FROM PRODUCTION TO DISPOSAL: LIFE CYCLE ASSESSMENT OF NITRILE GLOVES AND THEIR ENVIRONMENTAL IMPACT

KASTHURI A/P SUGUMARAN

MASTER OF ENVIRONMENTAL TECHNOLOGY

FACULTY OF ENGINEERING AND GREEN TECHNOLOGY
UNIVERSITI TUNKU ABDUL RAHMAN
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FROM PRODUCTION TO DISPOSAL: LIFE CYCLE ASSESSMENT OF NITRILE GLOVES AND THEIR ENVIRONMENTAL IMPACT

By

KASTHURI A/P SUGUMARAN

A dissertation submitted to
Faculty of Engineering and Green Technology,
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in partial fulfillment of the requirements for the degree of
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December 2025

DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name: KASTHURI A/P SUGUMARAN

Date: 15 DECEMBER 2025

APPROVAL SHEET

This final year project report entitled "**<u>FROM PRODUCTION TO DISPOSAL: LIFE CYCLE ASSESSMENT OF NITRILE GLOVES AND THEIR ENVIRONMENTAL IMPACT</u>**" was prepared by KASTHURI A/P SUGUMARAN and submitted as partial fulfilment of the requirements for the degree of Master of Environmental Technology at Universiti Tunku Abdul Rahman.

Approved by:

____

(Dr Guo Xinxin)

Date: 16/12/2025…………………

Supervisor

Department of Enviromental Engineering

Faculty of Engineering and Green Technology

Universiti Tunku Abdul Rahman

Approved by:

____

(ChM. Dr Wong Lai Peng)

Date: 16 Dec 2025……………………..

Co-Supervisor

Faculty of Engineering and Green Technology

Universiti Tunku Abdul Rahman

FACULTY OF ENGINEERING AND GREEN TECHNOLOGY

UNIVERSITI TUNKU ABDUL RAHMAN

Date: 15 December 2025

SUBMISSION OF DISSERTATION

It is hereby certified that KASTHURI A/P SUGUMARAN (ID No: 24AGM00585) has completed this dissertation entitled "_FROM PRODUCTION TO DISPOSAL: LIFE CYCLE ASSESSMENT OF NITRILE GLOVES AND THEIR ENVIRONMENTAL IMPACT" under the supervision of Dr Guo Xinxin (Supervisor) from the Department of Engineering Technology, Faculty of Engineering and Green Technology, and ChM. Dr. Wong Lai Peng (Co-Supervisor) from the Department of Engineering Technology, Faculty of Engineering and Green Technology.

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(KASTHURI A/P SUGUMARAN)

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ABSTRACT

FROM PRODUCTION TO DISPOSAL: LIFE CYCLE ASSESSMENT OF NITRILE GLOVES AND THEIR ENVIRONMENTAL IMPACT

Kasthuri A/P Sugumaran

The extensive reliance on disposable nitrile gloves has intensified concerns regarding their environmental footprint, particularly in major manufacturing hubs such as Malaysia. This research conducts a cradle-to-grave Life Cycle Assessment (LCA) of non-sterile, powder-free nitrile gloves produced in Kamunting, Perak, utilizing primary operational data gathered over a five-month period. The analysis was performed in openLCA with the ReCiPe Midpoint (H) 2016 methodology, encompassing eighteen impact categories from raw material extraction through end-of-life incineration. Findings reveal that the production phase is the predominant source of environmental burdens, driven by the fossil-based composition of nitrile butadiene rubber (NBR) and substantial electricity and natural gas usage. Key impact categories identified include fossil resource depletion, marine and terrestrial ecotoxicity, global warming, and human non-carcinogenic toxicity. A Monte Carlo simulation with 5,000 iterations indicated low to moderate uncertainty, affirming the robustness of the model. Overall, the study underscores the importance of advancing energy efficiency and innovating sustainable glove materials to mitigate environmental impacts across the industry.

TABLE OF CONTENTS

DECLARATION	ii
APPROVAL SHEET	iii
SUBMISSION OF DISSERTATION	iv
ACKNOWLEDGEMENT	v
ABSTRACT	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF ABBREVIATIONS	xi
CHAPTER 1	1
1 INTRODUCTION	1
1.1 Introduction	1
1.2 Background of Study	6
1.3 Problem Statement	8
1.4 Objectives	10
1.5 Scope of Study	10
CHAPTER 2	12
2 LITERATURE REVIEW	12
2.1 Introduction	12
2.2 Production of Nitrile Butadiene Rubber	13
2.3 Structure of Nitrile Butadiene Rubber	14
2.4 Production of Nitrile Gloves	15
2.5 End of Life	18
2.6 Environmental Concerns	21
2.7 Software Tools	25
2.8 Assessment Methods	27
2.9 Life Cycle Assessments of Gloves	29
2.10 Discussions	35
CHAPTER 3	37
3 METHODOLOGY	37
3.1 Introduction	37

3.2 Goal and Scope Definition 37
3.3 Life Cycle Inventory (LCI) 39
3.3.1 Life Cycle Inventory (LCI) Assumptions 40
3.3.2 Electricity Consumption 41
3.4 Life Cycle Impact Assessment (LCIA) 42
3.4.1 Scaling of Monthly Data to Annual Impact 44
3.5 Uncertainty Analysis 45
3.6 Life Cycle Interpretation 47
CHAPTER 4 49
4 RESULT AND DISCUSSION 49
4.1 Introduction 49
4.2 LCIA Results of ReCiPe Midpoint (H) Method 49
4.2.1 Fossil Resource Scarcity (FRS) 54
4.2.2 Marine Ecotoxicity (MEcotox) 55
4.2.3 Terrestrial Ecotoxicity (TEcotox) 56
4.2.4 Global Warming (GW) 57
4.2.5 Human Non-Carcinogenic Toxicity (HNCT) 57
4.3 Contributions by Life Cycle Stage 58
4.3.1 Fossil Resource Scarcity (FRS) 59
4.3.2 Marine Ecotoxicity (MEcotox) 60
4.3.3 Terrestrial Ecotoxicity (TEcotox) 61
4.3.4 Global Warming (GW) 62
4.3.5 Human Non-Carcinogenic Toxicity (HNCT) 63
4.4 Uncertainty Analysis 64
4.5 Discussion Key Finding 65
4.6 Mitigation Plan 69
CHAPTER 5 72
5 CONCLUSIONS 72
5.1 Conclusions 72
5.2 Limitation of Study 74
5.3 Recommendation of Future Study 75
REFERENCES 76
APPENDICES 87

LIST OF TABLES

Table		Page
1.1	Malaysia rubber glove export value from 2018 until 2023	2
2.1	Chemicals used for stabilization process	17
2.2	Environmental impacts associated with PPE supplied in England over February to August 2020 (functional unit: total PPE supplied during this period)	25
2.3	Comparison of LCA software tools	27
2.4	Comparison of LCA methodology	29
2.5	Summary of LCA studies on gloves	35
3.1	Normalisation reference value (annual global environmental load per capita) for impact categories	43
4.1	Baseline LCIA results for 100 pieces of nitrile gloves	52
4.2	Monte Carlo summary results (5000 iterations)	65

LIST OF FIGURES

Figures		Page
1.1	Export and import market of PPE's before and during COVID	3
2.1	Chemical structure of NBR	15
2.2	Glove manufacturing process	19
2.3	End of life of PPE waste	20
2.4	Overview of midpoint and endpoint categories	30
2.5	Sample boundaries of product lifecycle	31
3.1	LCA methodology framework	38
3.2	System boundary cradle to grave	39
4.1	Normalised annual impact score (per 100 pieces) for eighteen categories	54
4.2	Contribution impact for each life stages	59

LIST OFABBREVIATIONS

CR	Chloroprene rubber
CV	Coefficient of variation
EF	Environmental footprints
EIA	Environmental impact assessment
ELCD	European reference life cycle database
FPMF	Fine particulate matter formation
FRS	Fossil resource scarcity
FWEcotox	Freshwater ecotoxicity
FWEutrof	Freshwater eutrophication
GW	Global warming
HCT	Human carcinogenic toxicity
HNCT	Human non-carcinogenic toxicity
IR	Ionising radiation
ISO	International organisation for standardisation
kWp	kilowatt-peak
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use
MARGMA	Malaysian rubber glove manufacturers association

MEcotox	Marine ecotoxicity
MEutrof	Marine eutrophication
MRS	Mineral resource scarcity
NBR	Nitrile butadiene rubber
NR	Natural rubber
OFHH	Ozone formation, human health
OFTE	Ozone formation, terrestrial ecosystem
PV	Photovoltaic
PPE	Personal protective equipment
SOD	Stratospheric ozone depletion
TA	Terrestrial acidification
TEcotox	Terrestrial ecotoxicity
US	United states
WC	Water consumption

CHAPTER 1

INTRODUCTION

1.1 Introduction

Gloves are widely utilized across diverse sectors, including healthcare, industrial applications, household cleaning, agriculture, laboratory work, and food processing. Their essential role in ensuring hygiene and safety has led to global demand, with usage spanning nearly every country. Among these, the United States (US) stands out as the largest glove importer, driven by high consumption in healthcare institutions, food service operations, cleaning services, and manufacturing industries. According to market analyses, the healthcare sector alone accounted for over 65% of the US safety glove market share in 2019, underscoring the sector's significant contribution to national demand (GMI Insights, 2020).

Table 1.1 demonstrates export value of Malaysia's rubber gloves during the pandemic, escalating from RM 23.80 billion in 2018 to RM 61.69 billion in 2021 (Ministry of Plantation and Commodities, 2024). This sharp increase was fueled by elevated global demand. In the post pandemic period, however, the market has stabilized, with export values decreasing to RM 27.31 billion in 2022 and RM 20.43 billion in 2023, reflecting the global recovery and reduced urgency for personal protective equipment.

Table 1.1: Malaysia rubber glove export value from 2018 until 2023

Year	Rubber Glove (RM '000)
2018	23,795,674
2019	23,553,790
2020	41,632,533
2021	61,688,337
2022	27,313,852
2023	20,430,477

Source: Adapted from *"Data Statistic on Commodities"* by Ministry of Plantation and Commodities, 2024.

Malaysia has become a major leader in the global rubber glove market, supplying approximately 65% of the world's demand across hundred ninety-five countries (Ministry of Plantation and Commodities, 2021). The remained the leading global manufacturer for more than twenty years driven by a robust manufacturing ecosystem and abundant natural rubber resources (Hutchinson and Bhattacharya, 2020). The widespread use of rubber gloves spans various sectors, including healthcare, manufacturing, laboratories, and domestic applications. The industry's rapid growth originated in the late 1980s, when the global HIV and AIDS crisis triggered a surge in demand for disposable medical gloves. Recognising this opportunity, the Malaysian government issued numerous manufacturing licenses to local entrepreneurs, catalysing the expansion of the glove manufacturing sector (MARGMA, 2020). Subsequent outbreaks of infectious diseases such as SARS and Ebola further reinforced the importance of hygiene in healthcare settings, sustaining global demand for medical gloves.

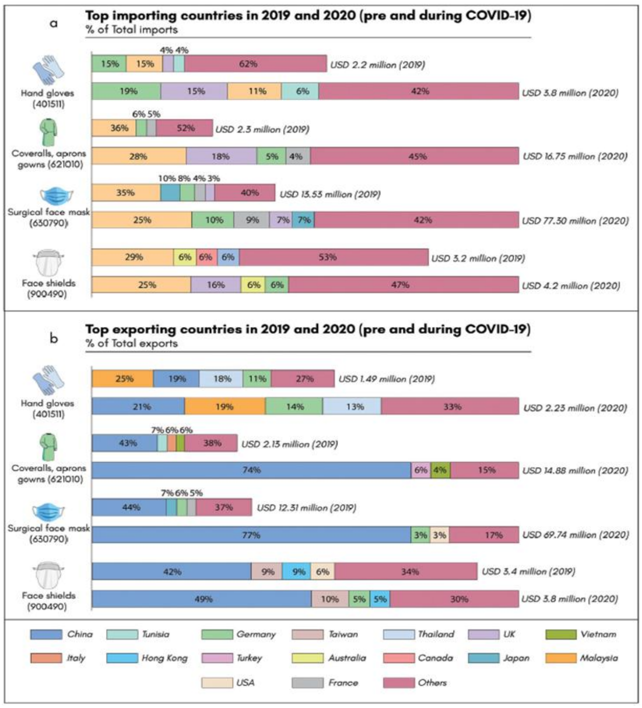

Figure 1.1: Export and import market of PPE's before and during COVID

Source: *"Environmental impacts of personal protective clothing used to combat COVID-19"* by Uddin et al., 2022.

Figure 1.1 illustrates the largest exporting and importing countries for personal protective equipment (PPE), with disposable gloves categorized as part of this list. The bar chart confirms that Malaysia ranks among the top glove exporters, contributing 25% to the world's total exports, followed by China and Thailand. In contrast, major importing countries include Germany, which accounts for 34% of total imports, and the US, with 26%. This strong demand for disposable gloves has significantly boosted Malaysia's economy, created job opportunities, and driven industrial growth. However, despite these economic benefits, the glove manufacturing industry also presents several environmental challenges.

The surge in global glove demand can be attributed to the wide-ranging applications of gloves across multiple industries. As a form of PPE, gloves serve to minimise human exposure to physical, biological, and chemical hazards. In the healthcare sector, they are primarily used to prevent transmission and cross contamination. In food processing and industrial settings, glove usage is centered on maintaining hygiene standards to prevent product contamination. Within the agricultural and farming sectors, gloves offer protection against insect bites and other occupational hazards encountered during fieldwork.

