Exploring the Coolest Path to Heat Retention

the Environmental Impacts of Material Substitution in the Wetsuit Industry

Rick Buijk

Exploring the Coolest Path to Heat Retention

the Environmental Impacts of Material Substitution in the Wetsuit Industry

by

Rick Buijk

in partial fulfilment of the requirements for the degree
of Master of Science in Industrial Ecology
at Leiden University and Delft University of Technology
to be defended publicly on 15 July at 10:00

First supervisor:	Dr. Mingming. Hu	CML	Leiden University
Second supervisor:	Dr.ir. S.T. Abrahami	3ME	Delft University of Technology

Duration: September 2023-July 2024

Preface

I would like to express my sincere gratitude to my supervisors, Mingming and Shoshan, for their patience, guidance, and advice throughout this research project. Their support for a topic so dear to me has been essential to the completion of this study. This research has provided me with a comprehensive understanding of wetsuits, a subject about which I am passionate. The intricacies of production systems have always fascinated me, and this industry is no exception.

Abstract

Wetsuits have been made from polychloroprene rubber (PCR) since they were invented in 1951. PCR is produced from the intermediate chemicals butadiene (oil, PCR-B) and acetylene (limestone, PCR-A). The production process of PCR is resource and energy-intensive, and requires large chemical production facilities, which directly and indirectly emit greenhouse gas emissions and process hazardous substances. Since 2016, a natural rubber (NR) alternative, harvested from the Hevea brasilensis was introduced to the wetsuit industry, aiming to reduce the environmental impacts associated of wetsuit production. Current literature and information regarding the environmental performance of rubber alternatives lacks comprehensive quantitative analyses, complicating comparison of alternatives. Additionally, the implications of substitution PCR with NR have not been documented yet.

The goal of this research is to improve the assessment of the environmental performance of NR in comparison to PCR-A and PCR-B through a comparative cradle-to-gate LCA study, encompassing raw material extraction and rubber production. Environmental impacts are quantified using the European Union Environmental Footprint assessment method. The study seeks to inform the development of more sustainable wetsuit production and explore the environmental and industrial implications of substituting PCR with NR regarding biogenic emissions, land use, and rubber supply. The functional unit defined for this study is 1000 kilograms of rubber suitable for wetsuit production.

The research findings reveal that NR generally exhibits lower environmental impacts compared to PCR-A and PCR-B across a comprehensive range of impact categories. NR demonstrates the lowest impact in almost all categories, except for land use, where it shows a higher impact. PCR-A shows the highest environmental impacts due to significant energy and resource consumption, while PCR-B performs slightly better than PCR-A in most categories. Adjustments in gas use and biogenic emissions from agricultural practices increased the environmental impacts of NR but did not significantly alter its comparative advantage over PCR alternatives.

Substituting PCR with NR in wetsuit production suggests no significant environmental implications regarding biogenic emissions, provided the NR supply comes from FSC-certified plantations, avoiding tropical forest conversion. Converting forests would lead to considerable biogenic emissions, though still lower than those from PCR alternatives. Industrial implications regarding land use and rubber supply at scale become significant in the worst-case scenario, where the lowest yield (1,600 kg/ha/year) necessitates 54% of Thailand's domestic NR supply (2018) to meet industry demand. Conversely, with the highest yield (5,640 kg/ha/year), this requirement drops to 16% of the national supply. Globally, the lowest yield scenario requires 5% of FSC-certified plantations to meet annual demand. FSC-certified plantations have also likely increased since 2018 due to promotion efforts.

This LCA study has several limitations that need to be taken into consideration when interpreting the results. The cradle-to-gate approach excludes the use and EOL phases, this may result in some impacts being overlooked. The lack of allocation in multifunctional processes for the PCR-A system potentially lead to overestimated environmental impacts. Additionally, the exploration of possible complications related to industry wide substitution is based on limited data points. It also does not consider economic or industry dynamics, which calls for careful interpretation of the results. The study's generalized representation of NR processing may underestimate its environmental burden, especially data related to wastewater treatment.

Future research should aim to address these limitations by including the use and EOL phases, providing more detailed data on waste streams and additives in rubber production, and exploring recycling and by-product allocations to achieve a more comprehensive understanding of the environmental impacts of wetsuit production.

Contents

Preface i

Abstract iii

Contents iv

List of abbreviations vi

List of figures vii

List of tables viii

1. Introduction 1
   - 1.1 Wetsuits and the industry 1
   - 1.2 Environmental impacts of PCR and NR wetsuits 4
   - 1.3 Goal of the study 6
2. Method 7
   - 2.1 Approach 7
   - 2.2 LCA framework 8
   - 2.3 Modelling choices 8
3. Goal and scope definition 9
   - 3.1 Goal definition 9
   - 3.2 Scope definition 9
   - 3.3 Functional unit 10
4. Inventory analysis 11
   - 4.1 Defining system boundaries 11
     - 4.1.1 Economy-evironment system boundary 11
     - 4.1.2 Cut-offs 11
     - 4.1.3 Multifunctionality and allocation 11
   - 4.2 Product systems 13
     - 4.2.1 Natural rubber (NR) 13
     - 4.2.2 Polychloroprene – Acetylene (PCR-A) 15
     - 4.2.3 Polychloroprene – Butadiene (PCR-B) 18
     - 4.2.4 Polymerization 21
   - 4.3 Life Cycle Inventory 21
   - 4.4 Inventory results 21
5. Impact assessment 22
   - 5.1 Characterisation method 22
   - 5.2 Missing characterization factors 22
   - 5.3 Characterisation results 22
6. Interpretation 24
   - 6.1 Consistency check 24

6.1.1 Methods 24
6.1.2 Models 24
6.1.3 Data 24
6.1.4 Assumptions 25
6.1.5 Comparison to other studies 25
6.2 Contribution analysis 27
6.2.1 Natural rubber (NR) 27
6.2.2 Polychloroprene – Acetylene (PCR-A) 28
6.2.3 Polychloroprene – Butadiene (PCR-B) 29
6.3 Sensitivity analysis 30
6.3.1 Characterization method 30
6.3.2 Land use 31
6.3.3 Gas use 33
6.3.4 Biogenic emissions 35
6.3.5 Concentrated latex production 37
6.4 Conclusion 39
7. Discussion 40
7.1 Limitations 40
7.1.1 Data assumptions / estimates 41
7.1.2 Data gaps 41
7.1.3 Recycling / by-products 41
7.2 Recommendations for future research 41
8. Conclusion 42
References 43
A. Supplier overview 48
B. Natural rubber data collection 50
C. Polychloroprene Acetylene data collection 51
D. Stoichiometry Acetylene 53
E. Polychloroprene Butadiene data collection 54
F. Stoichiometry Butadiene 55
G. Polymerization data collection 57

List of abbreviations

EF	Environmental Footprint
EOL	end of life
EPA	Environmental Protection Agency
EU	European Union
FSC	The Forest Stewardship Council
GHG	greenhouse gas
H2O	water
HCl	hydrogen chloride
IPCC	Intergovernmental Panel on Climate Change
ISO	the International Organization for Standardization
LCA	Life Cycle Assessment
LPG	liquified petroleum gas
MSc	Master of Science
NaCl	sodium chloride
NPP	Net Primary Production
NR	natural rubber
NRL	Natural rubber latex
OEM	Original Equipment Manufacturer
PCR	polychloroprene
PCR-A	polychloroprene from acetylene
PCR-B	polychloroprene from butadiene
PEFC	Programme for the Endorsement of Forest Certification
phr	per hundred to rubber
RAOT	Rubber Authority of Thailand
RRAF	Rubber Replanting Aid Func
SBR	styrene butadiene rubber
SIMA	Surf Industry Manufacturers Association
STR	block rubber
TPE	thermoplastic elastomer foam
US	United States
VOC	Volatile Organic Compounds

List of figures

Figure 1.1: Visual representation of the production process of laminated expanded foam 2
Figure 2.1: Life cycle assessment framework (Guinée, 2001) 8
Figure 4.1: Schematic diagram of production of primary and final rubber products (Jawjit et al., 2010)................13
Figure 4.2: Schematic diagram of the thorough treatment process (Martin & Mithcell, 2022) 14
Figure 4.3: Flow diagram of the NR product system and the EcoInvent background processes..............................14
Figure 4.4: Acetylene production based on description by Weissermel and Arpe (2003) and Schobert (2014) 15
Figure 4.5: Chemical steps to CR synthesis (Lynch, 2001), conversion rates (Weissermel & Arpe, 2003)................16
Figure 4.6: Flow diagram of the PRC-A product system and the EcoInvent background processes 17
Figure 4.7: Typical olefin plant producing ethylene and co-products (White, 2007)..18
Figure 4.8: Typical extractive distillation butadiene recovery process (White, 2007)...19
Figure 4.9: Chemical steps to CR synthesis (Lynch, 2001), conversion rates (Weissermel & Arpe, 2003)................19
Figure 4.10: Flow diagram of the PCR-B product system and the EcoInvent background processes 20
Figure 5.1: Normalized characterization results of NR, PCR-A, PCR-B to the highest value per impact category....23
Figure 6.1: Contribution analysis of NR characterization results 27
Figure 6.2: Contribution analysis of PCR-A characterization results..28
Figure 6.3: Contribution analysis of PCR-B characterization results 29
Figure 6.4: Normalized results for the sensitivity analysis of land use flows...31
Figure 6.5: Normalized results for the sensitivity analysis for yield of fresh latex per hectare per year 32
Figure 6.6: Normalized results sensitivity analysis LPG combustion..34
Figure 6.7: Normalized characterisation results sensitivity analysis forest conversion (FC).....................................36
Figure 6.8: Normalized characterisation results sensitivity analysis fresh latex block rubber (FLBR) 38
Figure A.1: Geographic distribution of key wetsuit production stages across Asia and rest of world 48
Figure C.1: Power grid structure Japan, 2020 EcoInvent (2020) and China, 2019, Huo et al. (2022).......................51
Figure C.2: Process overview and byproducts Denka, Japan (Denka, 2022) 52

List of tables

Table 1.1: Compound formulation with various ingredients for most rubber products (Chandrasekaran, 2007) 3
Table 1.2: Metric tonne CO_2 eq. for rubber alternatives and chemical intermediate (YULEX, 2023a) 5
Table 4.1: PCR-A producers and annual capacities in metric tonnes 17
Table 4.2: Butadiene content of different feedstocks (Weissermel & Arpe, 2003) 18
Table 4.3: PCR-B producers and annual capacities in metric tonnes 20
Table 5.1: Characterization results of NR, PCR-A, and PCR-B 22
Table 6.1: Characterization results of comparable studies for 1 kg of latex to solid NR 25
Table 6.2: CO_2 Eq. of NR, PCR-B, and chemical intermediate acetylene 26
Table 6.3: Characterization results for sensitivity analysis impact assessment method 30
Table 6.4: Land use related elementary flows, characterization results, and descriptions 31
Table 6.5: Percentage of total FSC certified supply to meet NR demand considering two scenarios 32
Table 6.6: Characterization results of sensitivity analysis LPG combustion 33
Table 6.7: Biogenic C and N_2O emissions (Jawjit et al., 2010) 35
Table 6.8: Characterization results sensitivity analysis forest conversion (FC) 35
Table 6.9: Characterization results sensitivity analysis fresh latex block rubber (FLBR) 37
Table A.1: Overview of manufacturers in the wetsuit supply chain 49

1. Introduction

This chapter begins by providing context for the main topic of this research in Section 1.1. It shortly introduces what a wetsuit is, its uses, and describes the industry and production process relevant to this study more in depth. Section 1.2 delves into the environmental impacts associated with wetsuit production. In Section 1.3, the goal of this research is articulated, along with the main research question and the sub-questions that guide the investigation.

1.1 Wetsuits and the industry

A wetsuit is a technical garment made to protect the person wearing it from hypothermia while being submerged in, or in close contact with water. Water is 25 times more conductive than still air making it a very efficient heat absorber. The movement of water causes a rapid convection of heat away from the body. A wetsuit improves the wearers thermoregulating capabilities by creating two layers of insulation, a layer of composite fabric, and a layer of trapped water resulting from a small amount entering the suit (Naebe et al., 2013).

Wetsuits are produced for various sports and professions, thereby dictating certain design choices. Wetsuits used for diving require less flexibility but often have thicker materials as effectiveness of the suit decreases under deep water conditions (Naebe et al., 2013). When wetsuits are for more dynamic activities such as sailing, surfing, and kayaking, flexibility and freedom of movement are as important as insulating performance. In swimming, wetsuits are often not solely used for warmth retention but also for increased buoyancy and reduced drag that result from wearing a suit. Material thicknesses generally range from 2mm to 7mm balancing insulation and movement restriction for each specific purpose.

Literature on the history of the wetsuit mentions 1951 as its year of invention when a UC Berkeley physicist, named Hugh Bradner, came up with its design, which was originally intended for the American navy. After it became clear that the navy would not be able to develop the product fast enough, its design was declassified (Rainey, 1998). Almost immediately after its declassification, wetsuits were brought to the consumer market. The brands O'Neill and Body Glove from the United States (US) were at the forefront of developing suits for the masses that would use them for diving and surfing in cold water. By 1965, wetsuits had become the bestselling surfing commodity. The wetsuit industry gradually spread around the globe in the years that followed. By 1980, Japan had developed a better performing fabric and started exporting it to wetsuit producing companies in the United States and Australia (Warshaw, 2010).

In 2023, the global value of the industry was estimated to be US$ 1,84 billion with a projected doubling in 2030 to US$ 3,64 billion, largely driven by the globally increased popularity of outdoor recreation and sports (Fact.MR, 2023). Exact numbers of global wetsuit production are not available through scientific literature. However, the market leader of wetsuit production, an Original Equipment Manufacturer (OEM) supplying to various brands, claims to hold 65% of the high-performance market. This company exported 4,5 million wetsuits in 2014 (Forbes, 2014) and currently has the capacity to produce 6 million wetsuits annually (SHEICO Group, n.d.). In 2022, it generated US$ 470 million in revenue (Chung, 2022). Considering the market share and production capacity of the largest manufacturer, an estimated 9.2 million wetsuits are produced annually.

Wetsuits are manufactured by cutting out patterns out of large sheets of laminated fabric. These patterns are assembled through a combination of techniques, such as stitching, glueing, and taping. The majority of the wetsuit consists of laminated fabric, with expanded foam being the primary material. This laminated fabric is a composite, comprising one or two layers of lining glued onto the expanded foam core of which a cross sectional view is shown The foam core provides the wetsuit's insulating properties. Figure 1.1 provides an overview of the production process of laminated fabric and its key ingredients. The first production step, 'compounding', is a kneading process requiring 50-80% rubber input by weight (Chandrasekaran, 2007).

Since the invention of the wetsuit, the industry has predominantly used polychloroprene (PCR), a synthetic rubber, as the primary input. PCR continues to be widely utilized today. Two types of PCR are distinguished: polychloroprene from acetylene (PCR-A), more commonly referred to as 'limestone neoprene', and polychloroprene from butadiene (PCR-B). Both PCR rubber types are chemically equivalent and made from the chloroprene (CR) monomer (Lynch, 2001). According to estimates, by 2026, 17.5% (58.1 metric tonnes) of the projected global CR market of 324.8 metric tonnes will be used for textiles (Global Industry Analysts, 2022). Commonly known as Neoprene, PCR was developed by Du Pont in 1931 and is chemically classified as 2-chloro-1,3-butadiene (Smith, 1985). Neoprene is often referred to as the laminated fabric within the industry and among users, but it only represents the base rubber used in the compounding process of making the insulative foam.

In 2013, solid natural rubber (NR) was developed as a 'drop-in' technology for wetsuit production, implying it can be used in current manufacturing procedures, through a partnership between a wetsuit brand and a corporation working on sustainable materials. After development, the technology was made available for the industry to adopt. The first wetsuit made using NR was harvested from Guayule, a shrub. In 2014, this innovation was awarded the Environmental Product of the Year and Wetsuit of the Year by the Surf Industry Manufacturers Association (SIMA), a trade association representing the collective interests of the industry. By 2017, Guayule rubber was replaced by rubber from *Hevea brasiliensis*, a species of rubber tree (YULEX, 2023a). Although the industry has gradually adopted this alternative, the majority of wetsuits are still made using PCR. No quantitative data about adoption of NR in the industry is available, but this is inferred from the product portfolios of numerous wetsuit brands.

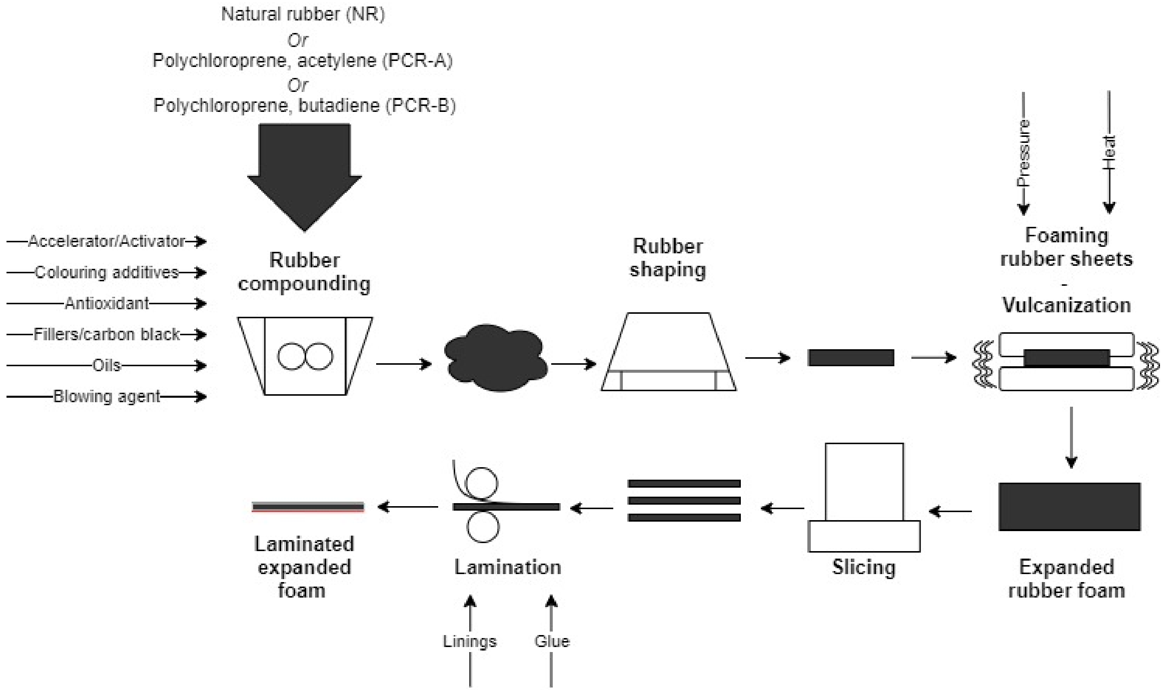
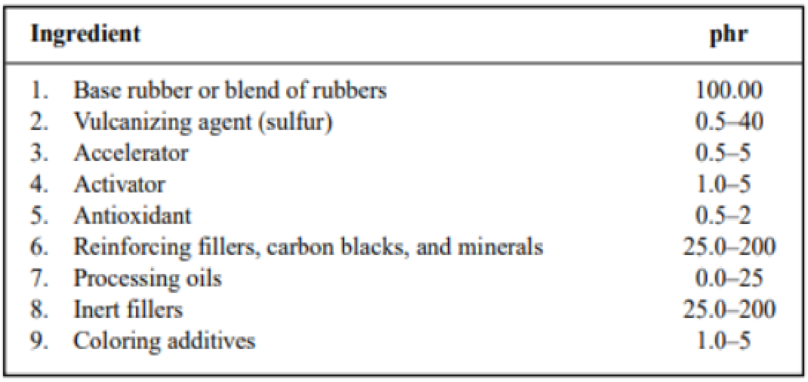


Figure 1.1: Visual representation of the production process of laminated expanded foam

Rubber, whether synthetic or natural, cannot be used in wetsuits without additional ingredients. These ingredients are added in the compounding process for specific contributions to the subsequent processes or the physical properties of the final product. Accelerators are chemicals added to reduce the time required for vulcanization, they also improve uniformity and physical properties. Activators improve filler incorporation and can affect physical properties such as tensile and tear strength. Antioxidants are added to prevent oxidation, because this reaction degrades the products properties and performance. Fillers can have a profound effect on physical properties such as tensile strength, abrasion an tear resistance, these are called reinforcing fillers. Carbon black -15-20% by weight- is one filler used in wetsuit production (Patagonia, 2024b). Inert fillers do not contribute directly to physical properties, but provide useful functions such as chemical and heat resistance, and ease of processing. Most importantly, fillers are used to reduce the costs of the compound. Oils are primarily added to aid in processing operations such as mixing but also affect physical properties. Blowing agents form open or closed cells, during the vulcanization process, creating small bubbles when the blowing agent decomposes at a specific temperature (Chandrasekaran, 2007; YULEX, 2023c).

Ingredients are added at exact proportions, typically parts per hundred to rubber (phr)-, according to the compound formulation. An exemplary compounding formulation representable for most rubber products is shown in Table 1.1: Compound formulation with various ingredients for most rubber products (Chandrasekaran, 2007). The rubber, or base polymer as it is also referred to, can be a single type of rubber or a blend.

Table 1.1: Compound formulation with various ingredients for most rubber products (Chandrasekaran, 2007)



Ingredient	phr
1. Base rubber or blend of rubbers	100.00
2. Vulcanizing agent (sulfur)	0.5–40
3. Accelerator	0.5–5
4. Activator	1.0–5
5. Antioxidant	0.5–2
6. Reinforcing fillers, carbon blacks, and minerals	25.0–200
7. Processing oils	0.0–25
8. Inert fillers	25.0–200
9. Coloring additives	1.0–5

For expanded foam products using PCR, a combination with styrene butadiene rubber (SBR) is sometimes made (Nam Liong, 2024b), but this is considered to be a lower quality foam (SRFACE, 2024c). The majority of offered expanded foam sheets, especially those used in the higher end wetsuit market, are not using blends but use 100% PCR-A, or PCR-B. In the case of expanded foam sheets made of NR, a blend of 85% NR and 15% of synthetic rubber is commonly used (Finisterre, 2024; Patagonia, 2024a). The addition of synthetic rubber improves the ozone resistance of the foam. Efforts are made to eliminate the use of synthetic rubber, already improving from 60% to 85% NR content within the last decade (Temperley, 2023). Very recently, Decathlon, a large sporting goods brand and manufacturer, launched YULEX100 products which offer 100% natural rubber in several of their products in their wetsuit portfolio, accounting for 34% of their wetsuit sales. Future expansions and continued development are planned to phase out synthetic rubber use (Decathlon, 2024).

1.2 Environmental impacts of PCR and NR wetsuits

The wetsuit production comprises three stages: first, rubber production, which represents production operations of PCR-A, PCR-B and NR. Secondly, expanded foam production and thirdly, wetsuit production, representing large scale cutting and assembly facilities. More in depth information on manufactures can be found in appendix A. Within the wetsuit industry, the rubber production stage causes most environmental concern (Copeland, 2008) [1]. The industry producing CR is resource and energy-intensive, and requires large production facilities, which directly and indirectly emit greenhouse gas (GHG) emissions (Teske, 2022). These GHG emissions contribute to global warming. Thus far, resulting in a surface temperature reaching 1,1°C above 1850-1900 in 2011-2020. Consequently, leading to widespread adverse effects and related losses and damages to nature and people. It is expected that global GHG emissions continue to increase with contributions from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between countries, and among individuals (IPCC, 2023).

Also, within the European Union (EU), CR is classified as a 'recognised' carcinogenic, meaning that the concern is indicated in an official source, which is the highest level of concern (ECHA, 2023). In the United States (US), CR is classified as reasonably anticipated to be a human carcinogen based on evidence of carcinogenicity from studies in experimental animals (National Toxicology Program, 2021). PCR in final products poses no health risks, manufacturing CR does, however, pose risks for the environment. Recently the Environmental Protection Agency (EPA) filed a complaint against the only US producer of CR, alleging health endangerment caused by the factories carcinogenic air pollution (EPA, 2023). This was followed by setting stronger standards for harmful soot pollution in an effort to better protect populations living close to the industrial site (EPA, 2024). These developments also sparked an ongoing debate among the wetsuit industry, consumers, and activists on whether PCR used for wetsuits is indirectly affecting the people's health (The Big Sea, 2024). According to the executive director of SIMA, PCR produced in the US is not used by brands represented in their trade organisation (Wavelength Surf Magazine, 2023). However, even if PCR produced in the US is not used by the industry, the negative aspects of using PCR do manifest in its dependency on the chemical industry, high energy and resource use, and elevated health risks in processing CR.

Due to the poor environmental performance related to PCR, the wetsuit industry is starting adopt NR. Several studies have been carried out to assess the performance characteristics of non-synthetic rubber alternatives to provide insights into potential substitution options with reduced environmental impact. First, there is a MSc thesis investigating the thermal and mechanical properties of a novel natural rubber based composite, showing higher thermal conductivity and less stretch, mostly due to its novel design, concluding that a different natural rubber latex could potentially improve this (Holmström & Mattsson, 2019). In addition to this work, a conference paper by Navodya et al. (2020) was found in which locally produced natural rubber foam and synthetic rubber are compared on thermal, mechanical, and sustainability aspects. The outcomes showed improved thermal conductivity and compromised stretch. However, the robustness of this comparison is questionable due to a difference in sample thickness. Another MSc thesis sampled and modelled the thermal properties of both NR (15% polymer content), and PCR (Busvold, 2023). The studies mentioned all refer to a blogpost by a wetsuit producer about the environmental performance of PCR when indicating the environmental superiority of NR in relation to PCR. This source however, contains no quantitative data providing insight into the amount of superiority or the difference between PCR made from butadiene or acetylene other than reasoned assumptions (Park, 2020).

