetic rubber.

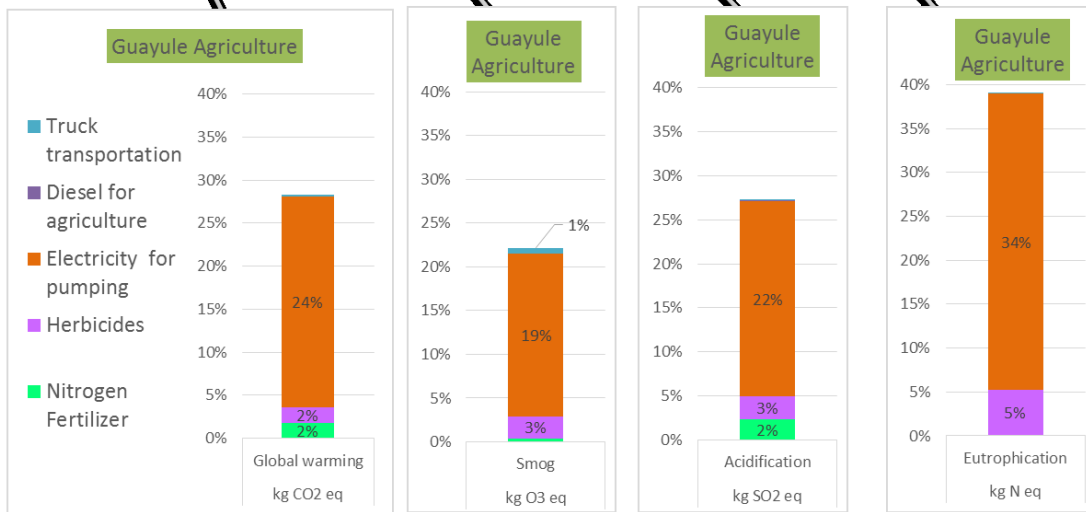
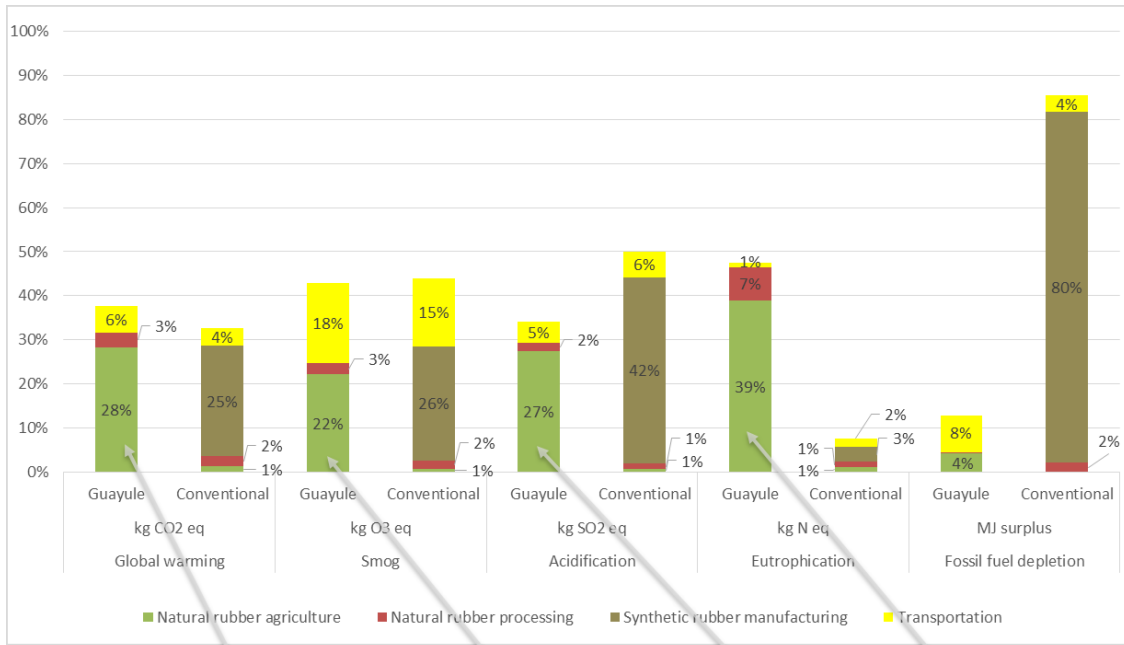


Figure 18. Normalized Impact Comparison of Total Rubber in Guayule Tire (guayule) and Total Rubber in Conventional Tire (Hevea+synthetic) Relative to Total Tire Production Impacts. The results in this figure do not include tire manufacturing; the impacts displayed include the production of natural rubber, which includes agriculture and processing, the manufacturing of synthetic rubber for conventional tires, and the transportation of the rubbers to the tire manufacturing facilities. NR=natural rubber.

The four lower graphs in Figure 18 show that electricity for pumping irrigation water contribute significantly to the agricultural impacts. Over 80% of the impacts in GW, smog, acidification and eutrophication impacts in guayule agriculture occur due to the electricity needed to pump the irrigation water. Although guayule is a shrub native to the desert, it requires high

amounts of applied water to achieve maximum rubber production and is comparable to alfalfa in water use (Foster and Coffelt 2005). Energy inputs for irrigation pumping commonly exceed the energy used for all other crop production practices, therefore selecting an efficient pump is an important farming consideration (Harrison 2012). Irrigation is thus an area that has great potential for improvement; alternative irrigation systems and higher efficiency pumps could reduce guayule agricultural impacts, which is discussed in more detail in the sensitivity analysis.

Arizona electricity is mostly from coal (36% coal, 29% nuclear, 27% natural gas, 8% renewable), where hard coal combustion contributes to eutrophication impacts more significantly than for the electricity mix used for tire manufacturing. Crude oil production needed for coal electricity is also a high eutrophication contributor. For GW impacts, natural gas used in the AZ mix is a significant contributor. The high eutrophication impacts for guayule occur due to the additional electricity that is needed for irrigation water pumping.

Hevea trees have traditionally been planted in the humid tropics where there is high rainfall throughout the year and additional irrigation is not usually applied. However, studies have shown that irrigation increases the latex yield (Sopheaveasna 2008). This LCA did not include irrigation for Hevea; however additional electricity inputs for irrigation purposes may be needed for Hevea rubber depending on the rainfall of the region where it is grown.

Synthetic rubber impacts alone exceed those of the total rubber needed for guayule tires in the categories of smog, acidification and FFD. This is also evident in Figure 16, where the raw material extraction impacts of the conventional tire exceed those of guayule tire raw material in the three impact categories. Synthetic rubber impacts greatly exceed the impacts of the other materials in acidification and FFD shown in Figure 17; synthetic rubber production is the key reason guayule tires are lower in impacts from acidification and FFD. The main processes contributing to the environmental impacts of the synthetic rubber proxy chosen in study (acrylonitrile-butadiene-styrene (ABS)) occur from ethylbenzene styrene production, polybutadiene production, and propylene production. These processes are associated with high impacts due to high inputs of natural gas, crude oil, and use of petroleum refining co-products, diesel and bituminous coal in their production. For synthetic rubber (ABS) production, the impacts

in GW and smog categories occur due to electricity use (30%) and bituminous coal combustion (6%); impacts in acidification and eutrophication categories occur due to electricity use (~15%) and ethylbenzene styrene production (~45%); and the FFD impacts are heavily dependent on ethylbenzene styrene (63.5%), polybutadiene (12.1%) and propylene (16%) production. All of these compounds are produced from petroleum.

Guayule rubber transportation impacts in Figure 18 are higher in GW, smog and FFD than impacts of the rubber for conventional tires, because guayule is assumed to travel across the U.S. via truck. Diesel truck transportation results in tailpipe emissions that are known to contribute to smog and GW potentials. The synthetic rubber is sourced closer to the tire manufacturing facilities locally in the U.S., and the Hevea is transported by transoceanic freight ships from Indonesia. Transportation is evaluated in further detail in the sensitivity analysis section.

3.3.3. A 1:1 Comparison of guayule and Hevea rubber

Hevea agricultural impacts are minimal in conventional tires. A 1:1 comparison of tire-grade guayule and Hevea rubber in Figure 19 shows that guayule agriculture and transportation of agricultural products cause the majority of environmental impacts for guayule, while transportation tends to dominate Hevea production. For GW, acidification and eutrophication, impacts resulting from guayule agriculture alone exceed all impacts from Hevea rubber production. The majority of these impacts resulted from the electricity use for pumping guayule irrigation water. For Hevea rubber, the majority of agricultural impacts are due to nitrogen and phosphorus fertilizer use, which contributed over 90% in every impact category except FFD where agricultural truck transport dominates impacts. Impacts from nitrogen fertilizer production (which is used in both guayule and Hevea) in GW, smog and acidification categories are mainly caused by ammonia production, and eutrophication impacts come from lignite mining leachate disposal. Phosphorus fertilizer (used in Hevea agriculture) production impacts from lignite burning in power plants were the major contributor to GW impact, diesel burned in building machines

contributes to smog and acidification impacts, and lignite mining leachate disposal is the main contributor to eutrophication impact.

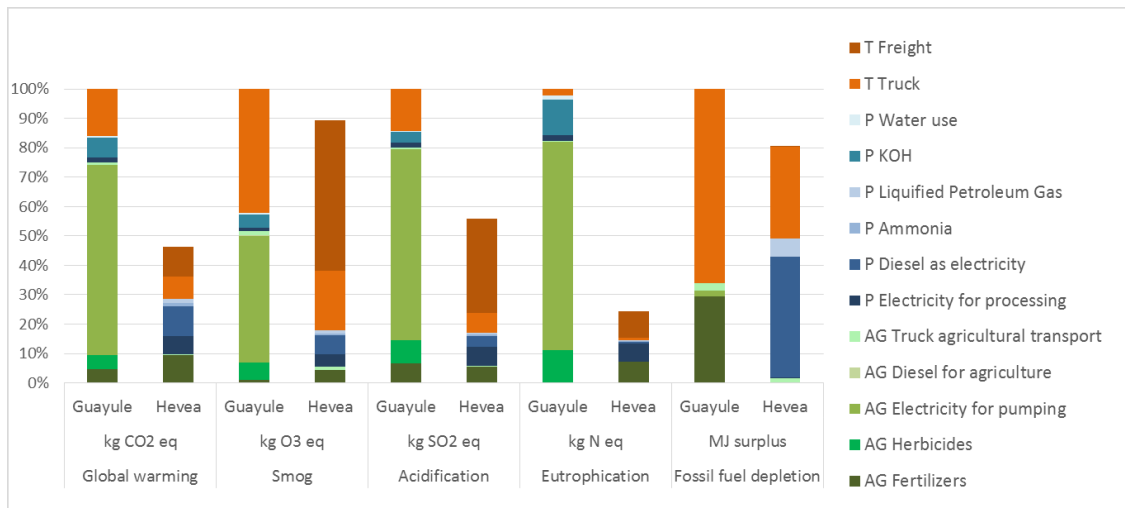


Figure 19. Comparing Normalized Tire Grade Guayule Rubber and Hevea Rubber Impacts: Agriculture (AG), Processing (P) and Transportation (T). Freight includes transoceanic transport; truck includes truck transport from rubber processing facilities to tire manufacturing facilities (distance to and from ports are included for Hevea rubber).

Total processing impacts for guayule are generally lower than those for Hevea (except in eutrophication). For guayule, the majority of processing impacts result from potassium hydroxide (KOH) use as a buffer for the rubber extraction. Impacts from KOH occur mainly from natural gas (contributing to GW), hard coal (smog and acidification), and lignite mining leachate disposal (eutrophication). Other chemicals can be used for guayule extraction such as ammonium hydroxide (NH₄OH), sodium hydroxide (NaOH), or sodium bicarbonate (NaHCO₃) (Cornish, McCoy et al. 2011). Hevea processing impacts are caused by ammonia (NH₃) use, which is a chemical added for latex preservation. The amount of ammonia added to latex varies with respect to how much fresh latex is used in the tire-grade rubber production. The ammonia consumed in this LCA represents a conservative estimate, since a large portion of tire-grade rubber is sourced from coagula which does not require ammonia to preserve the latex.

For the LCA study, guayule rubber transportation from Arizona to tire manufacturing facilities was assumed to be by truck. Hevea is shipped by transoceanic freight from Southeast Asia across the Pacific Ocean, and then transported by truck from the port to the tire manufacturing facilities. On a distance basis, trucking contributes higher environmental impacts

than freight ships. Trucking impacts result from crude oil production, coal electricity for diesel production, and diesel combustion. Transoceanic freight ship impacts occur from fuel used during operation of the ship, which includes the production and combustion of heavy fuel oil. However, the long oceanic shipping distances for Hevea rubber (over 25,000 km) contribute high smog, acidification and eutrophication impacts, especially when compared to the total guayule rubber transport. It is not likely that transportation substitutions can be made to reduce the Hevea rubber impacts from transoceanic freight; however, transportation impacts for guayule can be reduced through the substitution of rail instead of trucking, which is discussed later in the sensitivity analysis section.

3.3.4. Comparison of Tire Raw Materials and Components

Figure 20 displays the impacts from the raw materials used for tire production after the materials have been manufactured and transported to the manufacturing facilities (i.e. excluding tire manufacturing electricity at the plant). All raw materials except the rubbers are equivalent in the conventional and guayule tires.

The impact differences between the rubbers in the tires may seem less substantial in Figure 20 than Figure 18; this is because the difference between impacts is less apparent since other raw materials are included in the Figure 20 analysis, dedicating a smaller share of impacts to the rubbers when data is aggregated.

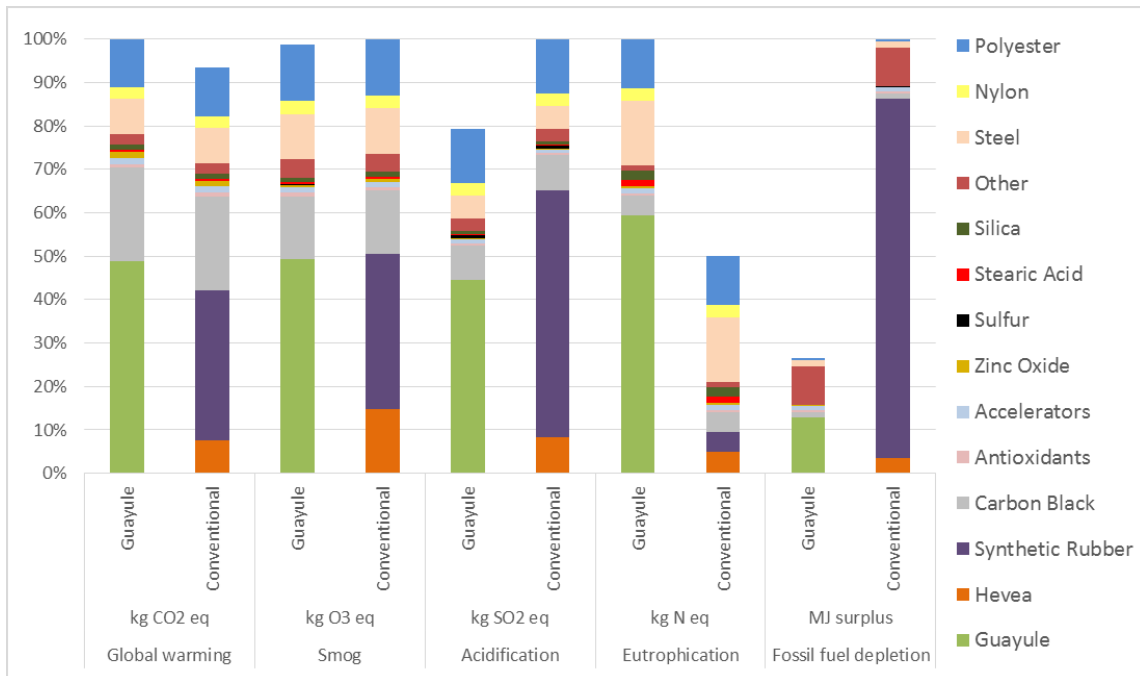


Figure 20. Tire Raw Material Manufacturing and Transportation to Tire Manufacturing Facilities Normalized Impacts.