All manufacturing processes generate both final products and by products. By products may either be recycled as inputs in subsequent production cycles or, if deemed non-recoverable or without economic value, require appropriate disposal. In the context of glove manufacturing, various by-products are generated, many of which cannot be reintegrated into the glove production process. One notable example is wastewater primarily arising from the leaching of chemicals during the dipping stages. A study conducted by Na Ayuthaya et al., (2022) to overcome Thailand's factory discharge treatment to comply with regulation. The study resulted in double the discharge wastewater volume which turned the freshwater into sewage. Given its extensive use, water serves as a fundamental resource throughout glove production. However, the chemically contaminated water must undergo treatment via wastewater treatment facilities before being safely discharged into municipal drainage systems. In addition to aqueous emissions, the use of raw materials such as natural and synthetic rubber, chemical additives, and chlorine contributes to airborne emissions during manufacturing. Furthermore, combustion gases used to generate the thermal energy required for glove curing also present environmental concerns. Collectively, these outputs underscore the environmental burden associated with glove manufacturing operations.

In light of the growing severity of environmental impacts associated with glove production, manufacturers have increasingly prioritized strategies to minimise their ecological footprint. One key approach involves optimising resource efficiency, particularly in the use of water and energy. Among the notable initiatives is the development of biodegradable gloves, which aim to reduce the environmental burden associated with landfill disposal and incineration. A study by Ab Rahman et al. (2020) demonstrated that polysaccharide-filled natural rubber latex (PFNRL) gloves retained 75% of their tensile strength for up to 2.8 years under shelf conditions, indicating their viability as a sustainable alternative to conventional gloves. In addition to biodegradable glove innovations, manufacturers have also begun adopting ecofriendly packaging materials as part of broader efforts to mitigate the overall environmental impact of glove production.

The environmental impacts associated with glove manufacturing originate from multiple stages within the production process. To effectively identify the underlying causes and implement appropriate mitigation strategies, a thorough and structured evaluation is essential. Life Cycle Assessment (LCA) provides a comprehensive and systematic framework for pinpointing the specific stages that contribute most significantly to environmental burdens, as well as the nature of those impacts. By gaining detailed insights into these effects, manufacturers are better equipped to develop targeted interventions that minimise environmental harm in the most impactful areas.

1.2 Background of Study

Gloves are manufactured using various materials, predominantly natural rubber and synthetic rubber. Malaysia's extensive rubber plantations support the production of natural rubber-based gloves, while synthetic rubber gloves are also produced to meet specific market demands. In addition, a range of chemical inputs including acids, ammonia, chlorine, calcium chloride, and sulfur are utilized to formulate blended rubber compounds for glove manufacturing.

From an environmental standpoint, the glove production process has impacts that span the entire product life cycle. These include the extraction and use of raw materials, utility consumption during manufacturing, and end-of-life disposal. Such impacts fall within the scope of a cradle to grave LCA, which examines all stages from raw material acquisition and production to product use and final disposal. Depending on the study scope, alternative LCA boundaries may be defined to comprehensively evaluate environmental implications. The life cycle of gloves encompasses their creation, distribution, usage, and eventual exit from the market, serving as a framework for systematic sustainability analysis.

As mentioned by Dos Muchangos et al., (2025) several methods can be used to design and carry out comprehensive environmental impact assessments (EIAs). These include Energy Analysis, Environmental Input-Output Analysis, Ecological Pricing, Environmental Footprints (EFs), and LCA. LCA is a globally recognised approach for assessing the environmental impacts of products and services (International Organization for Standardizations, 2006).

A study conducted by Boix Rodriguez et al., (2021) offers valuable guidance for developing eco-design face masks. The LCA approach in this study revealed that the quantity of material needed to produce a mask has a greater environmental impact than the total number of masks used over the same period. This LCA study used SimaPro software in order to assess the impact of masks from boundary cradle to grave. To carry out our same assessment, software that is widely available in the market can assist such as openLCA, SimaPro, GaBi, Umberto and others.

The software platform supports a wide range of impact assessment methodologies at both the midpoint and endpoint levels. Commonly used midpoint methods include CML, TRACI, and ILCD, while ReCiPe and Eco-indicator 99 are widely adopted for endpoint analysis. Midpoint indicators typically address specific environmental issues such as global warming, acidification, ozone layer depletion, , eutrophication, and human toxicity. In contrast, endpoint indicators capture broader consequences, including impacts on human health, ecosystem quality, and resource depletion.

1.3 Problem Statement

The surge in glove production and global demand particularly during healthcare emergencies has resulted in corresponding rise in waste generation, largely from single use disposable gloves. Owing to contamination risks, these products are commonly incinerated or landfilled, thereby imposing significant environmental burdens. In addition to waste management challenges, the extraction of raw materials and the energy-intensive nature of glove manufacturing contribute further to ecological impacts.

Nevertheless, existing LCA studies on nitrile and rubber gloves exhibit several notable limitations. First, many analyses concentrate narrowly on a single impact category, most often global warming (GW), while neglecting other critical dimensions such as water pollution, land degradation, toxicity, and resource depletion. Several researchers have pointed out that sustainability assessments should adopt a more holistic approach, integrating multiple ecological factors rather than concentrating solely on greenhouse gas emissions (Top Glove Corporation Berhad, 2024). This restricted scope hampers a comprehensive understanding of the broader environmental consequences across the glove's life cycle.

Second, the majority of LCAs depend heavily on secondary data sources, including commercial databases or prior publications. Such datasets frequently fail to capture current manufacturing practices, regional variations, and technological advancements, thereby introducing uncertainties and diminishing the accuracy and relevance of the findings. Many studies depend on previously published datasets, which may not reflect current manufacturing technologies, process improvements, or regional variations (Wang et al., 2025).

While many glove-related LCA studies demonstrate sound methodological foundations, a persistent shortcoming lies in their limited consideration of uncertainty and variability. Current literature indicates that only a minority of PPE-focused LCAs employ formal uncertainty evaluation techniques thereby compromising the robustness of their findings. This methodological gap aligns with broader critiques, including Zeng et al. (2024), who note that most PPE LCAs still lack "rigorous uncertainty or sensitivity analysis," which diminishes confidence in their conclusions. As a result, the reliability, comparability, and decision-making relevance of glove-related LCA outcomes remain limited, highlighting the urgent need for more systematic uncertainty treatment in future research.

To strengthen future LCA studies on nitrile gloves, researchers are encouraged to integrate primary data obtained directly from manufacturing facilities and expand their analyses to encompass multiple environmental impact categories. Such an approach would yield more precise and holistic life cycle assessments.

1.4 Objectives

By adopting the holistic approach of LCA method, this study determines to access the impact assessment for nitrile gloves cover all phases of existence. To complete the goal of this research some objectives have been outlined to guide through the study. The objectives are listed as below:

1. To determine the life cycle inventory of single-use nitrile gloves by capturing all inputs and outputs from real plant operations, covering raw material extraction, production, packaging, distribution, use, and end-of-life disposal.
2. To conduct a comprehensive Life Cycle Assessment (LCA) of nitrile gloves from production to disposal using openLCA software, applying the ReCiPe Midpoint (H) method for environmental impacts.
3. To conduct Monte Carlo simulation to quantify uncertainty and assess the robustness of the life cycle assessment results of nitrile gloves.

1.5 Scope of Study

Defining scope of study is an important step in research work so that the study can be done in the given boundary and align with limitations that have been set. For life cycle boundary that been included in this study from raw material extraction, material delivery, production processes, product delivery, product delivery, product usage and disposal. This boundary is called cradle to grave of nitrile gloves. The impact assessment will be using openLCA which is open-source access software. The main dataset that used in this study was obtain from real glove manufacturing plant at Kamunting, Perak, Malaysia. Main product of that plant is only nitrile gloves with different applications such as for industrial use, medical use and food processing.

First is the data that has been gathered for five months starting from January 2025 to May 2025 glove output. To ensure the feasibility of this study, several assumptions must be made. First is that the packing of gloves consists of a hundred pieces for one inner box for the month without any changes. Apart from wastewater and air emissions, municipal waste such as sewage have not been considered, as they are not directly related to the production process. It assumed that all gloves that produce have the same thickness and have been produced without changing any formulation during the month of data collection.

This study establishes a cradle to grave system boundary and integrates primary data from a local glove manufacturing plant providing a comprehensive and context specific environmental assessment of nitrile gloves using the openLCA software. Employing the ReCiPe Midpoint (H) 2016 impact assessment method, the analysis encompasses eighteen individual impact categories. The established assumptions contribute to the study's coherence and practicality, while the chosen methodological framework enables a rigorous assessment of environmental performance throughout the entire product life cycle.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The entire life cycle of disposable gloves, from production to disposal, has notable ecological impacts. The manufacturing process generates contaminated wastewater from product leaching, cleaning activities, and chemical testing in laboratories. If not properly managed, these pollutants can enter drinking water sources, agricultural land, and the atmosphere, ultimately harming the environment (Jagadale et al., 2015).

Among different glove types, nitrile gloves are often considered a more sustainable alternative to rubber gloves because their production does not rely on seasonal latex harvesting, which can disrupt supply chains and affect the availability of natural rubber. However, both nitrile and natural rubber gloves pose environmental concerns throughout their life cycle, including resource consumption, emissions, and waste generation. To systematically evaluate these impacts, LCA methodology is widely applied. LCA provides a comprehensive framework for assessing a product’s environmental footprint, considering factors such as raw material extraction, manufacturing emissions, and disposal related waste.

2.2 Production of Nitrile Butadiene Rubber

Gloves serve as a vital element of personal protective equipment, intended to reduce the likelihood of direct exposure to harm. The primary raw material for glove production is rubber. Gloves come in different types to serve various purposes, and each type is manufactured using different rubber sources. Different rubbers used in production include natural rubber (NR), polyisoprene, acrylonitrile-butadiene rubber (NBR), and chloroprene rubber (CR) (Akabane, 2016).

NR is commonly referred to as the white fluid collected from rubber trees. NR appears opalescent and is secreted during the cutting process of the tree. This viscous liquid contains resin, protein, sugar, and other components. In contrast, IR, NBR, and CR are synthetic rubber produced from polymer particles dispersed in water and stabilized by surfactants, which form a protective layer. This type of synthetic rubber is manufactured through polymer emulsification, also known as emulsion polymerisation. The process undergoes mechanical shearing to produce different types of polymers, such as batch, semi-batch, or seed polymerisation. These products vary in polymer composition, particle size, shape, and structure.

2.3 Structure of Nitrile Butadiene Rubber

NBR Gloves become spotlight after NR glove triggered the allergy reaction with certain individuals. A skin testing study showed that NR gloves have different brands, and their inner and outer surfaces contained widely varying protein and allergen contents (Mahler et al., 2000). Naturally NR that is secreted from rubber trees contains protein. These proteins create a reaction with human skin which becomes of the reason of transition to NBR source.

Apart from the NR allergy issue, the chemical link structure of NBR plays a crucial role in glove production. According to Tang & Zhang (2014) unsaturated molecular structure of NBR lead to prone to degradation. The molecule structure gives the NBR strength, durability, and is resistant to breaking easily. NBR contains acrylonitrile in concentrations ranging from 18% to 50%, which enhances its mechanical strength, heat resistance, hardness, abrasion and oil resistance. However, this also results in lower resilience and reduced flexibility at low temperatures (Yew et al., 2019).

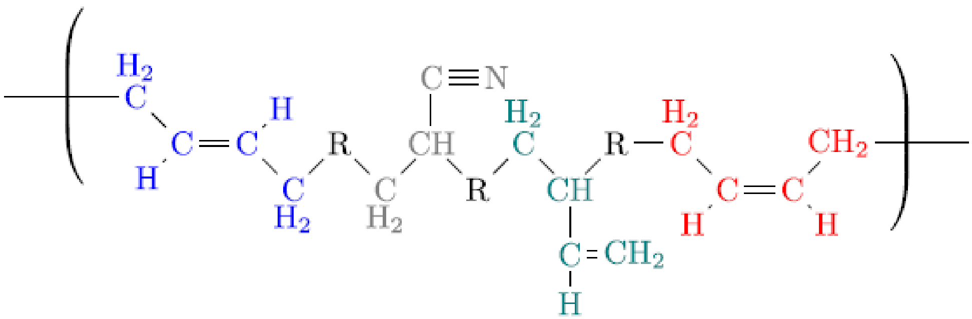

Figure 2.1: Chemical structure of NBR

Source: *"Aging characterization of different nitrile butadiene rubbers for sealing in a pneumatic system: Linking the change of the physicochemical state to the mechanical properties"* by Redon et al., 2023.

2.4 Production of Nitrile Gloves

The production process of nitrile gloves begins with a hand shaped former that serves as a mold for the gloves. First, the former undergoes a cleaning process, where it is dipped in an acid bath and then rinsed with clean water. Next, it is submerged in an alkaline tank to neutralize any remaining acid, followed by another rinse with clean water. To prevent dust or dirt from adhering, the former is brushed before proceeding to the coagulant dipping stage. In this stage, the former is dipped into a tank containing a coagulant, forming a thin coagulant film that later aids in rubber destabilization. The former is oven-dried following the first dipping before proceeding to the subsequent dipping process.

Compounded NBR supplied to the dipping tank undergoes several processes before being used. This preparation, known as the compounding process, ensures the compound remains stable and retains its properties during manufacturing. Before adding any chemicals, the NBR must be stabilized to prevent unwanted changes. Table 2.1 lists the chemicals used in compounding process and their functions.

The compounded rubber is then adjusted for solid concentration and pH. Additional chemicals are incorporated to enhance texture and viscosity as required. The compound then undergoes a maturation period to achieve optimal processability and maximize its physical and chemical performance (Akabane, 2016). Once matured, the compound is supplied to the dipping tank, where the former is immersed in it.

Table 2.1: Chemical used for stabilization process

Function	Description
pH adjustment	KOH is added to maintain pH range 10-11
Surfactants	To enhance stability of chemical suspensions
Resins	Some synthetic rubber, such as CR and IR, are formulated with colophonium resins, which effectively perform the function of particle stability and film forming

Source: Adapted from "*Performance-enhancing materials in medical gloves*" by Lovato et al., 2023.

The next stage, known as leaching and beading, involves using hot water to remove chemical residues. During beading, specific chemicals enhance vulcanisation to prevent glove degradation due to environmental conditions. Multiple ovens are used to aid drying in a single production cycle. Vulcanisation is a crucial process that strengthens the glove's tensile properties and elasticity by crosslinking polymer chains with sulfur.