---

[1] Copeland (2008) discusses the trade-offs and equally poor environmental performance of both petroleum-based (PCR-B) and limestone-based (PCR-A) PCR. Copeland (2008) highlights the environmental consequences of mining and the energy required to convert limestone to PCR-A. Based on this contextual assumption, he concludes that opting for the latter reduces dependency on oil and oil-derived chemicals. However, this assumption is contradicted by various brands and producers, who widely claim that PCR-A is less harmful to the environment compared to its butadiene-derived counterpart PCR-B (Bryja, 2023; Circle One, 2024; Jobe Sports, 2019; YAMAMOTO, n.d.). Yet, none of these sources provide quantitative evidence to support their claims.

A more thorough analysis is performed by YULEX, (2023a), a natural rubber producer. They estimate that NR production contributes 80% less CO_2 equivalent (eq.) compared to PCR-B from butadiene and the chemical intermediate acetylene needed for PCR-A, as shown in Table 1.2. This analysis was performed by using scientific and industry reported data, stating their efforts are best estimates and further filling on data gaps is needed. Considering this, YULEX (2023a) does exclude the final conversion from acetylene to PCR and indirectly assumes that 1 metric tonne of butadiene and acetylene produce 1 metric tonne of PCR. Spies (2016), representing a developing partner involved in improving NR since 2010, commented that these estimates are conservative. Thus far, the 80% CO_2 eq. reduction claim is widely adopted throughout the industry and often used in external communication. In almost all cases seen, without any additional evidence or reference to the work done by YULEX, (2023a).

Table 1.2: Metric tonne CO_2 eq. for rubber alternatives and chemical intermediate (YULEX, 2023a)

	Natural rubber	Polychloroprene (butadiene)	Acetylene
Metric tonne CO_2 eq. / metric tonne product	0.7	6.49	14.5

Outside the wetsuit research field Soratana et al. (2017) performed a comparative cradle-to-gate life-cycle-analysis (LCA) evaluating the environmental impacts of US produced Guayule, imported NR from the *Hevea brasiliensis,* and SBR. Showing bigger global warming and acidification impacts for Hevea and guayule compared to SBR. These impacts predominantly resulted from the use of liquified petroleum gas (LPG) and irrigation needs respectively. Indicating that synthetic rubber can have a better performance under certain conditions.

The current literature and industry practices reveal significant knowledge gaps regarding the environmental impacts of wetsuit materials. While some data exists on CO_2 eq., comprehensive quantitative analyses covering the full rubber value chain and a broad range of environmental impacts, such as water usage, land use, toxicity, and resource depletion, are lacking. There is also insufficient comparative analysis between NR and PCR, including both PCR-A and PCR-B. Finally, the extent of NR adoption in the industry and the practical implications for manufacturers, consumers, and the environment remain under-documented. Addressing these gaps requires a comprehensive LCA and an exploration of the feasibility of NR adoption, considering the land use impacts, potential impacts on carbon storage, and the capacity and reliability of rubber supply at scale.

1.3 Goal of the study

The goal of this research is to improve the assessment of the environmental performance of NR in comparison to PCR-A and PCR-B through an LCA study. It aims to provide a more holistic view by filling the knowledge gaps in previous efforts and expanding the environmental scope to include more impact categories. Ultimately, the study seeks to inform the development of more sustainable rubber for wetsuit production and explore the environmental and industrial implications of substituting PCR with NR.

How does the environmental performance of natural rubber (NR) compare to that of polychloroprene rubber variants (PCR-A and PCR-B) across a comprehensive range of impact categories, and what are the implications of substituting PCR with NR for wetsuit production regarding land use, biogenic emissions, and rubber supply at scale?

As part of the MSc program Industrial Ecology, this research aims to provide insights into the use of natural resources and the environmental impacts of industrial and economic activities. By methodologically identifying key problem areas and proposing impact reduction strategies, it helps to promote sustainable future development of the industry. The findings of this research are relevant to stakeholders in the wetsuit industry, including manufacturers, brands, retailers, and consumers. However, the insights are not limited to the wetsuit industry; they are applicable to anyone looking to improve the sustainability of rubber-dominated products. Additionally, this research is relevant for those involved in synthetic rubber production itself.

Two sub-research questions are formulated, together they cover the information required to answer the main research question:

1) What are the environmental impacts of natural rubber (NR) compared to polychloroprene rubber variants (PCR-A and PCR-B) across a comprehensive range of impact categories?
2) What are the environmental and industrial implications and uncertainties, of substituting polychloroprene rubber (PCR) with natural rubber (NR) in wetsuit production with regards to land use, biogenic emissions and rubber supply at scale?

This report continues with an introduction of the LCA methodology in Chapter 2. Chapter 3 defines the goal and scope, followed by the inventory analysis in Chapter 4, impact assessment in Chapter 5, and interpretation in Chapter 6. Chapter 7 contains the discussion. Finally, Chapter 8 presents the conclusion.

Hevea brasilenis

2. Method

This chapter elaborates on the methodological approach taken to answer the main research question. First, the LCA methodology and the sub research questions are introduced in Section 2.1. Section 2.2 explains the LCA framework in detail and Section 2.3 describes the modelling choices.

2.1 Approach

This study consists of LCA, taking a cradle-to-gate approach. LCA is a tool to quantify the environmental burden associated with the life cycle stages of a product. This product can represent physical goods as well as services. Cradle-to-gate analysis include limited life cycle stages, covering raw material extraction and production and ignoring the use and EOL phase which would be included in a cradle-to-grave approach. The environmental burden covers all types of impacts upon the environment that are associated with the stages, including resource extraction, (hazardous) emissions, and different types of land use. Common applications for LCA studies include origin analysis of environmental problems, designing new products, and choosing between comparable products (Guinée, 2001). LCA is found to be the best approach for this study because it is the most common method used to quantitively compare environmental performance of different products.

A cradle-to-grave approach does provide for a more thorough analysis compared to a cradle-to-gate approach because the former prevents overseeing certain ‘hidden’ impacts due to ‘problem shifting’, meaning certain burdens might, for example, only become evident after inclusion of disposal or recycling. In this study, this poses less of an issue as the (final) production, use, and EOL are the same across the material alternatives, making rubber production the only distinctive characteristic[2].

Conducting a cradle-to-grave study on wetsuit consumption would give a more holistic understanding of where the impacts occur. But it would also require more data on the lifespan of wetsuits and EOL treatment which has proven to be unfeasible in the given timeframe. Despite this limitation, the cradle-to-gate approach does contributes valuable insights into the resource demands of the chosen alternatives. Also, by transparently reporting on data and modelling choices, it enhances replicability for future studies covering all life cycle stages.

Important limitations of the LCA methodology is the incapability to address localised impacts. Furthermore, LCA only considers environmental aspects of products and does not consider their economic or social characteristics. Also, the impacts are referred to as “potential impacts” because they are not tied to a specific time or place and are related to an arbitrarily defined functional unit (Guinée, 2001). The results of an LCA study can never be solely judged as a simple good and bad, because making decisions on data and impact results is often a subjective process requiring value judgments. All data used and the assumptions or decisions made throughout the study should therefore be reported transparently to allow scrutiny, and to prevent the results to be taken out of context or misinterpreted (Curran, 2014). To test the robustness of the results, sensitivity analyses are performed.

---

[2] From a production perspective, NR is a ‘drop-in’ technology, utilizing existing manufacturing equipment (Temperley, 2023) and PCR from both sources is chemically equivalent (Lynch, 2001). In terms of use and lifespan, no information highlighting significant differences has been found and warranty policies do not distinguish between PCR and NR based suits (SRFACE, 2024b). Similarly, for EOL treatment, not a single operation mentions preference nor exclusivity of one over the other (Innovation Norway, 2023; Patagonia, 2024b; TerraCycle, 2024).

2.2 LCA framework

LCA projects are organised in four phases, an overview of the LCA framework is shown in Figure 2.1. This procedural approach for conducting LCA studies is prescribed in ISO 14041 (Guinée, 2001). The reciprocal arrows emphasize the iterative interaction between the different phases, highlighting LCA's explorative nature.

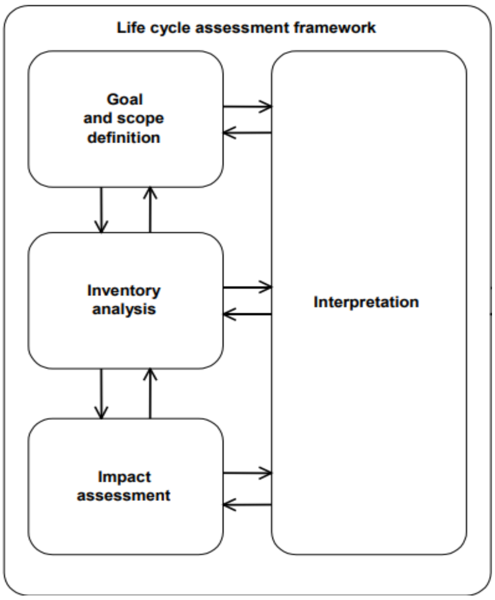


Figure 2.1: Life cycle assessment framework (Guinée, 2001)

The goal and scope phase outlines the initial choices that form the basis of the study. In this phase, the goal describes the aims of the study, the intended application of the outcomes, the reasons for performing the LCA, and the intended audience. The scope is defined by temporal, geographical, and technological coverage, and the level of sophistication of the study. Additionally, the object of the analysis is described in terms of function, functional unit, and reference flows. In the inventory analysis phase, product systems are defined. This includes setting the system boundaries, visualizing the product system through flow diagrams, collecting data for each process within the product system, identify processes that produce multiple products, and completing final calculations. These efforts result in an inventory table that lists all quantified inputs from, and outputs to, the environment associated with the functional unit. In the impact assessment phase, the data from the inventory analysis is examined to understand its environmental and social impacts. This is done by defining impact categories and selecting suitable category indicators that link the inventory data to these categories. This process results in characterization results, representing the actual environmental impacts. Further analysis through normalization, grouping, and weighting can be performed to provide context and prioritize results. The interpretation phase can be summarized as the evaluation phase. Choices and assumptions made in the analysis are assessed in terms of soundness and robustness in relation to the results. Lastly, conclusions are drawn (Guinée, 2001).

2.3 Modelling choices

The software used to calculate the LCA results is the Activity Browser. The Activity Browser is an open-source graphical user interface designed to facilitate LCA. It is built on top of the Brightway2 LCA framework, a Python-based platform that provides tools and libraries for performing LCA. The Activity Browser provides tools for data management, analysis, and visualization. (Steubing et al., 2020). The open-source nature of the Activity Browser ensures transparency in the modelling process, promoting reproducibility.

For the inventory data collection, a combination of scientific literature and industry reports was utilized as secondary data sources. Additional secondary data was obtained from the EcoInvent database, version 3.9.1, using the cut-off by classification method. This classification implies that the full burdens of waste treatment and generation are assigned to the waste-producing activities, while by-products of waste treatment or production processes are considered free of burdens.

3. Goal and scope definition

Section 3.1 introduces the goal of this study. Section 3.2 explains why rubber is considered a major material in wetsuit manufacturing, which processing steps are required and where they occur, and argues why the alternatives allow for a fair comparison. Section 3.3 contains a description of the scope of the LCA. In Section 3.4 the functional unit and the reference flows are defined.

3.1 Goal definition

The goal of this LCA is to quantify the impact of three rubber alternatives commonly used for wetsuit production (NR, PCR-A, and PCR-B), over a broad range of impact categories. Additionally, it aims to explore uncertainties concerning land use, biogenic emissions, and rubber supply, which could affect the substitution of PCR by NR in the wetsuit industry. These efforts aim to inform stakeholders in the industry of a possible trajectory that could lower the environmental impact associated with wetsuit production.

Although this study is comparative, it does not aim to make public assertions. It is solely conducted as part of an MSc thesis at Leiden University and Delft University of Technology. ISO LCA standards prescribe extra procedural and organizational efforts, including critical review processes, when conducting comparative assertions disclosed to the public, which are not feasible for this study. This research is, however, carried out under the supervision of researchers familiar with the method.

3.2 Scope definition

Guinée, (2001) provides a guideline for the most important considerations for the scope definition which have been followed in this section. This includes communicating the temporal, geographical, and technological scope, as well as key model considerations regarding the sophistication of the study. This study is conducted over a period of 9 months starting September 2023 and ending July 2024. This LCA study covers cradle-to-gate, solely including the raw material extraction, and rubber production phase. The study includes a limited number of foreground processes, which are the specific activities directly related to rubber production for which no readily available data existed. Data for these processes was gathered from scientific literature and industry reports. In contrast, most of the study relies on secondary data for background processes, which are the supporting activities, obtained from the EcoInvent database. This reliance on secondary data lowers the overall sophistication of the study.

The geographical scope considered is Asia because of its dominant presence of the industry, therefore best representing reality. The desired age of data for unit processes is not exact as it is largely dependent on availability. Data is, however, only used if it is justifiable as model-modern technology. In any case best available technology is chosen. Transport is excluded to lower the workload and is justified as similar research by Soratana et al. (2017) showed very small contributions to impact categories. Also, the majority of the companies are in relative close distance to one another. The use of infrastructure and manufacturing equipment is excluded from foreground processes, but included in background processes from EcoInvent. The impact assessment method defined by the EU, Environmental Footprint (EF) v3.1, is used.

3.3 Functional unit

The function studied in this LCA is that of providing suitable rubber for wetsuit production. This means the rubber is ready to be used as a compounding ingredient, commonly available, and adoptable within the industry on a large scale. The functional flow is 1000 kilogram of rubber.

Based on information about the production process of expanded foam and insights from industry data and interviews, it is assumed that the three rubber alternatives—NR, PCR-A, and PCR-B—are interchangeable in the production of expanded foam. This implies that they can be processed within the same manufacturing plant. Consequently, the 'gate' is defined as the point where rubber enters the compounding process, excluding further processing steps. Additionally, it is assumed that each alternative can be utilized as pure 100% rubber in production, allowing for an equal comparison.

The alternatives considered which are supposed to meet the requirements and are thus comparable, are Natural rubber (NR), Polychloroprene from acetylene (PCR-A), and Polychloroprene from butadiene (PCR-B).

The reference flows belonging to the alternatives are:

- 1000 kg of NR
- 1000 kg of PCR-A
- 1000 kg of PCR-B

4. Inventory analysis

In Section 4.1, the system boundaries are defined, establishing the limits within which the performance of alternatives is assessed. This includes specifying the processes, inputs, and outputs that are considered in the analysis. Section 4.2 introduces the product systems by describing the processes in detail and visually representing them in flow diagrams. Section 4.3 comments on the life cycle inventory data. Section 4.4 briefly summarizes the procedural decisions regarding life cycle inventory results.

4.1 Defining system boundaries

To clearly communicate which economic activities and inputs and outputs are considered and how these relate to the world surrounding it, a product system is defined. In this section, important modelling choices impacting the product system are discussed and cover the economic system boundary, cut-offs, multifunctionality and solving allocation.

4.1.1 Economy-evironment system boundary

A crucial aspect of performing a LCA is to follow each economic flow until all economic inputs and outputs have been converted into environmental interventions. These interventions are distinguished as inflows to the product system through use of land and resources, and outflows to the environment such as emissions and waste without human transformation. Flows directly interacting with the environment and thereby crossing the boundary of the product system are distinguished as elementary flows.

For the foreground processes modelled in this study, no issues were identified that complicate the distinction of these elementary flows. Worth mentioning is that biogenic emissions from rubber tree agriculture are considered to be in equilibrium. In the background processes, for which the EcoInvent database is used, these distinctions have been addressed using established conventions ensuring clear differentiation of flows.

4.1.2 Cut-offs

Cut-offs are flows that are not considered in the system to simplify the assessment and can apply to any type of flow in the system. The decision to cut-off flows often relates to a lack of data, time, and resources. If faced with these circumstances reasoned estimations are the best option. If there is no basis on which reasonable estimates can be performed, the decision to cut-off flows is considered the only option. These decisions have to be reported clearly, allowing others to interpret the outcomes in the right context.

In the NR product system, it is known that the purification process of NR latex produces waste. The documentation describing this process does, however, not provide any estimates of volume and composition of this flow. It is assumed that the majority of this substance is biodegradable, and its environmental impact is negligible. Water use in the Hevea agriculture process is assumed to be met by precipitation and cut-off.

4.1.3 Multifunctionality and allocation

Industrial processes often produce more than one product. This poses challenges for an LCA as it requires impacts to be distributed over multiple products. To cope with these challenges procedural steps are provided in order of preference.

- Avoid allocation by modelling the multinational process into smaller single function processes
- Avoid allocation by expanding the system boundaries to include the additional functions provided by co-products
- Allocate according to physical causality
    - Energy, mass balance, stoichiometry
- Allocate according to economic value
- Other methods
    - Allocate according to best estimates
    - Allocate economic value to similar products
    - Allocating all flows to the function investigated

It is generally not advisable to classify by-products as cut-offs and thus avoiding allocation because it can lead to unevenly distributed impacts which might not represent reality. This in turn can result in incomplete assessment or biased results. However, due to a lack of data it was not possible to solve the multifunctionality issues that arose. Arguments for the choices made in these situations are further elaborated on below. The decision is made to recognize these flows as possible by-products to provide transparency in the choices made.

In the PCR-A product system there are multiple processes that produce by-products. According to the literature and descriptions by a producer Denka (2022), calcium carbide (C_aC_2) production co-produces residual limestone (C_aCO_3) and calcium cyanamide (C_aCN_2) which are used for cement and fertilizer production, respectively. However, no information that could provide a quantitative basis for allocation has been found in the literature. Huo et al. (2022) and Zhang et al. (2021), who performed a cradle-to-gate LCA on calcium carbide production and acetylene from calcium carbide respectively, do not mention the aforementioned by-products and do not include them in their inventory analysis. Huo et al. (2022), solely mentions applying allocation for furnace gases. This research follows their approach by ignoring residual limestone and calcium cyanamide as by-products, assuming their quantities are insignificant.

Acetylene production co-produces calcium hydroxide ($C_a(OH)_2$) according to Schobert (2014) and Denka (2022). However, quantitative information on the production volumes of calcium hydroxide for the specific generator considered in this study is not found and thus ignored. Similarly, Zhang et al. (2021) do not consider calcium hydroxide as a by-product in their inventory table for acetylene production, solely mentioning its secondary use and thus characterizing it a waste flow.

The acetylene to CR conversion co-produces multiple chemical substances in addition to CR monomer according to Lynch (2001). These substances are, however, not included in the material balance of the process by the The World Bank (2015), which provided elaborate quantitative data for this process. Therefore, their quantities are considered negligible. In the PCR-B product system, CR production co-produces sodium chloride (N_aCl) and water (H_2O) according to Lynch (2001). Similarly to the acetylene to CR conversion, the quantitative description by The World Bank (2015) is used for this process, which does not mention either of these by-products. It is therefore ignored.

4.2 Product systems

This section describes the three product systems that are assessed in detail. The polymerization process used in both PCR systems is discussed separately. Every product system is introduced with a description providing insight into the production process based on literature. These findings are presented in the process map, showing the product system, the system boundary and the flows considered.

4.2.1 Natural rubber (NR)

Rubber crop cultivation originated from different countries in the Amazon Basin in the Americas, West Africa, and Southeast Asia as well as the Indian sub-continent. As the global demand for rubber increased, the area of rubber plantations increased from 3 million ha in 1961 to 12 million ha in 2019. The biggest production in terms of volume and net production value stems from Asian countries such as Thailand, Indonesia, Vietnam, and India. Holding a cumulative share of 73% of global production levels (Hilmi et al., 2021).

A major supplier of NR for the wetsuit industry mentions their supply chain is located in Vietnam and Thailand (YULEX, 2023a). Data and process descriptions align with this scope. Para rubber from the Hevea brasilensis is used to produce wetsuits (Patagonia, 2016). Hevea brasilensis is cultivated at designated private or state-owned plantations and so-called smallholders. In Vietnam, smallholders are distinguished by the area of land they cultivate which is limited to 1-3 ha. According to estimates there were 264.000 smallholder in Vietnam in 2017, producing more than 50% of the Vietnams annual production of 1.094,5 thousand tonnes (Go Viet, 2018).

Within the wetsuit industry major expanded foam producer source NR from Forest Stewardship Council (FSC) certified supply chains (Nam Liong, 2024c; SHEICO Group, 2023). FSC certification aids in ensuring and confirming that rubber products are deforestation free while improving transparency in the supply chain (Kędzia et al., 2022). Other suppliers expanded on this commitment to include the Programme for the Endorsement of Forest Certification (PEFC) which focusses on solving social inequity issues in the supply chain (Wellpower Sporting Goods, n.d.; YULEX, 2023d). In 2017, 4% of the global rubber plantations were FSC-certified (Kędzia et al., 2022). This number is expected to grow. For example, the Rubber Authority of Thailand (RAOT) promotes rubber plantations to comply to FSC standards by integrating FSC requirements in their Rubber Replanting Aid Fund (RRAF), only providing financial aid to those who comply (Kongmanee et al., 2020)..

The economic lifetime of a rubber tree is estimated to be around 20-25 years of which 7 years are needed for the tree to mature followed by 13-18 years of production (Allen, 2004). In this research, the NR production process starts with harvesting fresh latex from the tree. This is done by cutting the bark of the tree. The fresh latex is collected as a liquid. Shortly after, or during harvesting, ammonia is added to the fresh latex. This substance functions as a preservative and stabilizer. Fresh latex is further processed into different intermediate products for which examples are shown in Figure 4.1. The processing of collected latex happens at designated rubber mills (Jawjit et al., 2010).

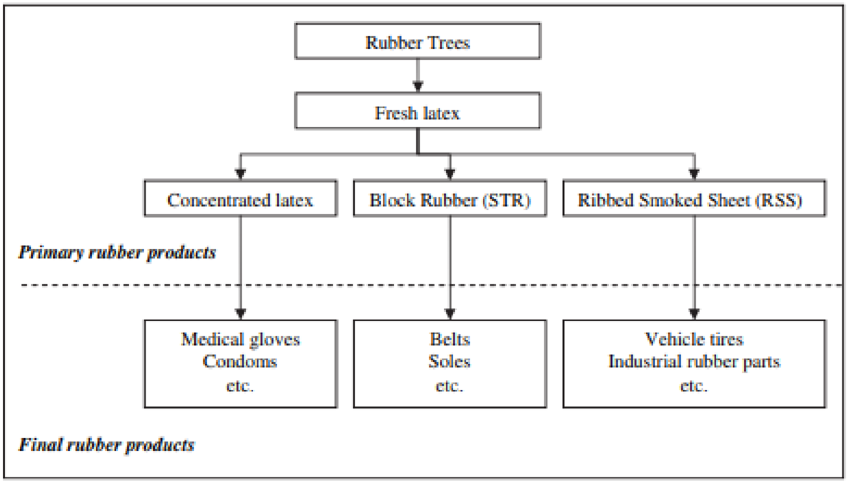


Figure 4.1: Schematic diagram of production of primary and final rubber products (Jawjit et al., 2010)

Fresh latex is an emulsion of water, rubber particles, fats, proteins, metals, oils, dirt, and plant particles. Various sources from the wetsuit industry indicate that fresh latex needs a purification process for it to be used in wetsuits (Patagonia, 2016; Spies, 2016; YULEX, 2022). To improve efficiency of transport, it is common practice to concentrate latex by centrifuging, thereby removing the water present in the latex and reaching a dry rubber content of at least 60% (Jawjit et al., 2010). But, the thorough purification treatment that industry sources refer to is more complex. It consists of adding a compound and a soluble surfactant to the fresh latex and processing it through one or more high speed centrifuges. This results in a purified natural rubber latex (NRL) consisting of no more than about 1% of protein. A schematic visualisation of the processing steps is shown in Figure 4.2. (Martin & Mithcell, 2022).

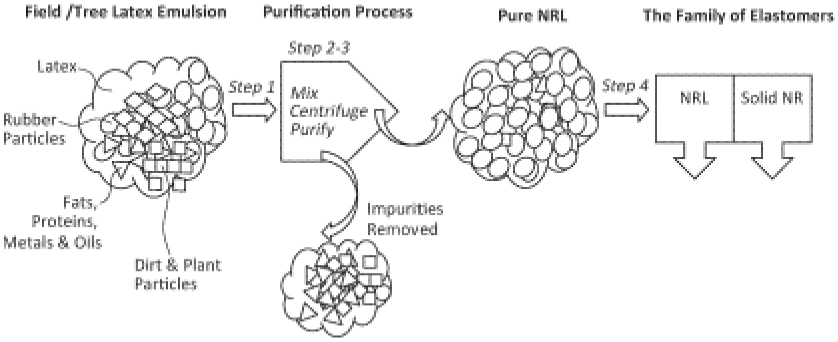


Figure 4.2: Schematic diagram of the thorough treatment process (Martin & Mithcell, 2022)

After purification the NRL is de-ammoniated and subsequently diluted with soft water. This is followed by coagulation. The coagulation process consists of a continuous acidic water flume, hot water washing, and volume reduction if necessary. Once fully coagulated, it is rinsed with clean water and either milled into small particles to promote drying or formed into thin sheets and dried in ovens or on dry racks (Martin & Mithcell, 2022). The coagulated rubber is then formed into block rubber, which also referred to as STR-20 (Thailand), SVR-20 (Vietnam), indicating country or origin. Block rubber production is a mechanical process which is relatively energy intensive in comparison to the other intermediate materials which were introduced in Figure 4.1, because high heat ovens are used (YULEX, 2022). Block rubber weight and size are standardised. For simplicity, the final purified block rubber is hereafter referred to as NR. Figure 4.3 shows the flow diagram of the product system. Additional, in-depth information on data and assumptions is added to Appendix B.