The results include raw material manufacturing and transportation to tire manufacturing facilities; excludes tire manufacturing electricity at tire manufacturing facilities. “Other” includes processing aids and materials necessary for the manufacturing of rubber compounds, such as tackifying resins, oils, fillers, etc.

As mentioned earlier in Figure 17, the guayule rubber in the guayule tire, and the synthetic rubber in the conventional tire contribute the majority of the impacts. Guayule, Hevea and synthetic rubber impacts were discussed in Figure 18 and Figure 19. Following rubber, the largest impacts occur from carbon black, steel, polyester, and “other” material production and transportation. The impacts displayed in Figure 20 do not include tire manufacturing inputs at the facilities; these results display raw material impacts upon arrival at manufacturing facilities.

Carbon black impacts are significant in GW impact (22%) and occur mostly due to crude oil production. Smog and acidification impacts for carbon black production also result from crude oil production and diesel burned in diesel-electric generating set. Steel contributes 15% of a tire’s raw material GW impact; these occur primarily from the disposal of manufacturing waste in landfills. Polyester impacts contributing to GW occur mainly from hard coal, mining waste disposal and transoceanic freight operation.

The “other” category is comprised of materials where proxies were chosen to represent other raw materials that were not available in existing LCA databases; these proxies included petroleum refining co-products, organic chemicals, phenolic resin and phenol formaldehyde. The “other” category is primarily comprised of petroleum refining co-products. These impacts are largely from crude oil production and ocean freighter transportation, contributing to approximately 9% of the FFD impacts. It should be noted that the results are an estimate of possible impacts, and additional databases are needed for a more accurate assessment.

Raw materials such as silica, stearic acid, sulfur, zinc oxide, accelerators and antioxidants comprise a smaller portion of the tire’s mass and contribute to significantly lower impacts than the previously mentioned materials. However, many of these materials were not available in databases and proxies were chosen as substitutes (listed in detail in Table 9); more specific supplier data could provide a more accurate assessment.

A tire is made up of 10 different components, which are displayed in Figure 22 along with their weight distribution within a tire. A comparison of the different components of a guayule and conventional tire is shown in Figure 21; this figure only includes the raw materials that comprise each part and does not include electricity from tire manufacture or transportation of raw materials. The three largest tire components by weight – the cap, belt and ply- are the major contributors to impacts in all categories; the weight distribution is presented in Figure 22. The cap is especially high in acidification and FFD impacts in conventional tires. There is a high amount of synthetic rubber in the cap which is contributing approximately 90% of the impacts for acidification and FFD. The replacement of guayule instead of synthetic rubber greatly reduces the FFD impacts of the cap, from a 52% contribution to total FFD of tire manufacturing to an 8% contribution.

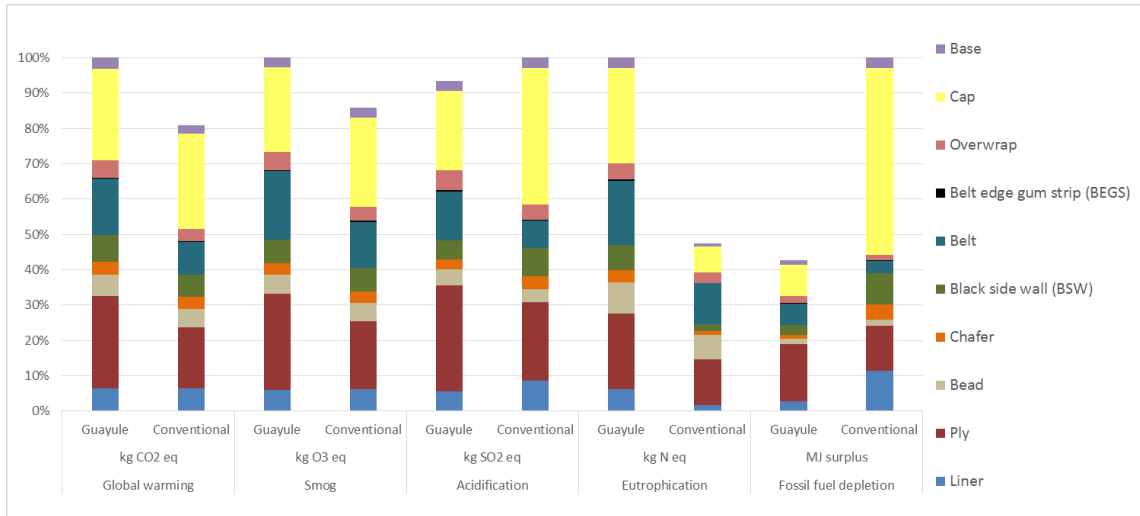


Figure 21. Normalized Component Raw Material Impact Comparison for a Guayule and Conventional Tire. The results include only the manufacturing impacts of the raw materials comprising the components; this includes the agricultural and processing inputs for guayule and Hevea. Raw material transport and tire manufacturing electricity are not included.

Belt and ply are traditionally made up primarily of Hevea rubber, thus replacing Hevea with guayule results in slightly higher impacts for guayule tires. The polyester in the ply of a conventional tire contributes over 50% of the impacts in GW, smog and acidification, and over 80% in eutrophication impacts of the total upstream impacts of the ply. Similarly, the steel in the belt of a conventional tire contributes over 50% of the impacts in GW, smog and acidification; over 70% in eutrophication impacts; and over 30% for FFD of the upstream production of the belt. For a guayule tire, impacts allocated to polyester and steel are reduced due to more impacts allocated to the guayule rubber replacement. For a conventional tire, the textiles contribute to 28%, and steel an additional 30%, of the total eutrophication for raw material manufacturing.

In the tire, a heavier component tends to be associated with higher environmental impacts, but there are a few exceptions. Figure 22 displays the comparative impact results for each component. In addition, Figure 22 shows the weight of the component in relation to the entire tire as well as the portion of electricity consumed to manufacture all 10 tire components within the facility. Each column in Figure 22 is equivalent to a certain fraction of the stacked columns in Figure 21; i.e. adding up all the GW impacts for a guayule tire from the 10 parts in Figure 22 will equal 100%, as displayed for the GW impact category in Figure 21, and so on.

Figure 22 is useful in assessing where a guayule rubber replacement has decreased or increased environmental impacts for a specific part, and how impacts relate to the weight and energy consumption of the part's manufacturing.



Figure 22. Normalized Guayule (green) and Hevea (orange) Tire Component Impact Comparison. The results include only the manufacturing impacts of the raw materials comprising the components; this includes the agricultural and processing inputs for guayule and Hevea. Raw material transport and tire manufacturing electricity are not included. Components' % Weight in Tire (blue), and % Manufacturing Electricity Consumption (red). *Note that the scale in impact graphs for these parts has been altered for ease of display. Abbreviations: GW – Global Warming; S – Smog; A – Acidification; E – Eutrophication; FFD – Fossil Fuel Depletion; %W – the mass portion of the particular component in relation to the total mass of tire components; %E – the portion of electricity consumed in the manufacturing of the particular part in relation to the total electricity consumed for component manufacturing.

As discussed in Figure 21, the impacts from the manufacturing of the ply and belt increase with the substitution of guayule rubber since natural rubber is a dominating material in these components. A guayule rubber replacement decreases impacts in several categories for the cap manufacturing, where synthetic rubber is a major raw material. Additionally, the conventional cap is by far the highest component in FFD due to the amount of synthetic rubber.

The energy consumption to produce the cap, ply and chafer are slightly lower than the typical trend for the components, i.e. in these three components, the %E is lower than %W, and/or lower than the % contribution of most impacts. This suggests that the raw material production impacts are more significant than the energy required for manufacturing for these components. The composition of these components could be altered to reduce impacts. A focus on reducing manufacturing energy to reduce impacts can be applied to components with a relatively high energy consumption fraction, i.e. where the %E is significantly larger than the %W and % contribution of impacts (e.g. BSW, overwrap, base).

3.3.5. Electricity consumption within the tire facility

There are eight processes in the tire manufacturing facility; however, seven electricity consuming processes considered for the tire manufacturing are proprietary and not discussed in this study. Mixing and milling is the only foreseen process where energy can be reduced when manufacturing a guayule tire. Mixing produces a more rapid reduction in the viscosity of guayule rubber than Hevea rubber, which reduces the optimum mixing time. Schloman Jr. estimated that the energy consumed in mixing the guayule is about 65-70% that of mixing Hevea rubber (Schloman Jr 1991). However, the Schloman Jr. study was performed on a small lab-scale mixer and may not apply to industrial scale mixing. After discussion with tire engineers at the tire manufacturing company, a conservative assumption for guayule rubber mixing energy would equal 90% of the energy needed for Hevea rubber mixing. This reduced the guayule tire's electricity consumption by almost 2% (Figure 23) of the electricity needed for tire manufacturing in the plant. Figure 23 shows additional scenarios where the mixing and milling energy for guayule was reduced to 80% and 70%, which reduced over 5% of the energy consumption at the tire manufacturing facility. Although these electricity savings may seem insignificant, thousands of tires are produced in the facilities on a daily basis and the savings could be substantial.

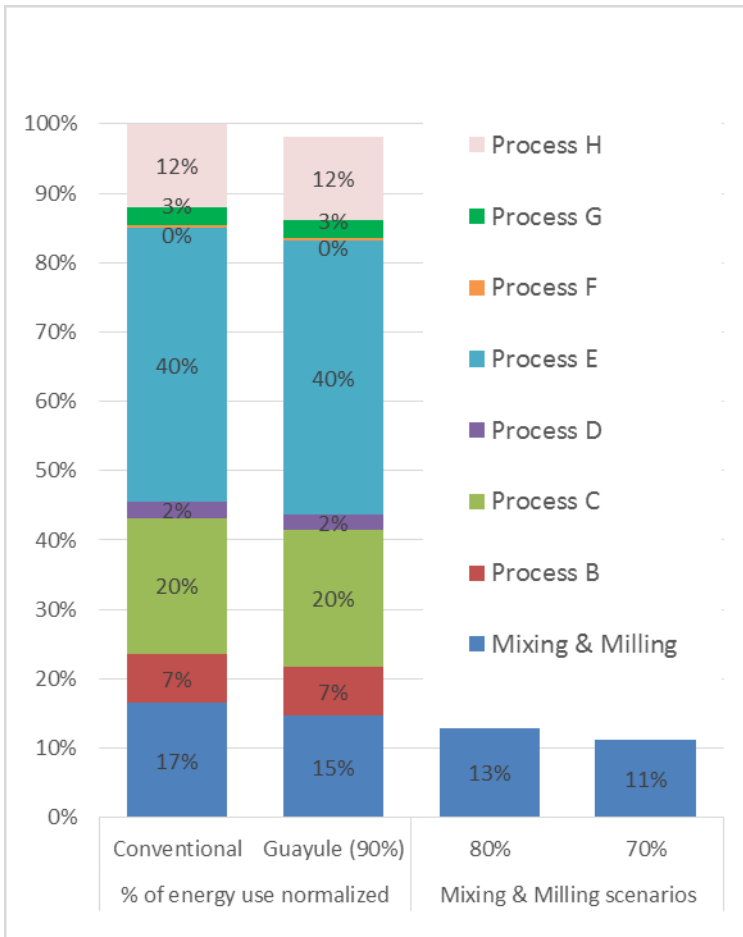


Figure 23. Normalized Comparison of Percentage of Electricity Use by Process in Tire Manufacturing Facilities.

3.3.6. Co-product energy off-sets

Data on the energy content of co-products was collected from literature (Table 6).

Guayule co-products include bagasse, which can be converted into bio-oil or used as biomass feedstock, and Hevea co-products include seeds that can be converted into seed oil and rubberwood used as biomass burned in a wood fired power plant. Available energy off-sets from each co-product are displayed in Figure 24.

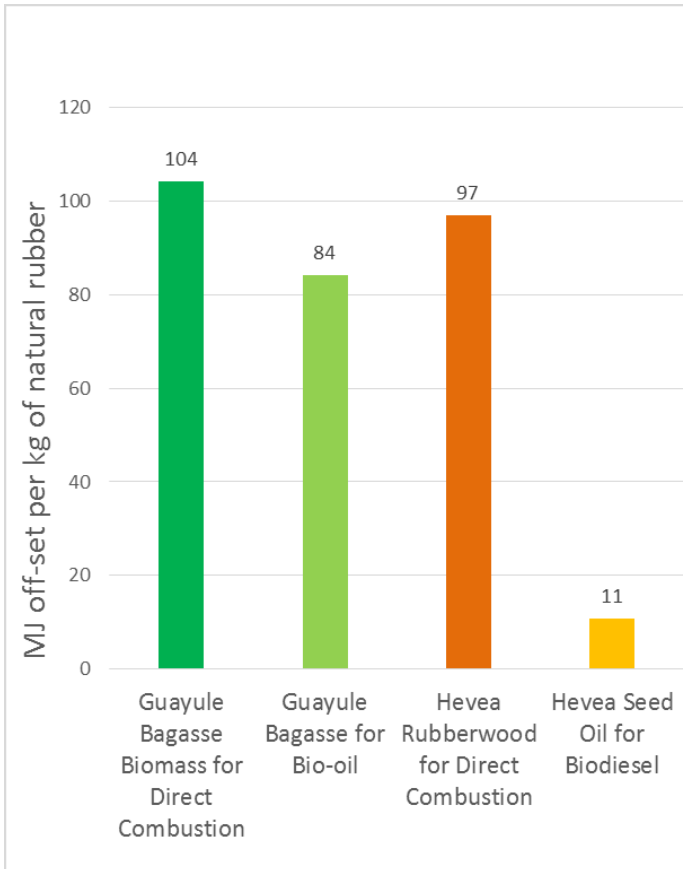


Figure 24. Energy Off-sets per Production of 1kg Natural Rubber.

Figure 25 displays the best case scenario available off-sets for each co-product. The bio-oil and biodiesel values incorporate the energy requirements of pyrolysis and transesterification, respectively, which slightly reduces the available off-sets. The energy inputs for pyrolysis and transesterification were estimated through literature, and this process is explained in detail in Appendix F. No energy for processing guayule bagasse biomass or Hevea rubberwood biomass was incorporated due to lack of data.