After vulcanisation, the former passes through several ovens to complete the crosslinking process. At this stage, the former reaches high temperatures and must be cooled before chlorination. This cooling process, which involves dipping the former in a cooling tank, is essential to prevent chlorine evaporation, ensuring safety by minimising chlorine gas release.

The final chemical treatment in glove manufacturing is chlorination, which reduces tackiness and improves grip for the stripping process. Some manufacturers use polymer coatings instead, applying polyurethane or polyacrylate to the inner glove surface to reduce friction and facilitate removal (Crepy & Hoerner, 2022).

After chlorination, the former is dipped into a post-leaching tank to wash away any chlorine residues before the final drying process. Once dried, the gloves are stripped from the former and undergo quality inspection for defects. High quality gloves are then packed and prepared for transport to customers.

Figure 2.2 presents the overall glove manufacturing process. The latex tank source varies based on the glove type either synthetic or natural rubber. Additionally, the production method differs depending on whether the gloves are powdered or powder free, and whether they are coated with chlorine or polymer, as determined by the manufacturer.

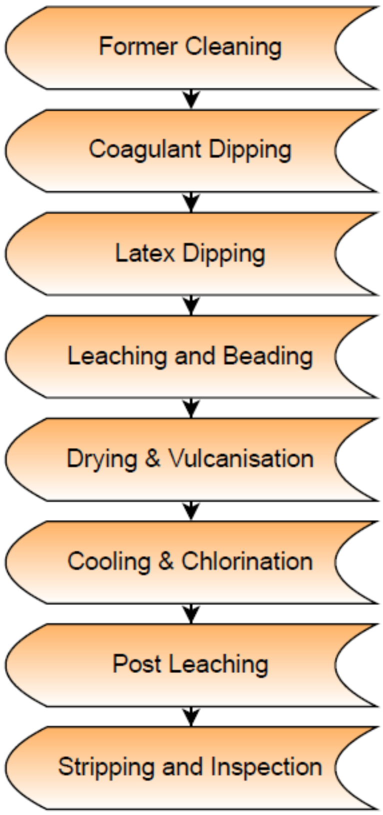

Figure 2.2: Glove manufacturing process

Source: Adapted from "*Life cycle optimization for synthetic rubber glove manufacturing*" by Poh et al., 2019.

2.5 End of Life

The end-of-life management of disposable gloves, particularly those made from synthetic rubber and natural rubber has become an increasing environmental concern due to their extensive use in medical, industrial, and household settings. With the rise in demand for PPE, especially during global health crises, improper disposal of gloves has contributed to significant waste management challenges (Bergman et al., 2021). Common disposal practices for waste include landfilling, incineration, and improper littering in the environment. Each of these methods carries specific environmental risks, chemical leaching into soil and water, increase landfill burden and emissions of greenhouse gases (Patricio Silva et al., 2021). As depicted in figure 2.3, PPE waste such as gloves can enter various disposal routes. Incineration contributes to air emissions, landfilling generates microplastic and chemical contamination, while careless disposal directly pollutes ecosystems.

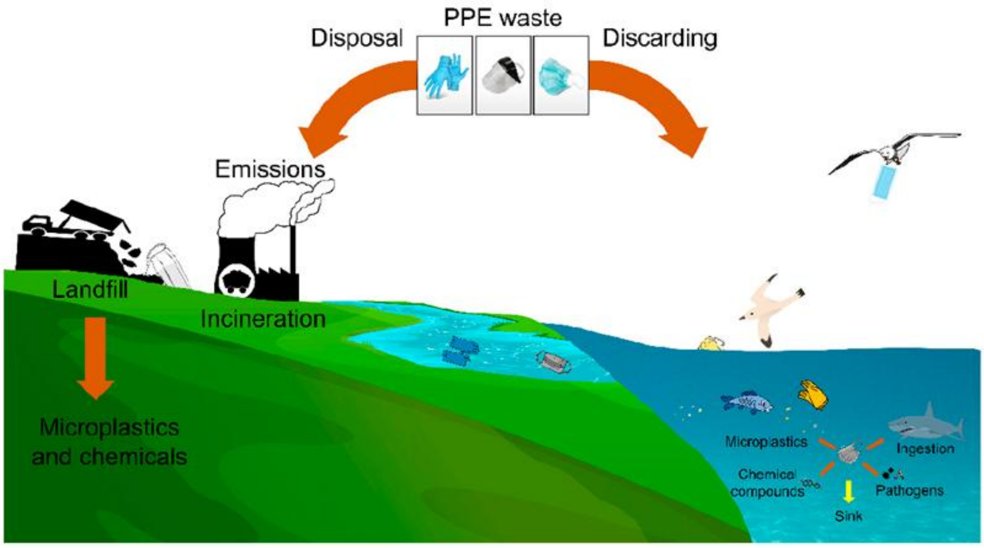

Figure 2.3: End of life of PPE waste

Source: *"A new challenge for the management and disposal of personal protective equipment waste during the COVID-19 pandemic"* by Wang et al., 2021.

In the context of the cradle to grave framework, the term "grave" represents the final phase of a product's life cycle, when it has reached the end of its usable life. Disposal at this stage typically involves physical, chemical, or biological treatment methods. For gloves in particular, end-of-life management is largely physical, relying mainly on landfilling and incineration.

Landfill is a designated land area whether on-site or off-site with engineered infrastructure designed to ensure containment, environmental safety, and continuous oversight (United Nations Office for Disaster Risk Reduction, 2023). Municipal solid waste (household waste) is most often managed in this way. Additionally, Westlake (2014) describes incineration as a thermal process where waste is combusted using high temperatures, producing ash residues, gases, and particulate emissions.

Incineration is a controlled process that utilizes thermal decomposition through high-temperature oxidation (typically 900°C or higher) to break down the organic fraction of waste and minimise its volume. This method is most suitable for combustible waste or waste with a high organic content. Moharir et al. (2019) stated that incineration is a thermal waste treatment method involving controlled combustion, primarily aimed at reducing waste volume and recovering energy from the waste stream. Like combustion, the incineration process also produces byproducts such as ash and gaseous contaminants. According to the According to the National Research Council (2000), incineration exhaust releases harmful pollutants such as particulate matter, sulfur, carbon monoxide, nitrogen compounds, and volatile organic compounds.

A persistent issue with the end-of-life treatment of NBR gloves is the long decomposition time in landfills. One of the most significant environmental concerns is that NBR gloves can take up to two hundred years to fully break down (PlastCare USA, 2024). This prolonged degradation period is due to the synthetic polymers used in producing nitrile rubber. Additionally, processes such as crosslinking and vulcanization further reinforce the structure, making it resistant to rapid decomposition.

To address this issue, researchers have focused on developing biodegradable nitrile gloves infused with bio-additives. Yew et al. (2020) explored the use of bio-based substances, such as food waste, natural plant extracts, and aquatic resources, to enhance the degradation rate of nitrile gloves under natural conditions. Ongoing research aims to improve landfill waste management strategies for nitrile gloves and develop sustainable alternatives.

2.6 Environmental Concerns

The Malaysia Rubber Glove Manufacturers Association (MARGMA) reported a nearly 20% increase in Malaysia's glove exports in 2020 during the COVID-19 crisis. This rise in production directly correlated with an increase in waste generation, leading to higher landfill disposal. According to Misman et al. (2014), rubber waste in landfills decomposes slowly due to sulfur and antioxidants added during compounding before dipping. Sulphur is used to facilitate the crosslinking process, which strengthens the rubber and prevents degradation from environmental exposure or biological activity.

The glove production process requires various resources to support operations from manufacturing to final production. The primary resources used in glove manufacturing include water, chemicals, energy, electricity, packaging materials, and machinery.

Water is a key resource, utilized throughout multiple stages, including compounding, former cleaning, leaching, cooling, and final cleaning. As mentioned earlier, the production process involves several drying ovens. Heat energy, typically generated by boilers, is required for drying and curing. Electricity is essential for operating machinery, lighting, and wastewater treatment systems. It supports the overall manufacturing process, ensuring smooth and efficient operations.

Apart from this, each stage of production involves input and output flows. The boiler, fueled by natural gas to generate heat for drying and curing ovens, is considered an input in the glove manufacturing process. However, heat production in the boiler results in carbon dioxide emissions, contributing to carbon emissions, and may also lead to energy losses. The cooling or leaching tanks, used to wash chemical residues from the gloves, generate contaminated wastewater as an output. This wastewater undergoes a separate treatment process, requiring additional chemicals before being discharged into the environment.

The downstream processes, such as glove inspection and packaging, also raise environmental concerns. Defective gloves, including torn or contaminated ones, contribute to landfill waste. Additionally, both gloves and packaging materials are discarded at this stage. Packaging types vary based on customer requirements, including cartons, plastic, and polybags. This manufacturing approach impacts both the environment and human well-being.

To address these issues, researchers have carried out evaluations to determine the overall environmental impact of glove production, aiming to raise awareness and support mitigation strategies. A study conducted by Rizan et al. (2021) in the United Kingdom revealed that PPE alone accounted for 106,478 tonnes of CO_2 eq emissions in England during the COVID-19 pandemic. The assessment covered the entire life cycle of PPE from cradle to grave using the ReCiPe Endpoint method. The study analysed 18 environmental impact categories related to various PPE items, including gloves. Table 2.2 below presents the published impact results specifically for gloves.

Table 2.2: Environmental impacts associated with PPE supplied in England over February to August 2020 (functional unit: total PPE supplied during this period)

Impact category	Apron	Face shield	Respirator	Nitrile gloves	Gown
Global warming (kg CO_2 eq)	28,792,521	10,487,030	3,749,353	48,261,870	5,419,004
Stratospheric ozone depletion (kg CFC 11 eq)	9	3	1	21	2
Ionising radiation (kBq Co-60 eq)	1,110,473	373,435	166,612	1,635,054	206,718
Ozone formation, Human health (kg NO_x eq)	69,028	26,751	8,445	103,536	12,212
Fine particulate matter formation (kg PM2.5 eq)	35,895	13,990	4,664	83,617	6,569
Ozone formation, Terrestrial ecosystem (kg Nox eq)	72,203	27,939	8,726	108,003	12,611
Terrestrial acidification (kg SO_2 eq)	86,847	34,296	11,342	161,236	15,825
Freshwater eutrophication (kg P eq)	8446	2,791	1,052	16,963	1,627
Marine eutrophication (kg N eq)	770	509	164	1,179	135
Terrestrial ecotoxicity (kg 1,4-DCB)	51,133,924	19,578,216	7,632,980	100,720,920	11,071,880
Freshwater ecotoxicity (kg 1,4-DCB)	759,210	286,495	110,292	1,730,262	168,812
Marine ecotoxicity (kg 1,4-DCB)	1,011.748	381,554	146,223	2,308,253	222,862
Human carcinogenic toxicity (kg 1,4-DCB)	1,735,767	582,944	228,986	2,860,153	336,096
Human non-carcinogenic toxicity (kg 1,4-DCB)	17,603,872	6,489,782	2,396,602	42,327,720	3,491,487
Land use (m^2a crop eq)	635,797	239,803	157,939	1,070,855	145,353
Mineral resource scarcity (kg Cu eq)	44,167	33,459	11,536	528,975	13,753
Fossil resource scarcity (kg oil eq)	10,131,513	3,790,965	1,290,985	15,959,889	2,007,022
Water consumption (m^3)	285,962	122,024	32,176	427,167	37,714

Source: Adapted from "*Environmental impact of personal protective equipment distributed for use by health and social care services in England in the first six months of the COVID-19 pandemic*" by Rizan et al., 2021.

The environmental impact of gloves is significant across multiple categories. Gloves contribute 48.26 million kg CO_2 eq to global warming, 1.64 million kBq Co-60 eq to ionizing radiation, and 103,536 kg NO_x eq to ozone formation (human health). They also account for 161,236 kg SO_2 eq in terrestrial acidification, 1.73 million kg 1,4-DCB eq in freshwater ecotoxicity, and 2.3 million kg 1,4-DCB eq in marine ecotoxicity. Additionally, 42.33 million kg 1,4-DCB eq contributes to human non-carcinogenic toxicity. Gloves also consume 427,167 m^3 of water and 15.96 million kg of fossil resources.

Compared to other PPEs such as aprons, masks, and gowns, gloves exhibit the highest environmental impact, particularly in terrestrial ecotoxicity, global warming, and human non-carcinogenic toxicity. "They significantly impact ozone depletion, acidification, water consumption, and fossil fuel depletion. These findings highlight the need for sustainable solutions to mitigate the environmental footprint of glove production.

2.7 Software Tools

Several software tools have been developed to facilitate LCA, enabling users to model environmental impacts of products, processes, or services throughout their life cycle. These tools assist in data management, impact assessment, and result interpretation based on international LCA standards such as ISO 14040 and 14044. The selection of appropriate LCA software depends on factors such as user-friendliness, database availability, compatibility with impact assessment methods, and intended application. Table 2.3 below provides a comparison of commonly used LCA software tools along with their key features.

Table 2.3: Comparison of LCA software tools

Analysis Criteria	GaBi	openLCA	SimaPro	Umberto
Software origin	Germany, Thinkstep	Germany, GreenDelta	Netherlands, PRe Consultants,	Germany, iFu Hamburg GmbH
Access	Paid	Free	Paid	Paid
User interface perception	Uses process modelling and diagrams for each unit process.	Uses process modelling and diagrams for each unit process.	Uses matrices for modelling of unit process.	Uses Petri nets for LCA modelling.
Presentation of LCA results	Uses Sankey diagram and bar charts to show LCA results.	Uses Sankey diagram and bar charts to show LCA results, and tables for inventory analysis.	Uses Sankey diagram and bar charts to show LCA results.	Uses Sankey diagram to show LCA results and tables for inventory analysis.
Positive aspects	- Good documentation of datasets - Costs and social aspects can be modelled too - It is possible to import/export datasets	- Costs and social aspects can be modelled too - Free for users - It is possible to import/export datasets.	- Good documentation of datasets - Social aspects can be modelled too - Integrated with ecoinvent.	- Costs aspects can be modelled too - Integrated with ecoinvent database and/or GaBi database - Good integration with Excel.
Negative aspects	-High cost of investment -Most of datasets are aggregated	-Lack of datasets freely available -Many datasets are poorly documented	-High cost of Investment -Limited number of dataset formats	-High cost of investment -Does not have uncertainty analysis.