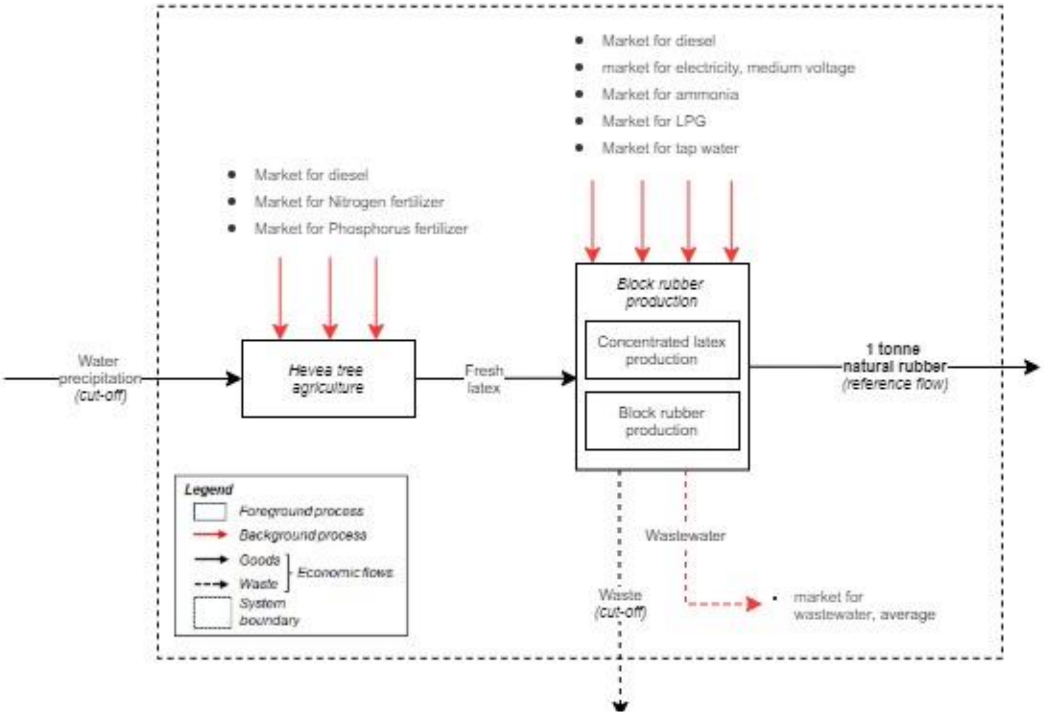


Figure 4.3: Flow diagram of the NR product system and the EcoInvent background processes

4.2.2 Polychloroprene – Acetylene (PCR-A)

Literature provided insight into various ways to produce acetylene, Schobert (2014) mentions an indirect (coal to synthesis gas, gas into liquids) or direct (liquids direct from coal) approach in his research on the production of acetylene from coal. Weissermel and Arpe (2003) mention other direct approaches in which a variety of inputs is used in addition to coal such as: natural gas, liquefied petroleum gas (LPG), oil, and methane. A selection of processes and their possible inputs mentioned in both sources is shown in Figure 4.4. The indirect approach is considered relatively simple but very energy intensive and therefore associated with high CO_2 emissions (Zhang et al., 2021). According to Shlyapin et al. (2022) investments in processes with gaseous feedstocks has grown as a consequence of this, and the expected rise of costs for oil feedstocks. However, the indirect approach, or carbide technology, still makes up for half of the acetylene market.

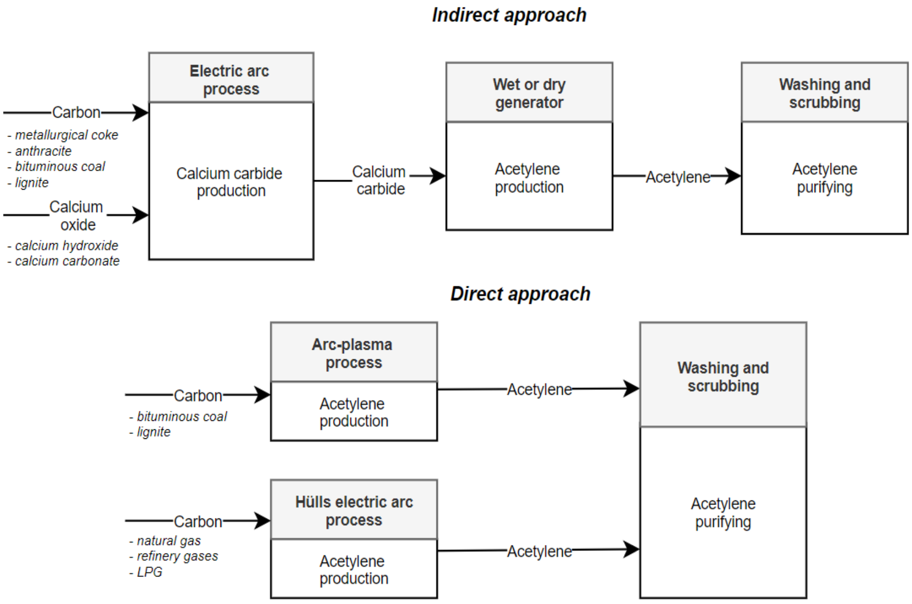


Figure 4.4: Acetylene production based on description by Weissermel and Arpe (2003) and Schobert (2014)

The wetsuit industry predominantly relies on the indirect approach for acetylene production. This is evident from the fact that various companies within the wetsuit value chain consistently mention using limestone (calcium carbonate, C_aCO_3) as a key ingredient in their products[3]. Since calcium carbonate is a crucial component in the production of calcium carbide (Schobert, 2014), which is exclusively used in the indirect process, this reliance confirms the industry's use of the indirect approach.

Limestone is usually found in large deposits with a generally consistent composition. High purity limestone is defined as carbonate rock containing at least 97% of calcium carbonate (Mitchell, 2011). It is this high purity limestone that is required for calcium carbide production. After mining, the limestone is broken in uniform sizes (ASCC, 2010). It is then further processed in a kiln at a temperature of 1100°C where quicklime (C_aO) or lime is derived, this product is then screened to homogenous particle sizes (Huo et al., 2022).

Calcium carbide is produced in an electric arc furnace. It requires coke (dried coal) and quicklime. The strong endothermic electrothermal reaction of calcium oxide and carbon occurs at 2000-2300 °C in a furnace powered by three electrodes. Production is predominantly taking place in China. Out of the >15 million metric tonnes of calcium carbide produced globally in 2006, 12 million was produced in China (Schobert, 2014). In 2018 China's domestic output of calcium carbide reached 26 million tonnes.

---

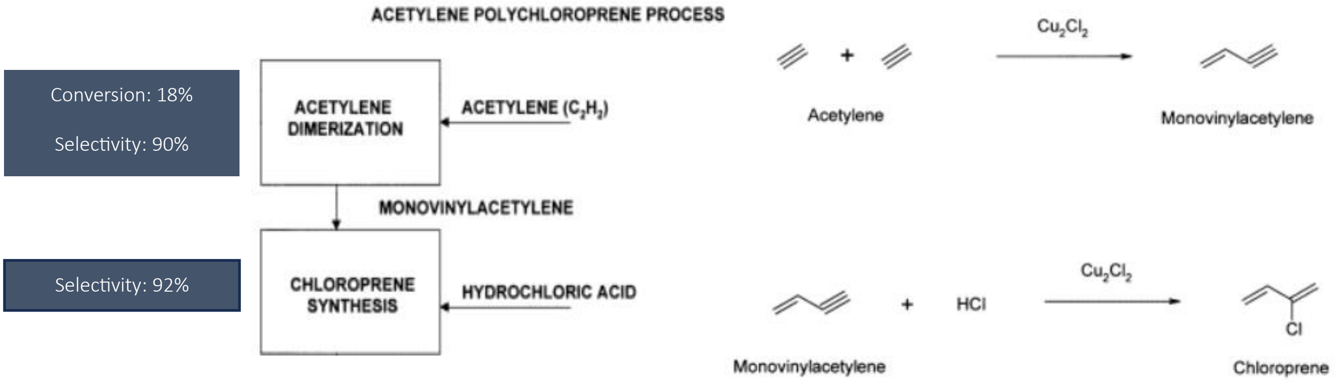
[3] This applies to producers of expanded foam (JAKO, n.d.-b; Possess Sea, n.d.; SHEICO Group, 2017; UOO, 2022; YAMAMOTO, n.d.), and finished wetsuit (Bare Sports, 2024; Circle One, 2024; Jobe Sports, 2019; Park, 2020; SRFACE, 2024a).

Calcium carbide can then be converted into acetylene on an industrial scale by an exothermic reaction with water. For this process a wet generator or a dry generator is used. The wet generator is technically simpler but creates wastewater. The dry generator uses an approximately stoichiometric amount of water, resulting in more efficient water use. Both generators produce the byproduct calcium hydroxide ($C_a(OH)_2$). Which, in some cases, can be recycled up to 50%, or used for construction (cement) and agricultural purposes (fertilizer) (Weissermel & Arpe, 2003). Pässler et al. (2011) mention that dry generators hold the advantage that their by-product can be used in other processes more easily, cheaply, and in a more diversified way than the slurry obtained from the wet generator, also allowing quicklime recycling. Commercial grade calcium carbide is available in different grades and particle sizes, top grades produce 288 L of acetylene/kg of carbide (Schobert, 2014).

Finally, the crude acetylene needs to be purified because of the impurities that stem from the use of limestone. Acetylene used as a feedstock for chemical manufacturing requires it to be 99% pure (Schobert, 2014). This purification process is described in three steps as: washing, scrubbing, and more washing with a variety of chemicals (Weissermel & Arpe, 2003).

Acetylene production with the indirect approach consumes large amounts of energy and resources. These dependencies dictate the locations where operations with this approach can take place. The most important conditions under which production is considered economically feasible are: access to cheap electrical energy for operating the furnace, and having options of disposing vast amounts of byproducts and waste (Schobert, 2014).

For acetylene to be converted into CR, and subsequently PCR, additional processes are required. Figure 4.5 shows a schematic overview of the different chemical reactions and their conversion and selectivity rates. The first step combines two acetylene molecules, reducing the original triple bond to a double bond resulting in monovinylacetylene (C_4H_4) (Lynch, 2001). This is done by dimerization in an aqueous hydrochloric acid solution at 80°C in a reaction tower. The resulting heat is controlled by the vaporization of water. This process also produces di-vinylacetyelene (C_6H_6) as a byproduct. Secondly, hydrogen chloride (HCl) is added to 60°C vinylacetylene. This step adds chlorine and hydrogen across the remaining triple bond to produce CR of which the main byproducts are methyl vinyl ketone (C_4H_6O) and 1,3-dichloro-2-butene ($C_4H_6Cl_2$) (Weissermel & Arpe, 2003).



Conversion: 18%

Selectivity: 90%

Selectivity: 92%

Figure 4.5: Chemical steps to CR synthesis (Lynch, 2001), conversion rates (Weissermel & Arpe, 2003)

Although the indirect approach is considered less modern and more energy intensive, it is still financially competitive with butadiene producers on the CR market, as shown in a study on the economic and technical feasibility of a CR production plant in Armenia (The World Bank, 2015).

Table 4.1 presents producers of acetylene derived PCR and their annual capacities. Figure 4.6 shows the flow diagram of the product system. Additional in-depth information on data, assumptions, and considerations is added to Appendix C.

Table 4.1: PCR-A producers and annual capacities in metric tonnes

Producer	Production site	Production capacity metric tonnes/annually	Sources
Denka	Omi, Japan	100.000	(Denka, 2022; Lynch, 2001; Rubber Journal Asia, 2018)
Shanna Synthetic Rubber	Datong, Shanxi, China	30.000	(European Rubber Journal, 2018; Lynch, 2001; Shanxi Synthetic Rubber Group, 2024)
Huojia Changshou Chemical	Changzhi, Shanxi, China	40.000	(European Rubber Journal, 2018; Integrity Chemicals Co., 2022; Lynch, 2001)

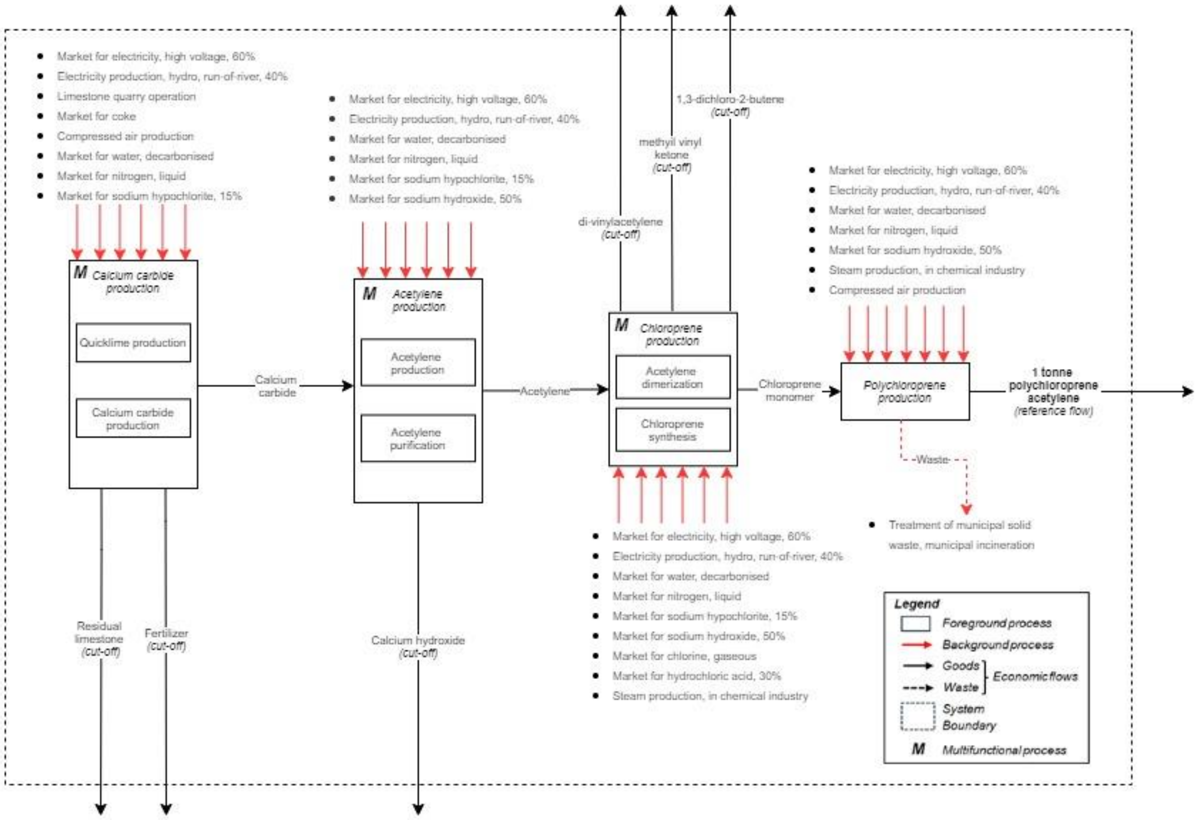


Figure 4.6: Flow diagram of the PRC-A product system and the EcoInvent background processes

4.2.3 Polychloroprene – Butadiene (PCR-B)

Butadiene (1,3-Butadiene, C_4H_6) is a major product of the petrochemical industry and an important intermediate product for many consumer and industrial products. It is hazardous gas due to its flammability, reactivity, and toxicity. Most of the butadiene produced is used for the production of synthetic rubbers and latex (72%). Styrene-butadiene-rubber (SBR) and Polybutadiene (PB) are dominant within that group with a 30% and 26% share respectively, with the majority of those materials being used in the tire industry. To put this in perspective, Chloroprene and Nitrile rubber hold a share of 1% and 4%, respectively.

Butadiene is traded globally. The majority of installed production capacity is located in Asia (The World Bank, 2015). The dominant process for producing butadiene is through steam cracking hydrocarbons, especially the C4 fraction. This fraction includes both butanes and butenes. Butanes are saturated hydrocarbons with four carbon atoms and single bonds, while butenes are unsaturated hydrocarbons with four carbon atoms and at least one double bond. This process accounts for over 95% of global butadiene production (White, 2007).

In this process, feedstocks such as ethane, propane, butane, naphtha, and gas oil are used with the goal of producing ethylene (C_2H_4). In the steam cracking process, feedstocks are fed to a pyrolysis furnace where they are combined with steam and heated to temperatures between 790-830 °C. In addition to ethylene, this process produces various by-products, including crude butadiene, hydrogen, propylene, and others, as shown in Figure 4.7. Plants are generally operated to meet ethylene demand, dictating by-product output (White, 2007).

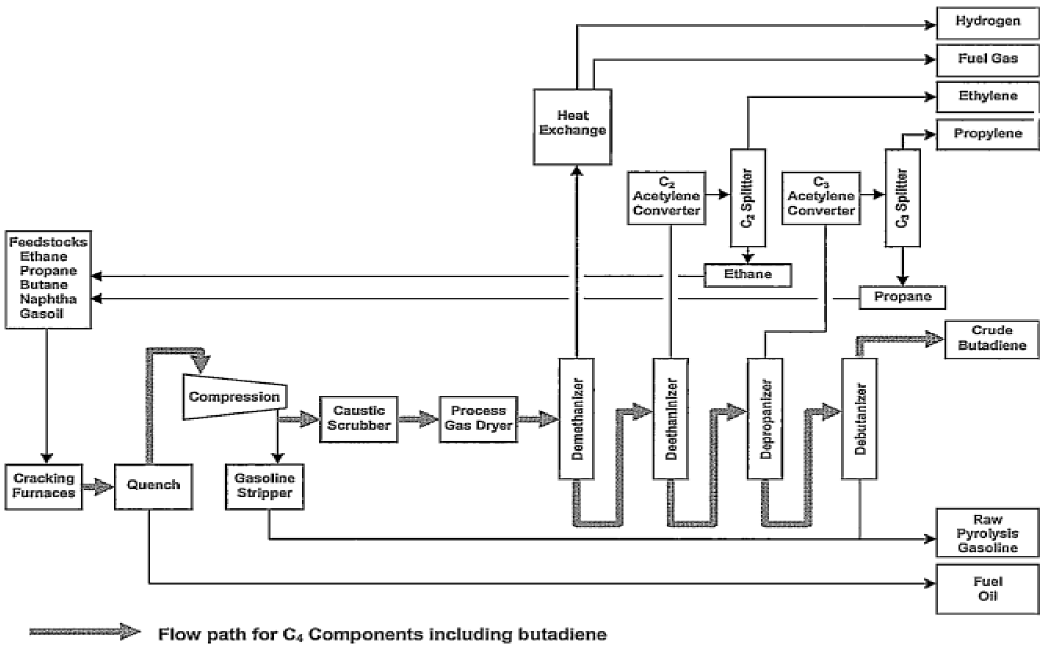


Figure 4.7: Typical olefin plant producing ethylene and co-products (White, 2007)

There are big differences in butadiene content that can be derived from the feedstocks mentioned earlier, as is shown in Table 4.2. Natural and refinery gasses like ethane and propane contain less butadiene then butane, naphtha and gas oil (Weissermel & Arpe, 2003). Operations are typically designed for a designated feedstock with either light (gas) or heavy (liquid) crackers. Due to their lower crude butadiene output, light crackers often do not include recovery units which purify the crude butadiene. Depending on feedstock and plant operation, crude butadiene generally contains 40-50% of butadiene but it can be as high as 75% (White, 2007).

Table 4.2: Butadiene content of different feedstocks (Weissermel & Arpe, 2003)

Feedstock (in kg per 100 kg ethylene)	**Butadiene content**
Ethane	1-2 kg
Propane	4-7 kg
n-Butane	7-11 kg
Naphtha	12-15 kg
Gas Oil	18-24 kg

In the process of recovering high-purity butadiene from crude butadiene, multiple other co-products are produced, such as: isobutylene, propylene, alkylate, and others as shown in Figure 4.8. After removal of impurities, purified butadiene generally contains >99,5% butadiene. Afterwards a stabilizer is added to prevent an undesirable polymerization reaction. Storing butadiene happens in the form of liquified or compressed gas. Stabilized butadiene can be transported using common chemical transport modalities such as pipeline and bulk liquid containers (White, 2007).

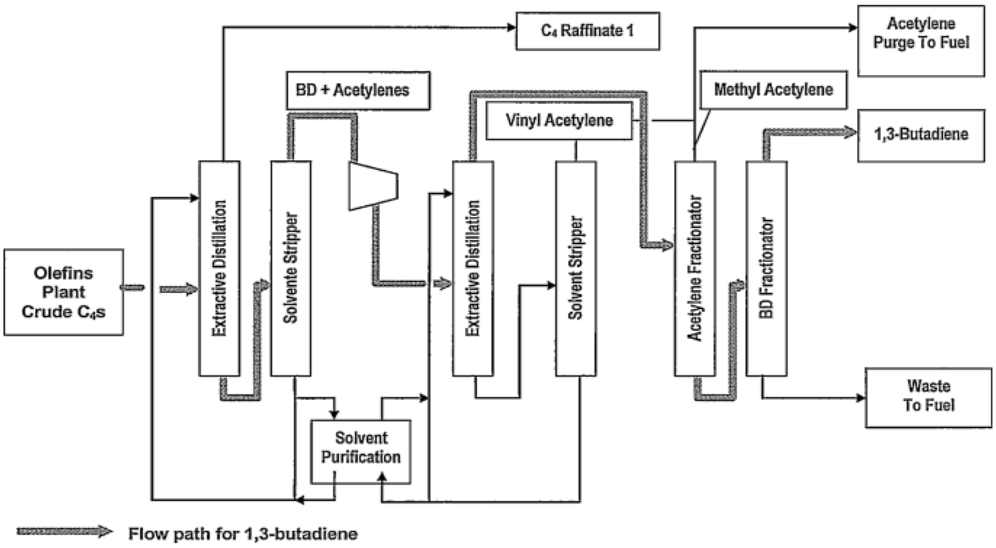


Figure 4.8: Typical extractive distillation butadiene recovery process (White, 2007)

The conversion of butadiene to CR is based on three key reaction stages of which a schematic overview is shown in Figure 4.9, including the corresponding conversion and selectivity rates. In the first stage, dichlorobutene (DCB) synthesis, a reaction of butadiene with chlorine occurs, producing a mixture of 1,4-dichlorobutene (1,4 DCB) and 3,4-dichlorobutene-1 (3,4 DCB), due to the non-selective nature of the chlorination process. The second stage, DCB refining, consists of isomerization of 1,4 DCB to 3,4 DCB in order to optimize the yield of the latter. This process is facilitated by a copper catalyst. But, this isomerization reaction is reversible, 3,4 DCB can potentially convert back to 1,4 DCB. In order to prevent this from occurring, 3,4 DCB is continuously removed from the reactor. The third stage, chloroprene synthesis, is dehydrochlorination of 3,4 DCB to CR through the use of sodium hydroxide (N_aOH). This process also generates sodium chloride and water as by-products.

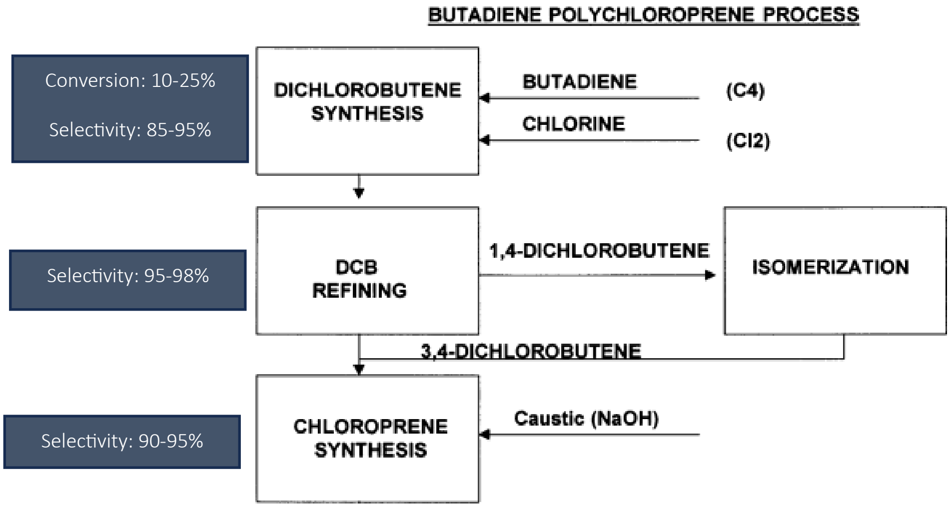


Figure 4.9: Chemical steps to CR synthesis (Lynch, 2001), conversion rates (Weissermel & Arpe, 2003)

Identified producers of butadiene derived chloroprene are shown in

Table 4.3. The locations of the production sites show a global spread with a strong presence in Japan. Figure 4.10 shows the flow diagram of the product system. Additional information on data, assumptions, and considerations is added to Appendix E.