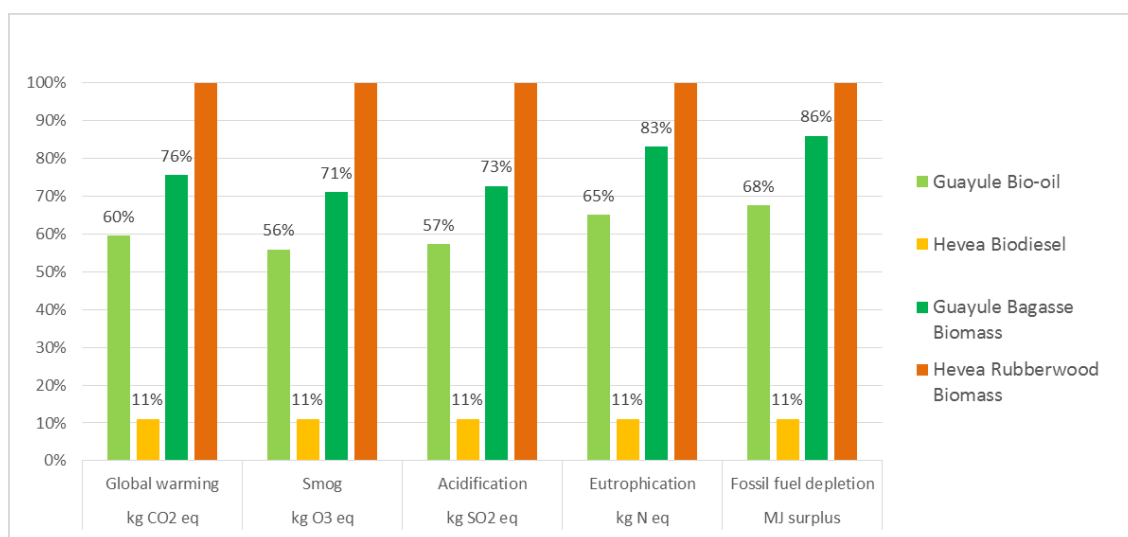


Figure 25. Comparing Available Electricity Impact Off-sets per Production of 1 kg Natural Rubber. *Guayule bagasse can be treated with pyrolysis to make bio-oil, Hevea seeds can be transformed into biodiesel through transesterification, guayule bagasse biomass can be compressed into logs or pellets as an energy source, and Hevea rubberwood can be used as biomass at a wood fired power plant. This figure compares each co-product's potential to off-set impacts. Hevea rubberwood shows to have the highest impact off-set availability since it is assumed to off-set a typical Indonesian electricity mix which is more environmentally intensive than an Arizona electricity mix. Guayule bagasse follows rubberwood with about 71%-86% impact off-sets available compared to rubberwood. Guayule co-products are assumed to off-set typical Arizona electricity.*

Guayule bio-oil is a valuable energy co-product and has shown to have an energy content of ~30 MJ/kg (Boateng, Mullen et al. 2009). This can be compared to the energy content of standard biodiesel (~42 MJ/kg) and diesel (43 MJ/kg) (Joshi and Pegg 2007), and also to Hevea seed oil (32 - 39 MJ/kg) (Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011, Gimibun, Ali et al. 2013, Ahmad, Yusup et al. 2014). With the inclusion of the recovered bio-oil in the condensers and the system piping, the overall guayule bio-oil yield is estimated at 64.1% for guayule bagasse (Boateng, Mullen et al. 2009) and results in high available energy off-sets. Since Hevea seed oil is available in far smaller quantities per kilogram rubber produced, the off-sets are smaller than for guayule bio-oil.

It is clear in Figure 24 that guayule bagasse biomass has the potential for the highest energy off-sets; this is a result of the high availability of co-product with every kilogram of rubber extraction, since only 10% of the total biomass will be used for latex and the remainder is either disposed or available to develop into useful products (Nakayama 2005). Hevea rubberwood

biomass availability and energy content is also high. Although only cultivated every 30 years, the trees yield 100-200m³ rubberwood per hectare (Balsiger 2000), which converts to 2,160-4,330 kg rubberwood/ha*year and is competitive with guayule bagasse. However, the electricity impact off-sets displayed in Figure 25 are highest for Hevea rubberwood. This is because Indonesian electricity would be off-set when utilizing Hevea co-products, and the Indonesian electricity mix results in higher impacts for all the evaluated impact categories. In other words, the off-set of 1 kWh of Indonesian electricity will avoid more impacts than the off-set of 1kWh of Arizona-based electricity.

Figure 26 shows how utilizing various amounts (25% or 100%) of the available guayule bagasse and Hevea rubberwood as electricity sources can off-set the impacts caused by electricity over the life cycle of a tire. The figure displays the potential impact off-sets resulting from a tire's entire manufacturing life cycle, including the raw material extraction, transportation and tire manufacturing. The available co-products could be used as an electricity source in guayule processing facilities in Arizona and Hevea processing facilities in Indonesia without much difficulty to off-set the impacts caused by the standard electricity mixes used for rubber processing. Co-product utilization could also off-set impacts resulting from other industries in Arizona and Indonesia.

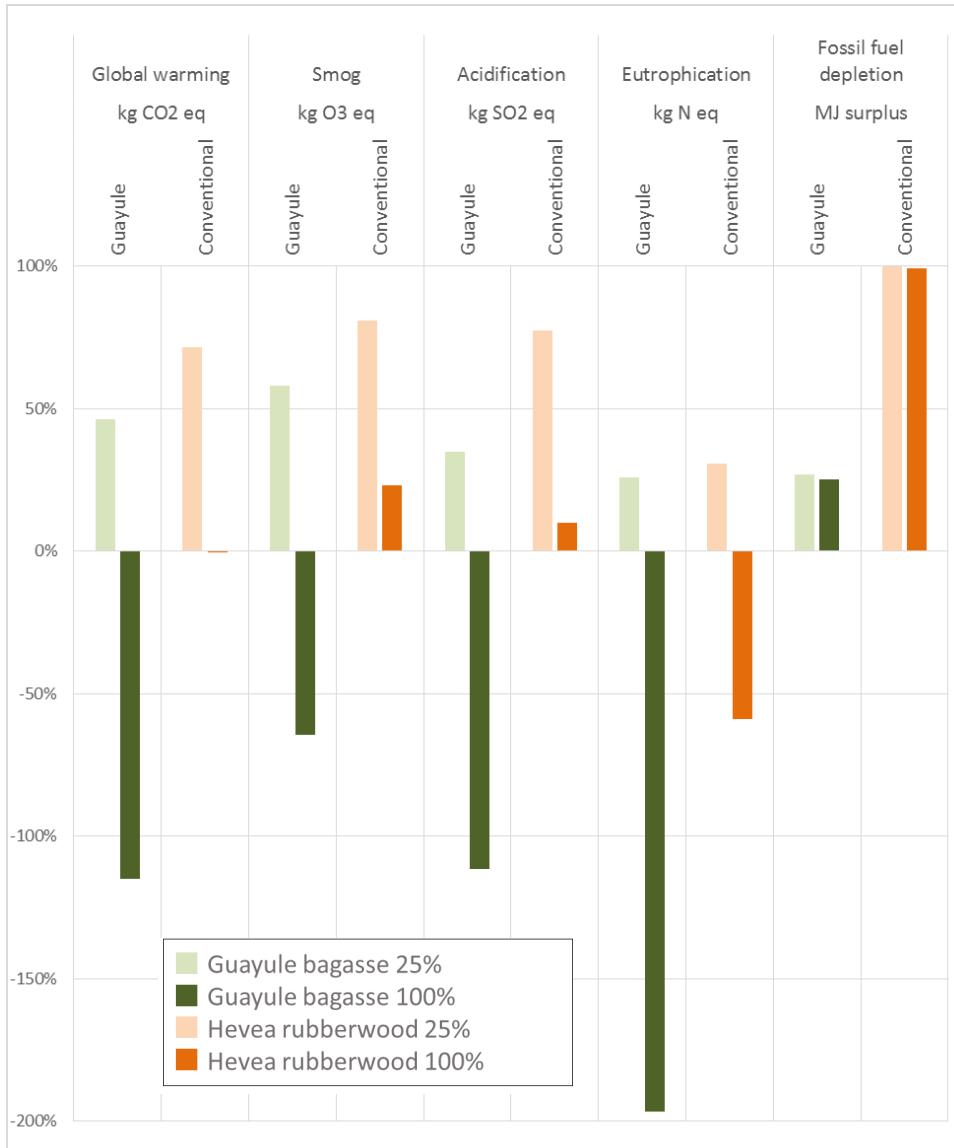


Figure 26. Tire Manufacturing Impact Reduction with Utilization of 25% or 100% of Available Guayule Bagasse and Hevea Rubberwood.
The guayule bagasse and Hevea rubberwood can be used as energy sources through direct combustion for electricity production. Guayule rubber's ability to off-set greater impacts in tire production is due to a higher amount of guayule rubber in a guayule tire versus Hevea rubber in a conventional tire; more rubber used in a tire's production provides more availability of the natural rubber co-product.

Results show that a guayule tire has a greater potential to reduce tire manufacturing impacts. This is due to the higher availability of bagasse as a feedstock from natural rubber agriculture, and also because more off-sets are available from the guayule rubber in a guayule tire, which comprises 47% of a tire, while Hevea rubber comprises only 16% of a conventional

tire. Guayule rubber represents the off-sets introduced when replacing an Arizona electricity mix, while Hevea off-sets are displaying Indonesian energy mix off-sets.

FFD impacts are minimally reduced because electricity generation is a minor contributor to fossil fuel depletion, therefore the off-sets created through implementation of an alternative electricity source will also be minor. The FFD impact category takes into account that the continued extraction and production of fossil fuels tends to consume the most economically recovered reserves first, so that continued extraction will become more energy intensive in the future. For example, energy from coal contributes minor impacts in this category, as opposed to crude oil use, which is assumed to be extremely high in FFD. Fossil fuel depletion impacts are mainly caused by synthetic rubber production in a conventional tire, and by production of organic chemicals, petroleum refining co-products and other tire raw materials for a guayule tire; an alternative energy source introduces insignificant reductions compared to the impacts from the production of these raw materials.

The results present a scenario where the co-product electricity production impacts are assumed to be equivalent to the impacts released during the utilization of the standard electricity mix. The goal of this co-product off-set analysis was to show the typical electricity mix (AZ or Indonesian) impact reductions available from co-product utilization. Further research is needed to assess the environmental impacts that occur from the co-product energy utilization (i.e. impacts from burning bagasse and rubberwood), which has potential to be lower than impacts from coal and natural gas, and further reduce environmental impacts.

The results in Figure 26 do not represent a feasible electricity substitution, since the impacts that are off-set do not necessarily occur during the electricity production phase. Future work could incorporate focusing on the electricity impacts that are feasible to off-set with the use of guayule bagasse and Hevea rubberwood. Biodiesel and bio-oil could be used to off-set transportation related impacts, but this approach was not included in the study.

3.3.7. Sensitivity Analysis

Several areas that could result in improved environmental impacts for guayule rubber include increasing rubber yields from the guayule plant to reduce impacts per quantity of rubber, using drip irrigation instead of flood irrigation to reduce water use thus reducing electricity use, increasing pump efficiencies to reduce electricity consumption, and utilizing rail transport instead of trucking when moving guayule rubber to tire production facilities. The impact categories chosen for the sensitivity analysis focus on the categories where the replacement of Hevea and synthetic rubber with guayule resulted in higher comparable impacts; these categories were global warming and eutrophication (see Figure 18). Several scenarios of changing the rubber yield, irrigation type, irrigation efficiency and transportation were selected to assess how the impacts of global warming and eutrophication could change. Scenarios 1-3 focused mainly on agricultural changes, while Scenario 4 incorporated transportation changes, and Scenario 5 combined both agricultural and transportation changes:

1. Scenario 1 involves the current yield with the addition of drip irrigation system (operating at 90% efficiency) to replace the current flood system (operating at 75%)(Howell 2003), and a higher pumping efficiency (30% electricity reduction);
2. Scenario 2 involves an alternative rubber yield, where the current yield of 1,183 kg/ha is increased to 2,000 kg/ha. The irrigation methods are not altered;
3. Scenario 3 is a combination of Scenarios 1 and 2, which involves the same irrigation improvements as Scenario 1 (drip irrigation at 90% efficiency and efficient pumping), along with the higher yield of 2,000 kg/ha;
4. Scenario 4 focuses on the current agricultural processes with a change in transportation from truck to rail;
5. Scenario 5 involves a combination of all the possible improvements: an increased yield, efficient irrigation utilizing drip, efficient pumping and rail transport as a replacement for truck transport.

Global warming impact sensitivity

Although guayule rubber global warming impacts on a mass-rubber basis are lower than for synthetic rubber, the impacts are equal to 215% of the GW impacts from Hevea rubber production (See Figure 27).

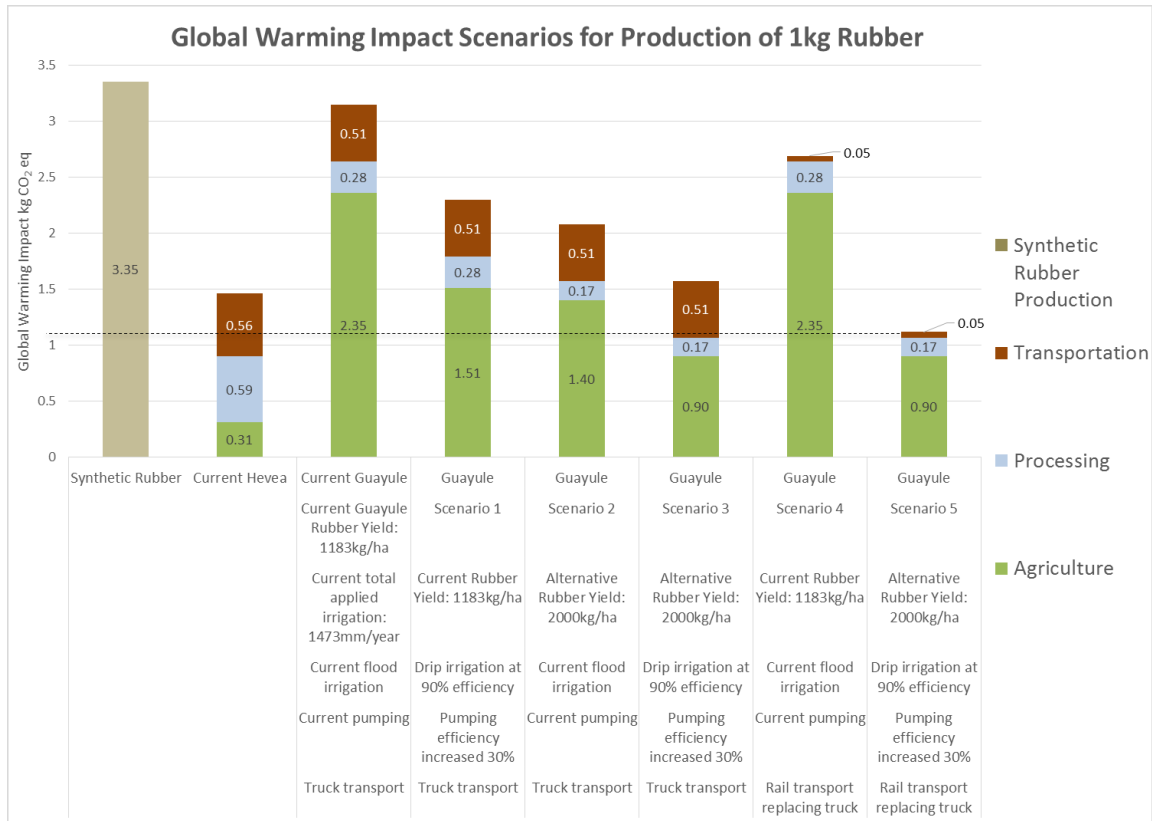


Figure 27. Global Warming Impact Scenarios for Production of 1kg Rubber. The dotted line indicates the impacts of guayule rubber when establishing improved irrigation practices, higher yields and an alternative mode of transportation. This impact reduction could make guayule rubber a favorable source of natural rubber in comparison with Hevea natural rubber.

Scenario 3 shows that by increasing rubber yields to 2000kg/ha, installing drip irrigation and increasing pump efficiency, guayule processing and agricultural impacts can be reduced by 60% (compared to the current guayule practices). High electricity is required for pumping water, and this scenario would reduce the water needed for agricultural pumping for each kg of guayule by approximately 2kWh, and 0.03kWh for processing. Introducing 30% higher efficiency pumps could reduce total agriculture GW impacts by approximately 13%, and the drip irrigation method reduces agricultural impacts by approximately 49%. Processing impacts are reduced with higher yields (Scenarios 2, 4, and 5), because a certain amount of guayule biomass will contain higher

rubber yields; this results in less electricity and water needed to produce a kilogram of guayule rubber.