Source: Adapted from "*How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto*" by Silva et al., 2017.

2.8 Assessment Methods

Impact assessment is the stage where the potential environmental effects linked to a product's entire life cycle are systematically evaluated. To conduct this analysis, a variety of internationally recognized methods can be used, such as CML-IA, ReCiPe 2016, TRACI 2.1, ILCD, USEtox, and EF 3.0, among others. Table 2.4 provides a comparative summary of these methodologies.

These Life Cycle Impact Assessment (LCIA) methods differ not only in their characterisation models and impact categories but also in the level at which impacts are assessed namely, midpoint or endpoint. Midpoint approaches evaluate impacts at an intermediate stage of the cause effect chain, focusing on specific environmental issues such as climate change, acidification, or eutrophication. They offer detailed, science-based indicators that are widely accepted for comparative assessments. Endpoint approaches, on the other hand, translate these midpoint impacts into damage on broader areas of protection like human health, ecosystem quality, and resource availability, making the results more interpretable for decision makers. The choice between midpoint and endpoint assessments often depends on the intended application, the desired level of detail, and the audience for the results (shown in figure 2.4).

Table 2.4: Comparison of LCA methodology

Methods	Types	Region/ Use	Impact Category	Reference
CML-IA	Midpoint	Global	Climate change, ozone depletion, human toxicity, photochemical smog, acidification, eutrophication, ecotoxicity, land use, water use, fossil & metal depletion.	PRe et al., 2014
TRACI 2.1	Midpoint	USA	Climate change, ozone depletion, human toxicity, photochemical smog, acidification, eutrophication, ecotoxicity, land use, water use, fossil & metal depletion.	Ryberg et al., 2014
ILCD	Midpoint	EU	Climate change, ozone depletion, human toxicity, photochemical smog, acidification, eutrophication, ecotoxicity, land use, water use, fossil & metal depletion.	Rosenbaum at al., 2020
USEtox	Midpoint	Global	Climate change, ozone depletion, human toxicity, photochemical smog, acidification, eutrophication, ecotoxicity, land use, water use, fossil & metal depletion.	Rosenbaum at al., 2020
ReCiPe 2016	Midpoint and Endpoint	Global	Climate change, ozone depletion, human toxicity, photochemical smog, acidification, eutrophication, ecotoxicity, land use, water use, fossil & metal depletion. Human health, ecosystem quality, resource scarcity	Goedkoop M et al., 2009
EF 3.0	Midpoint and Endpoint	EU	Climate change, ozone depletion, human toxicity, photochemical smog, acidification, eutrophication, ecotoxicity, land use, water use, fossil & metal depletion. Human health, ecosystem quality, resource scarcity	Rosenbaum at al., 2020

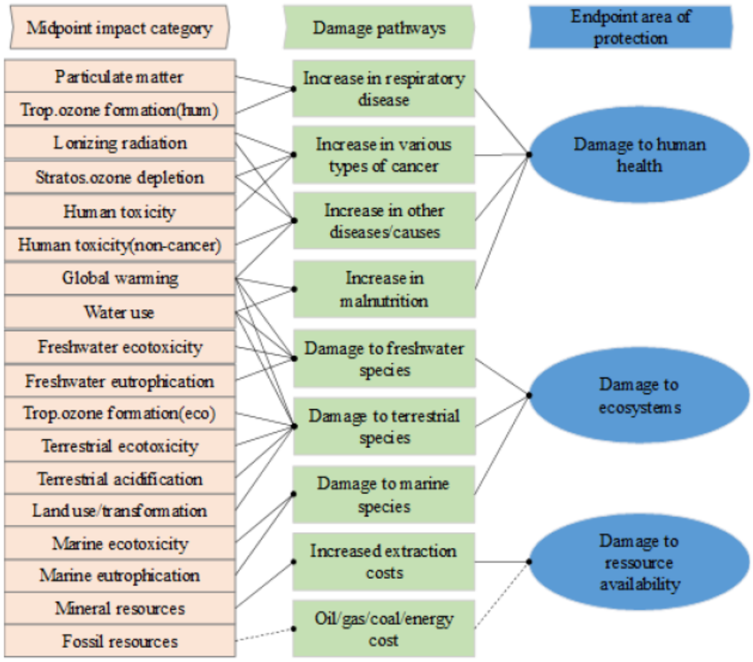

Figure 2.4: Overview of midpoint and endpoint categories

Source: "*ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level*" by Huijbregts et al., 2020

2.9 Life Cycle Assessments of Gloves

The ISO has developed a well-defined framework for LCA, which is used to assess the environmental impact of a product throughout its entire lifespan. Over the past three decades, ISO has continually updated and refined this framework to enhance the evaluation process. Its official documentation outlines essential principles and methodologies for applying LCA at various stages of a product's life cycle (De Benedetto et al., 2009).

A crucial step in LCA is defining the goal and scope, which involves setting boundaries for the assessment to ensure that no stage of the product's life cycle is overlooked. At this stage, any assumptions made must be clearly stated and transparently documented. Several commonly used boundary approaches in LCA include cradle to grave, cradle to cradle, and cradle to gate methodologies. Figure 2.5 below illustrates an example of the boundaries of product life cycle.

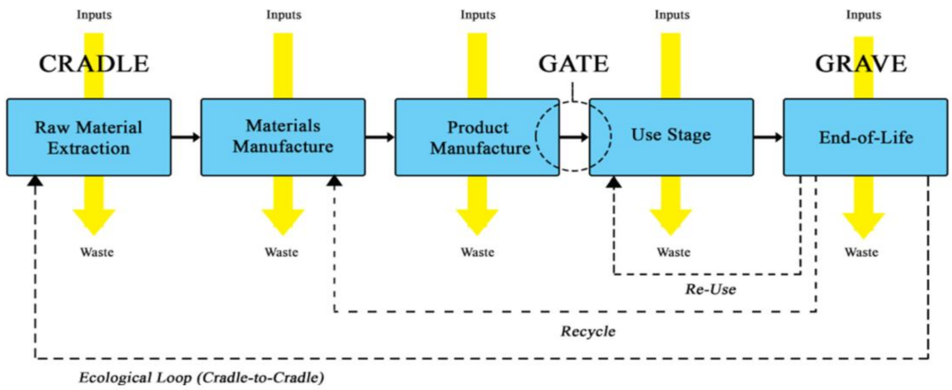

Figure 2.5: Sample boundaries of product lifecycle

Source: *"A quick guide to Life Cycle Assessments (LCAs)"* by Sorbom, 2025.

The second phase focuses on gathering input and output data related to emissions, mass balance, and energy flow. In the third phase, various software tools such as openLCA, SimaPro, and others are used to quantify the assessment data into different impact categories. These categories may include climate change, ozone depletion, human toxicity, ecotoxicity, resource depletion, and formation processes. The final phase involves evaluating the results to identify hotspot areas that contribute significantly to environmental impact. Based on this analysis, targeted mitigation measures can be implemented to minimise or eliminate adverse effects.

Several studies have been conducted using different scope boundaries to assess the environmental impact of nitrile gloves throughout their life cycle. Patrawoot et al. (2021) examined the life cycle of NBR and NR gloves, specifically comparing powdered and non-powdered variants. The data used in this study was obtained through interviews with respondents working at a manufacturing plant in Thailand, supplemented by secondary data from the Thai National Life Cycle Inventory Database. Their study adopted a cradle to grave approach, covering raw material extraction, transportation, production, distribution, and disposal via incineration.

To expand the research scope, the study also included powder-free gloves with chlorination and polymer coatings. The assessment was conducted using SimaPro software, while environmental impact calculations were performed using the ReCiPe Midpoint (H) method. The findings revealed that the production stage had the highest environmental impact, largely influenced by the technologies available at that time. A comparison between rubber sources showed that NBR had a greater environmental impact than NR during the extraction phase. However, this trend reversed during the production stage, where NR required significantly more energy than NBR.

Regarding coating methods, chlorination resulted in higher energy consumption due to additional drying processes compared to polymer coating. Overall, the study concluded that NR gloves had a slightly higher environmental impact than NBR gloves. However, the difference in impact was only around

10% to 20%, suggesting that the environmental footprint of NR gloves could be reduced by adopting renewable resources in raw material sourcing and production processes.

Wang et al. (2024) conducted a life cycle assessment on single-use nitrile gloves used at the University of British Columbia (UBC). The study applied a cradle to grave approach, assuming landfill disposal for the gloves and recycling for the packaging materials. Due to data limitations, certain assumptions were made, including an undefined disposal method, the assumption that all packaging materials were sent for recycling and using glove product system that had been researched by previous researcher Jamal et al., (2021). The researchers utilised openLCA, a free software tool, to evaluate the product's environmental impact. The findings indicated that the production phase had the highest environmental emissions, primarily due to the use of butadiene and acrylonitrile both petroleum-based compounds. To mitigate these emissions, the study suggested exploring bio-based alternatives.

Similarly, Eastwest Medico (2023) examined the manufacturing of nitrile gloves in Malaysia, China, and France. The study found that France had approximately 20% lower carbon emissions compared to Malaysia and China, with variations attributed to factors such as glove weight, the country of resin production, and energy consumption during manufacturing. Additionally, the study revealed that the disposal phase contributed an additional 12 g CO_2 eq per glove to overall emissions. To minimise the carbon footprint of end-of-life disposal, the study recommended using lighter gloves, sourcing products locally, and exploring alternative disposal methods beyond incineration.

The cradle-to-cradle approach, on the other hand, considers product reuse or recycling at the end of its life. Nortz et al. (2022) assessed the life cycle of natural rubber gloves, nitrile, and cotton gloves using this approach. In the study, cotton gloves were assumed to be reused, while rubber and nitrile gloves were either recycled or disposed of. The assessment was performed using openLCA software, with input data sourced from the Ecoinvent database. Results showed that landfill disposal generated lower carbon emissions compared to incineration, with incineration producing 40% more emissions, equivalent to 28 g CO_2 eq. While natural rubber had a lower overall carbon footprint, emissions increased by 20% due to transportation from manufacturers in Asia to end users in the US.

Table 2.5: Summary of LCA studies on gloves

Author	Product Functional unit Boundary	Software Method Data source	Findings
Patrawoot et al., (2021)	a) NBR, NR powdered (chlorination and polymer) and non-powdered b) 100 pcs of gloves c) Cradle to grave	a) SimaPro b) ReCiPe-Midpoint c) Onsite interview from Factory and survey data (Thailand)	a) Production stage contributes for impact; NBR contributes more than NR latex b) Coal usage in production stage contributes more compared to natural gas
Wang et al., (2024)	a) NBR (non-powdered and non-sterile) b) 100 pcs of nitrile gloves c) Cradle to grave	a) openLCA b) ReCiPe-Midpoint c) Previous study data	a) 100 pcs of glove emit 3.056 kg CO_2 eq b) Hotspot identify from production stage- contribute by synthetic rubber
Eastwest Medico (2023)	a) NBR (from China, France, Malaysia b) 1 pair of gloves c) Cradle to gate	a) Not stated b) Carbon emission c) Manufacturer data from selected factory	a) France had 25% lower carbon footprint due to energy source and production efficiency
Nortz et al., (2022)	a) NR, NBR, cotton glove b) 1 pair of gloves c) Cradle to grave & cradle to cradle	a) openLCA b) Carbon emission c) Survey data	a) carbon footprint; cotton glove 27 g CO_2 eq, NBR 26 g CO_2 eq and NR 13 g CO_2 eq b) Cotton highest due to large mass
Jamat et al., (2021)	a) Sterile (synthetic rubber) and non-sterile examination gloves b) 1 pair of gloves c) Cradle to grave	a) openLCA b) ReCiPe and ILCD c) Manufacturer data from Malaysia and China	a) Non-sterile gloves have a lower environmental impact than sterile surgical gloves
Poh et al., (2019)	a) NBR b) 1 kg c) Cradle to gate	a) GaBi b) Mathematical optimization c) Real production plant (Selangor)	a) Glove production process consumes 10.04 MJ of commercial electricity per kg of gloves- significant environmental impacts b) Usage of biodiesel reduces overall emission in glove production

2.10 Discussions

The literature reviewed offers significant insights into the environmental life cycle of nitrile gloves. A consistent theme across multiple studies is the high environmental burden associated with the production phase, largely due to substantial energy usage and resulting greenhouse gas emissions (Patrawoot et al., 2021; Wang et al., 2024). The end-of-life stage also poses considerable environmental concerns: landfilling can lead to prolonged ecological degradation, as nitrile gloves may persist for up to two hundred years. Incineration, while effective at reducing waste volume, contributes to atmospheric pollution through emissions of carbon monoxide and nitrogen oxides (Wang et al., 2024). As an alternative, recycling has been proposed by researchers such as Ragazzi et al. (2023), who suggest that it could reduce glove waste by 5% to 7%.

Notable gaps remain in the current body of research. Many existing LCA studies rely predominantly on secondary or modeled data, which can compromise real-world accuracy. The application of openLCA software remains limited in the context of nitrile gloves, especially in analyses incorporating primary data from industry sources.

To bridge these research gaps, this study utilizes openLCA paired with primary data collected from glove producers. This approach aims to enhance modelling precision by reflecting actual industry practices. The following chapter details the methodological framework employed in this research, including the definition of system boundaries, selection of the functional unit, data sources used, and modelling assumptions integrated into the openLCA platform.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This study follows the structured methodology outlined in ISO 14040 and ISO 14044 framework for conducting LCA as shown in figure 3.1. The research is divided into four key phases, beginning with the definition of the goal and scope of the study.