Table 4.3: PCR-B producers and annual capacities in metric tonnes

Producer	Production site	Production capacity metric tonnes/annually	Source
Bayer	Dormagen, Germany	70.000	(ARLANXEO, 2024; Lynch, 2001; Rubber News, 2019)
Denka	LaPlace, Louisiana	50.000	(Rubber Journal Asia, 2018)
Tosoh	Shinnanyo, Japan	34.000	(The World Bank, 2015; Threadingham et al., 2005; Tosoh, 2024)
Resonac	Kawasaki, Japan	23.000	(Lynch, 2001; Resonac, 2024; Rubber News, 2012)

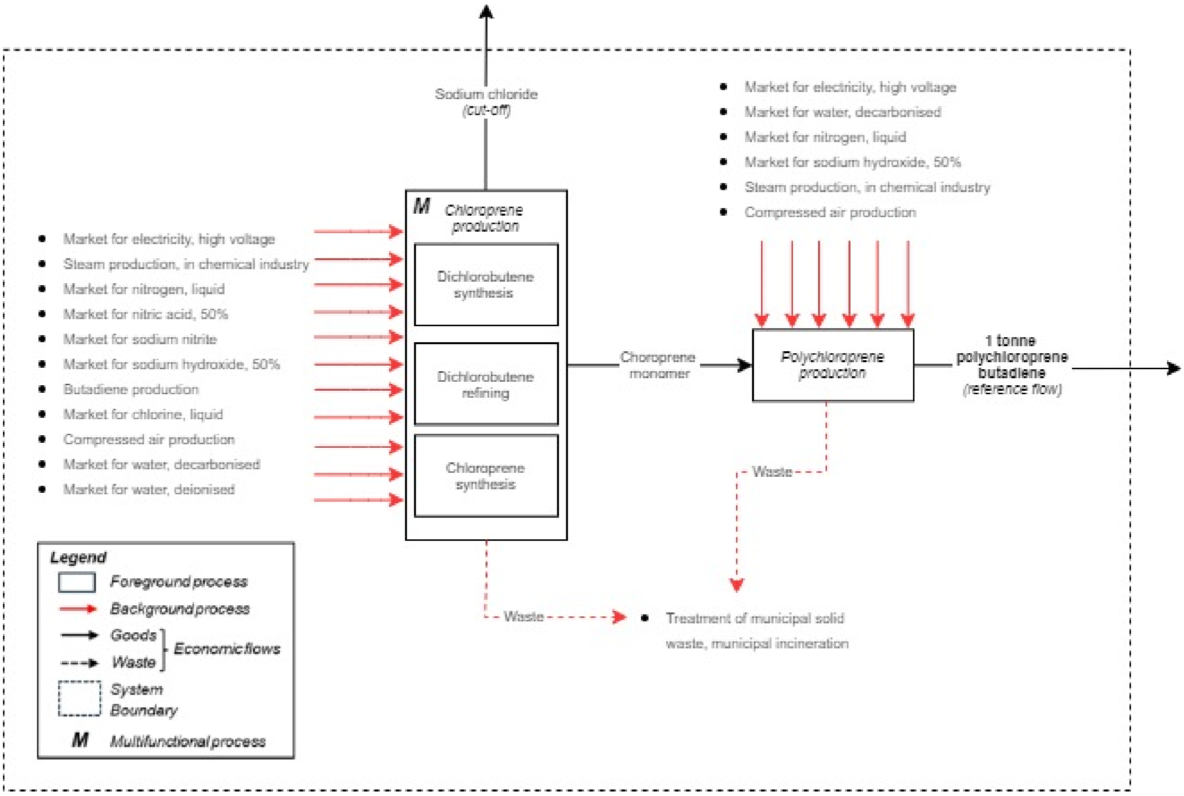


Figure 4.10: Flow diagram of the PCR-B product system and the EcoInvent background processes

4.2.4 Polymerization

PCR is manufactured by polymerizing the CR monomer. Both Lynch (2001) and The World Bank (2015) confirm that this final step in PCR production uses the same manufacturing equipment and inputs for acetylene and butadiene derived CR monomer. Lynch (2001) also mentions this process is common practice in the industry and can be performed as a batch- or continues process, of which the latter is more common. The following summarizes the steps of batch process as described by The World Bank (2015).

First, a measured quantity of CR monomer is collected in a monomer holding drum above a reactor. At the same time, measured quantities of demineralized water, initiators, promoters, regulators, emulsifiers, modifying/stabilizing agents, and caustic soda are also pumped to their respective drum above the reactor. Then the CR monomer and water solution are introduced and mixed by means of an internal stirrer. The polymerization reaction is started by introducing the substances at 35°C. The extent of polymerization conversion is measured by sampling on density, the polymerization reaction can be controlled by maintaining a constant temperature. The end product of polymerization is a latex. This latex is a stable blend of PCR and unreacted CR in water, also called crude latex. Crude latex is heated by steam, separating the unreacted CR, and transporting it to a designated recovery tank. The primary latex solution is recovered and stored for 24 hours for observation.

Subsequently, the 'pure' latex is pumped onto a rotating cooling drum. The latex coagulates when it touches the outside of the drum, and solidifies into a thin latex film, secreting the water that was present in the latex in the process. Then, the latex film is peeled of the rotating drum and washed with water to remove any remaining impurities. The film is then dried with hot air and subsequently cooled down on a chilled roll. Finally, talc is added and the rubber film is cut into irregular rubber 'chips' which are then packaged and ready for use.

The polymerization stage requires no additional flow diagram because it is already integrated in the flow diagrams of the PCR alternatives. Additional information on data and assumptions is added to Appendix G.

4.3 Life Cycle Inventory

The results of the data collection process for each product system are available in the Supplementary file. Data entries to the model include a reference to its source, show conversions if applicable, and are commented on if further elaboration or justification is deemed necessary.

4.4 Inventory results

The inventory results are the final collection of environmental interventions scaled to reference flow and aggregated to each elementary flow. This information, while providing some insights, is considered less suitable for interpretation until the environmental impacts become much clearer in the impact assessment phase.

5. Impact assessment

In the life cycle impact assessment phase, the inventory results are further processed to better understand their environmental impacts. In Section 5.1, a definitive selection of impact categories and category indicators is made. This is followed by calculating the characterization results in the LCA software based on the categorization factors chosen. In Section 5.2, a reference is made to the environmental flows without categorization factors. Finally, Section 5.3 presents the characterization results of the categorized flows and provides a normalized view for clarity.

5.1 Characterisation method

For this assessment, the Environmental Footprint (EF v3.1) method is used. Developed by the EU, this method aids LCA practitioners in measuring and communicating the environmental performance of products and organizations (European Commission, 2021). The EF framework is comprehensive, incorporating both midpoint and endpoint indicators. Midpoint indicators address specific environmental processes such as GHG emissions and acidification potential, indicating contributions to global environmental issues. Endpoint indicators reflect broader impacts on human health, ecosystem quality, and resource availability. This broad coverage aligns with goal of this study, which is to include impacts that were not considered in previous studies.

5.2 Missing characterization factors

After the characterisation step of this assessment, certain environmental flows were identified that lack categorization factors within the current LCA method. Consequently, these flows were excluded from the characterization results, implying that the actual environmental impacts are likely higher than reported. This exclusion occurred because it was not feasible to locate and apply appropriate categorization factors for every flow within the available time. The flows without categorization factors are available in the Supplementary file.

5.3 Characterisation results

The characterisation results are shown in Table 5.1. Indicating the final score for each impact category. To allow for easier comparison Figure 5.1 shows the characterisation results normalized to the highest value for each category.

Table 5.1: Characterization results of NR, PCR-A, and PCR-B

EF v3.1 Impact category	Natural rubber *NR*	Polychloroprene, acetylene *PCR-A*	Polychloroprene, butadiene *PCR-B*	**Unit**
Climate change, total	8,52E+02	1,73E+04	1,35E+04	kg $CO_{2\,eq}$
Ozone depletion	2,03E-05	5,26E-04	1,29E-03	kg CFC-11 $_{eq}$
Human toxicity, cancer	5,26E-07	4,38E-05	3,78E-06	CTUh
Human toxicity, noncancer	1,17E-05	7,93E-05	8,15E-05	CTUh
Particulate matter	3,24E-05	6,74E-04	5,77E-04	disease incidence
Ionising radiation	1,82E+01	6,71E+02	4,26E+02	kBq U^{235}_{eq}
Photochemical ozone formation	3,19	5,55E+01	3,55E+01	kg NMVOC $_{eq}$
Acidification	5,80	6,48E+01	5,24E+01	mol H+ $_{eq}$
Eutrophication, terrestrial	1,13E+01	1,11E+02	9,16E+01	mol N $_{eq}$
Eutrophication, freshwater	3,32E-01	4,15	2,30	kg P_{eq}
Eutrophication, marine	1,66	1,10E+01	8,95	kg N $_{eq}$
Ecotoxicity, freshwater	1,97E+04	5,25E+04	4,15E+04	CTUe
Land use	3,30E+05	3,11E+04	1,71E+04	Dimensionless (pt)
Water use	4,76E+02	1,99E+03	3,13E+03	m^3 water eq of deprived water
Resource use, minerals and metals	1,18E-02	2,30E-02	4,33E-02	kg Sb $_{eq}$
Resource use, fossils	1,32E+04	2,11E+05	2,03E+05	MJ

The characterization results show notable differences in the environmental impacts of NR, PCR-A, and PCR-B across various categories. PCR-A generally exhibits the highest impacts, except in the categories of ozone depletion, land use, water use, and resource use minerals and metals. In two of these instances, PCR-A and PCR-B have very similar impacts, as seen in human toxicity noncancer and resource use fossils. PCR-B shows the highest impacts in ozone depletion, water use, and resource use minerals and metals. In most cases, PCR-B's impacts are between 50-80% of PCR-A results. NR shows the lowest impacts across most categories, with a significant exception for land use, where it has much higher impacts compared to PCR-A and PCR-B. Besides this one category, NR displays major differences from the second-lowest result in each category, except for human toxicity, where PCR-B has similarly low impacts. Higher results are also noted for NR in the categories of ecotoxicity freshwater and resource use minerals and metals, though it still has about half the impact of the second-best performing material.

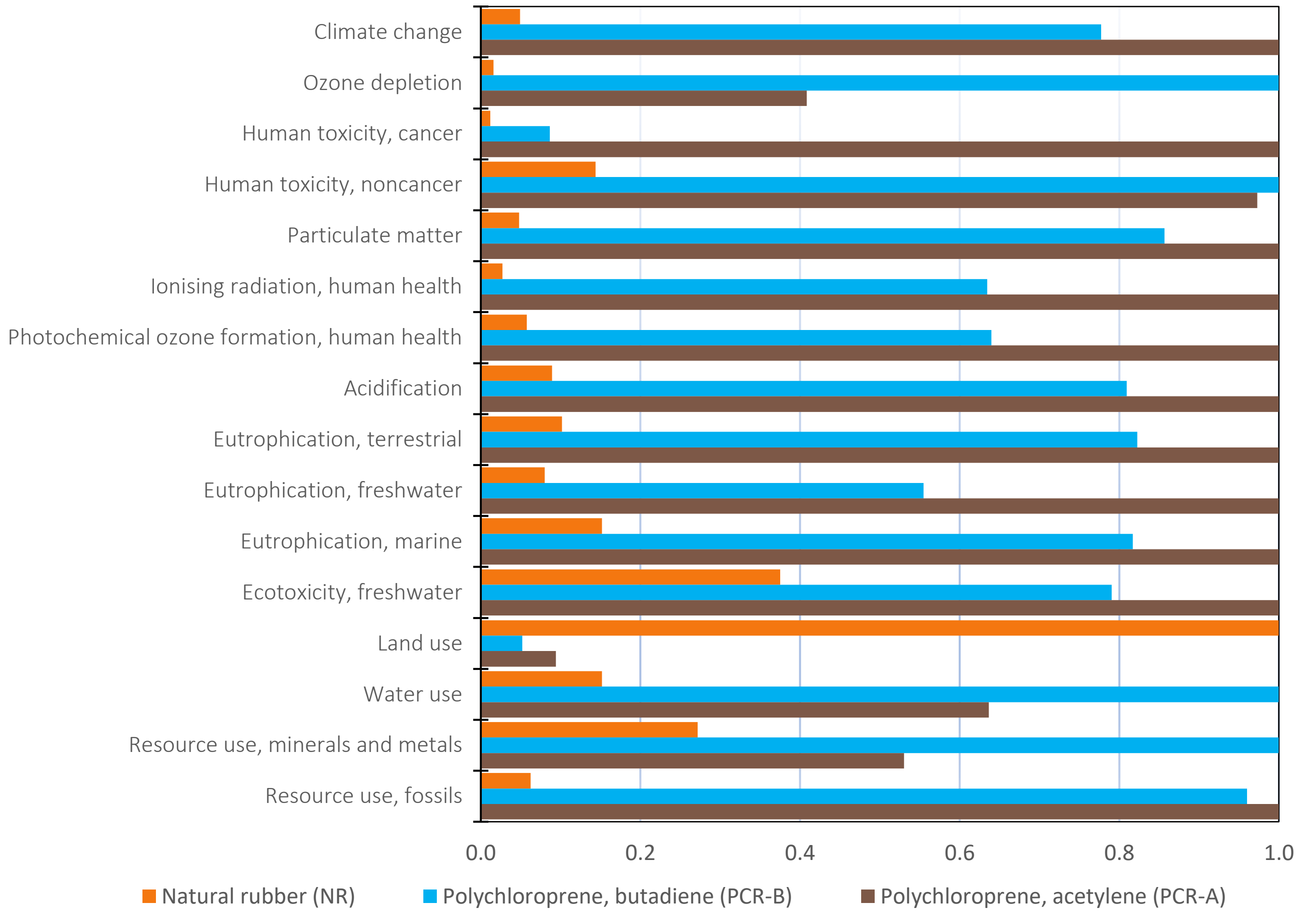


Figure 5.1: Normalized characterization results of NR, PCR-A, PCR-B to the highest value per impact category

6. Interpretation

In this chapter, the results, along with the choices and assumptions made during the assessment, are evaluated for soundness and robustness. This evaluation involves checking for consistency to ensure the reliability of the study. In Section 6.1, a consistency check is performed, assessing the method, model, data, and results for coherence. Section 6.2 consists of a contribution analysis, which helps to understand the root causes of the identified impacts. Section 6.3 presents the sensitivity analysis, verifying the robustness of the results by examining the influence of impact assessment model selection, modelling choices, key assumptions, and data. Finally, Section 6.4 summarizes the insights gained from this phase and presents the conclusion.

6.1 Consistency check

The goal of the consistency check is to ensure that the assumptions, methods, models, and data align with the goal and scope of the study. As recommended by Guinée, (2001), consistency should be addressed at the very beginning of the interpretation phase.

6.1.1 Methods

The LCA is performed according to the scope defined in Chapter 3. All product systems contain unit processes representing raw material extraction and rubber production, covering the cradle-to-gate life cycle phases, and meeting the reference flow. The geographical scope of Asia is maintained, except for background processes for which no regional alternatives were available. The technology level for primary data collection is justifiable as model-modern technology and the data collected for processes is representative. The same impact assessment method was applied for each alternative.

6.1.2 Models

Each product system is represented in a flow chart showing the background processes used from EcoInvent as well as the foreground processes for which data was collected. Decisions on important data and assumptions are mentioned and justified for each product system in appendix B (NR), C (PCR-A) and 0 (PCR-B). Life cycle inventory data is available in the Supplementary file and matches the model inputs. The decision to consider all by-products as cut-offs in the processes where multifunctionality occurred has been followed in the PCR-A and PCR-B product system. No allocation was applied, and thus all burdens are allocated to the function. Cut-offs were only considered in the NR product system.

6.1.3 Data

Incidentally, inputs provided in the literature were ignored. This was done because the environmental or economic flow was not available in the EcoInvent database or the composition of the input was unknown. In the PCR-A system, the output of VOCs was ignored because the composition of this output was unknown. In some cases, small amounts of inputs were ignored because of their limited quantity. However, this decision was not consistent across the assessment, as in some cases, smaller quantities were included. The effects of these choices are not expected to be significant due to their low quantities, but the approach to dealing with this lacks consistency. Economic and environmental flows left out of the model are reported and commented on in the Supplementary file.

For the CR production processes of the PCR alternatives, the same report was used to quantify inputs for both product systems, improving consistency. However, the level of detail provided by this report on the process inputs and outputs shows a discrepancy compared to the level of detail in the NR product system. This discrepancy is accounted for by testing key assumptions and modelling choices in the NR system through multiple sensitivity analyses.

An effort was made to include the most important and comprehensive reports available, ensuring consistency and reliability throughout the study. This approach has largely succeeded. Occasionally, additional insights were obtained from different sources to fill data gaps or provide more detail. These Supplementary data points are reported in the life cycle inventory table in the Supplementary file, with references to the sources used for the additional values, ensuring that any deviations from the main sources are transparent and justified.

6.1.4 Assumptions

The data on CR production and PCR conversion in both the PCR-A and PCR-B product systems include detailed information on the quantities involved in the internal flows of unreacted, produced, and stored CR. For simplicity, these internal flows are ignored. It is assumed that these flows are ultimately in equilibrium; therefore, only inputs of raw material and outflows of final product are considered.

6.1.5 Comparison to other studies

Similarly to this research, Soratana et al. (2017) compared the environmental performance of NR from Hevea brasiliensis to a synthetic rubber, SBR. Soratana et al. (2017) used the TRACI 2.1 impact assessment method for the impact categories: ozone depletion, climate change, and acidification. Their results, and the characterization results of the inventory data of this research calculated with the TRACI 2.1 method are shown in Table 6.1 for comparison. The results of Jawjit et al. (2010) are also added for reference because both studies used inventory data from this study.

The results of this research show significantly lower characterization results across all impact categories compared to Soratana et al. (2017), with reductions of 99%, 97%, and 93%, respectively. Two important explanations for these large discrepancies can be found in modelled biogenic emissions and LPG use, as both prove to be the biggest contributors to the impact categories climate change and acidification in their work. Concerning biogenic emissions, Soratana et al. (2017) include carbon (C) emissions originating from Hevea agriculture in their model, referring to the work by Podong (2014) who estimated total annual C emission to be 976,53 kg C /ha/yr, for a Hevea rubber plantation in Northern Thailand in 2011. However, Podong (2014) also mentions the Net Primary Production (NPP) to be 2,032.4 kg C /ha/yr, therewith quantifying the net amount of carbon that is captured and stored in the plants biomass across the same spatial unit. Data on NPP that could alter emissions associated with Hevea agriculture through C capture is seemingly not included nor mentioned in the justification made by Soratana et al. (2017). This indicates that important aspects of the biogenic cycle quantified by Podong (2014) might have been left out, which could potentially lower the associated 6 kg CO_2-Eq/kg rubber (16%) impact of Hevea agriculture.

Regarding the contribution of LPG use to the characterisation results, this research and Soratana et al. (2017), modelled LPG use for NR processing using the inventory data provided by Jawjit et al. (2010). According to , Jawjit et al. (2010) the characterization results related to LPG use are 0.079 kg CO_2-Eq./kg of NR using the IPCC (2006) characterization method. Similarly to Jawjit et al. (2010), this research found the contribution of LPG use to be insignificant and of similar magnitude to these results when using the TRACI v2.1 assessment method. Soratana et al. (2017) reports that LPG use contributes 27.6 kg CO_2-Eq./kg of NR (84%) to the climate change impact category, showing significantly higher results, while using the same quantity of LPG as input. The big difference in characterization results is arguably related to the modelling choice of Soratana et al. (2017), in which the combustion of LPG is accounted for, by using 'Liquefied petroleum gas, combusted in industrial boiler' as a background process. The chosen background processes representing LPG use in this research and Jawjit et al. (2010) might underestimate characterization results.

This comparison emphasizes the criticality of modelling choices concerning both biogenic emissions and the selection of background process of LPG use. A sensitivity analysis is performed on these two modelling choices with the goal of understanding their impact on the overall results and ensuring the robustness of the conclusions drawn from this research.

Table 6.1: Characterization results of comparable studies for 1 kg of latex to solid NR

Per kilo of NR block rubber	Ozone depletion *kg CFC-11-Eq.*	Climate change, global warming *kg CO_2-Eq.*	Acidification *kg SO_2-Eq.*	Assessment method
This research	2,27E-08	8,58E-01	4,71E-03	TRACI v2.1
Soratana et al. (2017)	1,21E-05	3,38E+01	7,69E-02	TRACI v2.1
Jawjit et al. (2010)		7,00E-01		IPCC (2006)

Additionally, the results of the study performed by YULEX (2023a) are compared to the results of this research. The YULEX (2023a) study focused solely on quantifying the characterization result for the climate change impact category, expressed in metric tonnes CO_2 Eq./metric tonne of rubber product. As shown in Table 6.2, characterization results from this research, calculated with the EF v3.1 assessment method, show higher values across all alternatives, requiring further elaboration to explain these discrepancies and highlight the knowledge gaps in the research by YULEX (2023a).

The assessment methods used to calculate the characterization results in the sources utilized by YULEX (2023a) are seemingly different across the alternatives and are not explicitly disclosed. In the case of PCR-B, reported industry data on CO_2 emissions are added to greenhouse gas index (GGI) values for products derived from fossil resources without, mentioning the assessment method used. This lack of transparency regarding the impact assessment methods, particularly when adding values, is noteworthy and could affect the validity of the comparisons. For PCR-A, the results from YULEX (2023a) only covered raw material extraction until the production of acetylene, ignoring the final conversion to CR and PCR. For PCR-B, the only input considered was butadiene, neglecting other input requirements for the production of CR, such as, chlorine and caustic soda. Additionally, a 1:1 conversion of butadiene to PCR was considered, which proved to be slightly smaller (0.8:1). In the case of NR, YULEX (2023a) used the production of block rubber as a benchmark without accounting for the purification process.

YULEX (2023a) concluded that NR production emits at least 80% less CO_2 Eq. (89% according to calculations but rounded to 80%) compared to both PCR alternatives. According to the outcomes of this assessment, NR production emits 93% less CO_2 Eq. compared to the best performing PCR alternative.

Table 6.2: CO_2 Eq. of NR, PCR-B, and chemical intermediate acetylene

Metric tonne CO_2 Eq.. / metric tonne product	**Natural rubber** *NR*	**Polychloroprene (butadiene)** *PCR-B*	**Acetylene** -
YULEX (2023a)	0.7	6.49	14.5
	Natural rubber *NR*	**Polychloroprene (butadiene)** *PCR-B*	**Polychloroprene (acetylene)** *PCR-A*
Cradle-to-gate LCA	0.85	13.48	17.34

6.2 Contribution analysis

Contribution analysis calculates the overall contribution to the total characterization result of each impact category, expressed as a percentage for each product system. Insights from this analysis can inform strategies to reduce the wetsuit industry's environmental impact by highlighting where these impacts occur. The analysis is based on process contributions, with a cut-off of 1.5% in the LCA software to filter out smaller flows and maintain a clear overview of the most significant processes.

Because this is a cradle-to-gate LCA, the impacts are related to extraction or production processes. Much of the modelling relies on background processes, which are interconnected with other background processes, complicating traceability. This resulted in approximately 70 processes for each product system. To better distinguish the types of processes involved, related background processes were categorized together. This was done to limit the number of individual processes that would otherwise clutter the graphs. The decisions on process grouping are detailed for each flow in the Supplementary file. If certain flows were deemed important, additional categories were created to distinguish them.

6.2.1 Natural rubber (NR)

The contribution analysis for this product system is presented in Figure 6.1. The analysis clearly demonstrates the significant impact of energy production & use processes across most impact categories. Hevea agriculture is nearly solely responsible (99%) for the entire land use impact category. Another important contributor is waste treatment and disposal, which has a notably large impact on freshwater ecotoxicity. Raw material extraction shows high contributions to resource use, particularly in minerals and metals, indicating that the grouping of processes is logical and reflective of their environmental impacts. Ammonia production shows a noticeable contribution to climate change and water use. This substance is used in the processing of NRL to prevent unwanted coagulation. Urea production negatively contributes to the climate change impact category through sequestration.

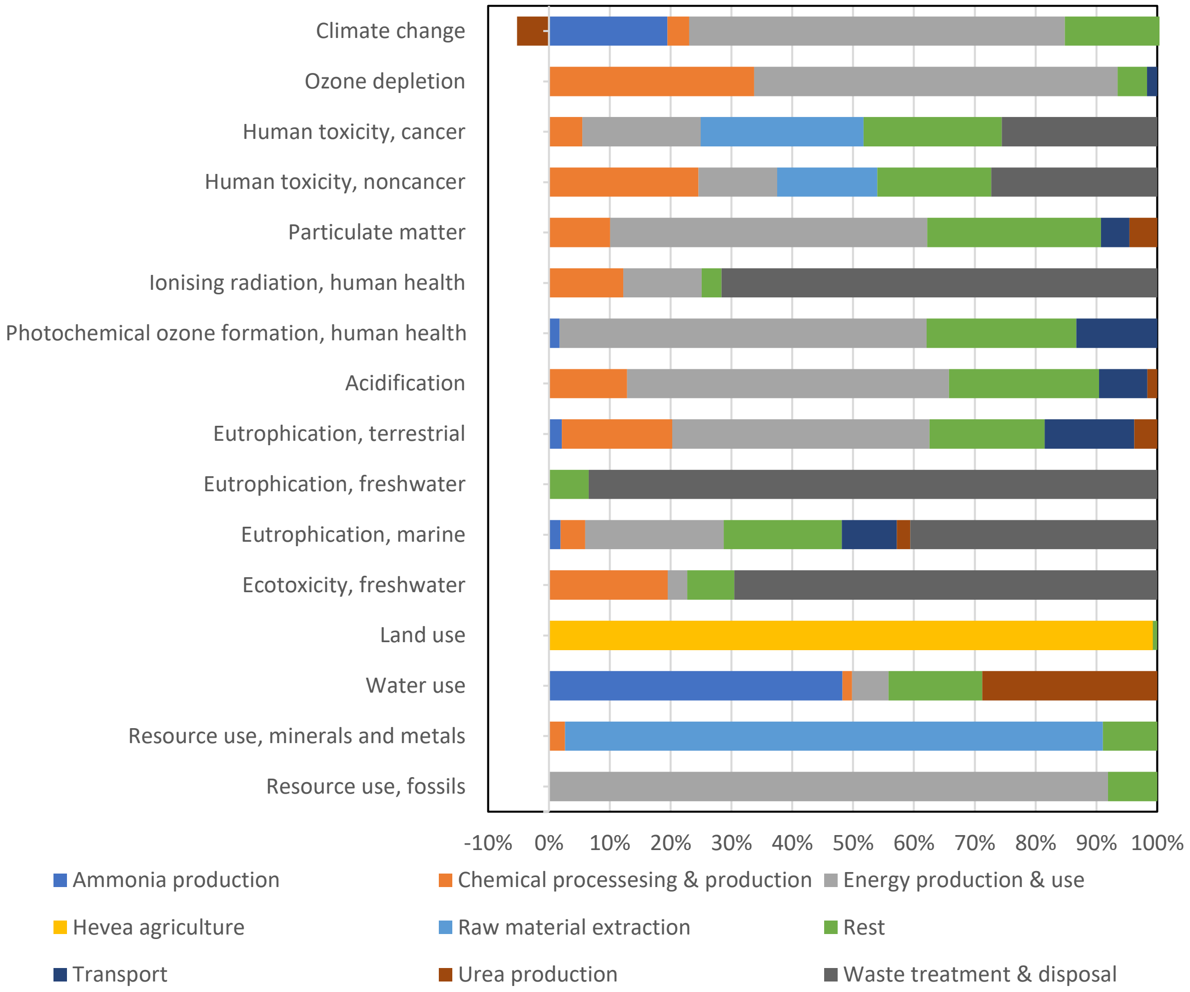


Figure 6.1: Contribution analysis of NR characterization results

In the contribution analysis ammonia is distinguished as a distinct category. The analysis show a contribution of 19% climate change impact, and 48% to the water use impact category. Ammonia is the most common preservative to protect fresh latex from unwanted reactions. This is necessary because fresh latex is a fragile substance, if left exposed to the environment, it coagulates within a few hours, and it is sensitive for bacterial growth (Kędzia et al., 2022). Inventory data for this LCA used 17 kg of ammonia per ton concentrated latex (Jawjit et al., 2010). Kędzia et al. (2022) mentions volumes of 2-7 kg per tonne of latex processed.