Transportation impacts can be reduced by a factor of 10 (Scenarios 4 and 5) by substituting rail instead of truck to transport guayule from Arizona to tire manufacturing facilities. Scenario 5 displays impacts of increasing guayule yields, installing drip irrigation, increasing pumping efficiency and utilizing rail transport; this results in guayule rubber becoming favorable to Hevea rubber with respect to global warming impacts. Carbon capture sequestration was not accounted for in this study, but could be a method to further reduce the CO₂ emissions of natural rubber agriculture.

Hevea rubber was modeled with reference to mainly one study by Jawjit, Kroeze et al. (2010) performed on rubber agriculture and processing in Thailand, and may not be an accurate representation of the Hevea rubber grown for the tire in this particular study. Jawjit, Kroeze et al. (2010) collected data through primary and secondary sources: primary sources include 33 Thai farmer interviews, questionnaires received from 8 Thai rubber mills, and visits to 4 rubber mills; and secondary sources include Thai rubber institutes, governmental institutions and publications. The Jawjit study included a large sample of data, but data specific to the rubber sourced for the passenger tire assessed in this LCA may result in different impacts. The reported values for Hevea may change with the incorporation of agricultural and processing practices specific to the rubber used in the assessed tire. Furthermore, it was assumed that irrigation was not applied to Hevea rubber trees in this study; depending on the rainfall in the region where the Hevea is grown, electricity inputs may be required in Hevea agriculture. This could lead to significant impact increases.

Even with irrigation modifications, agricultural impacts continue to contribute over 50% of total impacts (Scenarios 2, 3, 5) and agriculture remains an area of focus to reduce guayule-related impacts. In the guayule-growing region of Arizona studied, the Pinal Active Management Area, where Maricopa is located, 96% of the total water used is for agriculture, where 45% of this is sourced from groundwater, 49% from the Central Arizona Project (CAP), and 6% from surface water. The CAP, a major water source for the west, delivers Colorado River water through a

series of canals and pumping stations (ADWR 2014). Due to Arizona's low water availability, major electricity inputs for irrigation are unavoidable: water must be supplied through groundwater by pumping or through transporting water from great distances. The CAP delivery system is 336 miles long and lifts water a total of 2400 feet (ADWR 2014). This LCA study assumed well water supply for irrigation, which is often preferred by farmers that switch to drip irrigation due to better water availability and lower filtration requirements (ITRC 2003).

Water requirements for the guayule plant and the electricity requirements for pumping guayule irrigation water are unlikely to decrease, and water availability in Arizona is unlikely to increase; however, Arizona has potential to utilize solar power for irrigation pumps as a replacement for the state energy mix; solar could reduce impacts related to electricity for irrigation. Solar power impacts contribute a fraction of the typical AZ electricity mix impacts for the production of equivalent power, including only 8% of the typical GW, 9% smog, 5% acidification, 18% eutrophication, and 4% FFD impacts (based on ecoinvent database processes modeled with TRACI 2.1.). Arizona's reliable high solar insolation of 2300 kWh/m²*day and a solar panel efficiency of 17% (Vogel 2010) would require the average American farm (235 acres (USDA 2013)) approximately 0.24 acres of land covered with solar panels to produce the energy to irrigate guayule produced on the farm.

Eutrophication Impact sensitivity

As mentioned throughout the study, guayule rubber displays high eutrophication impacts due to the electricity consumed in agricultural irrigation. For eutrophication, current guayule rubber practices result in impacts 8 times greater than synthetic, and 4 times greater than Hevea rubber (see Figure 28).

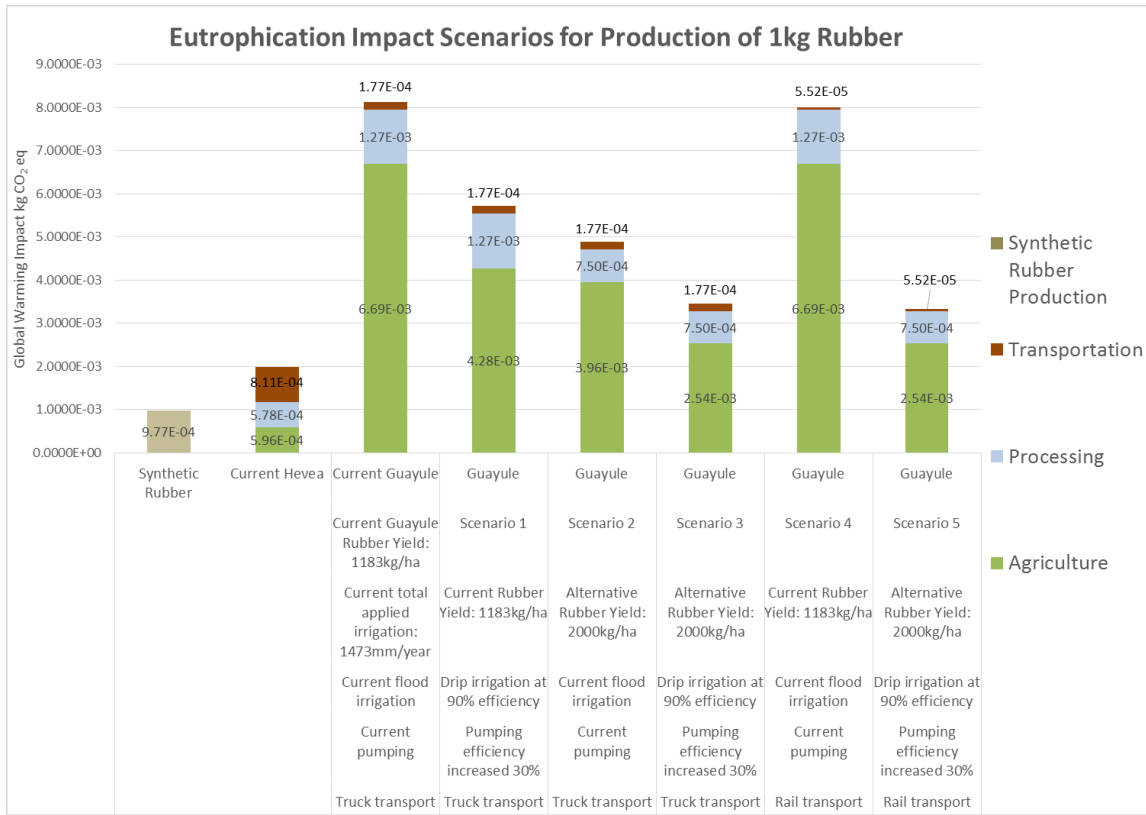


Figure 28. Eutrophication Impact Scenarios for Production of 1kg Rubber.

Figure 28 reiterates that guayule eutrophication impacts are largely due to agriculture which is mainly due to pumping electricity (discussed in Figure 18). For the current guayule scenario, transportation related impacts are insignificant in the overall eutrophication impacts, processing contributes 15%, and agriculture over 80% of eutrophication impacts. It is clear that reducing electricity use in agriculture will help reduce eutrophication impacts. A 59% reduction in impacts can be achieved by increasing guayule yields, implementing drip irrigation, increasing pumping efficiency and utilizing rail transport (current guayule and Scenario 5 compared).

Eutrophication is the fertilization of surface water by nutrients that were previously scarce. It is dominated by nitrogen and phosphorus which result as agricultural emissions, and NO_x (Ryberg, Vieira et al. 2014). Eutrophication is a regional impact, meaning that the impacts are site-dependent, unlike global warming where location of a process does not greatly influence fate, transport or potency. Characterization factors for eutrophication have been proposed for

large geographic areas such as east and west of the Mississippi River, U.S. census regions, and states (Bare 2003), but those factors are not detailed enough for countries with a wide geographic and climatic variability, such as the U.S. (Gallego, Rodríguez et al. 2010). TRACI 2.1, which is used in this LCA study, has maintained the original framework of TRACI, expanded the original list of substances, but the site-specific analysis was removed. Instead, the focus is on more comprehensive impact assessment, which would include processes that could occur outside the U.S. (Bare 2011, Bare 2012, Ryberg, Vieira et al. 2014).

Arizona geography is very specific and varies greatly from the general regions that have been used in eutrophication characterization for TRACI. The percent of inland and coastal water area in Arizona is one of the lowest in the U.S. (0.3%), exceeding only New Mexico (0.2%) (USGS 2014). Additionally, the number of impaired water bodies in AZ is one of the lowest in the U.S (EPA 2008) and no eutrophied water bodies are listed by the EPA (EPA 2014). Thus, the eutrophication factors do not accurately represent impacts occurring in Arizona. The results presented on eutrophication for guayule rubber are likely overestimated and in reality, are much lower.

3.3.8. Sustainability Discussion

This LCA study provides an environmental impact comparison of natural rubbers, but there are additional impacts that are not incorporated in the scope of the study. In Thailand, water and air pollution is a major concern of rubber processing. Rubber drying produces smoke particles that cloud the workspace due to poor ventilation systems and can spread to the surrounding cities. Wastewater from the rubber processing facilities is often acidic and the ammonia used for latex preservation introduces a strong smell that can have adverse effects on the workers' health (Tekasakul and Tekasakul 2006). In addition to the environmental problems, various socioeconomic issues are introduced with Hevea rubber production: monoculture

plantations of Hevea rubber reduce agrobiodiversity and livelihood flexibility, increased urbanization and timber extraction leads to more pressure on local resources, accelerated loss of forest for agriculture leaves less land for traditional use and livestock, and the rubber communities have developed a dependence on the rubber market (Liu 2006). Previously fallen rubber prices have forced tappers to increase tapping efficiency which temporarily increases production but damages the plantation in the long run. Problems in rubber plantations encourage tappers to begin to look for jobs elsewhere or switch to palm oil, which leads to rubber supply shortages (Balsiger 2000).

Furthermore, the Hevea industry might experience major changes in the near future. Rubber trees have traditionally been planted in the humid tropics where there is high rainfall throughout the year, but due to rubber tree plantations being replaced by more profitable palm-oil plantations (Cornish 1996, van Beilen and Poirier 2007b) where the obtained revenue from palm oil has shown to be double of rubber (Balsiger 2000), and an increase in the demand for rubber, future planting might be established in dry areas (Belcher, Rujehan et al. 2004). This could introduce supplementary irrigation which is not required for traditionally grown Hevea in rainfed conditions (Vijayakumar, Dey et al. 1998) and would introduce an electricity input that would result in additional environmental impacts.

The Hevea rubber industry follows an established model and is not likely to adapt major technological advances. Harvesting Hevea rubber is labor intensive and cannot be mechanized (van Beilen and Poirier 2007b) and is deeply rooted in traditions involving matrilineal inheritance and complex land tenure institutions (Suyanto, Tomich et al. 2001). On the other hand, the guayule industry is on the brink of development in an industrialized region with access to technological innovation and efficient practices. The guayule rubber industry is still at the early stages of development and has unforeseeable growth potential. Many other emerging bio-based technologies, such as biopolymers (Vink 2010) and biofuels (Rawat 2013), have progressed since their early development stages, and further advances in guayule have potential to lower the associated environmental footprint to improve the rubber's sustainability.

If guayule rubber were to replace the Hevea and synthetic rubber in all of the passenger car tires produced in the US every year (123.2 million units (TireBusiness 2013)), the agricultural land needed to harvest enough guayule (1.1 million ha) would be slightly smaller than the size of Connecticut (see Figure 29). This is equivalent to roughly 4% of the area of Arizona. An area of approximately 1124ha (4.3 mi²) covered by solar panels would produce the energy to irrigate the guayule needed to produce enough rubber for the production of passenger tires in the U.S.

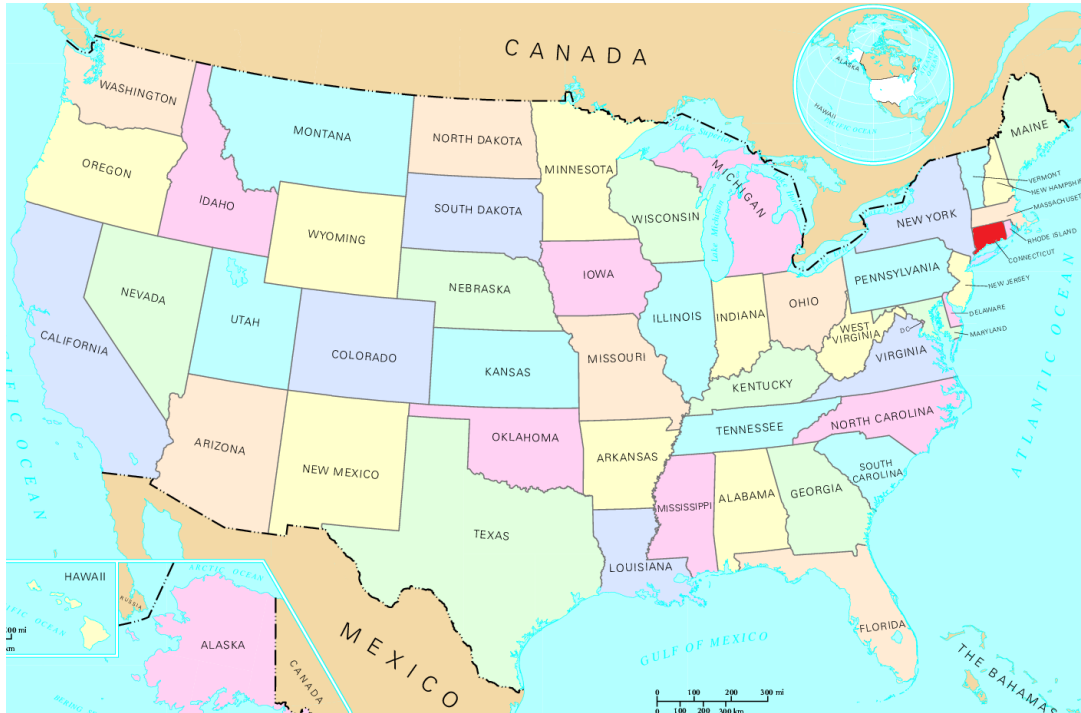


Figure 29. Area Needed to Grow Sufficient Guayule Rubber for Total U.S. Tire Supply. Area of Connecticut (in red) would be needed to supply enough guayule rubber to replace all the rubber in the production of U.S. passenger tires

3.4. Conclusions

A cradle-to-gate comparative life cycle assessment (LCA) was conducted for a conventional and guayule passenger automobile tire using the impact assessment method TRACI to report smog, global warming, acidification, eutrophication and fossil fuel depletion impacts. The study evaluated the processes with major impact contributions in tire manufacturing, discussed the availability of natural rubber co-products to displace electricity use and off-set impacts, and introduced potential methods to reduce guayule rubber impacts through agricultural modifications

and transport substitutions. The study found that reducing raw material extraction impacts can significantly improve a tire's environmental footprint, utilization of guayule and Hevea natural rubber production co-products for direct combustion could displace standard electricity use and off-set tire production impacts, and improvements in guayule agriculture and transport could establish guayule as a favorable source of natural rubber.

Several processes were omitted from this study. Due to lack of data, emissions and waste from natural rubber agriculture and processing and tire manufacturing were not included in the LCA; upstream emissions and waste were included. Primary upstream data was collected where available. Major assumptions on guayule processing electricity, tire raw material substitutions, and Hevea agricultural practices were made where data was not obtainable. Additional sensitivity analysis could be performed to assess impact contributions of these assumed inputs. The study acknowledged that the reported eutrophication impacts are likely to be overestimated due to Arizona's unique geographic conditions.