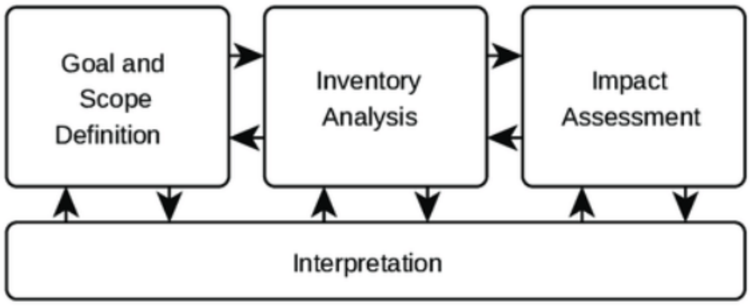

Figure 3.1: LCA methodology framework

Source: International Organisation of Standardisations (ISO) 14040.

3.2 Goal and Scope Definition

The aim of this research is to evaluate the environmental impacts associated with nitrile glove production, adopting a cradle-to-grave system boundary. The study is focused on a single product category: non-sterile, powder-free nitrile gloves that manufactured from a production facility located in Kamunting, Perak, Malaysia. Established in 2021, this facility operates twelve production lines with a monthly capacity of twenty-eight million pieces, producing various grades of nitrile gloves including medical, industrial, examination, and food handling types. Aligned with market demand, the facility's monthly output averages four million gloves, with NBR as the key raw material and electricity and natural gas as the main energy inputs.

The plant is equipped with environmental control systems such as an onsite wastewater treatment facility, scrubber operation, and sewage treatment plant. It also engages in research and development initiatives, including the innovative use of sericin extract naturally derived from silk cocoons for diverse glove applications. An overview of the included processes and defined system boundaries is presented in figure 3.2.

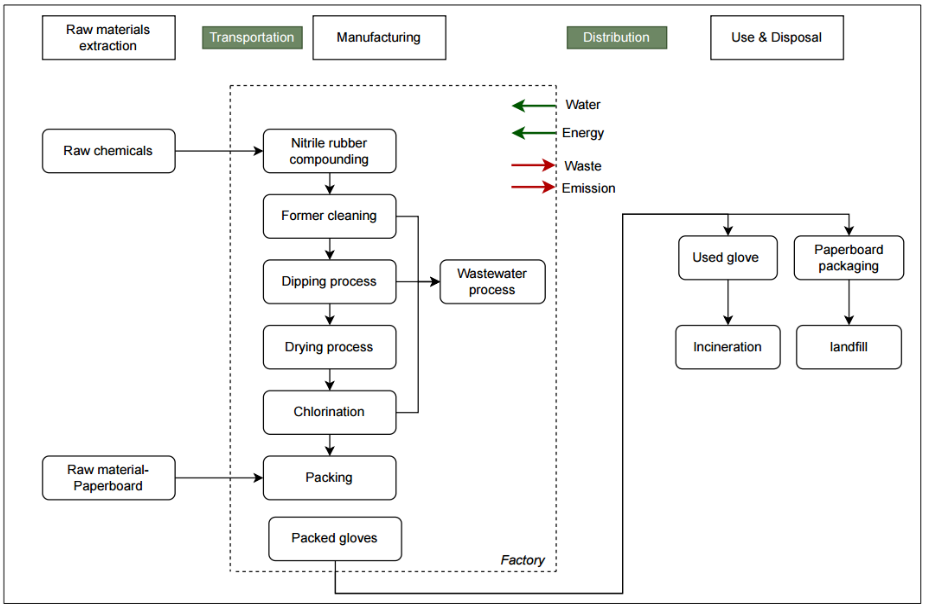

Figure 3.2: System boundary cradle to grave

For this LCA, the selected functional unit is 100 pieces of glove which is the one box of medium sized, non-sterile, powder free nitrile gloves. Standard packaging practices indicate that each box contains hundred individual gloves, enclosed with a paperboard. Primary operational data was collected from production facility for five-month period, from January 2025 to May 2025 which represents normal product trend months.

3.3 Life Cycle Inventory (LCI)

This stage focuses quantification and collection of relevant input and output of parameters value that involve with glove manufacturing. Input and output data that involve such as NBR consumption, electricity usage, water usage, chemicals, monthly glove outputs, wastewater discharge and natural gas usage. Waste such as solid waste, water discharge and air emission also were gathered during this inventory process.

Primary data were provided by the factory’s data collection while background data for upstream and downstream processes such as energy extraction, raw material extraction, end of life treatment were obtained from European Life Cycle Database (ELCD 3.2) which already integrated into openLCA. All data were adjusted to the functional unit of 100 pieces of gloves to ensure comparability.

3.3.1 Life Cycle Inventory (LCI) assumptions

To enable the LCA study, several assumptions were applied. First, operational processes such as inspection, glove stripping, and beading were excluded from the system boundary, as they were deemed to have minimal significance to the overall product system. The five-month (January 2025 to May 2025) production batch was assumed for export to the US for use in the healthcare sector.

At the end-of-life stage, gloves were assumed to be incinerated due to contamination concerns and classification as clinical waste. Due to the lack of significant data on the cost and feasibility of recycling used paperboard, it was assumed to be disposed of in a landfill.

For the product distribution activities, this study divided the logistics routes into two segments. The first segment involved road transport from the factory to the shipping port in Penang. The second segment comprised sea transport, with the container shipped to the US. In both cases, the distances were estimated using Google Maps measurements. This approach follows the method applied in the previous study by Wang et al. (2024), where Google Maps was used as a reference to assess transportation impacts.

The transported gloves are assumed to be utilised primarily by the healthcare sector in the US. The gloves used in healthcare settings are regarded as potentially hazardous waste. Consequently, incineration was selected as the final disposal method.

3.3.2 Electricity Consumption

Electricity use in the production of nitrile gloves at the Kamunting facility was modelled using the Malaysian national grid, which integrates multiple power generation technologies. The country's electricity supply is predominantly fossil fuel-based, with coal and natural gas providing the largest share, while hydropower and other renewable sources contribute a comparatively smaller fraction. In 2017, thermal power plants (coal and gas) accounted for over 80 % of Malaysia's total electricity generation, underscoring the grid's continued dependence on fossil fuels (Latif et al., 2021).

A key contributor to coal-based electricity is the Manjung coal-fired power station (Sultan Azlan Shah Power Plant) in Perak, one of the largest in Malaysia, which feeds into the national grid supplying the Kamunting facility. Since the factory draws electricity from the interconnected grid rather than a single source, the environmental impacts from various generation technologies including coal-fired plants such as Manjung, gas combined cycle stations, and hydropower facilities are reflected in the life cycle inventory.

3.4 Life Cycle Impact Assessment (LCIA)

Assessment for nitrile glove cradle-to-grave life cycle assessment was done using openLCA 2.4 free software source using primary data from real production plants. The impact of the product was assessed using ReCiPe Midpoint (H) 2016 method. This assessment was conducted based on eighteen midpoint impact categories. The eighteen categories; fine particulate matter formation, fossil resource scarcity, ecotoxicity (freshwater), eutrophication (freshwater), global warming, human toxicity (cancer), human toxicity (non-cancer), ionizing radiation, land use, marine ecotoxicity, eutrophication (marine), mineral resource scarcity, ozone formation (human health), ozone formation (terrestrial ecosystems), stratospheric ozone depletion, terrestrial acidification, terrestrial ecotoxicity, water consumption.

Each category was expressed in different units. To enhance comparative comparison among all impact categories, normalisation was applied. Normalisation is a procedure, as defined by the ISO 14044 standard (ISO, 2006b), that expresses the magnitude of impact category results relative to a reference system. In this process, the characterized result of each impact category is divided by a normalisation reference, producing dimensionless values that allow for meaningful comparisons across categories. Normalisation is particularly valuable in LCIA because it highlights the relative importance of each impact category and improves communication of results to stakeholders, including those without LCA expertise (Kim et al., 2013; Dahlbo et al., 2013).

In this study, normalisation was conducted using the ReCiPe 2016 (H) midpoint normalisation reference, provided in the openLCA LCIA methods v2.1.3 software package. Table 3.1 provides the normalisation reference values applied in this study, derived from the ReCiPe 2016 (H) midpoint method as implemented within the openLCA LCIA Methods v2.1.3 package. These references represent the annual global environmental load per capita (World Data 2010) for each impact category and are widely implemented in LCA software such as openLCA. These factors enable impact categories to be expressed in dimensionless ‘person-equivalent’ terms, underscoring each environmental aspect’s relative contribution to the life cycle profile (Huijbregts et al., 2017; Sleeswijk et al., 2007). This approach is aligned with other studies in the water sector, such as Barjoveanu et al. (2019), who examined the environmental performance of the wastewater applied the same normalization reference.

Table 3.1:Normalisation reference value (annual global environmental load per capita) for impact categories

Impact category	Unit	Normalisation value
Global warming [GW]	kg CO_2 eq/person/yr	7987.220447
Stratospheric ozone depletion [SOD]	kg CFC 11 eq/person/yr	0.059880
Ionizing radiation [IR]	kBq Co-60 eq/person/yr	480.769231
Ozone formation, human health [OFHH]	kg NO_x eq/person/yr	20.576132
Fine particulate matter formation [FPMF]	kg PM2.5 eq/person/yr	25.575448
Ozone formation, terrestrial ecosystem [OFTE]	kg NO_x eq/person/yr	17.761989
Terrestrial acidification [TA]	kg SO_2 eq/person/yr	40.983607
Freshwater eutrophication [FWEutrof]	kg 1,4-DCB/person/yr	0.649351
Marine eutrophication [MEutrof]	kg N eq/person/yr	4.608295
Terrestrial ecotoxicity [TEcotox]	kg 1,4-DCB/person/yr	1036.269430
Freshwater ecotoxicity [FWEcotox]	kg 1,4-DCB/person/yr	1.226994

Table 3.1 continued

Marine ecotoxicity [MEcotox]	kg 1,4-DCB/person/yr	1.031992
Human carcinogenic toxicity [HCT]	kg 1,4-DCB/person/yr	2.770083
Human non-carcinogenic toxicity [HCNT]	kg 1,4-DCB/person/yr	149.031297
Land use [LU]	m^2a crop eq/person/yr	6172.839506
Mineral resource scarcity [MRS]	kg Cu eq/person/yr	120048.019208
Fossil resource scarcity [FRS]	kg oil eq/person/yr	980.392157
Water consumption [WC]	m^3/person/yr	266.666667

Source: ReCiPe 2016 (H) midpoint normalisation factors (World, 2010), openLCA LCIA Methods v2.1.3.

3.4.1 Scaling of Monthly Data to Annual Impact

Normalisation was performed using the ReCiPe 2016 global reference values, which reflect the average annual environmental burden per capita. To maintain methodological consistency, all impact results were first annualised before applying the normalisation step.

The functional unit for this study is defined as 100 nitrile gloves. Primary inventory data collected from the factory were reported on a monthly production basis, in line with the company's operational practices. To ensure that the LCIA results could be interpreted at the factory scale while remaining consistent with the functional unit, a scaling procedure was introduced.

The process began by calculating the mean impact per functional unit using monthly inventory data. This figure was then multiplied by the annual production volume. On average, the factory produces 40,000 per functional unit per month. Accordingly, the annual environmental impact for each midpoint category was determined as:

$$\text{Annual Impact (per 100 pcs)} = \text{Monthly impact (per 100 pcs)} \times 480{,}000 \quad (3.1)$$

This scaling procedure does not alter the definition of the functional unit itself; rather, it enables interpretation of results at the level of annual factory output, which is necessary for applying ReCiPe normalisation factors. Since the ReCiPe 2016 references are expressed as annual per-capita environmental loads, converting the impact values to an annual basis ensures full methodological alignment.

The resulting normalised scores therefore indicate the relative contribution of producing 100 nitrile gloves scaled to the factory's annual output against the average annual environmental burden of a global citizen. Higher normalised values correspond to greater relative significance within each impact category.

3.5 Uncertainty Analysis

Uncertainty and robustness of LCA results of this study evaluated via Monte Carlo simulation analysis. This method helps to quantify uncertainty associated with the results that were generated (Lloyd & Ries, 2007). From the five-month (January 2025 to May 2025) data collected, April month data used as representative month for this simulation. April was chosen as the representative month since its production data demonstrated consistent homogeneity in glove size across all 30 days of April month.

A Monte Carlo simulation executed over 5,000 iterations under a 95% confidence interval using openLCA software. For each iteration, input values were randomly sampled from their respective probability distributions, and the LCA model was recalculated to obtain the corresponding environmental impact results using the ReCiPe Midpoint (H) method. This process produced a distribution of output values for each impact category, from which statistical indicators such as the mean (μ), standard deviation (σ), and percentile ranges were derived.

The variability of simulation represents using Coefficient of Variation (CV) which can be calculated using standard deviation ($\boldsymbol{\sigma}$) to mean (μ).

$$CV\ (\%) = \frac{\sigma}{\mu} \times 100 \qquad (3.2)$$

According to Heijungs & Huijbergts (2004) a limit of CV has been determined to indicate the greater stability of results that imply higher confidence in results output. According to Shechtman (2013), lower CV values indicate greater consistency and reliability of the data, whereas higher CV values reflect increased relative dispersion and potential uncertainty. In general, CVs below 10% are considered indicative of very good reliability, values between 10% to 20% suggest good reliability, while CVs exceeding 30% to 50% signal moderate to high variability, warranting caution in interpreting results and consideration of sensitivity or uncertainty analyses.

3.6 Life Cycle Interpretation

The LCIA for this study was performed using the ReCiPe 2016 (H) midpoint method, covering eighteen environmental impact categories associated with nitrile glove production. Inventory data for 100 pieces of gloves were collected over a five-month period, and the monthly LCIA outputs were averaged to represent typical operating conditions. This average impact was then extrapolated to the annual production capacity of the facility to estimate the full environmental burden generated over one year of glove manufacturing. All impact values were subsequently normalised using ReCiPe's global normalisation factors, enabling each category to be expressed as a dimensionless value and allowing direct comparison across categories with different units. The normalised results were ranked according to their relative contribution, and the five categories with the highest environmental load were selected for detailed analysis.