The use of ammonia is at least partly responsible for the challenges in the rubber processing industry illustrated by Nguyen & Luong (2012). They studied wastewater treatment processes in Vietnam and conclude that wastewater from fresh latex processing is heavily polluted. Pollution is expressed in remaining latex, high organic matter and nitrogen-containing pollutants, high acidity and strong smell. The authors warn that wastewater discharged directly into the environment without treatment will have serious ecological impacts. The wastewater generated through latex concentration -or purification as it was considered in this research- produces the most polluted source compared to block rubber production because of the high concentration of uncoagulated rubber particles and organic matter.

6.2.2 Polychloroprene – Acetylene (PCR-A)

The PCR-A contribution analysis is shown in Figure 6.2. Despite modelling that 40% of its energy demand is met by hydro run-of-river power generation, energy production & use processes still show significant contributions across most impact categories. It is important to note that energy use is still a significant contributor despite modelling that 40% of its demand is met hydro run-of-river power generation. The choice to distinguish calcium carbide production does affect its total in the climate change categories because this is a very energy intensive process as well and could be considered a major contributor of energy production and use as well. Large contributions are also shown for raw material extraction processes, marking a clear indication that this is a very resource intensive product system. Waste treatment & disposal have high contributions to eutrophication of freshwater and ionising radiation.

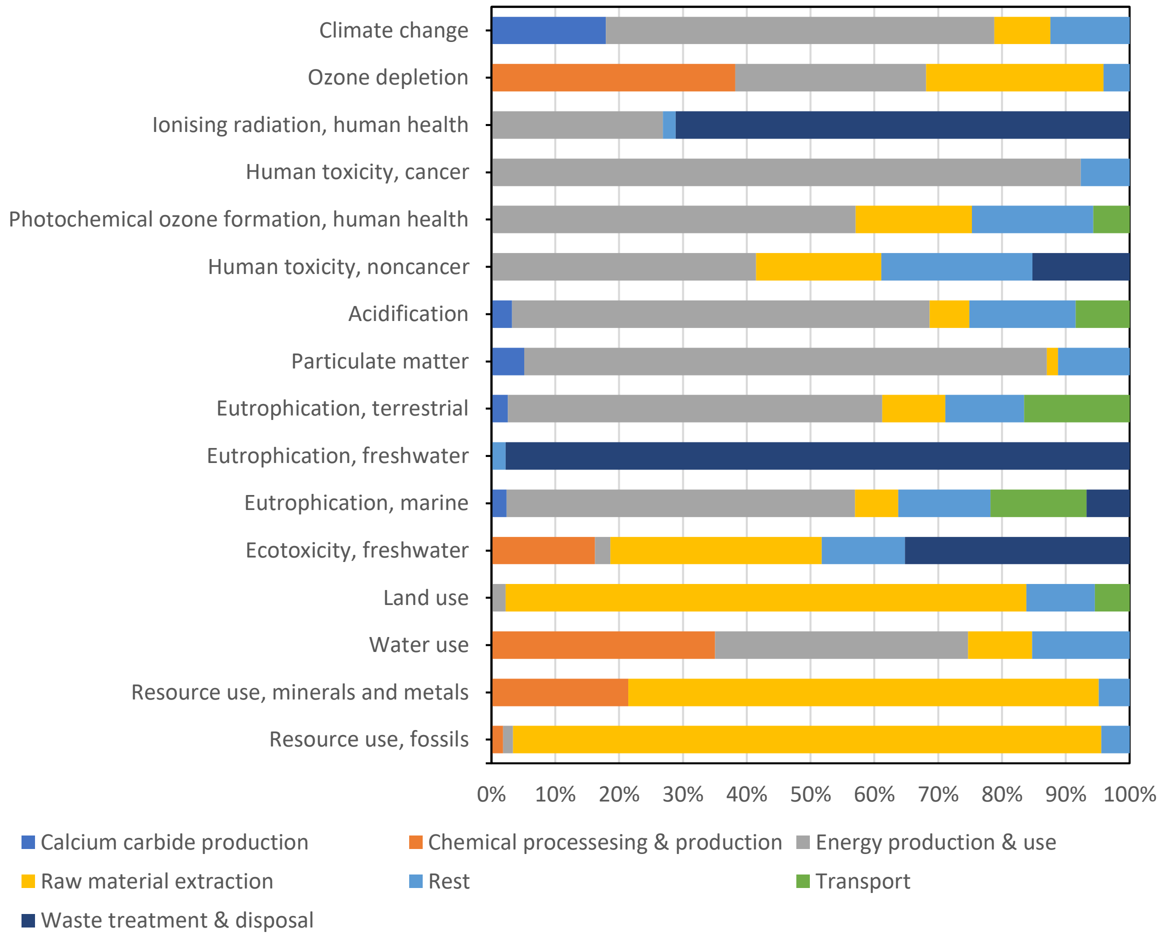


Figure 6.2: Contribution analysis of PCR-A characterization results

6.2.3 Polychloroprene – Butadiene (PCR-B)

Figure 6.3 shows the contribution analysis for the PCR-B product system. Energy production & use have dominant contributions across multiple categories. Substantial contributions are also shown for chemical processing & production for the ozone depletion, water use, and resource use impact categories. Raw material extraction shows the highest contribution in land use change and almost half the contribution to the resource use fossils impact category. Waste treatment & disposal has the highest contribution to ecotoxicity and freshwater and ionising radiation.

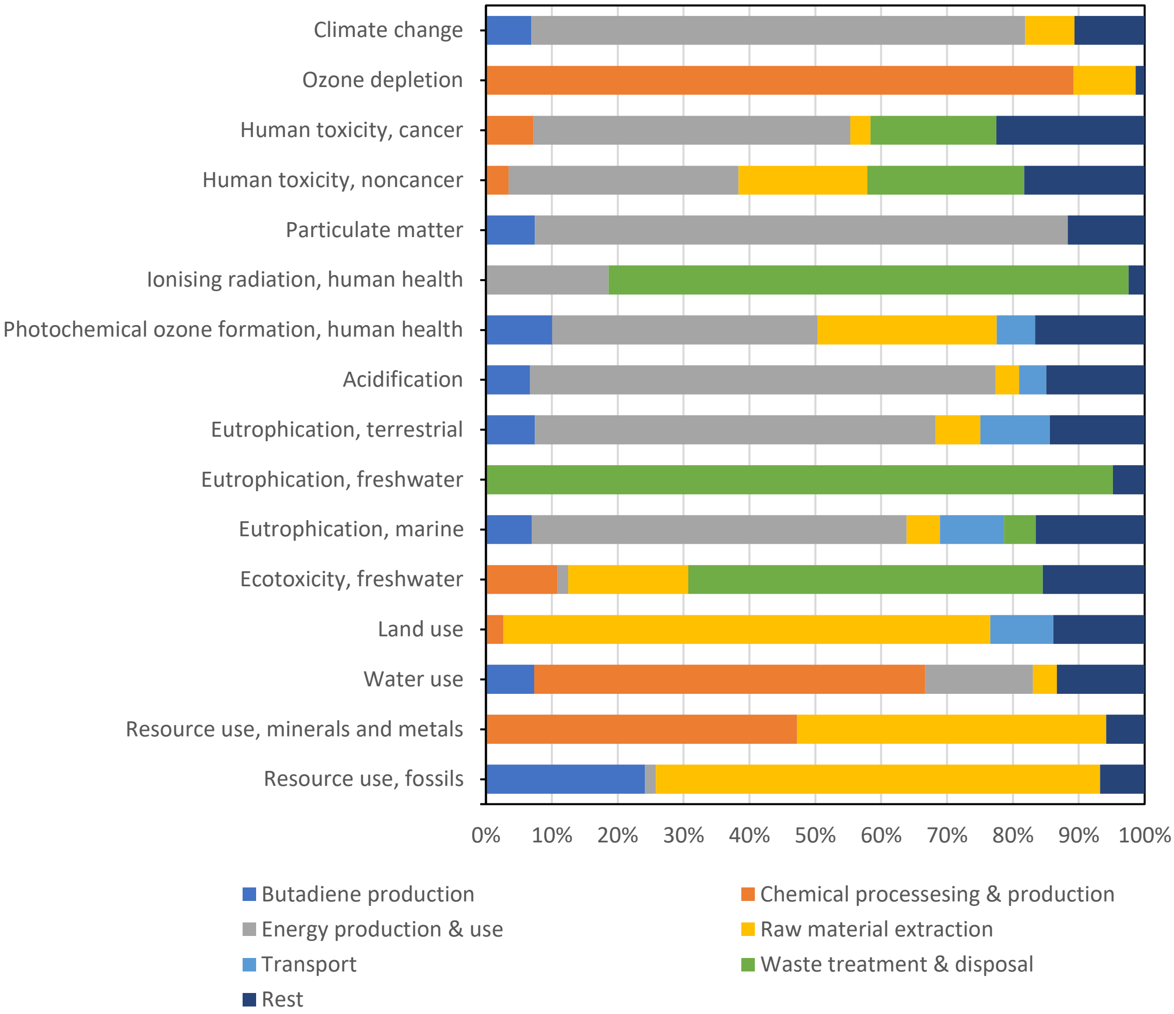


Figure 6.3: Contribution analysis of PCR-B characterization results

6.3 Sensitivity analysis

LCA studies are highly sensitive to changes in economic and environmental flows related to the functional unit, making the inventory data and modelling choices crucial for the study's results. To assess the robustness of the results, sensitivity analysis are conducted. In these analysis, different values and modelling choices are tested, after which the effects the results are studied. Five sensitivities were analysed. These sensitivities are, with exception of the first, focused on the NR product system, because this system is central to this research and has the most uncertainty in the data and the assumptions. First, the sensitivity of the impact assessment method on the characterization results is assessed. Secondly, different land use- related elementary flows related to the Hevea agriculture process were modelled. Third, a different background process representing LPG use was modelled, including combustion. Fourth, the effects of a different biogenic emission scenario was tested, assuming forest conversion. Lastly, the effects of ignoring the purification step in NR production were tested.

6.3.1 Characterization method

By applying a different impact assessment method the influence of this methodological choice can be assessed, for this sensitivity analysis the ReCiPe characterization method is used. ReCiPe is an internationally recognized and widely used method for environmental assessment, providing a common basis for comparison with EF. Table 6.3 shows the results of the comparison. Only the impact categories with a common unit are included. ReCiPe results are lower for the ionising radiation and marine eutrophication impact categories, but show higher results for ozone depletion and climate change. The differences observed can be attributed to the different characterization factors and underlying models used by the two methods. For instance, the higher results in climate change and ozone depletion with ReCiPe may reflect a different approach to modelling these impacts, potentially considering a broader range of substances or different global warming potentials. The results are consistent across the different product systems. This consistency indicates that the observed differences are related to the methodological choices rather than specific to a particular product system.

Table 6.3: Characterization results for sensitivity analysis impact assessment method

EF v3.1 Impact category	*NR*		*PCR-A*		*PCR-B*		**Unit**
Climate change, total	8,52E+02	↓	1,73E+04	↓	1,34E+04	↓	kg CO_2 eq.
Ozone depletion	2,03E-05	↓	5,26E-04	↓	1,29E-03	↓	kg CFC-11 eq.
Ionising radiation, human health	1,82E+01	↑	6,71E+02	↑	4,26E+02	↑	kBq U^{235} eq.
Eutrophication, freshwater	3,32E-01	=	4,14E+00	=	2,30E+00	=	kg P eq.
Eutrophication, marine	1,66E+00	↑	1,09E+01	↑	8,94E+00	↑	kg N eq.

ReCiPe 2016 v1.03, midpoint (H)	*NR*		*PCR-A*		*PCR-B*		**Unit**
climate change	8,89E+02	↑	1,79E+04	↑	1,40E+04	↑	kg CO_2 eq.
ozone depletion	1,42E-03	↑	3,12E-03	↑	3,68E-03	↑	kg CFC-11 eq.
ionising radiation	1,34E+01	↓	5,24E+02	↓	3,54E+02	↓	kBq U^{235} eq.
eutrophication: freshwater	3,32E-01	=	4,14E+00	=	2,30E+00	=	kg P- eq.
eutrophication: marine	2,61E-01	↓	3,76E-01	↓	2,69E-01	↓	kg N- eq.

6.3.2 Land use

The characterization results showed dominant land use results for the NR product system compared to PCR-A and PCR-B systems. Additionally, this research aims to explore the implications of PCR substitution with NR with regards to land use. First, the sensitivity of different land-use related flows is assessed. Thereafter, a different yield/ha/yr value is accounted for. The results provide context to the implications concerning land use and availability in light of industry wide substitution of PCR.

In the contribution analysis of the NR characterization results, this elementary flow contributed 99% of the total category, making it a significant flow that should be studied in more depth. This is done by assessing the effects of different land use-related elementary flows on the unit process, Hevea agriculture. In this sensitivity analysis, two additional land use flows are considered. The demand is quantified to meet the reference flow, which is 4000 kg of fresh latex. The description of the modelled elementary flows and the flow used for characterization are shown in Table 6.4.

Table 6.4: Land use related elementary flows, characterization results, and descriptions

Elementary flow land use, soil quality index	**Characterization result** Dimensionless (pt)	**Description**
Permanent crop, non-irrigated	3,29E+05	Perennial crops production based on natural precipitation (rainfed agriculture). + Use of fertilizer and pesticides is less than economically optimal.
Forest, extensive	1,30E+05	Forests (tree cover >15%), with extractive use and associated disturbance like hunting, and selective logging, where timber extraction is followed by re-growth including at least three naturally occurring tree species, with average stand age >30 years and deadwood > 10 cm diameter exceeds 5 times the annual harvest volume.
Forest, intensive	2,43E+05	Forests (tree cover >15%), with extractive use, with either even-aged stands or clear-cut patches exceeding 250 m length, or less than three naturally occurring species at planting/seeding, or average stand age

The modelled elementary flow shows significantly higher characterization results than the two flows characterized as forest. The former proves to be a modelling choice that should be reconsidered. As mentioned by Jawjit et al. (2010), rubber trees are tapped. This practice is more in line with the description given for “forest, extensive”, where little disturbance is involved. It is also very likely that the average stand age surpasses 30 years, as the scenario concerning forest management practices followed in this study considers relatively old (over 60 years) rubber plantations (Jawjit et al., 2010). Similarly, Podong (2014) argues that rubber plantations can be considered forest plantations because rubber trees have a production life of 20 years and increase in biological mass, possessing a high carbon stock capacity.

After modelling ‘Forest, extensive’ land use, the comparison to other product systems (PCR-A and PCR-B) indicates noticeable but not major changes in their normalized results as shown in Figure 6.4. Specifically, PCR-A's normalized value increased from 9% to 24%, and PCR-B's normalized value increased from 5% to 13%. These changes are noticeable but not dramatic, indicating that the sensitivity is moderate. This suggests that the higher land use impact for NR is a factor that must be acknowledged and accepted in light of its overall better performance across other impact categories as shown in the characterization results.

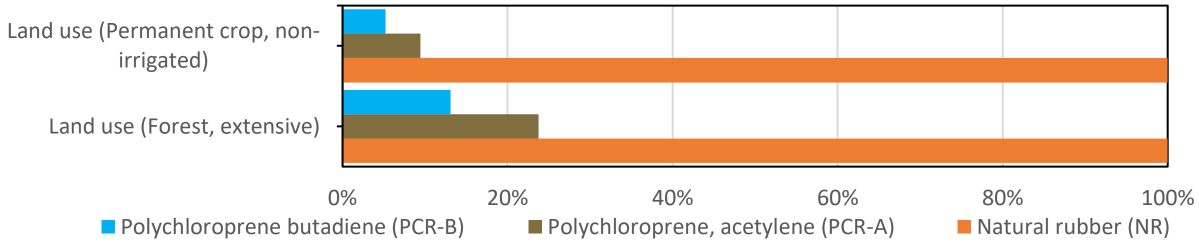


Figure 6.4: Normalized results for the sensitivity analysis of land use flows

In practical terms, land use plays a crucial role in meeting NR demand if the wetsuit industry substitutes PCR for NR. In such a scenario, the annual availability of hectares to produce NR must be sufficient to meet the demand of the entire wetsuit industry, considering that other industries require NR. Decisive in this simplified examination are estimates regarding fresh latex input for wetsuits, annual plantation yield of fresh latex, and annual wetsuit production volumes. Regarding the yield of field latex, this LCA assumes the average annual yield of field latex of 5,640 kg/ha/year in 2008 (Jawjit et al., 2010). However, this yield is subject to change. For instance, the same author reported a much lower average yield in later research, citing 1,600 kg/ha/year for 2011 in an LCA study on concentrated latex production (Jawjit et al., 2015). Data from an LCA study on condoms from 2021 indicates an average yield of 1,800 kg/ha/year based on ten rubber plantation sites-presumably in the same year the study was published (Jawjit et al., 2021). The sensitivity of this value on the impact category land use is limited as shown in Figure 6.5, with the 1,6 metric tonne yield scenario only showing a 1-2% reduction in normalized characterization results.

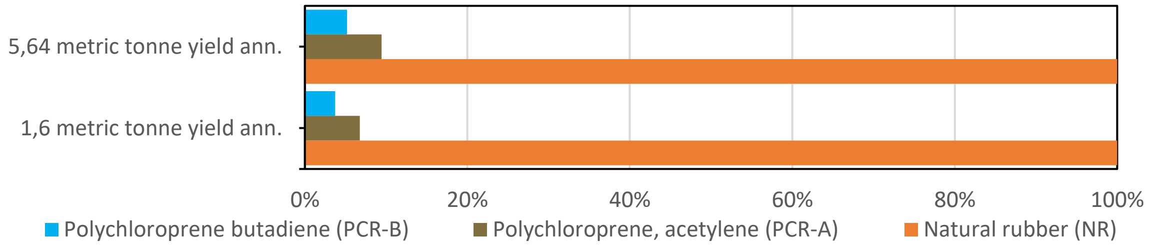


Figure 6.5: Normalized results for the sensitivity analysis for yield of fresh latex per hectare per year

The implications of the uncertainty on latex yield do become more evident when the yield is related to wetsuit production by including required latex input per wetsuit and annual production volumes. Estimates on the fresh latex input found in industry sources vary between 0,5 kg (Spies, 2016), and 1 kg per average wetsuit (Patagonia, 2016). Additionally, an industry source provided an estimate of 0.75 kg for an average wetsuit. To be clear, that is referring to raw material input, without processing losses included to meet the reference flow of NR. Assuming a 0.75 kg input and an industry wide annual production volume of 9.2 million (SHEICO Group, n.d.). This would result in an fresh latex demand of 6.9 million kg per year.

When adopting the fresh latex yield of 5.640 kg/ha/year provided by (Jawjit et al., 2010), *1224 ha/year* would suffice the demand for the entire industry, for simplicity from here on referred to as Scenario 1. Considering the 1,600 kg/ha/year (Jawjit et al., 2015), referred to as Scenario 2, the industries demand would be met with *4.313 ha/year* of rubber plantations.

In line with the agricultural practices described by(Jawjit et al., 2010), rainforest should not be cleared for rubber plantations. As discussed in Section 4.2.1, major suppliers within the wetsuit industry source FSC-certified NR, confirming this is common industry practice. Therefore, only FSC-certified plantations are considered in this analysis.

In 2018, Thailand registered 8,000 hectares of FSC-certified plantations (Forest Stewardship Council, 2018), Globally, 90,000 hectares were certified in the same year (Forest Stewardship Council, 2020). Table 6.5 summarizes the impact of full substitution, expressed as percentages of the total available hectares both domestically and globally. According to this estimation, substituting PCR with NR in the wetsuit industry would significantly affect domestic supply in Thailand under scenario 2, requiring 54% of the available FSC-certified plantations annually. From a global perspective, the impact is less significant, with full substitution in scenario 2 requiring only 5% of the globally available FSC-certified plantations for wetsuit NR demand.

Table 6.5: Percentage of total FSC certified supply to meet NR demand considering two scenarios

Scenario fresh latex yield/ha/year	Thailand *(2018)*	Global *(2018)*
Scenario 1 (*5,640 kg/ha/year)*	16%	2%
Scenario 2 (*1,600 kg/ha/year)*	54%	5%

6.3.3 Gas use

The comparison of the characterization results of this study to Soratana et al. (2017) showed significant differences in the contribution of gas use to the impact categories climate change and acidification for NR. Which could indicate that the results of this research underestimate the impact of LPG use. The sensitivity of this modelling choice is assessed by replacing the background process ‘market for liquefied petroleum gas’ by ‘heat production, propane, at industrial furnace >100kW’, to represent LPG combustion in the block rubber production process of the NR product system quantified as 1,252 MJ/ton NR. LPG combustion for heat was not available as a background process, propane gas was the found to be the most similar in composition out of the alternatives available, and is applied for this analysis. The characterization results are shown in Table 6.6, where the column "Natural rubber (GUA)" accounts for gas use adjusted results. The most significant difference can be seen in the climate change impact category. Other categories show limited sensitivity to this modelling change. Notably, the impact category ecotoxicity results show a 3% reduction.

While noticeable differences exist, they are not as pronounced as those reported by Soratana et al. (2017). Their study indicated that LPG use contributed 2,76E+01 kg CO_2-Eq/kg of NR, contributing 84% to the climate change impact category results. To accurately interpret this substantial difference, it is essential to note that the findings of Soratana et al. (2017) pertain to the impact of 1 kg of NR. In contrast, the results presented in Table 6.6 are based on a reference flow of 1000 kg of NR.

Table 6.6: Characterization results of sensitivity analysis LPG combustion

EF Impact category v3.1	*Natural rubber (NR)*	*Natural rubber (GUA)*	*% change*	Unit
Climate change	8,52E+02	9,44E+02	11%	kg $CO_{2\ eq}$
Ozone depletion	2,03E-05	2,11E-05	4%	kg CFC-11 eq
Human toxicity, cancer	5,26E-07	5,44E-07	3%	CTUh
Human toxicity, noncancer	1,17E-05	1,19E-05	2%	CTUh
Particulate matter	3,24E-05	3,27E-05	1%	disease incidence
Ionising radiation, human health	1,82E+01	1,92E+01	5%	kBq U^{235}_{eq}
Photochemical ozone formation, human health	3,19	3,22	1%	kg NMVOC eq
Acidification	5,80	5,81	0%	mol H+ eq
Eutrophication, terrestrial	1,13E+01	1,15E+01	2%	mol N eq
Eutrophication, freshwater	3,32E-01	3,38E-01	2%	kg P_{eq}
Eutrophication, marine	1,66	1,68	1%	kg N eq
Ecotoxicity, freshwater	1,97E+04	1,90E+04	-3%	CTUe
Land use	3,30E+05	3,30E+05	0%	Dimensionless (pt)
Water use	4,76E+02	4,78E+02	0%	m^3 water eq of deprived water
Resource use, minerals and metals	1,18E-02	1,20E-02	2%	kg Sb eq
Resource use, fossils	1,32E+04	1,33E+04	1%	MJ

Figure 6.6 shows the normalized characterization results of the NR (GUA) modelling choice in comparison to the other alternatives. The modification of this background process shows a similarly low sensitivity in relation to the PCR alternatives.