The LCA reported impacts from raw material extraction, transportation, and tire manufacturing processes for a guayule and conventional passenger tire. Results showed that raw material extraction contributes the majority of impacts, where the production of guayule rubber for guayule tires, and the production of synthetic rubber for conventional tires, were the main contributors. Transportation impacts had little significance compared to other stages in the life cycle, except for smog impacts (26%-29%), which occurred mainly from truck transport for guayule tires, and transoceanic transport for conventional tires. Tire manufacturing impacts resulted mainly from electricity use in the facilities and contribute 12%-23% of the impacts in most impact categories. Manufacturing impacts were slightly reduced with the utilization of guayule rubber in guayule tires.

A comparison of the two tire types showed that there are trade-offs in environmental impacts. Guayule tires were associated with lower acidification and fossil fuel depletion impacts, while conventional tires resulted in lower eutrophication potential impacts. Guayule tires were lower in acidification and fossil fuel depletion impacts due the utilization of guayule natural rubber as a replacement for synthetic rubber, the latter of which is associated with high impacts in

acidification and fossil fuel depletion. However, guayule tire impacts were larger in eutrophication due to the high electricity consumption for guayule irrigation water pumping. Electricity use in agriculture was a major impact contributor to guayule tires. Of the total impacts resulting in the assessed guayule tire's life cycle, 24% GW, 19% Smog, 27% acidification, and 34% eutrophication impacts were due to guayule agriculture electricity alone.

It was found that guayule bagasse and Hevea rubberwood have potential to be used in direct combustion to displace standard electricity use and off-set tire manufacturing impacts. An initial application of guayule bagasse as an energy source could be to power guayule processing facilities to avoid impacts from standard electricity use.

Several agricultural modifications were proposed to lower the electricity use for guayule. Raising guayule rubber yields, utilizing drip irrigation, and increasing pumping efficiency showed to decrease the combined agriculture and processing global warming impacts by 60%. With a scenario of reduced irrigation electricity use, higher yields and the replacement of truck transport with rail transport, total guayule rubber global warming impacts were reduced 64% compared to current practices; this presents guayule as an environmentally favorable rubber alternative to Hevea.

CHAPTER 4

FUTURE WORK AND CONCLUSIONS

Future Work

There are four recommended areas of focus for future work on the comparative life cycle assessment of conventional and guayule automobile tires.

1. The LCA was conducted as accurately as possible with the available data, but additional input and output data is needed.

Primary data on guayule agriculture would create a model specific for a certain area in Arizona that is representative of actual guayule agriculture. This could include collecting data on rubber yield, seeding practices, agricultural field practices, irrigation amounts, fertilizer and herbicide application rates, and emissions to water, soil and air. Additionally, primary guayule processing data, which includes equipment details, energy and water use, chemical use, emissions and waste, could be incorporated. If guayule is grown in areas outside of Arizona (e.g. West Texas), data specific to those regions would need to be collected.

Data could be collected on the specific practices to grow, harvest and process Hevea rubber used for tire manufacturing. Irrigation application will vary depending on the area where Hevea is grown, and incorporating accurate irrigation applications is important in the modeling process.

Additional data on the tire supply chain, including upstream impacts, would be valuable for the LCA. It is recommended that data collection from the tire manufacturing facilities is continued to obtain inputs and outputs that were not included in this LCA. This includes waste and emissions data, as well as the waste-to-energy potentials.

In addition to obtaining primary data, life cycle databases may be updated to include inputs to quantify emissions from upstream processes as secondary data.

2. Present results using altered characterization factors for eutrophication impacts in TRACI to represent Arizona-local impacts.

The study discussed that the reported eutrophication potential values may be inaccurate, thus researching characterization factors specific to Arizona and applying them to the modeling could result in more precise impacts.

3. Use and EOL phases will be incorporated to conduct an LCA of the full life cycle of an automobile tire.

The scope of this study did not include the use or end-of-life phase of tire manufacturing. These phases should be assessed to provide a comparative analysis of the full life cycle of each tire.

4. Model natural rubber off-sets potentials to the appropriate source: bio-oil and biodiesel for transportation, and bagasse/rubberwood to offsetting electricity.

Additional research can be performed on the natural rubber co-products and their off-set potential. The guayule and Hevea rubberwood biomass can be modeled to off-set electricity impacts, and guayule bio-oil from and Hevea biodiesel could off-set transportation impacts.

Conclusions

Natural rubber and rubber products can be produced from the guayule plant (*Parthenium argentatum* Gray), which is a low input perennial shrub native to Mexico and the American Southwest. Guayule rubber has the potential to replace Hevea (*Hevea brasiliensis*) rubber, the most common natural rubber, and synthetic rubber, which is derived from petroleum, in a wide variety of products, including automobile tires.

The objective of this study was to compare the environmental impacts of the raw material extraction, transportation and tire manufacturing processes for a conventional and guayule passenger tire, highlight the processes with major impact contributions, evaluate the availability of natural rubber co-products to off-set impacts and present a sensitivity analysis to assess the possibility of reducing guayule rubber impacts through changes in agricultural practices and transportation modes. A cradle-to-gate comparative life cycle assessment (LCA) was conducted for a conventional and guayule passenger automobile tire using the impact assessment method TRACI to report smog, global warming, acidification, eutrophication and fossil fuel depletion impacts. The study found that reducing raw material extraction impacts can significantly improve a tire's environmental footprint, utilization of guayule and Hevea rubber production co-products for direct combustion could displace standard electricity use, and improvements in guayule agriculture and transport could establish guayule as a favorable source of natural rubber.

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current practices; this presents guayule as an environmentally comparable rubber alternative to Hevea.

The guayule rubber industry is still at the early stages of development and has potential for growth. Many other emerging bio-based technologies, such as biopolymers and biofuels, have progressed since their early development stages, and further advances in guayule have potential to lower the associated environmental footprint to improve the rubber's sustainability and lower tire production impacts.

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APPENDIX A

NATURAL RUBBER AGRICULTURAL MODELING INPUTS

Table 7. Detailed Inputs for Natural Rubber Modeling in LCA Study.

Process	General inputs for Hevea rubber (raw publication data)		Inputs for 1kg Hevea tire rubber	Source
Agriculture	Yield	1.6 tons latex/ha*yr	800 kg Hevea rubber/ha*yr	Jawjit 2013, OAE 2012
	N fertilizer use	70 kg N/ha*yr	0.088 kg N/kg Hevea rubber	Jawjit 2010
	P fertilizer use	35 kg P/ha*yr	0.044 kg P/kg Hevea rubber	Jawjit 2010
	Diesel use in tillage	0.78 liter/ha*yr	0.001 liters/kg Hevea rubber	Jawjit 2010
	Diesel use for transport	2.5 l/ton of latex	0.005 liters/kg Hevea rubber	Jawjit 2013
	Distance from fields to processing	60 km/roundtrip		Jawjit 2013
Processing	Ammonia Use	17 kg/ton conc. latex	0.017 kg/kg Hevea rubber	Jawjit 2010
	Electricity	220 kWh/ton STR	0.220 kWh/kg Hevea rubber	Jawjit 2010
	LPG Use	1252 MJ/ton STR	1.252 MJ/kg Hevea rubber	Jawjit 2010
	Diesel use in block rubber (STR) mills	1000 MJ/ton STR	1 MJ/kg Hevea rubber	Jawjit 2010
Transportation from processing to tire manufacturing	Truck (processing->port)	250 miles		[assumption]
	Ship (port->port)	17033 miles		[assumption]
	Truck (port->tire manufacturing)	435 miles		[assumption]
Process	General Inputs for guayule rubber (raw publication data)		Inputs for 1kg of guayule tire rubber	Source
Agriculture				
Field inputs	Biomass Yield (averaged)	15732 kg/ha*yr		George 2005, van Beilen 2007a, Estilal 1991a
	Rubber Yield (averaged)	1183 kg/ha*yr		Foster 2005, Estilal 1991b, van Beilen 2007a, Thompson 1989
	Average yearly rainfall	203.2 mm/year		[assumption]
	Assumed flood irrigation efficiency	0.75		Howell 2003
	Assumed drip efficiency	0.9		Howell 2003
	Average energy use of water pump	0.264 kWh/m3		Great River Energy 2013
	Energy use for drip irrigation	0.270 kWh/m3		El-Shikha 2014
	Drip irrigation water application		10.376 m3/kg guayule rubber	[calculation]
	Max irrigation for guayule (averaged flood from literature)		12.451 m3/kg guayule rubber	Nakayama 1991a, Bucks 1985a, Bucks 1985c, Foster 2002
	Energy used for irrigation (flood)		3.289 kWh/kg guayule rubber	[calculation]
Max N application for guayule (averaged)		0.075 kg N/kg guayule rubber	Bucks 1985a, Nakayama 1991b, Bucks 1985c	
Herbicides	Max herbicide application (averaged DCPA, bensulide and pendimethalin)		0.015 kg total/kg guayule rubber	Ray 2010
Field activities (diesel)	Cultivator, row crop	0.45 gallons/acre*(2 yrs)	0.002 liters/kg guayule rubber	
	Planter, row crop (conventional ag)	0.5 gallons/acre*(2 yrs)	0.002 liters/kg guayule rubber	
	Forage harvester (corn silage)	3.6 gallons/acre*yr	0.028 liters/kg guayule rubber	Downs 1998
	Baler	0.45 gallons/acre*yr	0.004 liters/kg guayule rubber	
	Cultivator, Planter, Forage harvester, Baler		0.036 liters/kg guayule rubber	
Diesel use for transport (from fields to processing)	Truck mileage	5 mpg		Barnes 2003
	Distance to processing (roundtrip)	60 miles		[assumption]
	Total diesel use roundrip	12 gallons of diesel		[calculation]
	Truck capacity	48 m3		[assumption]
	Guayule bale density	280 kg/m3		Foster 1991
	Truck load when fully loaded	13440 kg		[calculation]
	Diesel use		0.045 liters/kg guayule rubber	[calculation]
Processing				
Electricity	Electricity use for sugarcane processing	70 MJ/7 tons sugarcane		Renouf 2007, Renouf 2008
		2.78 kWh/ton crop (sugarcane)	43.7 kWh/ha*yr	
		10.7 kWh/ton (sugarcane)	0.037 kWh/kg guayule rubber	
	Electricity (averaged through sugarcane assumptions)		168.3 kWh/ha*yr	0.142 kWh/kg guayule rubber
			0.090 kWh/kg guayule rubber	[calculation]
Water and Chemicals	Water (Ratio of liquid:bagasse)	5:1		Schloman Jr 2005
	Bagasse density	832 kg/m3		Holt 2012
	Chemical (KOH) dilution in water	0.2% dilution in water		McIntyre 2000
Transportation				
Transportation from processing to tire	Truck (processing->tire manufacturing)	1577 miles		[assumption]
	Rail (processing->tire manufacturing)	1440 miles		[assumption]

APPENDIX B

NATURAL RUBBER AGRICULTURE AND PROCESSING MODELING

Guayule Agriculture Modeling

Fertilizer

Nitrogen is normally the only fertilizer applied in guayule agriculture, and the commonly used type is UAN (urea ammonia nitrate). We are assuming that the nitrogen used for guayule agriculture is produced in the U.S., thus the USLCI process of “Nitrogen fertilizer, production mix” was used. This data was based on European processes.

Herbicides

Theecoinvent process “Herbicides, at regional storehouse” was used as a substitute for the herbicides used as a pre-treatment for direct-seeding. This ecoinvent process includes production of herbicides including materials, energy uses, infrastructure and emissions, and is modeled for Europe.

Irrigation energy

An assumption was made for the energy consumption of water pumped from a well. This was approximated at 1.00kWh per 1000 gallons of water (Great River Energy 2014). This is equivalent to approximately 0.26kWh per m³ of water extracted. An Arizona energy mix (36% coal, 29% nuclear, 27% natural gas, 8% renewable) is used to represent the pumping energy, which was found through the Southwest Energy Efficiency Project (SWEET) (SWEET 2014).

Pumping energy was discussed with representatives at U.S. Arid Land Services, and it was determined that the trial plots in Maricopa were using an average of 0.27kWh/m³ of water. This is a field wide average for all treatments (drip irrigated and flood irrigated).

This study focuses on flood irrigation as the primary scenario, with the assumption that the values found in literature reflect irrigation values for flood. An additional scenario includes a slightly lower irrigation value for a drip system. It is assumed that flood systems operate at an efficiency of 65-85%, and drip operate at 90% (Howell 2003). Direct-seeding was assumed to be the seeding method for guayule.

There were no inputs included related to greenhouse energy use, greenhouse irrigation or transport of transplants, since the study assumes direct-seeding and no transplanting.

Diesel used in agriculture

Primary data on guayule agriculture was not available, therefore assumptions were made to best quantify the diesel use in agriculture. The processes of cultivation, planting, harvesting and baling were expressed as the diesel consumption per acre. This was estimated through farm fuel requirements (Downs 1998). The USLCI process of “diesel, combusted in industrial equipment” was substituted to represent the diesel use of the field/agricultural equipment.

Diesel used to transport from agriculture to processing

The USLCI process of “Transport, single unit truck, diesel powered” was used to represent material transport by truck. This is the distance travelled from the agricultural fields to the processing location. This was assumed to be 30 miles (60 miles roundtrip).

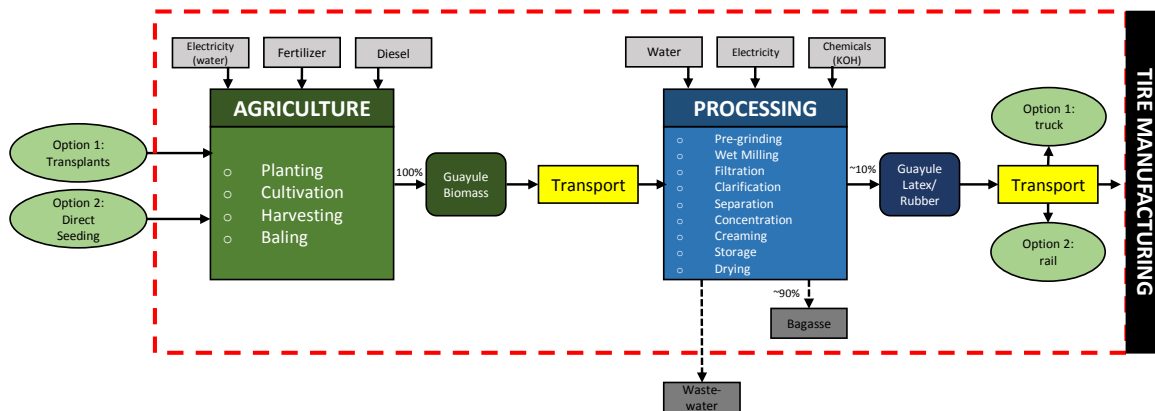


Figure 30. System Boundaries for Guayule Agriculture and Processing. The inputs, outputs and processes in the dotted red box were included in the LCA.

Guayule Processing Modeling

Electricity

Due to difficulties with obtaining primary data from a guayule agricultural and processing company and lack of publically available information, sugarcane electricity data for processing was used as a substitute. This is discussed in more detail in Appendix E.

The electricity mix used for guayule processing was modeled after Arizona electricity (36% coal, 29% nuclear, 27% natural gas, 8% renewable) through the Southwest Energy Efficiency Project (SWEET) (SWEET 2014).

Liquid Solution: Chemicals and Water

It is known that chemical solution containing water and a buffer, such as ammonium hydroxide (NH_4OH), potassium hydroxide (KOH), sodium hydroxide (NaOH), or sodium bicarbonate (NaHCO_3) (Cornish, McCoy et al. 2011) can be used in guayule processing. The only available buffer from this list in the databases was KOH, thus theecoinvent process “Potassium hydroxide, at regional storage” was used.