The interpretation phase combined these normalised results with the uncertainty analysis to identify the most critical environmental burdens within the cradle-to-grave life cycle. Higher normalised scores were used to determine the categories exerting the greatest influence on overall environmental performance. Based on these findings, several targeted mitigation measures were proposed, including improving energy efficiency, optimising production parameters, upgrading wastewater management systems, and exploring more sustainable raw materials. Integrating normalisation and uncertainty assessment ensures that the conclusions drawn are robust and evidence-based, providing reliable guidance for enhancing sustainability within the glove production process.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the findings of the LCA conducted for nitrile gloves using the openLCA platform. The evaluation is organized in line with the study objectives, emphasizing the environmental impact assessment of glove production through the ReCiPe Midpoint (H) methodology, followed by uncertainty analysis using Monte Carlo simulation. The LCI compiled in Chapter 3 served as the basis for this assessment and the subsequent interpretation of results.

4.2 LCIA Results of ReCiPe Midpoint (H) Method

The LCIA results for five months from January 2025 to May 2025 were compiled to establish the baseline environmental performance associated with producing 100 pieces of nitrile gloves. Table 4.1 summarises the minimum, maximum, and mean values for all eighteen midpoint impact categories. Overall, the five-month data show relatively small monthly variations, with most values fluctuating within a narrow range of approximately 5% to 10%, suggesting stable and consistent process conditions throughout the assessment period.

The monthly life cycle impact data for functional unit of 100 pieces of nitrile gloves collected between January 2025 and May 2025 revealed distinct patterns and variations across multiple environmental impact categories. Several categories exhibited moderate to substantial fluctuations, reflecting sensitivity to production parameters and process intensity. For instance, global warming (GW) ranged from 6.47 to 7.30 kg CO_2-eq, with April recording the highest value. A comparable trend was observed for fossil resource scarcity (FRS), which varied between 2.63 and 2.85 kg oil-eq, again peaking in April. These outcomes suggest that energy consumption and fossil fuel related processes were more intensive during this month, consistent with the uniform glove size production and stable operational load observed in April.

Toxicity related categories also displayed notable variability. Terrestrial ecotoxicity (TEcotox) showed one of the widest ranges, fluctuating from 1.01 to 1.49 kg 1,4-DCB, indicating differences in toxic substance emissions or exposure across months. Human non-carcinogenic toxicity (HNCT) similarly ranged from 0.072 to 0.101 kg 1,4-DCB, with April once more recording the highest value. These variations likely reflect changes in material inputs, upstream chemical processes, or waste management practices throughout the production period. In contrast, human carcinogenic toxicity (HCT) exhibited a narrower but still discernible pattern, increasing gradually from 0.00093 to 0.00120 kg 1,4-DCB toward April.

Other categories remained relatively stable. Freshwater eutrophication (FWEutrof) showed near constant values between 0.00033 and 0.00034 kg P-eq, suggesting minimal variation in nutrient related emissions. Marine eutrophication (MEutrof) also remained within a narrow range of 0.00020 to 0.00021 kg N-eq. Stratospheric ozone depletion (SOD) consistently recorded zero values, reflecting the absence of ozone-depleting substances within the defined system boundary.

Moderate variation was observed in categories such as ionizing radiation (IR) (0.0339 to 0.0412 kBq Co-60 eq), land use (LU) (0.00036 0.00054 m^2a crop eq), and ozone formation, human health (OFHH) and ozone formation terrestrial ecosystem (OFTE), all of which showed elevated values in April. The consistent peak across several categories during April can be attributed to the operational conditions of that month, particularly the homogeneous glove size production maintained throughout all 30 days. In contrast, other months involved mixed glove sizes, introducing variability in material inputs, energy demand, and processing loads. The uniformity of April's production thus provided more stable and representative environmental load profiles, making it the most suitable month for detailed simulation and further analysis.

Table 4.1: Baseline LCIA results for 100 pieces of nitrile gloves

Impact category	Unit	January	February	March	April	May	Maximum	Minimum	Mean
FPMF	kg PM2.5 eq	0.00594	0.00574	0.00615	0.00730	0.00718	0.00730	0.00574	0.00646
FRS	kg oil eq	2.65311	2.62916	2.69004	2.84780	2.80398	2.84780	2.62916	2.72482
FWEcotox	kg 1,4-DCB	0.00028	0.00027	0.00029	0.00033	0.00032	0.00033	0.00027	0.00030
FWEutrof	kg P eq	0.00034	0.00034	0.00034	0.00034	0.00033	0.00034	0.00033	0.00034
GW	kg CO_2 eq	6.56320	6.46760	6.70019	7.29738	7.15394	7.29738	6.46760	6.83646
HCT	kg 1,4-DCB	0.00096	0.00093	0.00102	0.00120	0.00111	0.00120	0.00093	0.00104
HNCT	kg 1,4-DCB	0.07574	0.07217	0.08002	0.10079	0.09760	0.10079	0.07217	0.08526
IR	kBq Co-60 eq	0.03457	0.03393	0.03681	0.04120	0.03732	0.04120	0.03393	0.03677
LU	m^2a crop eq	0.00038	0.00036	0.00040	0.00054	0.00053	0.00054	0.00036	0.00044
MEcotox	kg 1,4-DCB	0.00127	0.00120	0.00135	0.00176	0.00173	0.00176	0.00120	0.00146
MEutrof	kg N eq	0.00020	0.00020	0.00020	0.00021	0.00020	0.00021	0.00020	0.00020
MRS	kg Cu eq	0.00133	0.00133	0.00134	0.00136	0.00134	0.00136	0.00133	0.00134
OFHH	kg NO_x eq	0.00865	0.00847	0.00889	0.00999	0.00978	0.00999	0.00847	0.00916
OFTE	kg NO_x eq	0.00891	0.00873	0.00915	0.01026	0.01005	0.01026	0.00873	0.00942
SOD	kg CFC 11 eq	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
TA	kg SO_2 eq	0.01981	0.01916	0.02050	0.02429	0.02387	0.02429	0.01916	0.02153
TEcotox	kg 1,4-DCB	1.07618	1.01499	1.13749	1.48602	1.45701	1.48602	1.01499	1.23434
WC	m^3	0.08581	0.08506	0.08658	0.09144	0.09094	0.09144	0.08506	0.08797

All midpoint impact values derived from the ReCiPe 2016 method were initially calculated on a monthly, per-functional-unit basis. Since the impact categories are expressed in different measurement units, direct comparison was not feasible. To enable comparability, the results were normalised using the ReCiPe global reference values. The ReCiPe 2016 global normalisation references represent the average annual environmental load per capita. Accordingly, converting the glove production impacts into annual values ensures methodological consistency between the study's results and the reference dataset applied for normalisation.

Once annualised, each impact value was divided by its corresponding ReCiPe reference, yielding dimensionless normalised scores. These scores reflect the relative importance of each impact category in comparison to the global average environmental burden of one individual. Higher scores indicate categories where glove production contributes more significantly to global environmental pressures.

Figure 4.1 illustrates the normalised results obtained using the ReCiPe Midpoint (H) 2016 method across all eighteen impact categories. Normalisation expresses each category relative to the annual per-capita environmental load, meaning that higher scores denote greater contributions compared with the reference individual. Among the categories, FRS yields normalised score value of 1334 p/yr indicating that the process contributes FRS impact which is equivalent to 1334 p/yr average person's yearly impact in this domain. MEcotox scores value of 680 p/yr equivalents to impact which reflect 680 average individuals. HNCT score 572 p/yr, reflecting impact of 572 average person. Categories score value negligible is LU and MRS, represent comparatively minor impacts relative to the reference scale. Based on these normalised magnitudes, the most influential categories highlighted in the subsequent discussion are FRS, MEcotox, TEcotox, GW, and HNCT.

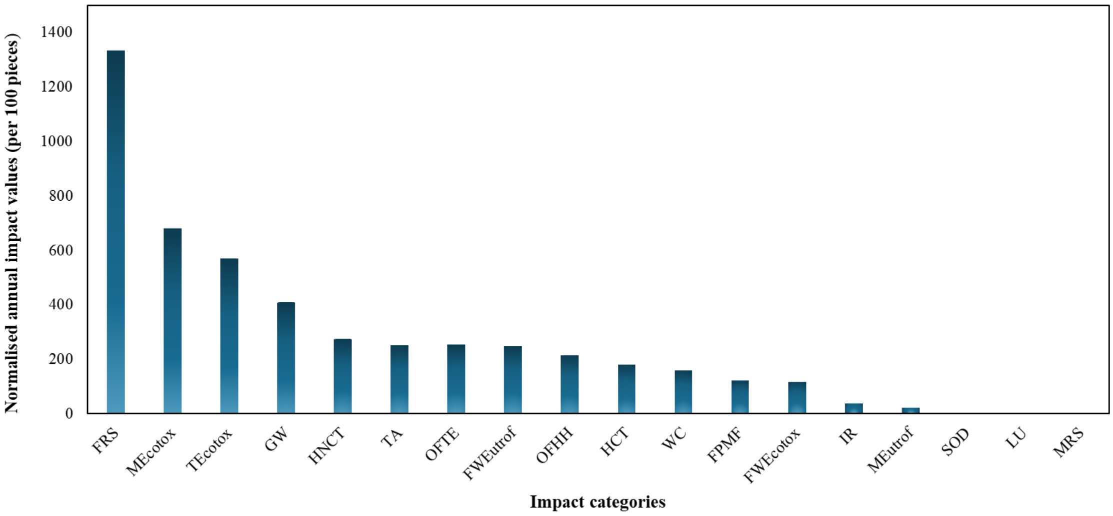

Figure 4.1: Normalised annual impact score (per 100 pieces) for eighteen categories

4.2.1 Fossil Resource Scarcity (FRS)

FRS recorded the highest normalised annual score at 1334 p/yr, equivalent to 1334 times an average person's yearly fossil resource depletion. This establishes FRS as the most dominant impact category in the LCA results. The elevated score reflects the fossil-based origin of NBR, the primary glove material. NBR relies on petroleum-derived monomers acrylonitrile and butadiene produced through energy-intensive petrochemical processes. Literature consistently highlights the high fossil depletion intensity of synthetic rubber manufacturing, driven by both raw material extraction and thermal processing (Zhu et al., 2015).

Electricity consumption further amplifies this burden. Malaysia's grid mix is heavily dependent on natural gas and coal, which increases the fossil resource footprint. Patrawoot et al. (2021) similarly identified energy use as the principal driver of fossil depletion in glove production systems. Thus, the high normalised FRS score underscores the intrinsic material and energy dependencies of nitrile glove fabrication.

4.2.2 Marine Ecotoxicity (MEcotox)

MEcotox was the next major contributor, with a normalised annual value of 680 p/yr which represents approximately 680 person-equivalent per year of the global per-capita ecotoxicity load. In Malaysia, the main drivers of MEcotox are pollutant emissions from electricity generation and the extraction of NBR raw materials. Fossil fuel and coal fired power plants emit sulfur dioxide, nitrogen oxides, particulate matter, acid gases, and trace heavy metals such as mercury, lead, copper, zinc, and arsenic, which can enter aquatic ecosystems through atmospheric deposition and runoff from ash disposal sites (Abdul Latif et al., 2021). NBR production contributes additional chemical complexity: acrylonitrile monomer is volatile and toxic to aquatic organisms, and NBR materials and waste have been shown to contain heavy metals including zinc, lead, likely originating from fillers added during compounding stages (Luo et al., 2023; Sorensen et al., 2023).

Wastewater from glove manufacturing further exacerbates marine pollution, as exemplified by a Kedah plant discharging chemical oxygen demand of 1,280 mg/L into drainage systems, vastly exceeding the regulated limit of 80 mg/L under Standard A discharge limit Malaysia's Environmental Quality (Industrial Effluent) Regulations 2009 (Bernama, 2024). These pollutants both organic compounds and heavy metals can reach marine environments via riverine transport, direct discharge, and atmospheric deposition, posing toxicity risks to aquatic organisms.

4.2.3 Terrestrial Ecotoxicity (TEcotox)

TEcotox ranked third, with a normalized annual score of 572 p/yr, equivalent to the terrestrial toxicity burden experienced by approximately 572 individuals per year. The dominant drivers of this impact are toxic releases associated with NBR extraction, which tend to accumulate in soil ecosystems. Evidence from petrochemical research highlights that petroleum-derived pollutants can significantly impair soil quality and intensify ecotoxicity risks (Wu et al., 2024). Acrylonitrile, a critical monomer in NBR production, is both volatile and highly toxic, with documented cases of contamination at hazardous waste sites and adverse effects on soil ecosystems (Agency for Toxic Substances and Disease Registry, 2022). Collectively, these findings suggest that the TEcotox outcomes observed in this study are primarily linked to upstream emissions generated during raw material extraction.

4.2.4 Global Warming (GW)

The GW of synthetic gloves mean value for 5 months data is 6.83646 kg CO_2 eq per 100 pieces, positioning it as a major contributor to the overall environmental footprint of glove production. This impact is largely attributable to fossil fuel combustion, with electricity use and energy intensive manufacturing processes serving as the primary drivers. As highlighted by Poh et al. (2019), synthetic glove manufacturing is heavily dependent on electricity and heating utilities derived from fossil fuels, which amplifies its greenhouse gas emissions. Although the raw LCA results reveal a comparatively high GW, the normalised GW score of 411 p/yr ranks only fourth among the assessed impact categories. This indicates that the overall life cycle impacts of nitrile glove production are not predominantly driven by GW but are instead significantly shaped by other categories. Expressing the GW results in absolute terms 6.83646 kg CO_2-eq for the production of 100 nitrile gloves offers a clearer and more transparent depiction of the actual emissions generated.

4.2.5 Human Non-Carcinogenic Toxicity (HNCT)

HNCT ranked as the fifth with a score of 275, corresponding to 275 p/yr of the annual load. This indicator highlights potential health risks to workers and surrounding communities from exposure to non-carcinogenic toxic substances throughout the glove life cycle. This indicator reflects potential health risks to workers and communities from exposure to non-carcinogenic substances throughout the glove life cycle.