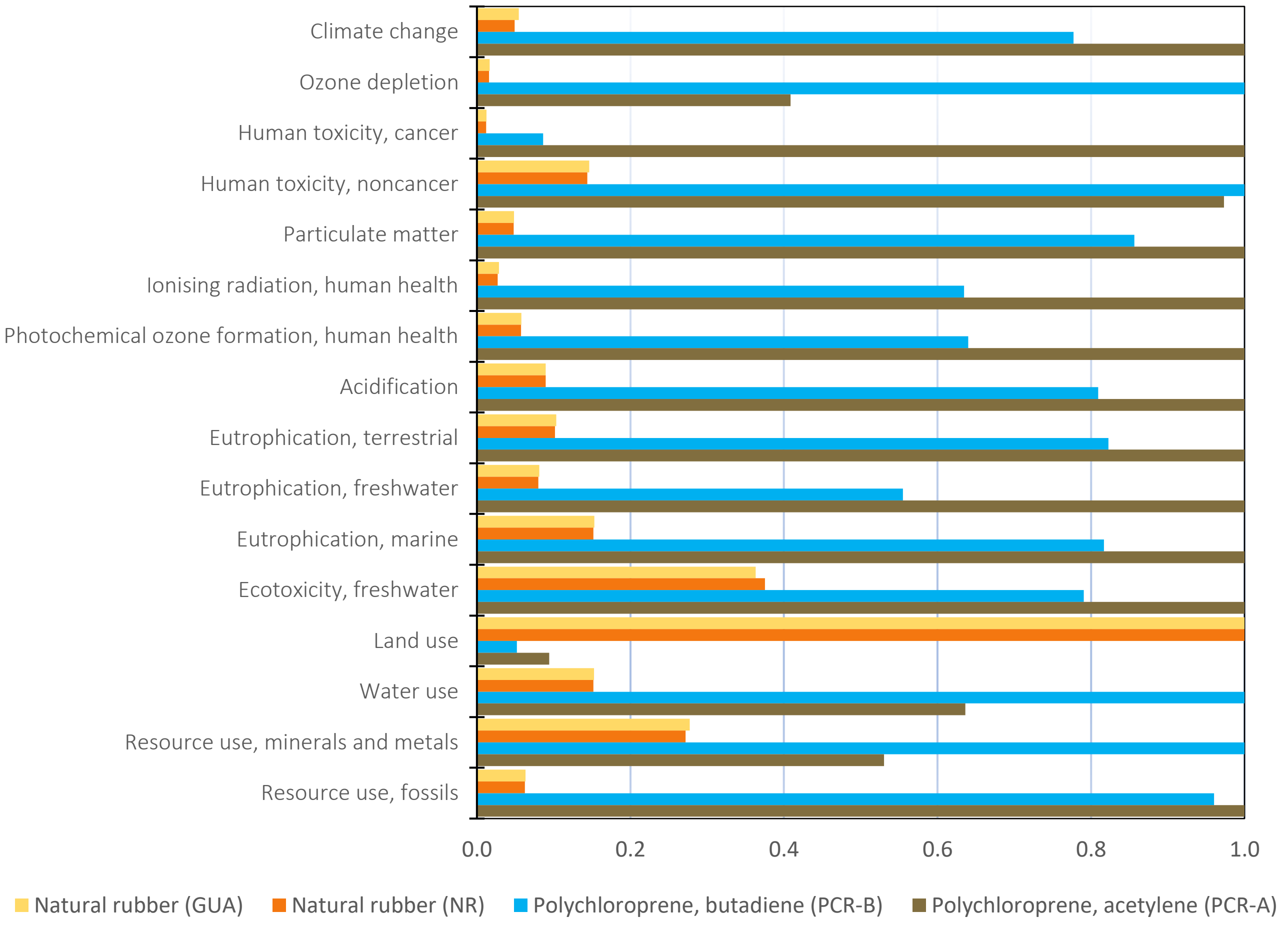


Figure 6.6: Normalized results sensitivity analysis LPG combustion

6.3.4 Biogenic emissions

Important data concerning the NR product system, including process descriptions, quantified inputs, and assumptions regarding biogenic emissions, originate from the research conducted by Jawjit et al. (2010).

Jawjit et al. (2010) introduced two scenarios in their research. Scenario 1 assumes that after 20 years, carbon stocks in rubber plantations reach a new equilibrium, with no net change in carbon stock. Scenario 2 estimates the emissions associated with converting tropical forests to rubber plantations, demonstrating a net carbon loss because tropical forests sequester more carbon than rubber plantations. For this research, scenario 1 was considered as the primary scenario. Through a sensitivity analysis, the effects of scenario 2 on the characterization results are assessed. To evaluate the sensitivity of biogenic emissions on the environmental performance of NR compared to PCR alternatives, the data presented in Table 6.7 (scenario 2) are incorporated as elementary flows into the Hevea agriculture process within the NR product system.

Table 6.7: Biogenic C and N_2O emissions (Jawjit et al., 2010)

Land conversion from forests to rubber plantations *Emission (kg/ton fresh latex)*	*CO_2*	CH_4	N_2O
C above-ground loss	4288	0	0
C below-ground loss	975	0	0
Soil carbon loss	834	0	0
N_2O direct emissions from cultivation of mineral forest soil	0	0	0.24

The characterization results of this sensitivity analysis are presented in Table 6.8. The column “Natural rubber FC” resembles scenario 2, forest conversion. The most significant impacts are observed in the climate change impact category, showing a drastic 508% increase. There are notable increases in the photochemical ozone formation category (6%) and the eutrophication categories, both terrestrial and marine, with 6% and 4% increases respectively.

Table 6.8: Characterization results sensitivity analysis forest conversion (FC)

EF Impact category v3.1	*Natural rubber (NR)*	*Natural rubber (FC)*	*% change*	**Unit**
Climate change	8,52E+02	5,18E+03	508%	kg $CO_{2\ eq}$
Ozone depletion	2,03E-05	2,03E-05	0%	kg CFC-11 $_{eq}$
Human toxicity, cancer	5,26E-07	5,26E-07	0%	CTUh
Human toxicity, noncancer	1,17E-05	1,17E-05	0%	CTUh
Particulate matter	3,24E-05	3,27E-05	1%	disease incidence
Ionising radiation, human health	1,82E+01	1,82E+01	0%	kBq $U^{235}{}_{eq}$
Photochemical ozone formation, human health	3,19	3,36	5%	kg NMVOC $_{eq}$
Acidification	5,80	5,92	2%	mol H+ $_{eq}$
Eutrophication, terrestrial	1,13E+01	1,20E+01	6%	mol N $_{eq}$
Eutrophication, freshwater	3,32E-01	3,32E-01	0%	kg P_{eq}
Eutrophication, marine	1,66	1,73	4%	kg N $_{eq}$
Ecotoxicity, freshwater	1,97E+04	1,97E+04	0%	CTUe
Land use	3,30E+05	3,30E+05	0%	Dimensionless (pt)
Water use	4,76E+02	4,76E+02	0%	m^3 water eq of deprived water
Resource use, minerals and metals	1,18E-02	1,18E-02	0%	kg Sb $_{eq}$
Resource use, fossils	1,32E+04	1,32E+04	0%	MJ

Figure 6.7 presents the normalized characterization results of the sensitivity analysis. The biogenic emission values for scenario 2 (Natural rubber, FC) demonstrate significant sensitivity in the characterization results. But, despite the substantial increase in the climate change impact category, NR FC continues to exhibit the lowest results across nearly all impact categories, except for land use. Given these findings, the overall sensitivity of NR to biogenic emissions can be considered moderate.

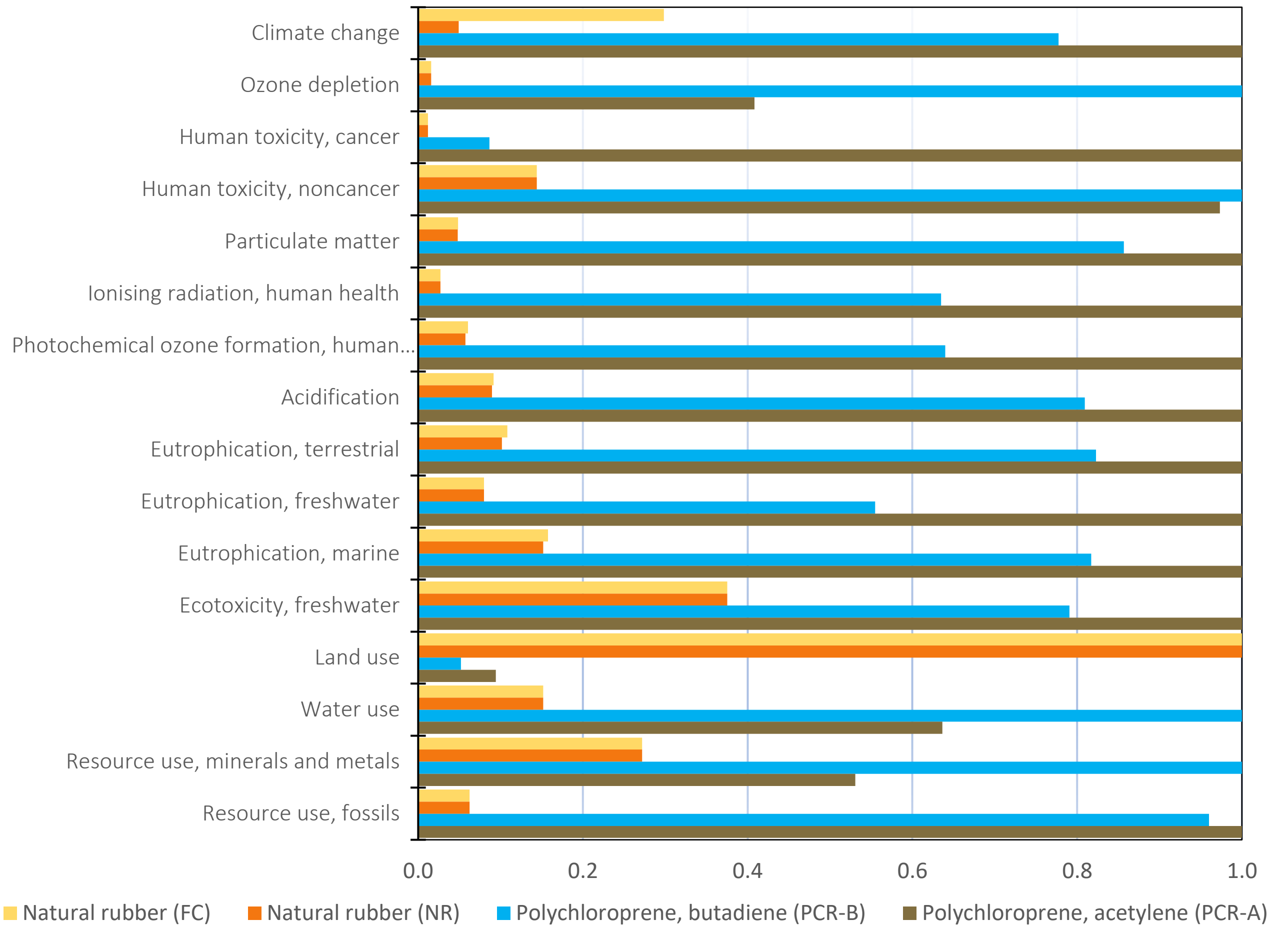


Figure 6.7: Normalized characterisation results sensitivity analysis forest conversion (FC)

6.3.5 Concentrated latex production

This research considered the concentration and purification of fresh latex as necessary steps prior to block rubber production for wetsuits. This assumption was based on sources within the wetsuit industry including Patagonia (2016), Spies (2016) and YULEX (2022). Consequently, this purification step was integrated into the model. However, feedback from an industry expert[4] suggested that this purification step may not be necessary. While the LCA model is based on reported industry practices, a sensitivity analysis was conducted to explore the potential impact of excluding the purification process. This approach allows for a comprehensive assessment, considering both documented procedures and industry expert insights, thereby strengthening the overall analysis.

For this analysis the concentration step was removed from the model and fresh latex was used as input for block rubber production, also representing the coagulation process. The results of this analysis are shown in Table 6.9, column "Natural rubber (FLBR)" shows the characterization results of fresh latex block rubber. The sensitivity analysis reveals that excluding the purification step in rubber production substantially reduces environmental impacts across all categories. With the lowest percent change of 29%, all impact categories show significant decreases. These large differences can partially be explained by the conversion loss accounted for in the concentration process, which assumes a 2:1 conversion of fresh latex to purified latex. This conversion loss is particularly evident in the land use, and resource use, minerals and metals impact category.

Table 6.9: Characterization results sensitivity analysis fresh latex block rubber (FLBR)

EF Impact category v3.1	*Natural rubber (NR)*	*Natural rubber (FLBR)*	*% change*	Unit
Climate change	8,52E+02	4,19E+02	-51%	kg $CO_{2\ eq}$
Ozone depletion	2,03E-05	1,25E-05	-38%	kg CFC-11 $_{eq}$
Human toxicity, cancer	5,26E-07	3,03E-07	-42%	CTUh
Human toxicity, noncancer	1,17E-05	6,73E-06	-43%	CTUh
Particulate matter	3,24E-05	1,80E-05	-45%	disease incidence
Ionising radiation, human health	1,82E+01	1,05E+01	-42%	kBq $U^{235}{}_{eq}$
Photochemical ozone formation, human health	3,19	1,74	-46%	kg NMVOC $_{eq}$
Acidification	5,80	3,09	-47%	mol H+ $_{eq}$
Eutrophication, terrestrial	1,13E+01	5,95	-47%	mol N $_{eq}$
Eutrophication, freshwater	3,32E-01	2,15E-01	-35%	kg P_{eq}
Eutrophication, marine	1,66	1,18	-29%	kg N $_{eq}$
Ecotoxicity, freshwater	1,97E+04	1,32E+04	-33%	CTUe
Land use	3,30E+05	1,65E+05	-50%	Dimensionless (pt)
Water use	4,76E+02	2,03E+02	-57%	m^3 water eq of deprived water
Resource use, minerals and metals	1,18E-02	5,83E-03	-50%	kg Sb $_{eq}$
Resource use, fossils	1,32E+04	7,14E+03	-46%	MJ

---

[4] An experienced materials engineer with significant expertise in the natural rubber polymer industry, who co-authored a patent on methods for making purified natural rubber (Martin & Mithcell, 2022), provided this feedback.

Figure 6.8 shows the normalized characterization results to the highest value of this sensitivity analysis in comparison to the PCR alternatives and NR. The reduction in characterization results is clearly visible in most impact categories. Notably, land use results remain a dominant impact category compared to the PCR alternatives despite the significant reduction. The modelling choice for purification is very sensitive to the characterization results of NR. In comparison to the PCR alternatives, sensitivity is limited, except for the land use impact category.

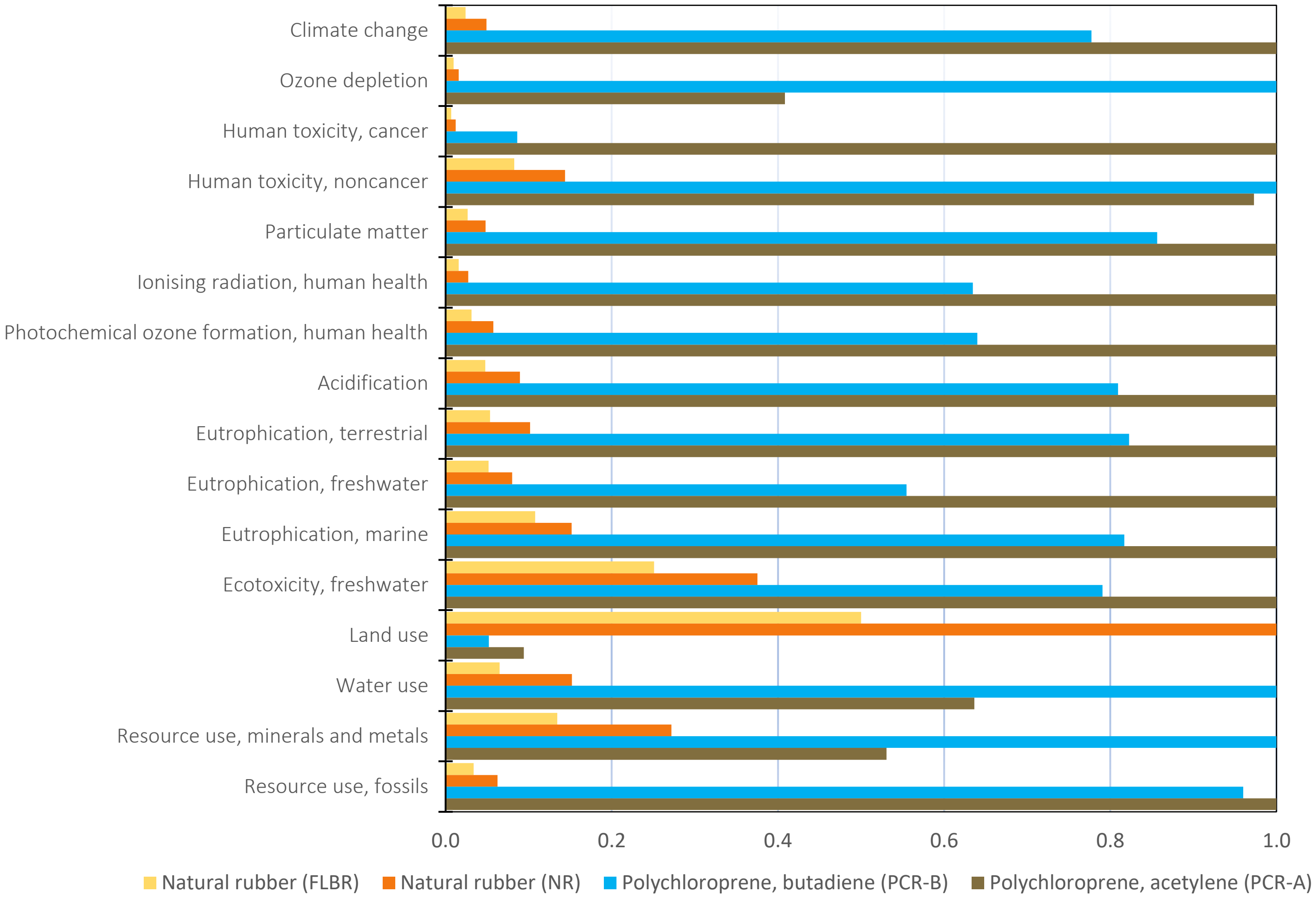


Figure 6.8: Normalized characterisation results sensitivity analysis fresh latex block rubber (FLBR)

6.4 Conclusion

The interpretation phase has resulted in a better understanding of the environmental performance of NR compared to PCR-A and PRC-B over a broad range of impact categories. Further analysis also showed uncertainties related to these results. The insights gathered from this phase provide the information required to answer the two sub research questions that were formulated in the introduction of this report.

1) What are the environmental impacts of natural rubber (NR) compared to polychloroprene rubber variants (PCR-A and PCR-B) across a comprehensive range of impact categories?

Considering a comprehensive range of impact categories, resulting from the EF v3.1 impact assessment method, NR, overall, shows the lowest impact on almost all impact categories, except for land use. PCR-A shows the highest impacts compared the other alternatives. This is due to high energy and resource use in the product system. PCR-B performs slightly better than PCR-A on most impact categories. Further analysis showed that the results of NR in the land use impact category are insensitive to significant changes in fresh latex yield/ha/year. Moderation of the elementary flow representing land use showed similarly small effects on the comparison, suggesting that the higher land use impact for NR is a factor that must be acknowledged in light of its overall better performance across other impact categories. Additionally, modifications of gas use and biogenic emissions stemming from agricultural practices showed notable increases in environmental impacts compared to the NR baseline but did not significantly alter the environmental performance of NR compared to the PCR alternatives. Similarly, a process redesign, excluding the purification of fresh latex, showed a very substantial decrease across all impact categories of the NR system but did not alter the general conclusion of the comparison, even in the land use category.

2) What are the environmental and industrial implications and uncertainties, of substituting polychloroprene rubber (PCR) with natural rubber (NR) in wetsuit production with regards to land use, biogenic emissions and rubber supply at scale?

Substituting PCR with natural rubber NR in wetsuit production would likely pose no significant environmental implications regarding biogenic emissions if the supply stems from FSC-certified rubber plantations. FSC-certified plantations assumably maintain biogenic emissions in equilibrium, avoiding the conversion of tropical forests to rubber plantations. If forests were converted, it would result in significant biogenic emissions to meet annual NR demand, though still considerably less than the kg CO_2 eq./kg emissions from PCR alternatives.

Based on the amount of hectares that were FSC-certified in 2018, and data points used in this research, substitution with FSC-certified NR would only pose industrial implications regarding land use and rubber supply at scale in the worst-case scenario. In this scenario the lowest identified yield is used, and the supply is met solely through domestic production in Thailand. In that case, considering a yield of 1,600 kg/ha/year of fresh latex in, 54% of the domestic supply would be needed to meet the industry's demand, which would be unfeasible considering other industries also require NR. With the highest yield considered (5,640 kg/ha/year), this requirement would drop to 16% of the domestic annual latex supply. On a global scale, the lowest considered yield would require 5% of globally available FSC-certified plantations to meet the industry's annual demand. This figure is notable but not considered problematic, especially as the number of FSC-certified hectares has likely increased since 2018 due to the promotion of FSC-certified plantations.

These results carry significant uncertainty regarding the need for fresh latex purification, as feedback from an industry expert suggested that this processing step might not be necessary. If purification is not required, this modification would dramatically improve all scenarios, given that this research assumes a 2:1 fresh latex to purified latex conversion prior to NR production. This uncertainty, however, would only positively affect all aspects considered in this research question.

7. Discussion

In this chapter, the limitations of this research are discussed in Section 7.1. This is followed by Section 7.2 which provides recommendations for future research.

7.1 Limitations

While this LCA provides valuable insights into the environmental impacts of the rubber alternatives, it is important to acknowledge that the results are not all-encompassing. The inherent subjectivity in selecting system boundaries, data, impact categories, and performing contribution analysis, all influence the outcomes and the interpretation thereof. For this research, efforts have been made to document each data point and report transparently on decisions made to easily interpret the results in the right context. When conducting a cradle-to-gate approach, and thus excluding the use and EOL phase, one always risks overseeing 'hidden' impacts due to 'problem shifting' when, for example, wetsuits reach their EOL (Guinée, 2001). This is a legitimate limitation of this research, as currently, wetsuits often end up as invaluable waste [5].

Another important limitation of this research is that no allocation was performed on the multifunctional processes for the PCR-A system, thus allocating all impacts to the functional unit. As a result of this, the environmental impact of the PCR-A system might be overestimated.

The research on the environmental and industrial implications of substituting PCR for NR is very simplified and only based on limited data points such as, average yield, average latex input per wetsuit, and estimated global annual wetsuit production volumes. It does not take into account economic or industry dynamics. Results should be interpreted considering these limitations and uncertainties.

In the contribution analysis of NR in Section 6.2.1, waste generation and wastewater treatment are identified as environmental challenges related to NR processing. This research does not adequately represent the composition of wastewater and common treatment practices in the NR industry, as it is constructed using background processes representing average treatment processes from EcoInvent. Consequently, the current modelling of the latex concentration process and block rubber production may underestimate the environmental burden associated with these processes.

Through the comparison of this studies' results with similar studies, an underestimation of the impacts associated with LPG use was in the NR product system was identified, caused by a modelling choice in foreground processes. Through sensitivity analysis the impact of this modelling choice was explored and found to be of limited significance in the comparison. Similarly to LPG, diesel was also only considered as an input without combustion. Although the inclusion of combustion of "light fuels" would not alter the comparisons outcomes, it is important to point out that current model underestimates the environmental impact associated with NR production.

---

[5] This is partly due to the construction of the laminated fabric as a composite, making it hard to separate materials. In addition to this, recycling CR itself poses challenges (Kameda et al., 2008). Recently developed large scale operations are limited to downcycling (Innovation Norway, 2023; TerraCycle, 2024), or operations of such a scale use pyrolysis methods to break down EOL wetsuits and produce carbon black which is then used as an ingredient in foam production (Patagonia, 2024b).

7.1.1 Data assumptions / estimates

The purification step in the NR product system which was described by (Martin & Mithcell, 2022), was modelled with inputs for the standard concentrating process for fresh latex provided by (Jawjit et al., 2010 these are assumed to be comparable in yield and inputs. More detailed data on this processing step could alter the results.
Electricity modelled to Vietnam, and background processes, most of the literature related to Thailand. Important supplier sources from both. Assumed it is similar/comparable.

7.1.2 Data gaps

In the PCR-A inventory, electrodes required for calcium carbide were not included as inputs because the composition of the electrodes was unknown. Volatile Organic Compounds (VOC) were mentioned as outputs in the carbide production process but outputs were ignored because the composition was unknown. Particle matter, an output of calcium carbide was excluded because the composition was unknown. Similarly, brine make up was excluded because no representative background process was available. It is expected that inclusion of this data would increase the environmental burden of PCR-A.

7.1.3 Recycling / by-products

Process descriptions of CR and PCR production show internal recycling processes including recovering unreacted CR and storage. This is ignored for simplicity, assuming input ultimately equals output.
Allocation on the by-products produced in the PCR-A system could potentially lower the environmental impact.

7.2 Recommendations for future research

This study has provided valuable insights into product systems that have not previously been assessed for wetsuit production, future research could build upon these findings by including the use and EOL phases, and performing a detailed LCA. Given that current technology does not yet allow for full recyclability, it would be beneficial to understand the environmental costs of current disposal methods, such as incineration with partial input recovery, or downcycling, as a benchmark for future advancements. A comprehensive future LCA should also aim to incorporate the waste streams of water and solid waste involved in the NR product system, as this issue is well-documented in the literature. Additionally, future studies could consider the various additives used in the rubber compounding process, which involves multiple chemical or bio-based materials. It would be particularly interesting to assess the environmental impacts of these additives compared to the entire constructed wetsuit. By addressing these areas, future research can provide a more holistic understanding of the environmental footprint of wetsuit production and identify opportunities for improvement.

8. Conclusion

Wetsuit manufacturing has been reliant on the synthetic rubber material PCR for its insulative core since its invention of the wetsuit in 1951. PCR is produced from the intermediate chemicals butadiene and acetylene. The production process of PCR is resource and energy-intensive, and requires large chemical production facilities, which directly and indirectly emit GHG emissions and process hazardous substances. Since 2016, a NR alternative, harvested from the Hevea brasilensis was introduced to the wetsuit industry, aiming to reduce the environmental impacts associated with rubber use. However, current literature and claims made regarding environmental performance, lack comprehensive comparative quantitative assessment, showing knowledge gaps in impact categories considered and partial coverage of production processes. Additionally, little information is documented on the implications and uncertainties involved of substituting PCR for NR. The goal of this study is to improve the assessment of the environmental performance of NR, PCR-A, and PCR-B, and to explore the environmental and industrial implications of substituting PCR with NR.