For water volume, it is known that a “dilute latex dispersion is produced by milling freshly harvested shrub in water or other aqueous medium at a liquid to solids ratio of about 5:1 to 20:1” (Schloman Jr 2005). The biomass (bagasse + rubber) weight is assumed to be the solids content. In this study, the ratio of 5:1 was used. The density of bagasse was assumed to be the same as guayule particle boards (832 kg/m^3) (Holt, Chow et al. 2012), but this assumption is most likely conservative.

To determine the ratio of KOH, a patent by McIntyre and Schloman (2000) was referenced where rubber was mixed with “an aqueous solution containing about 1.1 parts by weight potassium hydroxide and about 543 parts by weight water to form an emulsion”. This is equal to 0.2% KOH in the emulsion.

Hevea Agriculture Modeling

Data on Hevea was collected primarily from a study by Jawjit, Kroeze et al. (2010) which reported GHG emissions from the rubber industry in Thailand. The study covers the agricultural inputs as well as

the processing for different types of Hevea rubber products, one of which includes block rubber used in tires.

Figure 31 shows the schematic overview of fresh latex and the primary rubber products and associated emissions used in the study by Jawjit, Kroeze et al. (2010). The dotted lines indicate activities that were not included in the study.

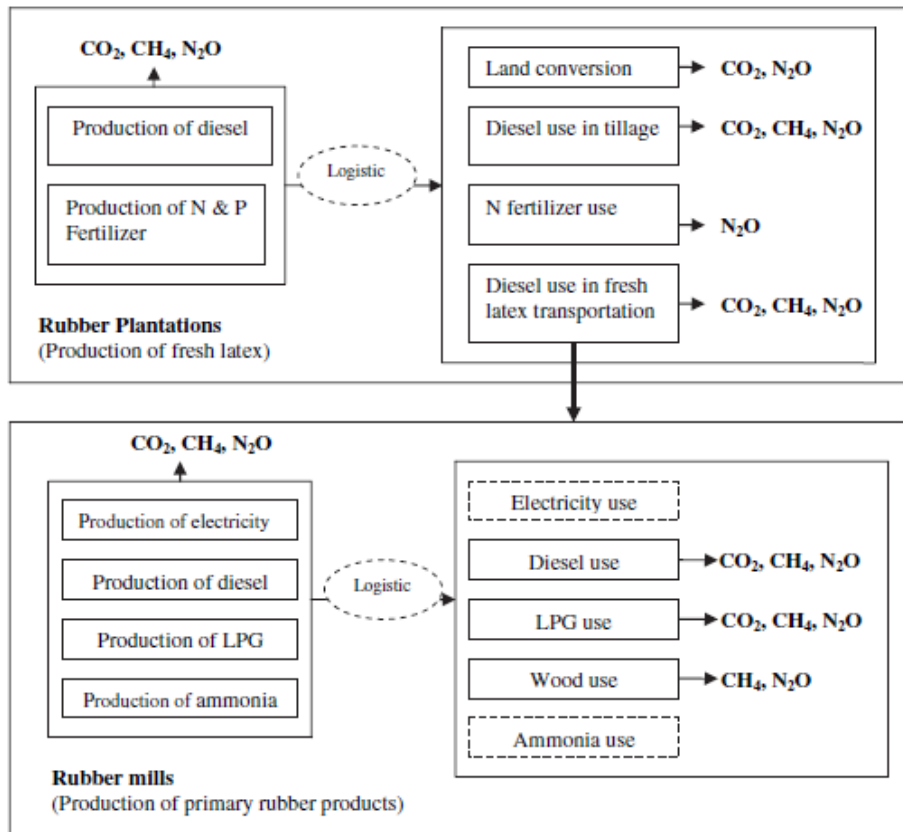


Figure 31. Schematic Overview of Hevea Latex and Primary Rubber Production. From Jawjit, Kroeze et al. (2010).

Fertilizer

For this LCA study, it was assumed that the form of nitrogen used in Hevea agriculture was in the form of urea. It is one of the dominant fertilizers produced and used in Indonesia and it is the common form applied on crops in the region (Food and Agriculture Organization of the United Nations 2005). The ecoinvent 2.2 database “Urea, as N, at regional storehouse/RER” was used.

Phosphate rock is known to be used as the phosphorus source on rubber plants (Y. Waizah 2011), thus the ecoinvent process of “Phosphate rock, as P₂O₅, beneficiated, wet, at plant/US U” was used. The process includes mining process, transport to beneficiation plant, wet processing including screening, washing and flotation. There are large uncertainties for data on particle emissions from transfer and storage. Also data of emissions to water and soil are uncertain due to missing data of uncontrolled run off which was estimated. Energy consumption data related to mass of rock moved.

Diesel used in agriculture

The value found in Jawjit, Kroeze et al. (2010) for Hevea was recorded as diesel used for tillage with the value of 0.78 liter/ha*yr. The USLCI process of “Diesel, combusted in industrial equipment” was substituted to represent the diesel use of the field/agricultural equipment.

Diesel used to transport from agriculture to processing

The USLCI process of “Transport, single unit truck, diesel powered” was used to represent material transport by truck. This is the distance travelled from the agricultural fields to the processing location. The distance estimates were taken from (Jawjit 2013) which were estimated at 60km/roundtrip.

Hevea Processing Modeling

Ammonia

In the production of block rubber for tires chemical use is rare, and can usually be considered negligible (there are chemicals used for the production of concentrated latex, which is not used for tires) (Jawjit, Kroeze et al. 2010). However, it is known that ammonia is needed to preserve the latex for producing solid block rubber (Sethuraj 1992), thus the number from Jawjit, Kroeze et al. (2010) for concentrated latex was used as an assumption for ammonia inputs. The ecoinvent process of “Ammonia, liquid, at regional storehouse” was used as a substitute.

Electricity

Electricity for Hevea processing was taken from Jawjit, Kroeze et al. (2010) where the authors collected industry data in Thailand, then completed, compared, and validated values with secondary data from governmental publications. Electricity is mainly used in the centrifugation process for Hevea latex. Warit Jawjit was contacted to confirm that the water pumping energy is included in the electricity reports, and the contribution of the pumping on electricity use is small. An Indonesian electricity mix was accessed through EIA (EIA 2014)(44% coal, 31% natural gas, 13% oil, 7% hydropower, 5% geothermal, 1% renewables).

Diesel and LPG

Diesel and LPG are used in the drying process of Hevea rubber (Jawjit, Kroeze et al. 2010). Diesel was substituted with theecoinvent process “Electricity, diesel, at power plant” and LPG was substituted with the USLCI process “Liquidied petroleum gas, combusted in industrial boiler”.

Table 8. Natural Rubber Agriculture and Processing Inputs, Data Inventory, Substitutions from Databases.

Life Cycle Stage	Inputs	Data Source	Process name	Database	Location
Raw materials: Natural rubber inputs	Guayule Agriculture				
	N Fertilizer	(Bucks 1985a), (Bucks 1985c), (Nakayama 1991b), (Personal communication with K. Bronson 2014)	Nitrogen fertilizer, production mix, at plant/US	USLCI 1.6.0	US Southeast
	Herbicides	(Ray 2010)	Herbicides, at regional storehouse/RER U	ecoinvent 2.2	Europe
	Electricity (irrigation pump)	(Great River Energy 2014), (Personal Communication with D. El-Shikha 2014)	Electricity, production mix Arizona	*ecoinvent 2.2	US/AZ
	Diesel use during agriculture	Assumption/average from (Downs 1998)	Diesel, combusted in industrial equipment/US	USLCI 1.6.0	US
	Diesel use for transport	Assumption	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Guayule Processing				
	Electricity consumption	Assumption from (Seabra 2011), (Renouf 2007), (Renouf 2008)	Electricity, production mix Arizona	*ecoinvent 2.2	US/AZ
	KOH	Average from (McIntyre 2000)	1 kg Potassium hydroxide, at regional storage/RER U	ecoinvent 2.2	Based on US industry/RER
	Water use	Average from (Schloman 2005)	1 kg Tap water, at user/RER U	ecoinvent 2.2	Switzerland/Germany
	Hevea Agriculture				
	N Fertilizer	(Jawjit 2010)	Urea, as N, at regional storehouse/RER U	ecoinvent 2.2	Europe
	P Fertilizer	(Jawjit 2010)	Phosphate rock, as P2O5, beneficiated, wet, at plant/US U	ecoinvent 2.2	US/RER
	Diesel use in tillage	(Jawjit 2010)	Diesel, combusted in industrial equipment/US	USLCI 1.6.0	US
	Diesel use for transport	(Jawjit 2013)	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Hevea Processing				
	Electricity consumption	(Jawjit 2010)	Electricity, production mix Indonesia	*ecoinvent 2.2	US/Indonesia
	Diesel	(Jawjit 2010)	Electricity, diesel, at power plant/RNA	USLCI 1.6.0	North America
	Ammonia use	(Jawjit 2010)	Ammonia, liquid, at regional storehouse/RER U	ecoinvent 2.2	Europe
	LPG use	(Jawjit 2010)	Liquefied petroleum gas, combusted in industrial boiler/US	USLCI 1.6.0	Europe

APPENDIX C

TIRE RAW MATERIAL AND TIRE MANUFACTURING MODELING

Raw Material Modeling

Synthetic rubber

Synthetic butadiene rubber (SBR) can be solution or emulsion. No current database exists on styrene butadiene rubber (SBR). To our knowledge, there were 2 databases compiled on SBR: Franklin Associates released a database in 1998, and an IDEMAT process was available in 2001. These databases are not publically available anymore and were not used in this study.

It was decided that the best approach for this LCA would be to substitute an available database that most closely represents SBR emulsion rubber. After discussing with tire engineers, it was determined that acrylonitrile-butadiene-styrene (ABS) rubber might be the closest substitute. Butadiene is the major harmful chemical in the production of SBR, and since it is also included in ABS rubber, this seemed to be the closest substitution. The USLCl process of “Acrylonitrile-butadiene-styrene copolymer resin, at plant” was used. This set includes acrylonitrile production and ABS resin production.

Natural rubber (Hevea and guayule)

Data on the agriculture and processing of STR (Standard Thailand Rubber) was found in Jawjit, Kroeze et al. (2010) and Jawjit (2013). The emissions associated with the production of STR 20 (307 kg CO₂-eq/ton STR 20) are higher than of concentrated latex and smoked sheet rubber (RSS). This is because the STR 20 production is mainly a mechanical process and relatively energy intensive (Jawjit, Kroeze et al. 2010). Electricity is used for driving machines, including creepers, shredders, slab cutters, pre-breakers, rotary cutters, and packaging machines (Jawjit, Kroeze et al. 2010).

The Franklin Associates 1998 includes a database on Natural Rubber (Hevea), but it is no longer available. The system model includes only the preparation of a natural rubber crumb additive for plastic products or for tires. Subsystems in the study include fuels, electricity, natural rubber growing and tapping, centrifugation, coagulation and rubber crumb production. The energy required for each process is listed by fuel. The transportation models uses USA statistical data combines with the fuels models.

There was no single database used for either of the natural rubbers. Literature data was collected to represent the inputs for the agriculture and processing of both guayule and Hevea (see Appendix A).

Guayule agricultural data was verified with employees at Agricultural Research Services in Maricopa, AZ.

Carbon black

Two major processes are used in the US to manufacture carbon black – the oil furnace process and the thermal process (EPA 1985). The production process determines carbon black properties such as particle size, surface area, and pH (Matar 2000). The carbon black produced through the thermal process produces large average particle size that is not suitable for tire bodies and tread bases, but (for tires) can be used in inner tubes. Instead, the oil-furnace process is important for making a form of carbon black that is used for the tread and body (Matar 2000).

For the LCA, a genericecoinvent database from was used where the carbon black was produced through the oil furnace process. Since the oil-furnace process is common for tire tread and body, it is a valid assumption that most of the carbon black in the conventional tire can be represented by the genericecoinvent process.

Categories with major substitutions: antioxidants, accelerators and others

Databases are not available for the various antioxidants, accelerators and other materials in a tire, thus substitutions were made to represent these raw materials as closely as possible. The assumptions were made after researching the chemical composition, manufacturing process and common uses for each of the materials. These substitutions were discussed with tire engineers to confirm that the assumptions were reasonable.

The processes assumed to be the best replacements include (Table 9):

- 1) Petroleum refining co-product. This was used to substitute materials that are associated with petroleum production, which were mostly oils and waxes.
- 2) Phenol formaldehyde. Formaldehyde is used almost exclusively in the production of phenolic resins, regardless of the type of phenol (encyclopedia, volume 7). The resins in the tire formulation containing forms of phenol and formaldehyde were categorized as Phenol Formaldehyde. The USLCI process based on the Pacific Northwest was used to represent the material.
- 3) Phenolic resin. If the resin included only forms of phenol.

- 4) Organic chemicals. This was used to substitute the largest amount of tire materials. If the tire material was not an apparent substitute for any of the other substitution categories, it was categorized as an organic chemical.

Of all the materials categorized as “other”, two materials were assigned specific substitutions instead of the one of the 4 proxies. Kaolin was found in databases and categorized as “Kaolin, at plant”. The functional unit represents 1 kg of kaolin, but there is quite a large uncertainty of the process data due to weak data on the production process. Cobalt salt was categorized as “Cobalt” from ecoinvent. Cobalt data approximated with data from nickel mining and beneficiation, but there is large uncertainty of the process data due to weak data on the production process.

Zinc oxide

Zinc oxide was represented by the ecoinvent 2.2 process. The functional unit represents 1 kg of solid zinc oxide powder, but there is large uncertainty of the process data due to weak data on the production process and missing data on process emissions.

Sulfur

A database in USLCI or ecoinvent on sulfur was not available, therefore “Secondary sulfur” was substituted. This process includes processes on the refinery site, excluding the emissions from combustion facilities, including waste water treatment, process emissions and direct discharges to rivers. This process used flows of materials and energy due to the throughput of 1kg crude oil in the refinery. The multioutput-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated to the different products. Major indicators like energy use have been estimated based on a survey in European refineries. Other data and indicators have been estimated based on different environmental reports.

Stearic acid

Stearic acid is also called Octadecanoic Acid, which is one of the most common long-chain fatty acids, found in combined form in natural animal and vegetable fats. Theecoinvent 2.2 process of “Fatty acids, from vegetarian oil” was substituted. The database is based on the oil from soya, palm kernel and coco nuts.

Silica

There was no available silica in the databases, therefore “Sodium silicate, spray powder 80%, at plant” from ecoinvent was substituted as the closest form of silica to the one used in tires. This was discussed with tire engineers.

Steel

Two databases were used to represent steel wires in tires: the ecoinvent database of “Steel, low-alloyed, at plant”, and the USLCl database of “Wire drawing, steel”. The low-alloyed steel process represent an average of World and European production and is assumed to correspond to the consumption mix in Europe. The data related to plants in the EU.

The wire drawing process includes the process steps pre-treatment of the wire rod (mechanical descaling, pickling), dry or wet drawing (usually several drafts with decreasing die sizes), in some cases heat treatment (continuous-/discontinuous annealing, patenting, oil hardening) and finishing. Wire drawing is a process in which wire rods/wires are reduced in diameter by drawing them through cone-shaped openings of a smaller cross section, so called dies. The input usually is wire rod of diameters ranging from 5.5 to 16 mm obtained from hot rolling mills in form of coils. The final diameter size of dry drawn wire is between one and two millimeters, wet drawn wire has an even smaller diameter. This diameter is slightly thicker than for the wire used for tires (around 3mm), but it was the best assumption available in databases.