According to Mun Global (2023), non-carcinogenic substance includes vulcanization accelerators such as zinc diethyldithiocarbamate (ZDEC) which are widely used in nitrile glove production to enhance elasticity and tensile strength during the vulcanization process. Chemicals such as vulcanization accelerators may remain in the finished gloves and migrate to the wearer's skin, even at trace levels (Hansen et al., 2021). Although the manufacturing and disposal stages present potential risks, the usage stage where gloves are in direct contact with the wearer typically results in the highest level of human exposure. This makes it a critical phase for evaluating HNCT. Consequently, the usage stage can be regarded as a major contributor to HNCT within the overall life cycle of nitrile gloves.

4.3 Contributions by Life Cycle Stage

In addition to highlighting the key impact, this section further disaggregates the environmental impacts across the four main life cycle stages of production, distribution, usage, and end-of-life. This stage-oriented analysis provides a broader perspective on how burdens are structurally allocated along the glove's cradle-to-grave pathway. Based on five months (January 2025 to May 2025) of LCA data, the environmental impacts associated with the production of 100 nitrile gloves were evaluated across all ReCiPe Midpoint (H) categories. Figure 4.2 presents the relative contributions of each stage of five most impact categories. The findings clearly indicate that production and distribution stages are the primary drivers of environmental burdens, while the contributions from usage and disposal stages fluctuate according to the specific impact mechanism being assessed.

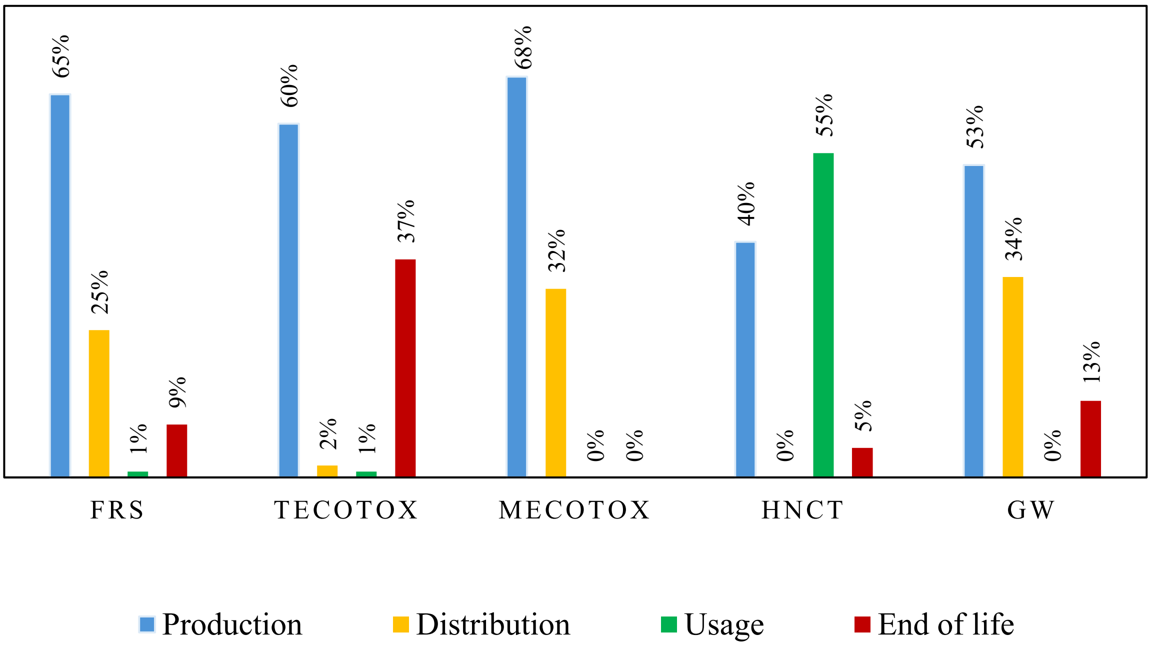

Figure 4.2: Contribution impact for each life stages

4.3.1 Fossil Resource Scarcity (FRS)

The production stage is the dominant contributor to FRS, accounting for 65% of total fossil resource depletion. This stage encompasses the extraction of fossil-derived monomers, high-temperature emulsion polymerisation, and energy-intensive glove processing steps such as coagulation, leaching, and drying. The consumption of petrochemical feedstocks is the primary driver of fossil depletion (Robinson, 2024).

The distribution stage contributes 25%, reflecting Malaysia's role as the world's largest exporter of nitrile gloves. Long distance marine and air freight to major markets such as the US and Europe entails significant fuel consumption. Studies of medical supply chains confirm that international transportation is a critical source of fossil fuel depletion, particularly for lightweight yet high volume products (Ashworth et al., 2025).

The end-of-life stage adds 9%, largely due to incineration of NBR waste, which requires fossil-fuel-based energy inputs and releases CO_2 from synthetic polymers. The usage stage contributes only 1%, as glove wearing does not involve direct fossil resource consumption.

4.3.2 Marine Ecotoxicity (MEcotox)

Marine ecotoxicity impacts are predominantly associated with the production stage, which contributes 68% of the total burden. This is largely driven by emissions from electricity generation, wastewater discharge, and upstream petrochemical processes involved in NBR synthesis. Petrochemical refining and polymerisation are well-documented sources of polycyclic aromatic hydrocarbons (PAHs), heavy metals, and persistent organic compounds that can enter marine ecosystems through atmospheric deposition or effluent release (Erabee, 2024).

The distribution stage accounts for 32%, reflecting emissions linked to maritime transport. Shipping activities are recognised contributors to marine ecotoxicity through the release of heavy metals such as vanadium, nickel, and oily water residues (International Maritime Organization, 2021). By contrast, the usage and end-of-life stages show negligible contributions 0%, indicating minimal direct release of ecotoxic substances during glove application or disposal.

4.3.3 Terrestrial Ecotoxicity (TEcotox)

Terrestrial ecotoxicity is largely driven by the production stage of 60% and end-of-life disposal 37%. The production-related impacts stem from emissions of heavy metals, residual monomers, and chemical additives such as zinc oxide, sulfur-based accelerators, and stabilisers commonly employed in nitrile glove manufacturing. Similar findings have been reported in broader industrial contexts, where petroleum mining and processing activities release arsenic, cadmium, lead, mercury, and zinc into soils, disrupting microbial communities and reducing fertility (Dehkordi et al., 2024).

The significant contribution from end-of-life management is linked to incineration and landfill practices. Incineration of NBR generates trace metal emissions and persistent organic pollutants, while landfill disposal may lead to the leaching of zinc oxide and other chemical residues into surrounding soils (Rogoff & Screve, 2019). Such pathways have been extensively documented in studies of synthetic rubber waste streams. By contrast, the distribution stage of 2% and usage stage 1% contribute minimally, reflecting the limited direct release of ecotoxic substances to terrestrial environments during these phases.

4.3.4 Global Warming (GW)

The GW results show that the production stage contributes 53% of the overall climate impact. This is primarily driven by electricity consumption during heating, dipping, and curing operations in glove manufacturing lines, which rely heavily on grid electricity generated from fossil fuels such as natural gas and coal in Malaysia (Tenaga Nasional Berhad, 2023).

The distribution stage accounts for 34%, reflecting the export-oriented nature of Malaysia's glove industry. Marine freight generates significant CO_2 emissions per tonne-kilometre, while air freight commonly used for urgent deliveries exhibits even higher carbon intensity (McKinnon, 2018). The end-of-life stage contributes 13%, largely due to CO_2 and nitrous oxide emissions released during the incineration of synthetic rubber waste. In contrast, the usage stage shows negligible impact, as glove application does not involve direct energy consumption.

4.3.5 Human Non-Carcinogenic Toxicity (HNCT)

Human non-carcinogenic toxicity (HNCT) exhibits a distinctive pattern in which the usage stage accounts for the largest share of 55%. This outcome is linked to potential dermal exposure to residual chemicals present on glove surfaces, including accelerators like thiurams, surfactants, and other processing additives. Previous studies have shown that such substances can migrate during use, contributing to skin irritation and allergic contact dermatitis, particularly among healthcare workers exposed to rubber glove accelerators (Cao et al., 2010).

The production stage contributes 27%, mainly from worker exposure to chemical additives during mixing, dipping, and curing. The end-of-life stage adds 15%, reflecting community exposure risks from incineration residues and potential leachate from landfills. The distribution stage contributes 3%, representing minimal exposure associated with transportation activities.

4.4 Uncertainty Analysis

To assess the robustness and reliability of the dataset applied in the LCA uncertainty analysis, a Monte Carlo simulation with 5,000 iterations was conducted in openLCA using the ReCiPe Midpoint (H) method as the impact assessment framework. The Monte Carlo approach is widely recognized as an effective technique for addressing parameter uncertainty in LCA, as it generates probabilistic distributions of potential outcomes rather than relying on single-point estimates. It is evident that the Monte Carlo simulation is the preferred approach for propagating both uncertainty and variability in LCA (Michiels & Geeraerd, 2020). Table 4.1 presents the minimum, maximum, mean, standard deviation, and CV for all impact categories, using April data as representative.

CV values reflect the relative reliability of the dataset and quantify the extent of uncertainty in the results. As shown in Table 4.1, the highest CV is recorded at LU of 7.5%, whereas the lowest occurs in FWEcotox of 4.8%. According to Shechtman (2013), lower CV values indicate greater data consistency and reliability, while higher values imply increased variability and potential uncertainty. Similarly, Igos et al. (2019) suggest that CV values below 10% are generally acceptable in LCA uncertainty assessments, indicating strong data consistency. In this study, all eighteen impact categories exhibit CV values below 10%, signifying that the dataset demonstrates high reliability and low uncertainty. This outcome supports the robustness of the LCA results and their credibility for environmental decision-making.

Table 4.2: Monte Carlo summary results (5000 iterations)

Impact category	Reference unit	Minimum	Maximum	Mean	Standard deviation	CV (%)
OFTE	kg NOx eq	0.008526	0.012204	0.010278	0.000511	5.0
WC	m3	0.070602	0.115742	0.091529	0.005689	6.2
GW	kg CO2 eq	5.932699	8.847420	7.306025	0.374784	5.1
FPMF	kg PM2.5 eq	0.006184	0.008658	0.007316	0.000391	5.3
HCT	kg 1,4-DCB	0.000996	0.001487	0.001197	0.000066	5.5
MEcotox	kg 1,4-DCB	0.001388	0.002264	0.001767	0.000124	7.0
OFHH	kg NOx eq	0.008316	0.011858	0.010005	0.000496	5.0
FWEutrof	kg P eq	0.000252	0.000438	0.000337	0.000024	7.1
TA	kg SO2 eq	0.020595	0.028760	0.024327	0.001293	5.3
IR	kBq Co-60 eq	0.034681	0.050893	0.041271	0.002104	5.1
SOD	kg CFC11 eq	0.000000	0.000000	0.000000	0.000000	5.8
LU	m2a crop eq	0.000413	0.000698	0.000536	0.000040	7.5
FRS	kg oil eq	2.244834	3.547843	2.850723	0.162750	5.7
MRS	kg Cu eq	0.001040	0.001746	0.001365	0.000089	6.6
TEcotox	kg 1,4-DCB	1.170806	1.904623	1.489236	0.103741	7.0
MEutrof	kg N eq	0.000158	0.000263	0.000206	0.000013	6.4
HNCT	kg 1,4-DCB	0.081325	0.125961	0.100988	0.006396	6.3
FWEcotox	kg 1,4-DCB	0.000281	0.000387	0.000330	0.000016	4.8

4.5 Discussion Key Finding

LCA results of this study yield several critical insights that refine current perspectives on the environmental implications of nitrile glove manufacturing. Whereas earlier glove-related LCAs often emphasized GW as the primary indicator of environmental burden, the present analysis identifies FRS as the most dominant category. This marks a conceptual shift, showing that the environmental profile of nitrile gloves is shaped less by operational energy consumption and more by the material foundation of the product system specifically its reliance on petrochemical feedstocks.

NBR the principal raw material, is an unsaturated copolymer derived from acrylonitrile and butadiene (Cheremisinoff, 2001). The upstream production of these monomers is inseparable from fossil resource extraction. For example, butadiene is largely obtained as a byproduct of steam cracking of naphtha and gas oil, processes central to ethylene and olefin production (Linde Engineering, 2018). NBR synthesis itself involves an energy-intensive copolymerisation process (Monmouth Rubber & Plastic Corp., 2025), compounding its environmental load. Moreover, butadiene is classified as a toxic substance under the Canadian Environmental Protection Act due to its hazardous emissions profile (Environment and Climate Change Canada, 2023). Collectively, these findings highlight that the environmental challenges of nitrile gloves extend beyond carbon emissions, pointing to structural constraints embedded in fossil-derived polymer supply chains an aspect still underexplored in glove LCA literature.

Beyond FRS, four other impact categories like MEcotox, TEcotox, GW, and HNCT emerge as notable hotspots. MEcotox and TEcotox are strongly influenced by Malaysia's fossil fuel dependent electricity mix, which generates ecotoxic emissions during power generation. These burdens are further intensified by the extraction and synthesis of NBR precursors, particularly acrylonitrile and butadiene, which release toxic substances during petrochemical processing. GW, though not the leading category, remains significant due to electricity use in compounding and dipping operations, combined with transportation emissions. HNCT impacts are linked to glove formulation chemicals such as zinc oxide, sulfur, and vulcanisation accelerators, which can contribute to toxicity through wastewater discharges and residual traces on finished gloves.

Stage based contribution analysis reinforces these insights. The production stage dominates FRS, MEcotox, TEcotox, and GW, driven by raw material extraction, chemical synthesis, and energy-intensive manufacturing processes. The usage stage contributes negligibly, consistent with the fact that glove wearing does not consume energy or resources. The end-of-life stage, modelled through landfill and incineration scenarios, adds modest contributions to ecotoxicity categories, reflecting potential contaminant releases depending on disposal pathways.