In this study, the rubber alternatives mentioned were assessed for their environmental impacts over a broad range of impact categories. This was done through a comparative cradle-to-gate LCA. Considering the raw material extraction and rubber production life cycle stages. The functional unit was 1000 kilogram of rubber, suitable for wetsuit production. The research question is:

How does the environmental performance of natural rubber (NR) compare to that of polychloroprene rubber variants (PCR-A and PCR-B) across a comprehensive range of impact categories, and what are the implications of substituting PCR with NR for wetsuit production regarding land use, biogenic emissions, and rubber supply at scale?

To answer this question, two sub question were formulated. The first question had to clarify how the environmental impacts of the alternative compared. This was determined by assessing the characterization results through contribution and sensitivity analysis. NR showed the lowest impact across almost all categories, except for land use. PCR-A showed the highest impacts compared to the other alternatives. PCR-B performed slightly better but also showed the highest results in several categories. Land use modifications did not alter the comparison for this impact category, showing that this impact of NR is high in contrast to PCR alternatives. Under all sensitivities and other impact categories considered, NR consistently showed the lowest impact results.

The second question explored the uncertainty that would entail complete substitution of PCR for NR regarding biogenic emissions, land use, and rubber supply at scale. Substitution would likely not affect biogenic emissions because the wetsuit industry has already adopted FSC certified supply. FSC certified plantations likely balance biogenic emissions, unlike converting forests, which would significantly increase emissions, though still less than PCR alternatives. Industrial implications would likely only arise in a worst-case scenario, using the lowest yield (1,600 kg/ha/year), 54% of Thailand's domestic supply would be needed, which is impractical given other industries' demand for NR. With the highest yield (5,640 kg/ha/year), this drops to 16%. Globally, the lowest yield would require 5% of FSC-certified plantations, which is manageable, especially as FSC-certified land has likely increased since 2018. Uncertainty exists regarding the necessity of purifying fresh latex. If purification is unnecessary, the scenarios improve significantly, as the study assumed a 2:1 fresh to purified latex conversion. This uncertainty would only positively impact the research findings. To conclude, the results of this assessment show that NR has the potential to substitute PCR as a lower burden alternative without significant implications concerning biogenic emissions and rubber supply, though land use may be a potential complicating factor.

This LCA study has several limitations that need to be taken into consideration when interpreting the results. The cradle-to-gate approach excludes the use and EOL phases, this may result in some impacts being overlooked. The lack of allocation in multifunctional processes for the PCR-A system potentially lead to overestimated environmental impacts. Additionally, the simplified analysis substitution exploration, based on limited data points, does not consider economic or industry dynamics, which calls for careful interpretation of the results. The study's generalized representation of NR processing may underestimate its environmental burden due to certain data and modelling choices. Data gaps and assumptions, especially those related to wastewater treatment, purification steps, and emissions, further limit the findings. Future research should aim to address these limitations by including the use and EOL phases, providing more detailed data on waste streams and additives, and exploring recycling and by-product allocations to achieve a more comprehensive understanding of the environmental impacts of wetsuit production.

References

Allen, P. W. (2004). NON-WOOD PRODUCTS | Rubber Trees. In J. Burley (Ed.), *Encyclopedia of Forest Sciences* (pp. 627–633). Elsevier. https://doi.org/10.1016/B0-12-145160-7/00260-X

ARLANXEO. (2024). *Chloroprene Rubber | ARLANXEO*. Chloroprene Rubber. https://www.arlanxeo.com/en/families/cr

ASCC. (2010). *Calcium Carbide—Detailed Project Report* (Version 1.0). https://www.ascconline.com/img/services/project_report/Calcium_Carbide_Project_Report_Sample.pdf

Bare Sports. (2024). *Drysuit materials*. https://www.baresports.com/drysuit-materials/

Bryja, J. (2023, August 23). Wetsuit Buyer's Guide: The Rise of Yamamoto Limestone Rubber. *Kitesurfing Magazine*. https://kitesurfingmag.com/wetsuit-buyers-guide-the-rise-of-yamamoto-limestone-rubber/

Busvold, M. H. (2023). *Thermal properties of neoprene and natural rubber in wetsuits* [Master thesis, UiT The Arctic University of Norway]. https://munin.uit.no/handle/10037/30643

Chandrasekaran, V. C. (2007). *Essential rubber formulary formulas for practitioners*. William Andrew Pub.

Chung, O. (2022, July 1). Making a Splash. *Taiwan Today*. https://taiwantoday.tw/news.php?unit=8&post=222080

Circle One. (2024). *What is Limestone Neoprene—Circle One Sustainability*. https://www.circle-one.com/blog/general-news/what-is-limestone-neoprene/

Copeland, T. (2008). *Developing Our First Wetsuit—That's Also Sustainably Made—Patagonia Stories*. https://www.patagonia.com/stories/green-neoprene/story-20409.html

Curran, M. A. (2014). Strengths and Limitations of Life Cycle Assessment. In W. Klöpffer (Ed.), *Background and Future Prospects in Life Cycle Assessment* (pp. 189–206). Springer Netherlands. https://doi.org/10.1007/978-94-017-8697-3_6

Daiwabo. (2024a). *Business Locations and Group Companies | Company Information | Daiwabo Co., Ltd.* https://www.daiwabo.co.jp/en/company/base-group/#al-section2

Daiwabo. (2024b). *Product Info*. https://www.daiwabo.co.jp/product/uses/industrial-materials/

Decathlon. (2024). *DECATHLON UNVEILS YULEX100*. https://www.decathlon-united.media/pressfiles/decathlon-unveils-yulex100

Denka. (2022). *The Denka Way* (Volume 10). https://www.denka.co.jp/eng/pdf/corporate/thedenkaway/thedenkaway_2022_winter.pdf

Denka. (2023). *Denka Performance Elastomer LLC*. https://denka_sustainability.disclosure.site/en/themes/615

ECHA. (2023, June 9). *Substance Information—2-chlorobuta-1,3-diene*. https://echa.europa.eu/substance-information/-/substanceinfo/100.004.381

EcoInvent. (2022). *Butadiene production* [dataset]. https://ecoquery.ecoinvent.org/3.9.1/cutoff/dataset/1495/documentation

EPA. (2023, February 28). *EPA and Justice Department File Complaint Alleging Public Health Endangerment Caused by Denka Performance Elastomer's Carcinogenic Air Pollution* [News Release]. https://www.epa.gov/newsreleases/epa-and-justice-department-file-complaint-alleging-public-health-endangerment-caused

EPA. (2024, February 7). *EPA finalizes stronger standards for harmful soot pollution, significantly increasing health and clean air protections for families, workers, and communities* [News Release]. https://www.epa.gov/newsreleases/epa-finalizes-stronger-standards-harmful-soot-pollution-significantly-increasing

European Commission. (2021). Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. In *OJ L* (Vol. 471). http://data.europa.eu/eli/reco/2021/2279/oj/eng

European Rubber Journal. (2018). *New chloroprene rubber capacity emerges in China*. https://www.european-rubber-journal.com/article/2066875/new-chloroprene-rubber-capacity-emerges-in-china

Fact.MR. (2023). *Wetsuit Market Forecast by Product Type*. https://www.factmr.com/report/856/wetsuit-market

Finnisterre. (2024). *Women's Nieuwland 5s Yulex Hooded Wetsuit in Ink*. Finisterre. https://finisterre.com/products/womens-taped-5mm-hooded-yulex-ink

Forbes. (2014). *Warm Even In Chilly Waters, Taiwan's Sheico Group Dominates The Wet Suit Market*. Forbes. https://www.forbes.com/sites/forbesasia/2014/08/27/taiwans-sheico-group-dominate-in-water-sports/

Forest Stewardship Council. (2018). *FSC welcomes Thai Government's support on certifying rubber under FSC certification scheme*. Forest Stewardship Council. https://asiapacific.fsc.org/newsfeed/fsc-welcomes-thai-governments-support-on-certifying-rubber-under-fsc-certification-scheme

Forest Stewardship Council. (2020). *Factsheet New Approaches project*. https://fsc.org/sites/default/files/2020-04/FSC%20NA%20Factsheet%20-%20Value%20chain%20approach%20for%20Smallholder%20produced%20natural%20rubber%20latex%20-%20FINAL%20TI.pdf

Global Industry Analysts. (2022). *Global Chloroprene Rubber Market to Reach 324.8 Thousand Metric Tons by 2026*. https://www.prnewswire.com/news-releases/global-chloroprene-rubber-market-to-reach-324-8-thousand-metric-tons-by-2026--301502447.html

Go Viet. (2018). *Vietnam Rubber Industry: Current status and sustainable development solutions*. https://goviet.org.vn/bai-viet/vietnam-rubber-industry-current-status-and-sustainable-development-solutions-9039

Guinée, J. (2001). Handbook on life cycle assessment—Operational guide to the ISO standards. *The International Journal of Life Cycle Assessment*, *6*(5), 255–255. https://doi.org/10.1007/BF02978784

Hilmi, Y. S., Komarudin, N. A., & Tarigan, E. B. (2021). Relationship between Economy and Environment of the Natural Rubber Plantation in Major Producers. *E3S Web of Conferences*, *305*, 05001. https://doi.org/10.1051/e3sconf/202130505001

Holmström, E., & Mattsson, J. (2019). *Thermal and Mechanical Analysis of a Sustainable Alternative to Neoprene Wetsuits*. http://lup.lub.lu.se/student-papers/record/8968209

Huo, H., Liu, X., Wen, Z., Lou, G., Dou, R., Su, F., Fang, J., & Jiang, Z. (2022). Life cycle assessment and sustainable production evaluation of calcium carbide industry in China. *Journal of Cleaner Production*, *360*, 132176. https://doi.org/10.1016/j.jclepro.2022.132176

Innovation Norway. (2023, February). *Bulgaria: Recycled Neoprene for Wetsuits in a Circular Economy Approach to Water Sports: The WavErest Method*. https://www.innovasjonnorge.no/en/start-page/eea-norway-grants/success-stories/bulgarianeoprene-recycling-for-circular-economy-the-waverest-method/

Integrity Chemicals Co. (2022). *Factory*. https://www.integrity-chem.com/?about_16/

IPCC. (2023). *Summary for Policymakers* (Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change).

JAKO. (n.d.-a). *History | JAKO CHEMICAL*. Retrieved March 14, 2024, from http://www.jakochem.com/company/history.php

JAKO. (n.d.-b). *Technology | JAKO CHEMICAL*. Retrieved May 7, 2024, from http://www.jakochem.com/products/technology.php

Jawjit, W., Kroeze, C., & Rattanapan, S. (2010). Greenhouse gas emissions from rubber industry in Thailand. *Journal of Cleaner Production*, *18*(5), 403–411. https://doi.org/10.1016/j.jclepro.2009.12.003

Jawjit, W., Pavasant, P., & Kroeze, C. (2015). Evaluating environmental performance of concentrated latex production in Thailand. *Journal of Cleaner Production*, *98*, 84–91. https://doi.org/10.1016/j.jclepro.2013.11.016

Jawjit, W., Pavasant, P., Kroeze, C., & Tuffrey, J. (2021). Evaluation of the potential environmental impacts of condom production in Thailand. *Journal of Integrative Environmental Sciences*, *18*(1), 89–114. https://doi.org/10.1080/1943815X.2021.1949354

Jobe Sports. (2019, August 13). *The benefits of Limestone neoprene*. Jobe Sports International. https://www.jobesports.com/nl/blog/the-benefits-of-limestone-neoprene-2872/

Kameda, T., Watanabe, Y., Grause, G., & Yoshioka, T. (2008). Dehydrochlorination behavior of polychloroprene during thermal degradation. *Thermochimica Acta*, *476*(1), 28–32. https://doi.org/10.1016/j.tca.2008.07.004

Kędzia, J. R., Sitko, A. M., Haponiuk, J. T., Lipka, J. K., Kędzia, J. R., Sitko, A. M., Haponiuk, J. T., & Lipka, J. K. (2022). Natural Rubber Latex—Origin, Specification and Application. In *Application and Characterization of Rubber Materials*. IntechOpen. https://doi.org/10.5772/intechopen.107985

Kongmanee, C., Ahmed, F., & Longpichai, O. (2020). Cost-Benefit Analysis and Challenges of Implementing FSC Standards in Rubber Plantations in Southern Thailand. *The Journal of Asian Finance, Economics and Business*, *7*(12), 423–431. https://doi.org/10.13106/jafeb.2020.vol7.no12.423

Lynch, M. (2001). Manufacture and use of chloroprene monomer. *Chemico-Biological Interactions*, *135–136*, 155–167. https://doi.org/10.1016/s0009-2797(01)00188-0

Martin, J. A., & Mithcell, S. J. (2022). *Methods for Making Purified Natural Rubber and Compositions*. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2022006393&_cid=P12-LUX0JW-92594-1

Mitchell, C. (2011). High purity limestone quest. *Industrial Minerals*, *531*, 48–51.

Naebe, M., Robin, N., Wang, X., & Collins, P. (2013). *Assessment of performance properties of wetsuits*. https://doi.org/10.1177/1754337113481967']

Nam Liong. (2024a). *Factory Profile | High-Tech, Functional, Green Textile Fabrics & Foam Composite Materials Manufacturer Since 1972 | Nam Liong*. Nam Liong Global Corporation,Tainan Branch. https://www.namliong.com.tw/en/page/factory-profile.html

Nam Liong. (2024b). *Oeko-Tex standard 100 Certificated Rubber Foam Laminate*. https://www.namliong.com.tw/en/product/eco-friendly-rubber-sponge.html

Nam Liong. (2024c). *USDA Certified Bio-Based Rubber Sponge For Greener Wetsuit*. Nam Liong Global Corporation. https://technical-fabric.namliong.com.tw/en/page/BIO-II-USDA-Certified-Bio-Based-Rubber-Sponge-For-Greener-Wetsuit/biobased-neoprene.html

Nankaigosen. (n.d.). *Durable High Stretch Wetsuit Liners | Nankaigosen | Wetsuit Materials*. Retrieved June 11, 2024, from https://www.nankaigosen.com

National Toxicology Program. (2021). Chloroprene. In *15th Report on Carcinogens [Internet]*. National Toxicology Program. https://www-ncbi-nlm-nih-gov.tudelft.idm.oclc.org/books/NBK590875/

Navodya, U., Keenawinna, G., & Gunasekera, U. (2020, September 10). *The Development of Sustainable Alternative to Neoprene Wetsuit Fabric*. https://doi.org/10.1109/MERCon50084.2020.9185195

Nguyen, H. N., & Luong, T. T. (2012). Situation of wastewater treatment of natural rubber latex processing in the Southeastern region, Vietnam. *Journal of Vietnamese Environment*, *2*(2), 58–64. https://doi.org/10.13141/jve.vol2.no2.pp58-64

Norris, S. R. (1945). *The Chemical Process Industries* (International student edition). Mcgraw-hill Book Company, Inc. New York. https://dl.icdst.org/pdfs/files1/eff2b8e8743e1059b04e4e665fa876b6.pdf

Park, S. A. (2020). *Neoprene: The Inside Story*. https://www.seventhwave.co.nz/blogs/library/neoprene-the-inside-story

Pässler, P., Hefner, W., Buckl, K., Meinass, H., Meiswinkel, A., Wernicke, H.-J., Ebersberg, G., Müller, R., Bässler, J., Behringer, H., & Mayer, D. (2011). Acetylene. In *Ullmann's Encyclopedia of Industrial Chemistry*. John Wiley & Sons, Ltd. https://doi.org/10.1002/14356007.a01_097.pub4

Patagonia. (2016). *The future of wetsuits*. https://issuu.com/thecleanestline/docs/patagonia-the-future-of-wetsuits?e=1043061/38029799

Patagonia. (2024a). *Men's R3® Wetsuits: Cold Water Wetsuits by Patagonia*. https://www.patagonia.com/shop/gear/wetsuits/mens/r3

Patagonia. (2024b, June 13). *PATAGONIA DEVELOPS FIRST END-OF-LIFE SOLUTION FOR WETSUITS*. Patagonia Works. https://www.patagoniaworks.com/press/2024/6/13/patagonia-develops-first-end-of-life-solution-for-wetsuits

Podong, C. (2014). Estimate of soil organic carbon and greenhouse gas emissions in para rubber (Hevea brasiliensis Mull. Arg) plantation by DNDC model in Upland Area Northern, Thailand. *Computational Ecology and Software*, *4*(4), 269–275. https://doi.org/10.0000/issn-2220-721x-compuecol-2014-v4-0019

Possess Sea. (n.d.). *Neoprene Sponge Manufacturer*. Possess Sea. Retrieved May 7, 2024, from https://www.neoprene.asia/neoprene_sponge.html

Possess Sea. (2024). *Neoprene Derivatives Products Manufacturer*. https://www.possesssea.com/index.html

Rainey, C. (1998). *Wet Suit Pursuit: Hugh Bradner's Development of the First Wet Suit*. https://escholarship.org/uc/item/7353g3dj

Resonac. (2024). *Chloroprene*. Resonac Asia Pacific. https://www.ap.resonac.com/product/chloroprene/

Rip Curl. (2022). *Social Compliance*. https://www.ripcurl.com/us/explore/social-compliance.html

Rip Curl International. (2021). *Rip Curl Countries of Production*. https://www.ripcurl.com/media/wysiwyg/explore/Policies/Rip_Curl_Countries_of_Production.pdf

Rubber Journal Asia. (2018, May 18). *Denka to increase production of CR by 10,000 tonnes*. Rubber Journal Asia- News on Rubber Machinery , Manufacturers , Rubber Chemical Producers and Rubber Processors. https://rubberjournalasia.com/denka-to-increase-production-of-cr-by-10000-tonnes/

Rubber News. (2012, November 14). *Showa Denko strives to make bigger inroads in latex industry*. Rubber News. https://www.rubbernews.com/article/20111011/NEWS/310119994/showa-denko-strives-to-make-bigger-inroads-in-latex-industry

Rubber News. (2019, October 8). *Arlanxeo upgrades sites in Germany, France*. Rubber News. https://www.rubbernews.com/suppliers/arlanxeo-upgrades-sites-germany-france

Schobert, H. (2014). Production of Acetylene and Acetylene-based Chemicals from Coal. *Chemical Reviews*, *114*(3), 1743–1760. https://doi.org/10.1021/cr400276u

Seaskin. (2024). *Company Profile-Professional surfing wetsuits, scuba diving wetsuits,swimwear,shenzhen seaskin wetsuit manufacturer*. https://www.sea-skin.com/company-profile/

Shanxi Synthetic Rubber Group. (2024). *Introduction*. http://www.lxsx.chemchina.com/sxjten/27687.html

SHEICO. (2023). *Location—SHEICO - The Professional Sportswear Manufacturer*. https://www.sheico.com/en-ww/about/location.php

SHEICO Group. (n.d.). *Company—SHEICO - The Professional Sportswear Manufacturer*. Retrieved June 23, 2023, from https://sheico.com/en-ww/about/about.php?pid=1

SHEICO Group. (2017). *ECO-flyer_2018.pdf*. https://www.eliossub.com/wp-content/uploads/2018/10/ECO-flyer_2018.pdf

SHEICO Group. (2023). *News—SHEICO - The Professional Sportswear Manufacturer*. https://www.sheico.com/en-ww/news/news.php

Shlyapin, D. A., Afonasenko, T. N., Glyzdova, D. V., Leont'eva, N. N., & Lavrenov, A. V. (2022). Acetylene Production Technologies in the 21st Century: Main Trends of Their Development in the Paradigm of Low-Carbon Economy of the Future. *Catalysis in Industry*, *14*(3), 251–267. https://doi.org/10.1134/S2070050422030023

Smith, J. K. (1985). The Ten-Year Invention: Neoprene and Du Pont Research, 1930-1939. *Technology and Culture*, *26*(1), 34–55. https://doi.org/10.2307/3104528

Soratana, K., Rasutis, D., Azarabadi, H., Eranki, P. L., & Landis, A. E. (2017). Guayule as an alternative source of natural rubber: A comparative life cycle assessment with Hevea and synthetic rubber. *Journal of Cleaner Production*, *159*, 271–280. https://doi.org/10.1016/j.jclepro.2017.05.070

Spies, A. (2016, September 20). *Interview: Hub Hubbard über die neoprenfreien Wetsuits von Patagonia*. Surfmagazin | Travel Magazin | BLUEMAG. https://www.bluemag.eu/surfmagazin-features/interview-hub-hubbard-ueber-die-neoprenfreien-wetsuits-von-patagonia

SRFACE. (2024a). *Men's Remix Yamamoto Wetsuit | SRFACE® | The Ultimate Wetsuit For Every Surfer*. SRFACE®. https://srface.com/shop/mens-yamamoto-wetsuit/

SRFACE. (2024b). *SRFACE Wetsuit Warranty | The Ultimate Wetsuit Made Affordable*. SRFACE®. https://srface.com/warranty/

SRFACE. (2024c). *What Is Limestone Neoprene?* https://srface.com/what-is-limestone-neoprene/

Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser—An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*, 100012. https://doi.org/10.1016/j.simpa.2019.100012

Temperley, E. (2023, December 1). A Flex: How Yulex Cleaned Up the Wetsuit Business. *A Flex: How Yulex Cleaned up the Wetsuit Business*. https://wavelengthmag.com/a-flex-the-yulex-story/

TerraCycle. (2024). *Rip Curl Wetsuit Free Recycling Program*. TerraCycle. https://www.terracycle.com/en-AU/brigades/ripcurl-au

Teske, S. (2022). *Achieving the Paris Climate Agreement goals. Part 2, Science-based target setting for the finance industry—Net-zero sectoral 1.5°C pathways for real economy sectors* (1–1 online resource (lxxviii, 384 pages) : illustrations (chiefly color)). Springer. https://doi.org/10.1007/978-3-030-99177-7

The Big Sea. (2024). *The Big Sea*. The Big Sea. https://thebigsea.org/

The World Bank. (2015). *Assessment of Technical and Financial Viability of Nairit Chemical Plant Operation*. https://documents1.worldbank.org/curated/zh/850081468185353880/99259-WP-PUBLIC-Box393196B.docx

Tosoh Corporation. (2014). *Chloroprene rubber—Skyprene*. https://www.tosoheurope.com/our-products/specialty-polymers/brochures

UOO. (2022, July 21). *Neoprene Sheet | UooSport*. https://uoosport.com/neoprene-sheet

UOO. (2023, April 24). *UOO Factories Organizational Structure | UooSport*. https://uoosport.com/uoo-factories-organizational-structure/

Warshaw, M. (2010). *The History of Surfing*. Chronicle Books.

Wavelength Surf Magazine. (2023, July 10). The Surf Industry Responds To The Big Sea Documentary. *Wavelength Surf Magazine - since 1981*. https://wavelengthmag.com/the-surf-industry-responds-to-the-big-sea-documentary/

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., & Wernet, G. (2013). *Overview and methodology. Data quality guideline for the ecoinvent database version 3* (Ecoinvent Report 1(v3)). Swiss Centre for Life Cycle Inventories. https://ecoinvent.org/app/uploads/2024/02/dataqualityguideline_ecoinvent_3_20130506_.pdf

Weissermel, K., & Arpe, H.-J. (2003). *Industrial organic chemistry* (4th completely rev. ed). Wiley-VCH.

Wellpower Sporting Goods. (n.d.). *Natural rubber*. Retrieved May 17, 2024, from http://www.wellpowersports.com/pd_products.php?m1=61

Wetop. (2024). *Custom Made Wetsuit, Diving Equipment Manufacturer*. Xiamen Wetop Sports Co., Ltd. https://www.wetopsports.com/about-us/

White, Wm. C. (2007). Butadiene production process overview. *Chemico-Biological Interactions*, *166*(1), 10–14. https://doi.org/10.1016/j.cbi.2007.01.009

YAMAMOTO. (n.d.). *Limestone Rubber*. Retrieved May 7, 2024, from https://yamamoto-bio.com/material-e/sus2.html

YAMAMOTO. (2024). *Yamamoto Chemical Industry Co., Ltd. - Company Profile* -. https://yamamoto-bio.com/company.html

YULEX. (2022). *Chronicle 11: What is YULEX PURE? | YULEX®*. https://www.yulex.com/post/chronicle-11-what-is-yulex-pure

YULEX. (2023a). *Chronicle 18: Tetsuya Ohara*. https://www.yulex.com/post/chronicle-18-tetsuya-ohara

YULEX. (2023b). *Chronicle 19: CO2e Emissions of Natural Rubber, Neoprene, Geoprene and SBR | Yulex*. https://www.yulex.com/post/rubber-chronicle-19-co2e-emissions-of-natural-rubber-neoprene-geoprene-and-sbr

Yulex. (2023). *Responsibility | YULEX*. https://www.yulex.com/responsibility

YULEX. (2023c). *YULEX® PRIME Natural Rubber Solid Technical Data Sheet*. https://www.yulex.com/product-downloads

YULEX. (2023d). *Yulex Announces Equitable Agriculture, a Smallholder Profit-Sharing Program for Natural Rubber | YULEX®*. https://www.yulex.com/post/yulex-announces-equitable-agriculture-a-smallholder-profit-sharing-program-for-natural-rubber

Zhang, S., Li, J., Li, G., Nie, Y., Qiang, L., Bai, B., & Ma, X. (2021). Life cycle assessment of acetylene production from calcium carbide and methane in China. *Journal of Cleaner Production*, *322*, 129055. https://doi.org/10.1016/j.jclepro.2021.129055

A. Supplier overview

Research into the wetsuit production value chain of wetsuit production revealed the geographic distribution shown in Figure A.1. Three different production stages are distinguished: first, rubber production, which represents production operations of NR, PCR-A, and PCR-B. Secondly, expanded foam production. Thirdly, wetsuit production, representing large scale cutting and assembly facilities. The numbers indicate entities present in that country and do not account for multiple production locations in the same country. The same entity can be present in multiple countries. All identified entities are summarized in Table A.1.