Textiles: polyester and nylon

Textiles were substituted with 2 genericecoinvent processes: 'Yarn production, cotton fibres' and 'Weaving bast fibres'. The yarn production inventory refers to the processing of 1 kg lint cotton only, without the production of the cotton itself. The technology of cardening and spinning are the main processes of the yarn production. Mechanical cleaning and no chemical cleaning was assumed for this study. The weaving bast fibres inventory refers to the weaving of 1 kg yarn into textile, but the production of the yarn itself is not included. The geography includes Asian bast fibres products, mostly from India. The energy consumption may be overestimated, since the production processes were based for India for weaving, and yarn production mostly in China (60%). Textiles produced in the U.S. may have lower associated environmental impacts due to higher efficiency of production.

Table 9. Tire Raw Material Inputs, Data Inventory and Substitutions from Databases.

Life Cycle Stage	Inputs	Data Source	Process name	Database	Location
Raw Materials: Other	Synthetic Rubber	Industry Data with assumptions	Acrylonitrile-butadiene-styrene copolymer resin, at plant/RNA	USLCI 1.6.0	North America
	Carbon Black	Industry Data with assumptions	Carbon black, at plant/GLO U	ecoinvent 2.2	Global
	Antioxidants	Industry Data with assumptions	Chemicals organic, at plant/GLO U	ecoinvent 2.2	Global
			Petroleum refining co-product, unspecified, at refinery/kg/US	USLCI 1.6.0	US
	Accelerators	Industry Data with assumptions	Chemicals organic, at plant/GLO U	ecoinvent 2.2	Global
			Petroleum refining co-product, unspecified, at refinery/kg/US	USLCI 1.6.0	US
			Phenolic resin, at plant/RER U	ecoinvent 2.2	Some European data used
			Phenol formaldehyde, at plant/US	USLCI 1.6.0	US Pacific Northwest
	Zinc Oxide	Industry Data with assumptions	Zinc oxide, at plant/RER U	ecoinvent 2.2	Europe
	Sulfur	Industry Data with assumptions	Secondary sulphur, at refinery/RER U	ecoinvent 2.2	Europe
	Stearic Acid	Industry Data with assumptions	Fatty acids, from vegetarian oil, at plant/RER U	ecoinvent 2.2	Europe
	Silica	Industry Data with assumptions	Sodium silicate, spray powder 80%, at plant/RER U	ecoinvent 2.2	Europe
	Other	Industry Data with assumptions	Chemicals organic, at plant/GLO U	ecoinvent 2.2	Global
			Petroleum refining co-product, unspecified, at refinery/kg/US	USLCI 1.6.0	US
			Phenolic resin, at plant/RER U	ecoinvent 2.2	Some European data used
			Phenol formaldehyde, at plant/US	USLCI 1.6.0	US Pacific Northwest
			Cobalt, at plant/GLO U	ecoinvent 2.2	Global
			Kaolin, at plant/RER U	ecoinvent 2.2	Europe
	Textile	Industry Data with assumptions	Yarn production, cotton fibres/GLO U	ecoinvent 2.2	Global (40% USA, 60% Asia)
			Weaving, bast fibres/IN U	ecoinvent 2.2	Asia (India)
Steel	Industry Data with assumptions	Steel, low-alloyed, at plant/RER U	ecoinvent 2.2	World and Europe average	
		Wire drawing, steel/RER U	ecoinvent 2.2	EU	

Tire Manufacturing Modeling

Electricity

A Mississippi electricity mix was created to represent the energy used in Tire Manufacturing. The U.S. Energy Information Administration was used as the reference (EIA 2012) (54.4% natural gas, 25% coal, 17.8% nuclear, 2.8% biomass, 0.2% other renewables).

Cement

The ecoinvent process “Cement, unspecified, at plant” included a mix of different types of cement, based on CH statistics (2% blast furnace slag cement, 50% portland calcareous cement, 40% portland cement, resistance class Z 42.5, 6% portland cement, resistance class Z 52.5, 2% portland slag sand cement). The geography was based on Switzerland, and for some exchanges RER-modules have been used as proxy.

Propane

The ecoinvent process “Propane/butane, at refinery” was used to represent propane use during the tire manufacturing process. Propane is used by the tuggers in the facilities. The ecoinvent process includes the processes on the refinery site, excluding the emissions from combustion facilities, including waste water treatment, process emissions and direct discharges to rivers. The process is an assumption for the European average, and statistical data for the throughput and production volumes were available for the year 2000. Major indicators like energy use have been estimated based on a survey in European refineries. Other data and indicators have been estimated based on different environmental reports.

Diesel

Diesel impacts were determined with the use of the USLCI process “Diesel, combusted in industrial equipment”. This was considered the best substitute, although it is specialized for industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment.

Natural gas

Natural gas is used to heat the steam required in the curing process for tire manufacturing. Using an average of 1000Btu needed to produce 1lb of steam (OIT 2010), the natural gas needed to steaming each tire was found to be 0.085 m³.

Table 10. Tire Manufacturing Inputs, Data Inventory, Substitutions from Databases.

Life Cycle Stage	Inputs	Data Source	Process name	Database	Location
Tire manufacturing	Electricity consumption	Industry Data	Electricity, production mix	*ecoinvent 2.2	US/MS
	Natural gas consumption	Industry Data	Natural gas, processed, at plant/US	USLCI 1.6.0	US
	Cement	Industry Data	Cement, unspecified, at plant/CH U	ecoinvent 2.2	Swiss
	Propane	Industry Data	Propane/butane, at refinery/RER U	ecoinvent 2.2	Europe
	Diesel	Industry Data	Diesel, combusted in industrial equipment/US	USLCI 1.6.0	US

APPENDIX D

TRANSPORTATION MODELING

Three methods of transport were used for the raw materials: transoceanic freight ship, single unit truck and train (see Table 11).

Theecoinvent process for “Transport, transoceanic freight trip” was used to represent the materials imported into the US from Asia. This process includes the operation of vessel, production of vessel, construction and land use of port, operation, maintenance and disposal of port. The inventory refers to the entire transport life cycle. Data from one port in Netherlands is employed as an estimate for international water transportation. The technology includes steam turbine and diesel engines. Specific details on the transportation carriers for the raw materials are not known, therefore this process was assumed to be a valid substitution.

The USLCI process of “Transport, single unit truck, diesel powered” was used to represent material transport by truck. This is assigned to materials that are transported from foreign manufacturing location to port, from port to tire manufacturing, and from US manufacturing location to tire manufacturing. Using an ecoinvent process to represent trucking in Asia was considered (“Transport, lorry >16t, fleet average/RER U), but the variation in impacts could have added uncertainty. It is known that the materials are transported on diesel powered trucks, and the type of truck is assumed to be single unit, rather than combination. A single-unit truck is defined as a medium or heavy truck in which the engine, cab, drive train, and cargo area are all on one chassis (U.S. DOT 2014).

The USLCI process of “Transport, train, diesel powered” was used to represent the material transport by rail. Train transport is only assumed to be used in the US. This method of transport was applied to guayule rubber as an alternative scenario.

Guayule rubber

For this project, it is assumed that the rubber processing facilities are located in Casa Grande, AZ. An alternative scenario of rail transport was applied for the uncertainty analysis. It is assumed that the guayule rubber packaging is not returned to the suppliers.

Hevea rubber

The exact location of the Hevea rubber processing facilities are not known, but the plantations in the South Sumatra region of Indonesia produce most of the country's natural rubber. A conservative average distance of 250 miles is assumed between the processing facilities and port, which is transported by truck.

An average value of 17,033 miles was used as the assumption of distance covered by sea cargo vessel from Indonesian to U.S. ports.

The Hevea is brought into the tire manufacturing facilities by truck. Trucks pick up the shipment at the ports, and transport it to the tire manufacturing facilities. An average value of 435 miles was used as the assumption of distance covered by truck from the U.S. ports to the tire manufacturing facilities.

The Hevea is shipped in metal boxes that are reusable. The empty metal boxes are returned to the source in Southeast Asia. For the transportation modelling, an additional 9% of the total distance travelled from Asia to the U.S. was added to the Hevea distance travelled to account for the impacts of shipping the empty boxes back. This was calculated given the received-returned ratios ($1/(14/150)=0.09$).

Carbon black

Carbon black is received by bulk hopper truck (diesel) or by bulk hopper railcar (diesel). The truck shipments are received in quantities of 42,500 lbs (this is assumed to be fully loaded), and the railcars are loaded at 110,000lbs. The average distance travelled for diesel truck is 440 miles and for railcar is 522 miles. It is assumed that the packaging is not returned.

Beadwire and Steel tire cord (steel)

The beadwire is transported by diesel truck where the load is approximately 38,000lbs, and the trucks are assumed to be loaded to capacity. An average distance of 486 miles is travelled from the suppliers to tire manufacturing for the beadwire. Steel tire cord is imported from abroad, and both transoceanic freight ship and truck were used for the modeling.

Reinforcement packaging materials that are marked as 'reused' are sent back to the suppliers' manufacturing locations to be reused again. An additional 25% of transportation distance was added to

this material to account for the returns. It is assumed that the weight of the densely packed empty packaging is equal to the previously received product (material + packaging) on a fully loaded mode of transportation (i.e. truck or ship).

Polyester and Nylon (textiles)

Polyester and nylon are locally sources as well as imported from abroad, and both transoceanic freight ship and truck were used for the modeling.

Reinforcement packaging materials that are marked as 'reused' are sent back to the suppliers' manufacturing locations to be reused again. An additional 25% of transportation distance was added to this material to account for the returns. It is assumed that the weight of the densely packed empty packaging is equal to the previously received product (material + packaging) on a fully loaded mode of transportation (i.e. truck or ship).

Other raw material transportation (silica, stearic acid, sulfur, zinc oxide, accelerators, antioxidants, others)

The supplier transportation information related to these raw materials was not provided by the tire manufacturing company. Therefore, it was assumed that each of these "other" materials are locally produced in the US, and are transported by truck. The distance attributed to each material is the average distance the known materials (synthetic rubber, carbon black, steel, and textiles) were transported. It is assumed that these materials are shipped in disposable packaging and there are no transportation impacts related to their return to manufacturing facilities.

Table 11. Transportation Data Inputs, Data Inventory, Substitutions from Databases.

Life Cycle Stage	Inputs	Data Source	Process name	Database	Location
Transportation: Raw materials (from material producer to Cooper Tire)	Guayule Natural Rubber	Assumption	Transport, single unit truck,	USLCI 1.6.0	US
		Assumption	Transport, train, diesel powered/US	USLCI 1.6.0	US
	Hevea Natural Rubber	Industry Data	Transport, transoceanic freight ship/OCE U	ecoinvent 2.2	International water
		Industry Data	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Synthetic Rubber	Industry Data	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Carbon Black	Industry Data	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
		Industry Data	Transport, train, diesel powered/US	USLCI 1.6.0	US
	Antioxidants	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Accelerators	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Zinc Oxide	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Sulfur	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Stearic Acid	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Silica	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Processing Aids	Averaged	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Textile (polyester)	Industry Data	Transport, transoceanic freight ship/OCE U	ecoinvent 2.2	International water
		Industry Data	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Textile (nylon)	Industry Data	Transport, transoceanic freight ship/OCE U	ecoinvent 2.2	International water
		Industry Data	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US
	Steel	Industry Data	Transport, transoceanic freight ship/OCE U	ecoinvent 2.2	International water
		Industry Data	Transport, single unit truck, diesel powered/US	USLCI 1.6.0	US

APPENDIX E

SUGARCANE SUBSTITUTION MODELING

The available information on guayule did not contain enough detail to model a representative processing schematic. We were not able to locate the equipment listed in patents or the specific inputs, outputs and equipment running time needed to model the guayule processing. Instead, the alternative scenario uses sugarcane processing to substitute guayule processing. There are similarities between these two processing methods:

- The sugarcane agricultural material must be shredded by a shredder and cane knives. This is compared to the material reduction step needed for guayule material before processing can begin.
- Cane preparation requires rupturing the cells containing the cane juice for later extraction (Magalhaes 2010), which is performed by milling or crushing (FAO 2010). With sugarcane, the extraction can be performed with conventional mills by pressure using a screen diffuser, or with dewatering mills by the process of lixiviation (Magalhaes 2010) (extracting a soluble constituent by washing or percolation). This is comparable to the process of wet milling and filtration performed with guayule rubber.
- Cane juice is then extracted and clarified, which generates filter cake (FAO 2010). Filter cake is a residue of sugar production, but has some similar qualities to bagasse. This process is compared to clarification with guayule processing.
- Sugarcane processing also includes juice evaporation, crystallization, centrifugation and sugar drying. Sugar drying might be comparable to guayule processing with the process of drying the latex to make solid bulk rubber for tire manufacturing.

It is not clear whether sugarcane processing could be overestimating or underestimating the energy needed for guayule processing. Literature has shown that the energy needed to process 7t of harvested crop into cane sugar requires 70 MJ of energy (Renouf 2007). The useful product (sucrose) of this process makes up approximately 14% of the input (Seabra, Macedo et al. 2011). This is comparable to the product of the guayule process, where 10% of the total guayule biomass is developed into latex (Nakayama 2005). Both processes produce bagasse as a byproduct.

Two values were found in literature to represent the energy requirement of sugarcane processing: 70MJ/7 t (Renouf 2007) (or 2.8kWh/t) and 10.7kWh/t cane (Seabra, Macedo et al. 2011). Assuming that

these were the energy values to process harvested guayule, calculations incorporating the guayule rubber yields show that the energy is equal to 0.04kWh/kg guayule rubber and 0.14kWh/kg guayule rubber, respectively, to process guayule. An average of these two values was used as the processing energy value for this LCA.

APPENDIX F

NATURAL RUBBER CO-PRODUCT MODELING

Both guayule and Hevea have co-products that can be processed into an energy source (See Figure 32). Guayule bagasse can be treated with pyrolysis to make bio-oil, or the bagasse itself can be compressed and used as an energy source. Hevea seeds can be transformed into biodiesel through transesterification, or the rubberwood can be used as energy-rich biomass.

Bio-oil and bagasse biomass from guayule

There are various methods to utilize guayule co-products for energy, such as compressing the leftover bagasse from processing into fireplace logs, briquettes, or pellets. These materials have higher energy content than other wood sources because of the remaining resin (approximately 10% of the dry mass) (Nakayama 2005). This LCA includes guayule bagasse as a potential energy source. In addition to bagasse as a biomass, an analysis is included on bagasse treated with pyrolysis to produce bio-oil. This conversion of bagasse to liquid fuel could become an economic source of diesel-type fuel (Nakayama 2005).

Bio-oil is a renewable liquid fuel produced by the fast pyrolysis of biomass, which is the direct thermal decomposition of the organic matrix in the absence of oxygen to obtain an array of solid, liquid and gas products (Yaman 2004, Fatih Demirbas, Balat et al. 2011). Pyrolysis is a relatively simple, inexpensive and robust thermochemical technology for transforming biomass into bio-oil (Laird, Brown et al. 2009). The liquid and gas products can be used in engines and turbines for power generation and in industrial boilers. Bio-oil is made from various forest and agricultural waste materials, such as sugar cane bagasse, rice hulls and straw, peanut hulls, switchgrass, wheat straw, wood, and bark. Bio-oil is considered an excellent source of fuel and chemicals, but currently cannot be used as transportation fuel due to properties such as high viscosity, acidic nature, high water and oxygen content and incompatibility with conventional fuels (Fatih Demirbas, Balat et al. 2011). Bio-oil produced from guayule has an energy content much higher than the typical biomass pyrolysis oils. The bagasse needed to produce the bio-oil is an attractive bioenergy feedstock, because it is an industrial by-product that requires no transportation and/or major pre-processing, which can be a major cost in biomass conversion (Boateng, Mullen et al. 2009).