The wetsuit industry is predominantly centred around Asia. There are only two PCR producers outside of Asia: one located in Germany and one in the US. Multiple expanded foam producers process NR as well as PCR, because it uses the same manufacturing equipment and the technology is available (Temperley, 2023). One NR supplier was identified with clear links to the wetsuit industry. Supply from this company arrives from Thailand and Vietnam. These rubber production operations consist of far more entities as the rubber supply chain is much more diversified than the supply chain of PCR. No entity was identified that controlled the entire value chain from raw material processing to wetsuit production. Two companies vertically integrated expanded foam production and wetsuit production within their entities. Thereby decreasing dependency and increasing possibilities for own development (Nam Liong, 2024a; SHEICO Group, n.d.).

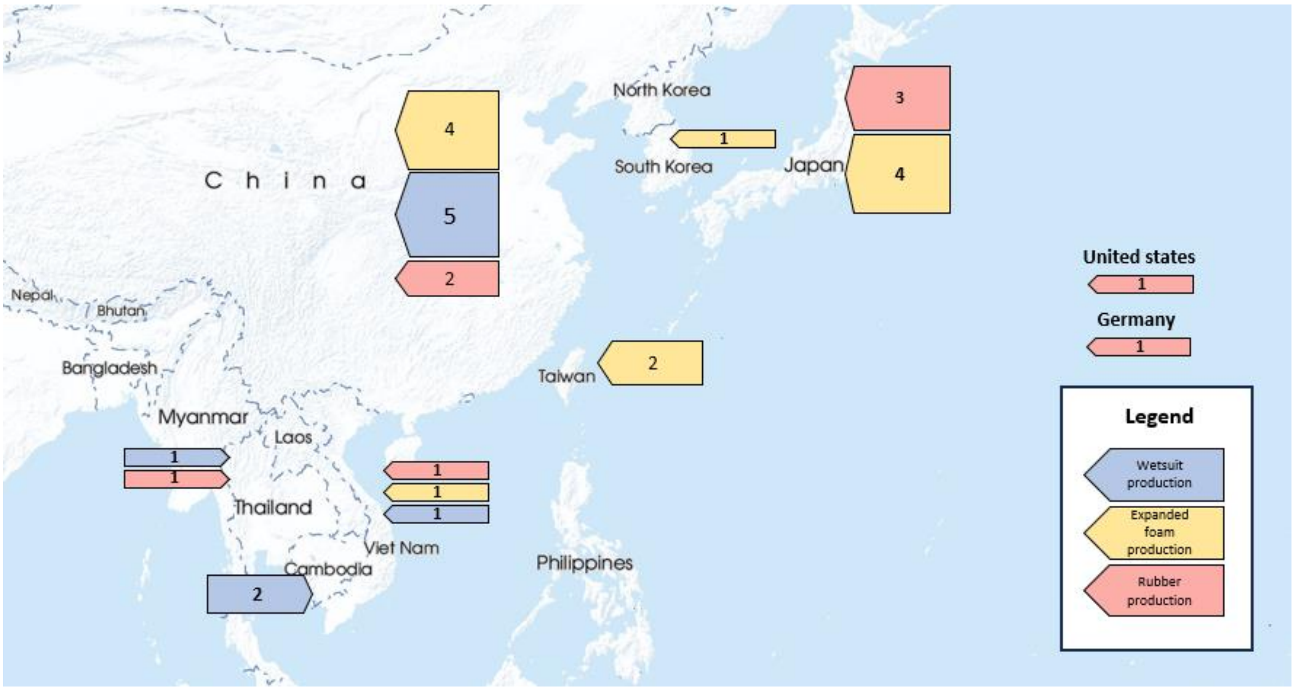


Figure A.1: Geographic distribution of key wetsuit production stages across Asia and rest of world

Table A.1: Overview of manufacturers in the wetsuit supply chain

Wetsuit production				
Corporation	Location(s)	Comments		Source
Sheico	Thailand, Rayong Cambodia, Pnohm Penh Cambodia, Svay Rieng Vietnam, Ho Chi Minh	OEM finished products		(SHEICO, 2023)
Posess Sea	China, Huicheng	OEM finished products		(Possess Sea, 2024)
Wetop	China, Xiamen	OEM finished products		(Wetop, 2024)
UOO	China, Jiangsu	OEM finished products		(UOO, 2023)
Seaskin	China, Dongguan	OEM finished products		(Seaskin, 2024)
On Smooth Thai	Thailand, Chaingmai	Wetsuit production		(Rip Curl, 2022)
Wellpower Sporting Goods	China, Dong Guan	OEM finished products		(Wellpower Sporting Goods, n.d.)
Expanded fabric rubber production / slicing / lamination				
Corporation	Location(s)	Type of material	Comments	Source
Sheico	Taiwan, Yilan County	Natural rubber / chloroprene rubber	Knitting mill and neoprene plant	(SHEICO, 2023)
Yamamoto	Japan, Okayama Japan, Osaka	Chloroprene rubber, acetylene	Foam production, slicing, lamination	(YAMAMOTO, 2024)
Nankaigosen	Japan, Wakayama	Chloroprene rubber, acetylene	Slicing, lamination	(Nankaigosen, n.d.)
Nam Liong	Taiwan, Yongkang Vietnam, Binh Duong China, Guangdong	Natural rubber / chloroprene rubber / styrene butadiene rubber	Foam production, slicing, lamination	(Nam Liong, 2024a)
UOO industry	China, Dongguan	Natural rubber / chloroprene rubber, acetylene, butadiene / styrene butadiene rubber	Slicing, lamination	(UOO, 2023)
Jako	South Korea, Busan	Chloroprene rubber, acetylene	Foam production, slicing	(JAKO, n.d.-a)
Posess Sea	China, Guangdong	Chloroprene rubber, butadiene, acetylene	Slicing, lamination	(Possess Sea, 2024)
Daiwabo	Japan, Hyogo	Chloroprene rubber, butadiene / styrene	Foam production	(Daiwabo, 2024b, 2024a)
Wellpower Sporting Goods	China, Dong Guan	Natural rubber	Foam production	(Wellpower Sporting Goods, n.d.)
Natural and synthetic rubber production				
Corporation	Location(s)	Type of material	Comments	Source
Denka	Japan, Niigatta United states, Louisiana	Acetylene – limestone Butadiene- ethylene		(Denka, 2022, 2023)
Yulex	Vietnam,- Thailland,-	Natural rubber	Partner factories, block rubber production, latex purification	(Yulex, 2023)
Shanna Synthetic Rubber	China, Datong, Shanxi	Acetylene – limestone		(European Rubber Journal, 2018; Lynch, 2001; Shanxi Synthetic Rubber Group, 2024)
Huojia Changshou Chemical	China, Changzhi, Shanxi	Acetylene- limestone		(European Rubber Journal, 2018; Integrity Chemicals Co., 2022; Lynch, 2001)
Tosoh	Japan, Shinnanyo	Butadiene- ethylene		(The World Bank, 2015; Threadingham et al., 2005; Tosoh, 2024)
Resonac	Japan, Kawasaki	Butadiene- ethylene		(Lynch, 2001; Resonac, 2024; Rubber News, 2012)
Bayer	Germany, Dormagen	Butadiene- ethylene		(ARLANXEO, 2024; Lynch, 2001; Rubber News, 2019)

B. Natural rubber data collection

No background data on NR production was available in the EcoInvent database. The majority of the inventory data for this product system is from an LCA study by (Jawjit et al., 2010) on greenhouse gas emissions from the rubber industry in Thailand. It quantifies the GHG emissions associated with block rubber production. A major supplier of FSC and PEFC certified rubber for the wetsuit industry mentions that this particular study is representative for their supply chain in Vietnam and Thailand, which solely consist of small holder suppliers (YULEX, 2023a).

A highly relevant aspect of this study are the biogenic carbon emissions related to NR production. A significant aspect of the study by (Jawjit et al., 2010) is the analysis of greenhouse gas emissions resulting from agricultural practices of rubber plantations. The study gives two scenarios, The first scenario represents the majority (70%, or 1,78 million ha) of sites in the south of Thailand, where rubber trees have been planted for 60-80 years. Assuming that after 20 years, carbon stocks in rubber plantations reach a new equilibrium, with no net change in carbon stock.

The second scenario involves plantations that have converted primary forest into rubber plantations (30%, 0,68 million ha). In this scenario, large changes in biomass carbon stocks -both above and below ground, as well as in soil carbon- occur due to land conversion. Primary forests store more carbon then rubber plantations, leading to an estimated net loss of 6,1 tonne CO_2 Eq./ton of fresh latex, when they are converted. This finding is consistent with earlier studies on palm oil plantations (Jawjit et al., 2010).

Considering the broad adoption of FSC certified supply chains within the wetsuit industry it is assumed that the first scenario best represents the NR product system. This information does emphasize a great deal of importance on rubber plantation management.

The study by Jawjit et al. (2010) does not consider land use as an impact category as their study solely focusses on GHG emissions. Land use is expressed as an elementary flow. Given the context provided, the most appropriate land use class would be one that reflects long-term, stable land use with minimal intervention. To replicate this practice, permanent crop, non-Irrigated, extensive is chosen. This flow is described as: '*Perennial crops production based on natural precipitation (rainfed agriculture), with the use of fertilizer and pesticides significantly less than economically optimal*' (Weidema et al., 2013). This reflects the long-term establishment of rubber plantations that do not rely heavily on irrigation, fertilizers, and pesticides. Thus matching the scenario provided by Jawjit et al. (2010), despite it not mentioning agroforestry.

Jawjit et al. (2010) mention centrifugation as a means of concentrating latex. It is assumed that this process is technically comparable with the purification process described by Martin & Mithcell (2022) although yields and energy inputs will most likely differ. To model this, both the concentration of latex and the production of block rubber studied by Jawjit et al. (2010) are included to represent the production of purified block rubber. Martin & Mithcell (2022) mention that waste is generated in the purification process, this is not accounted for in the system due to a lack of data.

Concerning water use, Jawjit et al. (2010) did not account for water use as their efforts were focussed on GHG emissions. It is assumed that Hevea agriculture water demand is met through precipitation. Martin & Mithcell (2022) mention a 1:1 dilution liquid added to the NRL prior to purification of which 99,36% is water. Other substances added are ignored.

The coagulation and milling process are described to be water intensive by Nguyen & Luong (2012). Their research mentions 25 m3 of wastewater is discharged for the production of 1 tonne of Standard Vietnamese Rubber (similar to STR). This is assumed to be representative for the coagulation and milling process mentioned by Martin & Mithcell (2022). An equal amount of water is modelled as input for simplicity.

C. Polychloroprene Acetylene data collection

In constructing the model, the decision not to use background data from the EcoInvent database on acetylene production was made because it represented the Hülls electric arc process. Which, as mentioned in the systems description, would inadequately represent the value chain. Consequently, a more thorough data collection approach was deemed necessary to ensure an accurate depiction.

Zhang et al. (2021) performed an LCA study on acetylene production in China, utilizing the indirect approach. Their findings show the substantial impact of energy generation on the environmental performance of this particular process. Energy for the operation studied is predominantly (64%) met by thermal power generation through hard coal combustion, followed by hydropower (17%), representing the Chinese power grid in 2019, visualised in Figure C.1.

There is evident consensus across multiple sources regarding the significant energy consumption (primarily electricity for heating), resulting in substantial GHG emissions stemming from chosen means of electricity production. Therefore, modelling choices affecting the structure of the power grid supplying energy to the product system are of significant importance in this study.

In an article written by YULEX (2023a), the results of Zhang et al. (2021) are used as a benchmark to compare the environmental performance of acetylene to PCR-B and NR. Which, in terms of processes used is correct. However, considering the pivotal role of the power grid structure in environmental performance, it could be argued that the results only partially reflect the wetsuit industry. Several companies within the wetsuit value chain have evident ties to the only Japanese supplier of PCR-A, Denka, who mention that 40% of its operational energy demand is met by run-of-river hydropower (Denka, 2022). While no public statements explicitly confirm these trade relations, evidence of such relationships can be inferred from descriptions of raw material usage (YAMAMOTO, n.d.), a published supplier list (Rip Curl International, 2021), and statements from the industries trade organization, SIMA. For instance, SIMA notes that the largest wetsuit manufacturing entity, likely SHEICO given its market share and production for the brands mentioned, sources acetylene derived chloroprene from Denka in Japan (Wavelength Surf Magazine, 2023).

LCA research on calcium carbide production in China by Huo et al. (2022) demonstrates that energy derived from hydropower and wind significantly alter impacts across various categories compared to thermal power generated through coal combustion. Thus, for this study the energy supply for the PCR-A product system incorporates 40% hydropower, additional energy requirements are met by the electricity mix Japanese power grid network as provided in EcoInvent. The distribution is shown in Figure C.1. Thus, using the practices of Denka as a benchmark.

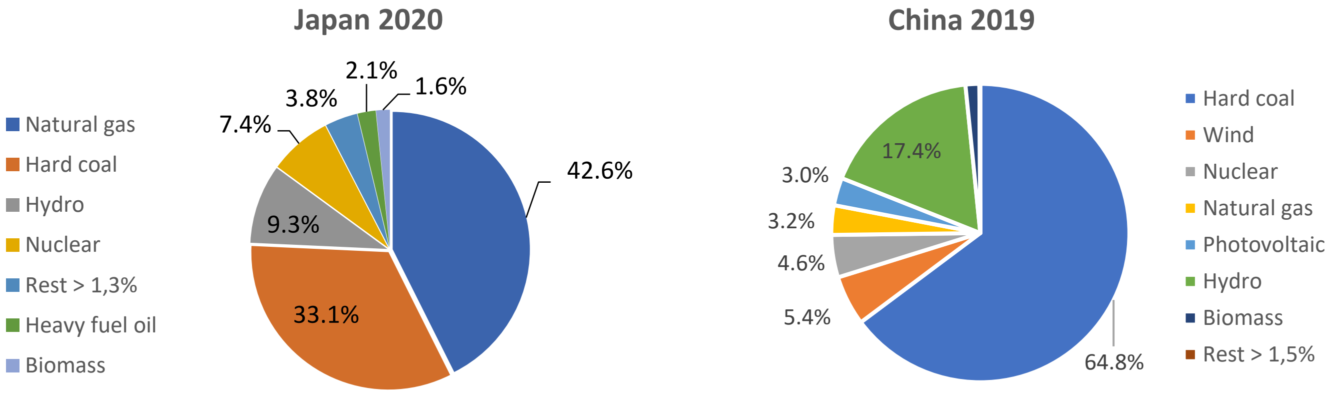
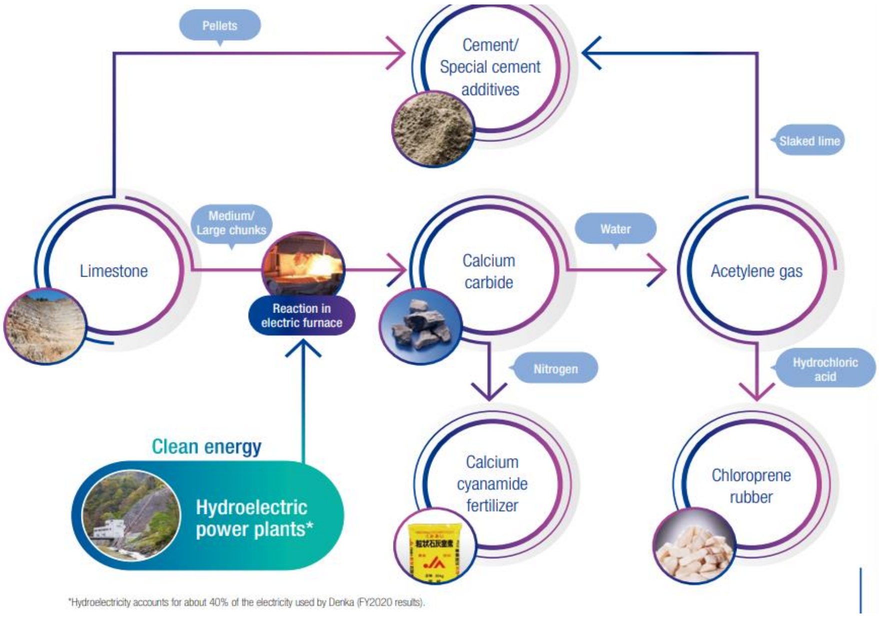


Figure C.1: Power grid structure Japan, 2020 EcoInvent (2020) and China, 2019, Huo et al. (2022)

Denka controls the entire CR production chain including limestone mining, carbide production, acetylene conversion, and finally chloroprene production. Denka mentions their production is a continuous operation and produces byproducts. An overview of this is shown in Figure C.2. Byproducts include smaller sized limestone pellets used for cement production, byproducts from carbide production used for fertilizer, and slaked lime (calcium hydroxide) from the carbide-acetylene conversion which is used in cement production (Denka, 2022). In this study these by-products are cut-off in the product system as there is insufficient data available to perform allocation within the timespan of this study. Thereby acknowledging that allocation on these processes could lower the impact of the reference flow.



*Hydroelectricity accounts for about 40% of the electricity used by Denka (FY2020 results).

Figure C.2: Process overview and byproducts Denka, Japan (Denka, 2022)

Denka mentions the use of an electric arc furnace and the use of quicklime and coke as inputs for the calcium carbide production process in external communication (Denka, 2022). Huo et al. (2022) distinguish a semi-closed and closed furnace in their LCA research into the Chinese calcium carbide industry, of which the former is considered less modern and declining in practice. Their results show that closed furnaces have higher resource efficiencies and less environmental impact, partly because electric arc furnace gasses are reused in quicklime production. Zhang et al. (2021) also chose a closed furnace operation in their study for calcium carbide production. For this research it is assumed Denka has a closed furnace operation. Inventory data for the LCA are therefore based on these characteristics.

D.Stoichiometry Acetylene

(Weissermel & Arpe, 2003)

Vinylacetylene C4H4 - > Chloroprene C4H5Cl (selectivity 92%)

Hydrochloric acid = HCl = 1 * 1,00794 + 1 * 35.453 = 36,4609 g/mol
Vinylacetylene = C4H4 = 4 * 12,0107 + 4 * 1.00794 = 52,0746 g/mol

Chloroprene = C4H5Cl = 4 * 12,0107 + 5 * 1.00794 + 1 * 35.453 = 88,5355 g/mol

Converting mass to moles:
1 kilogram of chloroprene = $\frac{1000\ g}{88{,}54\ g/mol}$ = 11,29 mol

Adjust for selectivity
Moles of vinylacetylene needed = $\frac{11{,}29\ moles}{0{,}92}$ = 12,28 moles

The reaction is 1:1, one mole of vinylacetylene reacts with one mole of hydrochloric acid to produce one mole of chloroprene.

Convert moles to grams
Mass of vinylacetylene = $12{,}28\ moles\ \times 52{,}08\ g/mol$ = 639,54 gram
Mass of hydrochloric acid = $12{,}28\ moles\ \times 36{,}46\ g/mol$ = 447,73 gram

To produce 1 kilogram of chloroprene with a selectivity of 92%, 639,54 grams of vinylacetylene and 447,73 grams of hydrochloric acid are needed.

Acetylene (C2H2)- > vinylacetylene (C4H4) (conversion 18%, selectivity 90%)

Vinylacetylene = C4H4 = 4 * 12,0107 + 4 * 1.00794 = 52,0746 g/mol

Acetylene = C2H2 = 2 * 12,0107 + 2 * 1.00794 = 26,0373 g/mol

Converting mass to moles:
639,54 grams of vinylacetylene = $\frac{639{,}54\ g}{52{,}075\ g/mol}$ = 12,28 moles

The reaction is 2:1, two moles of acetylene react to produce one mole of vinylacetylene.

Adjust for selectivity:
Moles of acetylene needed = $\frac{(12{,}28\ moles \times 2)}{0{,}90}$ = 27,29 moles

Adjust for conversion
Moles of acetylene needed = $\frac{27{,}29\ moles}{0{,}18}$ = 151,61 moles

Convert moles to grams
Mass of acetylene = $151{,}61\ moles\ \times 26{,}04\ g/mol$ = 3947,92 gram

To produce 639,54 gram of vinylacetylene with a conversion of 18% and a selectivity of 90%, 3947,92 grams of acetylene are needed.

E. Polychloroprene Butadiene data collection

LCI data on butadiene production from the EcoInvent database is used as a background process, thus no modelling is required for the co-products that are produced in that process. The technological description mentions using the steam cracking of naphtha as a means of butadiene production. Which is a common feedstock as described in Section 4.2.3. It is assumed that the database accounts for purification as it mentions to cover all processes from raw material extraction until delivery at plant (EcoInvent, 2022). Because of the global distribution of production sites and butadiene trade, a geographical scope representing global averages is considered a right depiction of reality.

For additional background processes, of which electricity production is considered the most impactful, the geographical scope of Japan is maintained to align with the PCR-A product system. Given the presence of two suppliers of butadiene-derived chloroprene in Japan, this modelling choice is considered well-supported and appropriate for ensuring a fair comparison.

For inventory data on the unit process of chloroprene production, a 25 kta butadiene production unit described in a financial feasibility study on the Nairit Chemical Plant Operation for the World Bank is used as a benchmark. This particular plant is mentioned by Lynch (2001) as a chloroprene manufacturer, back in 2000 it still produced some output according to the introduction of the study. The plant has not been operational since 2011. Despite this, the process description in the study by The World Bank (2015) aligns with the description of chloroprene production from butadiene provided by Lynch (2001) and the Japanese chloroprene producer Tosoh (Tosoh Corporation, 2014). This alignment provides sufficient validation to infer that the values presented are a reasonable representation of common industrial practice.

Calculations of the raw material input of butadiene, chlorine, and caustic soda based on the conversion and efficiency rates presented in Appendix F, do not align with the data on input for CR production provided by The World Bank (2015). The input for the processes show big differences even under the most favourable rates of a 25% conversion and the highest possible efficiencies in the different process steps. The data provided by The World Bank (2015) includes detailed information on electricity and heat consumption, providing a more detailed overview of all requirements, and is modelled for this process.

F. Stoichiometry Butadiene

(Weissermel & Arpe, 2003)

Refined dichlorobutenes (C4H6Cl2) - > Chloroprene (C4H5Cl) (selectivity, 90-95%)
Sodium hydroxide (NaOH)
Average selectivity of 92,5%
Dichlorobutene = C4H6Cl2 = 4 * 12,0107 + 6 * 1,00794 + 2 * 35,453 = 124,9964 g/mol
Sodium hydroxide= NaOH = 1 * 22,9898 + 1 * 15,9994 + 1 * 1,00794 = 39,99711 g/mol

Chloroprene = C4H5Cl = 4 * 12,0107 + 5 * 1,00794 + 1 * 35,453 = 88,5355 g/mol

Converting mass to moles
1 kilogram of chloroprene = $\frac{1000\ g}{88{,}54\ g/mol}$ = 11,29 mol

Adjust for selectivity
Moles of dichlorobutene needed = $\frac{11{,}29\ moles}{0{,}925}$ = 12,21 moles

The reaction is 1:1, one mole of vinylacetylene reacts with one mole of hydrochloric acid to produce one mole of chloroprene.

Convert moles to grams
Mass of dichlorobutene = $12{,}21\ moles\ \times 124{,}996\ g/mol$ = 1.526,2 gram
Mass of sodium hydroxide = $12{,}21\ moles\ \times 39{,}997\ g/mol$ = 488,36 gram

To produce 1 kilogram of chloroprene with a selectivity of 92,5%, 1.526,2 grams of dichlorobutene and 488,36 grams of sodium hydroxide are needed.

Crude dichlorobutenes - > refined dichlorobutane (selectivity, 95-98%)
Average selectivity of 96,5%

Calculate mass of crude dichlorobutene needed
Dichlorobutene required = $\frac{1526{,}2\ g}{0{,}965}$ = 1.581,55 grams

To produce 1.526,2 grams of refined dichlorobutene, 1.581,55 grams of crude dichlorobutene is needed.

Butadiene (C4H6) - > dichlorobutenes (C4H6Cl2) (conversion 10-25%, selectivity 85-95%)
Chlorine (Cl2)
Assuming an average conversion of 17,5% and a selectivity of 90%.
Butadiene = C4H6 = 4 * 12,0107 + 6 * 1,00794 = 54,0904 g/mol
Chlorine = Cl2 = 2 * 35,453 = 70,9060 g/mol

Dichlorobutene = C4H6Cl2 = 4 * 12,0107 + 6 * 1,00794 + 2 * 35.453 = 124,9964 g/mol

Converting mass to moles
1.581,55 grams of crude dichlorobutene = $\frac{1581{,}55\ g}{124{,}996\ g/mol}$ = 12,65 moles

Adjust for selectivity
Moles of crude dichlorobutene needed = $\frac{12{,}65\ moles}{0{,}90}$ = 14,056 moles

Adjust for conversion

Moles of crude dichlorobutene needed = $\frac{14{,}056\ moles}{0{,}175}$ = 80,37 moles

The reaction is 1:1, one mole of butadiene reacts with one mole of chlorine to produce one mole of dichlorobutene.

Convert moles to grams

Mass of butadiene = $80{,}37\ \ moles\ \times 54{,}0904\ g/mol$ = 4.347,25 grams

Mass of chlorine = $80{,}37\ \ moles\ \times 70{,}9060\ g/mol$ = 5.698,72 grams

To produce 1.581,55 grams of crude dichlorobutene, 4.347,25 grams of butadiene and 5.698,72 grams of chlorine is needed.

G.Polymerization data collection

The inventory data for this process is collected from the study by (The World Bank, 2015). This study describes the inputs for a 25 kta polymerization unit. Which, according to the description has been licensed from DuPont. Although both PCR-A and PCR-B use the same process a distinction in energy use is made. Because the PCR-A product system represents the Denka operation, 40% of its energy needs is met through run-of-river hydro energy. Whereas the PCR-B product system solely relies on the Japanese power grid.