Biodiesel and rubberwood from Hevea

Hevea rubber trees produce seeds that can be converted into biodiesel, and the rubberwood remaining after a plantation that is no longer productive can be used as a source of biomass. The biomass resulting from a Hevea plantation is high in weight and volume (100-200m³/ha), but can only be harvested every 30 years or so (Balsiger 2000). And energy content of 17.9MJ/kg is available for a wood fired power plant running on rubberwood (Krukanont and Prasertsan 2004).

Biodiesel is derived from vegetable oil, animal fats and grease through the chemical process of transesterification. The high cost of biodiesel is currently a major obstacle to commercialization (Fatih Demirbas, Balat et al. 2011). An advantage of producing biodiesel from Hevea seeds is that it is an inedible crop that would not compete with food materials. The Hevea oils seed biodiesel extraction process involves steps such as breaking down the seed, screw pressing, acid esterification, and transesterification to mono-ester (Melvin Jose, Edwin Raj et al. 2011). The productivity of rubber seed oil per hectare per year is known to be 217kg oil/ha (Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011), and each tree yields about 800 seeds (1.3 kg) twice a year. A rubber plantation is estimated to be able produce about 800-1200 kg rubber seed per ha per year (Eka 2010).

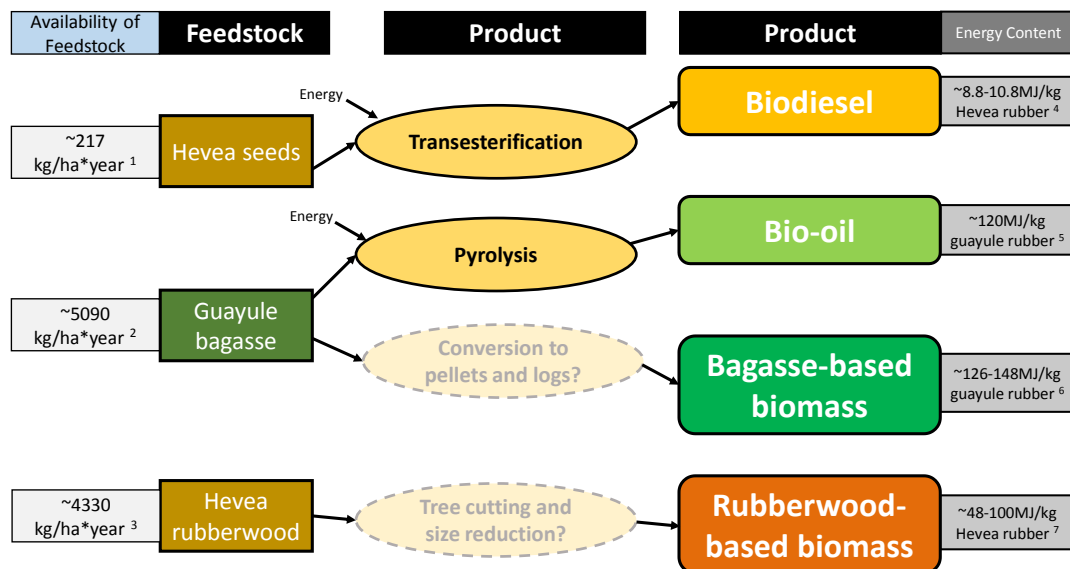


Figure 32. Feedstock, Processing and Final Product of Energy-rich Hevea and Guayule Co-products. The processing required to make bagasse-based and rubberwood-based biomass was not available, therefore the energy for the processing was not included in the LCA.

¹ (Morshed, Ferdous et al. 2011); ² Calculations; ³ (Balsiger 2000); ⁴⁻⁷ Calculations

Co-product Modeling

The energy off-set analysis for this LCA is analyzed as an additional scenario to collect preliminary results for future work. The energy inputs for the processes of pyrolysis and transesterification were estimated from values found in literature. The processing of bagasse and rubberwood feedstocks into practical sources of energy was unknown, and not included in the LCA. This might include energy to convert bagasse into pellets, and energy to cut down rubber trees and size reduce to logs.

A study performed by Fan, Kalnes et al. (2011) was referenced to estimate the energy requirements to produce 1 MJ-worth of bio-oil through pyrolysis. Only the process energy was used in order to keep the process modelling consistent with biodiesel modeling. Figure 33 shows the exact values used from the (Fan, Kalnes et al. 2011) study. For this LCA study, we will assume that the listed electricity and natural gas inputs are needed to produce 1 MJ of bio-oil, which can be recovered from approximately 0.033kg of guayule bio-oil (this is assuming that the energy value of guayule bio-oil is 30MJ/kg (Boateng, Mullen et al. 2009)).

Inventory inputs of pyrolysis oil production from woody biomass feedstock.

<i>Products</i>		
Pyrolysis Bio-oil	1	MJ
<i>Materials</i>		
Poplar (dry basis)	0.08	kg
Sand, at mine/CH S	0	kg
Water, completely softened, at plant/RER S	7.2	kg
<i>Processes</i>		
Electricity, medium voltage, US (PyOil Production)	0.01	kWh
Electricity, medium voltage, US (wood pretreat)	0.01	kWh
Transport, lorry 16t/RER S (poplar transport)	0	tkm
Natural gas, burned in industrial furnace low-NOx >100kW/RER S	4.5×10^{-5}	MJ
PyOil Char Combustion Emission	1	MJ

Figure 33. Inventory Inputs of Pyrolysis Oil Production from Woody Biomass Feedstock. From Fan, Kalnes et al. (2011).

For the biodiesel production modeling, a study by Pleanjai and Gheewala (2009) on palm oil biodiesel was used as a reference to estimate energy requirements for biodiesel production. In their study, the electricity required to refine the palm oil and produce the biodiesel was equal to 0.31MJ for 1kg of palm methyl ester (see Figure 34). For this LCA, we will assume that 0.31MJ is required to produce 1 kg of Hevea seed biodiesel.

Table 12. Natural Rubber Co-product Energy Content.

Data Collection from Literature			Energy Value Modelling							
Co-product	Energy Content range		Production of feedstock for energy production		Oil Yield	Potential energy value range		Per kg of rubber		References
GUAYULE										
Bagasse feedstock (after latex extraction, with any remaining resin in the woody and bark fractions of the stem)	20490-24177	kJ/kg	7274.33	kg/ha*yr	-	149051-175872	MJ/ha*yr	126.0-148.6	MJ/kg guayule rubber	Boateng 2009, Nakayama 2005
Bio-oil after bagasse pyrolysis (smaller value for the whole shrub, larger value for the bagasse)	30428-30508	kJ/kg	7274.33	kg/ha*yr	64%	141881-142254	MJ/ha*yr	119.9-120.2	MJ/kg guayule rubber	Boateng 2009
HEVEA										
Seed oil	32600-39700	kJ/kg	217	kg/ha*yr	40%-60%	7074-8615	MJ/ha*yr	8.8-10.8	MJ/kg Hevea rubber	Ahmad 2014, Gim bun 2013, Morshed 2011, Ramadhas 2005a
Rubberwood	17.9	MJ/kg	4333.33	kg/ha*yr	-	38783-77567	MJ/ha*yr	48.5-97.0	MJ/kg Hevea rubber	Krukanont 2004, Balsiger 2000

Energy inputs and energy outputs in PME system.

Life cycle biodiesel production	Per ton PME	MJ/kg PME
Input		
<i>Oil palm plantation</i>		
N-fertilizer (kg)	54.01	3.10
P ₂ O ₅ -fertilizer (kg)	0.35	0.0024
K ₂ O-fertilizer (kg)	99.90	0.68
Glyphosate (kg)	1.94	0.52
Paraquat (kg)	0.69	0.18
Seed (kg)	67.77	0.07
Diesel used (for transport FFB) (kg)	69.16	2.89
(a) Sub-total		7.45
<i>Crude palm oil extraction</i>		
Electricity (MJ)	22.58	0.02
Diesel used (for starting turbine) (kg)	5.25	0.22
(b) Sub-total		0.24
<i>Palm oil refining</i>		
Electricity (MJ)	12.20	0.01
Diesel used (for transport RPO) (kg)	49.16	2.06
(c) Sub-total		2.07
<i>Biodiesel production</i>		
MeOH (kg)	180.00	5.45
NaOH (100%) (kg)	10.00	0.18
Electricity (MJ)	297.00	0.30
Diesel used (for transport PME) (kg)	1.23	0.05
(d) Sub-total		5.98
Total (a + b + c + d)		15.75
Output		
Palm methyl ester (PME) (kg)	1000.00	38.07
Glycerol (kg)	180.00	3.42
Palm kernel (kg)	374.38	6.36
Shell (kg)	457.58	8.45
Total		56.30

Figure 34. Energy Inputs and Energy Outputs in Palm Methyl Ester (PME) System. From Pleanjai and Gheewala (2009).

The guayule bio-oil, which is made by pyrolysis of bagasse, shows to have an energy content of ~30MJ/kg (Boateng, Mullen et al. 2009). With the inclusion of the recovered bio-oil in the condensers and the system piping, the overall bio-oil yield is estimated at 64.1% for guayule bagasse (Boateng, Mullen et al. 2009).

It has been found that the productivity of rubber seed oil per hectare per year is 217kg/ha (Ramadhas, Jayaraj et al. 2005a, Morshed, Ferdous et al. 2011) and the oil content in the rubber seed is approximately 40-60 wt.% (Ramadhas, Jayaraj et al. 2005b, Melvin Jose, Edwin Raj et al. 2011).

Qualities considered for the analysis include energy content, feedstock yields, temporal availability for harvesting, oil content, wood density and natural rubber yield.

Results

Guayule bio-oil vs Hevea biodiesel

The impacts from processing guayule bagasse into 1MJ of bio-oil and Hevea seed into 1 MJ of biodiesel are not significantly different.

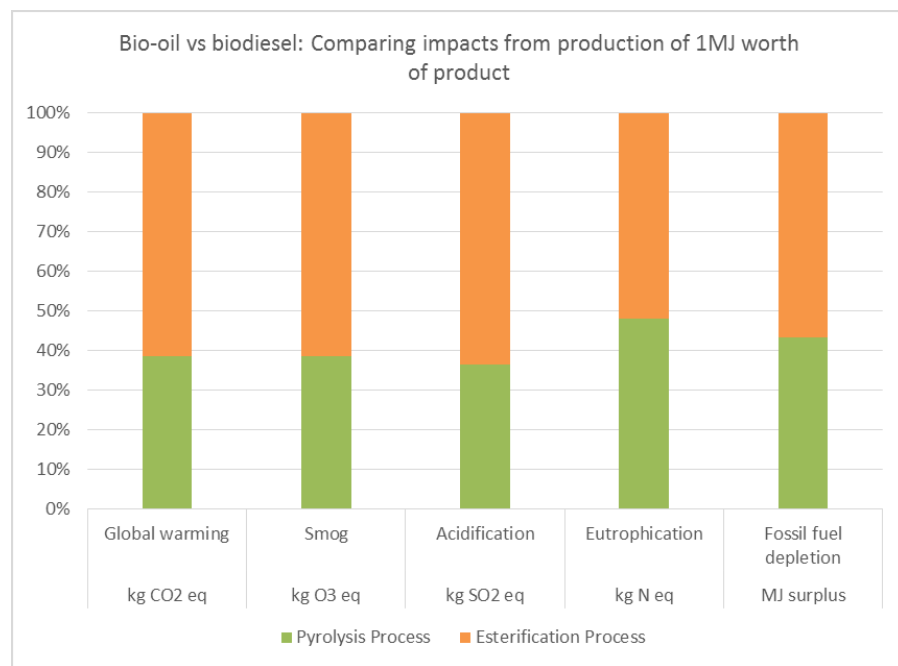


Figure 35. Bio-oil Vs Biodiesel: Comparing Impacts from the Production of 1MJ Worth of Product.

It is assumed that guayule bagasse is available for use when the rubber is harvested, i.e. every 2 years. A major advantage of guayule bagasse is that it is a high-mass co-product of the rubber extraction process, and approximately 90% of the biomass is leftover bagasse (Nakayama 2005). The rubber seed oil availability is reported as an annual value.

Guayule bagasse vs Hevea rubberwood

For this co-product-to-energy analysis, there was no energy or inputs assigned to the processing of guayule bagasse biomass or rubberwood. For guayule, it may be necessary to compress the bagasse to use as energy. For Hevea, the trees must be cut and reduced in size. The energy and material inputs for these processes are unknown.

One of the key reasons Hevea rubberwood is associated with less off-sets compared to guayule bagasse is due to the less frequent harvesting ability. Although Hevea rubberwood has approximately 4 times more feedstock available per ha with a similar energy content (see Table 6), it can only be utilized every 23-35 years when trees are replanted (Balsiger 2000). This significantly reduces the available energy when focusing on the production of natural rubber. Guayule bagasse can be harvested every 2 years and the feedstock availability as leftover materials is extremely high.

APPENDIX G

IMPACT CATEGORIES

This LCA was modelled using TRACI 2.1. (v1.01) (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) , which is a midpoint oriented LCIA methodology developed by the U.S. Environmental Protection Agency specifically for the U.S. using input parameters consistent with US locations.

Acidification

Acidification represents the increasing concentration of hydrogen ions (H^+) within an environment. It can be caused by the addition of acids into the environment, the addition of substances which increase the acidity of the environment, or by natural circumstances (Bare 2012). TRACI makes use of the results of an empirically calibrated atmospheric chemistry model to estimate total North American terrestrial deposition (wet, dry and cloud) as a function of the emissions location. Acidification is expressed in H^+ mole equivalent deposition per kilogram of emission (Bare 2003).

Eutrophication

Surface waters are affected by eutrophication with the addition of a previously scarce (limiting) nutrient which leads to an increase of aquatic photosynthetic plant life. The most common cause of eutrophication in the U.S. is related to excessive inputs of phosphorus and nitrogen. The characterization factors estimate the eutrophication potential of a release of chemicals to air or water relative to 1 kg N discharged directly to surface freshwater (Bare 2003).

Global Warming/Global Climate Change

Also called global warming potential, this impact category refers to the potential change in the earth's climate caused by the buildup of chemicals (greenhouse gases, such as CO_2 , CH_4 and N_2O) that trap heat inside the earth's atmosphere. TRACI uses global warming potentials, a midpoint metric proposed by the International Panel on Climate Change (IPCC). This calculates the potency of GHGs relative to CO_2 . TRACI incorporates a 100-year time horizon recommended by the IPCC (Bare 2003, Bare 2011).

Photochemical Smog Formation

Chemical reactions that occur between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in sunlight create ground level ozone. Ozone can cause human health effects through respiratory issues, and ecological impacts through damage to various ecosystems and crop damage. The primary sources of ozone precursors are vehicles, electric power utilities and industrial facilities (Bare 2012). Various options exist for smog modeling, one of which is the Maximum Incremental Reactivity (MIR) values, developed by Carter (Carter 1994). Some of this work was conducted specifically for TRACI. MIRs have been developed specifically for the US, they contain comprehensive human and environmental impacts, comprehensive substance coverage, and is the method used by environmental programs, including cap and trade programs (Bare 2012). The MIRs are updated to include the latest studies, more chemicals were added and the total number of pollutants now quantified in this category is nearly 1,200 substances (Bare 2011).

Resource Depletion

The quantification of resource depletion is the most controversial due to a lack of legislation or international agreements. A non site-specific recommendation for fossil fuel use characterization is included in TRACI 2.1, which will be updated over the next few years (Bare 2012). TRACI incorporates an existing technique from EcoIndicator '99 to measure fossil fuel depletion. This method takes into account that the continued extraction and production of fossil fuels tends to consume the most economically recovered reserves first, so that continued extraction will become more energy intensive in the future.