A particularly striking outcome is the unexpectedly high burden of the distribution stage. While Jamal et al. (2021) estimated transportation to account for roughly 12% to 15% of cradle-to-grave impacts, this study finds distribution impacts nearly comparable to production. This deviation stems from Malaysia's reliance on long-distance export markets, especially the United States, which accounted for nearly 60% of glove exports in early 2025 (New Straits Times, 2025). Extended transoceanic freight routes, coupled with the maritime sector's dependence on heavy fuel oil, substantially elevate emissions related to fossil resource depletion and climate change. These results underscore that the environmental footprint of Malaysian nitrile gloves is shaped not only by domestic production but also by globalized supply chain structures an element often overlooked in glove LCAs.

It is important to note several methodological limitations. The ELCD 3.2 database lacks a dedicated dataset for NBR, requiring proxy materials that may introduce uncertainty in upstream estimates. Assumptions regarding freight distances, shipping routes, and allocation of transportation burdens also influence distribution-stage results. End-of-life modelling is subject to regional variability, as actual disposal practices may differ from assumed scenarios. Nonetheless, sensitivity checks confirm the robustness of the main trends identified.

Overall, the findings reveal that the environmental burdens of nitrile gloves are driven by two interconnected factors: the fossil-based origin of raw materials and the export-oriented supply chain model of Malaysia's glove industry. These insights carry important implications for both industry and policy. Potential mitigation strategies include developing bio-based nitrile alternatives, integrating renewable energy into glove manufacturing, pursuing material substitution or reduction, and optimizing supply chains to reduce reliance on distant export markets. By broadening the sustainability perspective beyond carbon emissions, this study provides a foundation for more targeted interventions to reduce the life cycle impacts of this essential medical and industrial product.

4.6 Mitigation Plan

The results of this study suggest that the environmental footprint of nitrile glove production can be reduced or effectively controlled through targeted measures. The production stage contributes the most significant burden, largely due to high energy demand and reliance on raw materials. One promising pathway to lessen life cycle impacts is the adoption of bio-based NBR. Substituting petroleum-derived inputs with renewable alternatives can substantially decrease overall impacts, particularly in relation to FRS. Since butadiene the primary component of NBR can be sourced from plants, this transition is feasible. El-Shekeil et al. (2024) demonstrated that integrating bio-based reinforcements such as date palm fibers (DPF) into NBR composites preserves mechanical performance while improving strength and hardness. This innovation reduces environmental pressures during both resource extraction and manufacturing. Similarly, S&S Glove (2022) reported that utilizing agricultural and forestry residues as renewable heat sources lowers dependence on fossil fuels, enhances air quality, and mitigates climate change effects.

Energy use represents another critical challenge. Electricity drives essential glove production operations, including conveyor systems, boiler heating, and automated chemical mixing. According to Muthukannan et al. (2024), a typical glove facility consumes about 1.83 million kcal per hour of thermal energy for drying and curing, alongside 2,128.73 kW of electricity for machinery and utilities. They proposed a hybrid solar solution that combines concentrated solar power (CSP) for thermal requirements with photovoltaic (PV) panels for electricity generation. Industry practices confirm this potential; Hartalega's 2025 Annual Report documents the installation of a 1.65 MW solar PV system (total capacity 2,357 kWp), producing around 2,735 MWh of renewable electricity annually, thereby reducing grid dependence and emissions.

Moreover, energy efficiency improvements also play a vital role. Heat recovery systems, waste reduction, and circular economy practices strengthen environmental outcomes. Poh et al. (2019) showed that heat exchangers reduce water consumption in glove manufacturing, while Masa et al. (2023) recommended recycling glove scrap into feedstock for other rubber applications, thereby maintaining performance, enhancing thermal stability, and extending material lifespan.

Beyond specific process interventions, a broader sustainability framework can further enhance performance. Achieving green product certification is an important milestone, signalling that products deliver reduced environmental impacts compared to conventional alternatives (Dangelico & Pontrandolfo, 2010). In Malaysia, the Green Technology and Climate Change Corporation (MGTC) facilitates manufacturers in securing certification under the myHIJAU program, which formally acknowledges environmentally sustainable products and promotes broader implementation of green practices across the industry.

Taken together, these strategies embody sustainable manufacturing and circular economy principles. They align with Malaysia's national sustainability agenda outlined in the Green Technology Master Plan (2017–2030) and the National Low Carbon Aspiration 2040, both of which emphasize industrial decarbonization and adoption of green technologies. By combining renewable energy integration, bio-based materials, process optimization, waste minimization, and end-of-life recycling, Malaysia's nitrile glove sector can substantially reduce its ecological footprint and contribute to long-term sustainable development goals.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

This chapter concludes the interpretation of environmental impacts across the cradle-to-grave life cycle of single-use nitrile gloves. The analysis was grounded in a comprehensive life cycle inventory (LCI) derived from actual plant operations, encompassing all relevant inputs and outputs from raw material extraction through production, packaging, distribution, use, and end-of-life disposal. This robust LCI provided a solid foundation for the assessment, ensuring that the results accurately represent industry-relevant conditions.

The environmental evaluation employed the ReCiPe Midpoint (H) method in openLCA, supported by normalised LCIA results and Monte Carlo uncertainty analysis. Five key impact categories were identified FRS, MEcotox, TEcotox, GW, and HNCT. Among these, FRS was the most dominant, underscoring that the primary environmental burden arises from the petrochemical origin of NBR. This finding marks a departure from the conventional emphasis on climate-related impacts in glove LCAs, highlighting instead that fossil-derived feedstocks are the central drivers of environmental pressure.

Stage-level analysis further illuminated the main hotspots. The production stage contributed the largest share of impacts, driven by energy-intensive unit operations and upstream emissions from NBR synthesis. Distribution also played a significant role, reflecting Malaysia's export-oriented glove industry and the long transport distances to major markets such as the US. End-of-life incineration added notable contributions to toxicity and climate indicators, while the usage stage had negligible influence due to minimal resource demand. Collectively, these findings show that the environmental profile of nitrile gloves is shaped by both upstream material characteristics and downstream supply chain dynamics. Monte Carlo simulations revealed coefficients of variation below 10% across all categories, demonstrating strong result stability and reinforcing confidence in both the normalised and stage-level interpretations. This reliability confirms that the identified hotspots provide a robust basis for targeted improvement strategies.

Overall, the results highlight two overarching drivers of environmental impact: the fossil-based composition of NBR and Malaysia's long-distance distribution model. Addressing these challenges requires more than incremental efficiency gains. Potential strategies include developing bio-based nitrile alternatives, integrating renewable energy into production, optimising manufacturing processes, strengthening wastewater and chemical management, enhancing waste valorisation, and adopting greener logistics practices. Implementing such measures can significantly reduce the life cycle footprint of nitrile gloves and support Malaysia's transition toward low-carbon, resource-efficient manufacturing.

5.2 Limitation of Study

This research is subject to several constraints that may affect the precision and representativeness of its findings. First, the background database applied in openLCA ELCD 3.2 does not fully capture the Malaysian geographical and technological context. Given that many datasets reflect European conditions, uncertainties occur in modeling processes like electricity generation, upstream raw material extraction, and chemical production.

Second, the distribution phase was simplified by assuming that all finished gloves were transported to a single destination. In practice, export routes vary considerably across regions, and Malaysia's heavy reliance on international markets particularly the US may result in greater transportation-related impacts than those reflected in this model. This assumption could therefore underestimate or obscure variability in distribution burdens.

Third, the end-of-life stage was modelled using generic incineration datasets due to limited availability of local waste management data. Actual practices in Malaysia, including incinerator technology and emission control measures, may differ substantially from the datasets used, potentially influencing impact categories such as global warming and toxicity.

Despite these limitations, the study offers a meaningful overview of the environmental profile of nitrile glove production and provides a foundation for further refinement in future research.

5.3 Recommendation of future study

Future investigations can be broadened in several important ways to deepen the understanding of the environmental impacts linked to nitrile glove production. First, comparative studies examining gloves of varying weights and thicknesses could reveal how product mass influences life cycle impact values. Such analyses would highlight opportunities for reducing material use without compromising glove functionality.

Second, researchers are encouraged to adopt more comprehensive background databases, such as Ecoinvent, which provide wider global coverage and region-specific datasets. This would enable more geographically relevant modelling and help minimize uncertainties associated with relying on European centric databases like ELCD.

Third, future work could include a more detailed evaluation of distribution impacts by contrasting local and international transportation scenarios. Considering Malaysia's position as a leading global exporter, assessing differences in export routes, travel distances, and transport modes would yield a more accurate picture of distribution related burdens.

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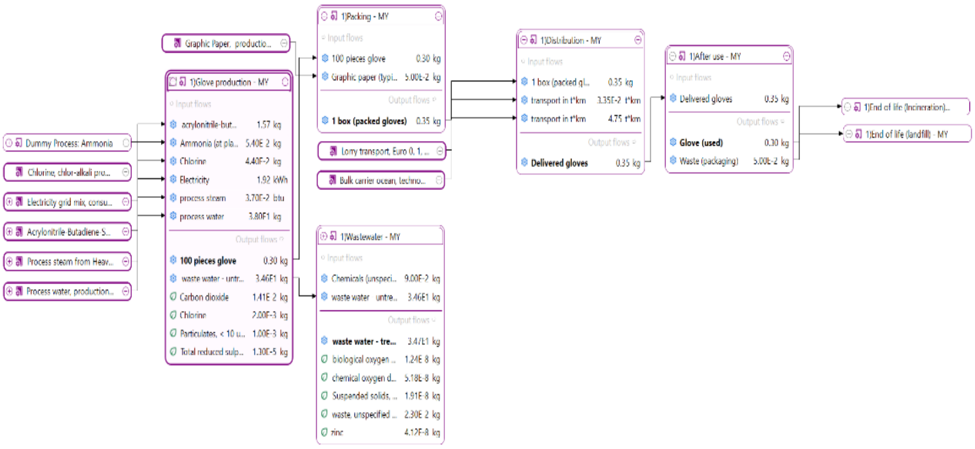
APPENDIX A- INPUT RAW DATA JANUARY 2025 TO MAY 2025 FOR LCI

Month / Parameters	Units	January Input	February Input	March Input	April Input	May Input
Acrylonitrile-butadiene	kg/100 pieces	1.566	1.569	1.571	1.569	1.550
Ammonia	kg/100 pieces	0.053	0.054	0.055	0.054	0.051
Chlorine	kg/100 pieces	0.042	0.044	0.050	0.044	0.040
Process water	kg/100 pieces	37.602	38.240	40.268	38.020	30.739
Process steam	btu/100 pieces	0.031	0.037	0.037	0.037	0.036
Electricity	kWh/100 pieces	1.320	1.228	1.399	1.915	1.900
Chemicals	kg/100 pieces	0.080	0.086	0.102	0.090	0.070
100 pieces of glove	kg/100 pieces	0.300	0.300	0.300	0.300	0.300
Paperboard	kg/100 pieces	0.050	0.050	0.050	0.050	0.050
Transport (ocean)	t*km	4.748	4.748	4.748	4.748	4.748
Transport (road)	t*km	0.034	0.034	0.034	0.034	0.034

APPENDIX B- OUPUT RAW DATA JANUARY 2025 TO MAY 2025 FOR LCI

Month	Units	January	February	March	April	May
Parameters		Output	Output	Output	Output	Output
100 pieces of glove	kg/100 pieces	0.300	0.300	0.300	0.300	0.300
Waste water-untreated	kg/100 pieces	32.902	34.863	35.821	34.646	26.735
Waste water-treated	kg/100 pieces	31.899	34.955	36.012	34.713	25.893
waste	kg/100 pieces	0.022	0.022	0.024	0.023	0.021
COD	kg/100 pieces	5.18E-08	5.18E-08	5.18E-08	5.18E-08	5.18E-08
BOD	kg/100 pieces	1.24E-08	1.24E-08	1.24E-08	1.24E-08	1.24E-08
SS	kg/100 pieces	1.91E-08	1.91E-08	1.91E-08	1.91E-08	1.91E-08
Zinc	kg/100 pieces	4.12E-08	4.12E-08	4.12E-08	4.12E-08	4.12E-08
Carbon dioxide	kg/100 pieces	0.0141	0.0141	0.0141	0.0141	0.0141
Chlorine	kg/100 pieces	0.002	0.002	0.002	0.002	0.002
Particulates (stationary)	kg/100 pieces	0.001	0.001	0.001	0.001	0.001
Sulphur	kg/100 pieces	0.000013	0.000013	0.000013	0.000013	0.000013

APPENDIX C- PROCESS FLOW DIAGRAM



APPENDIX D-NORMALISED IMPACT VALUES ACCORDING TO CATEGORIES

Impact category	January	February	March	April	May	Mean
FRS	0.00271	0.00268	0.00274	0.00290	0.00286	0.00278
MEcotox	0.00123	0.00116	0.00131	0.00171	0.00167	0.00142
TEcotox	0.00104	0.00098	0.00110	0.00143	0.00141	0.00119
GW	0.00082	0.00081	0.00084	0.00091	0.00090	0.00086
HNCT	0.00052	0.00052	0.00054	0.00068	0.00065	0.00058
TA	0.00051	0.00049	0.00052	0.00059	0.00058	0.00054
OFTE	0.00050	0.00048	0.00052	0.00058	0.00057	0.00053
FWEutrof	0.00048	0.00047	0.00050	0.00052	0.00051	0.00050
OFHH	0.00042	0.00041	0.00043	0.00049	0.00048	0.00045
HCT	0.00035	0.00033	0.00037	0.00043	0.00040	0.00038
WC	0.00032	0.00022	0.00032	0.00034	0.00034	0.00031
FPMF	0.00023	0.00022	0.00024	0.00029	0.00028	0.00025
FWEcotox	0.00023	0.00007	0.00024	0.00027	0.00026	0.00021
IR	0.00007	0.00004	0.00008	0.00009	0.00000	0.00006
MEutrof	0.00004	0.00000	0.00004	0.00004	0.00000	0.00003
SOD	0.00001	0.00000	0.00001	0.00001	0.00000	0.00000
LU	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
MRS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

APPENDIX E-NORMALISED ANNUAL IMPACT VALUES ACCORDING TO CATEGORIES

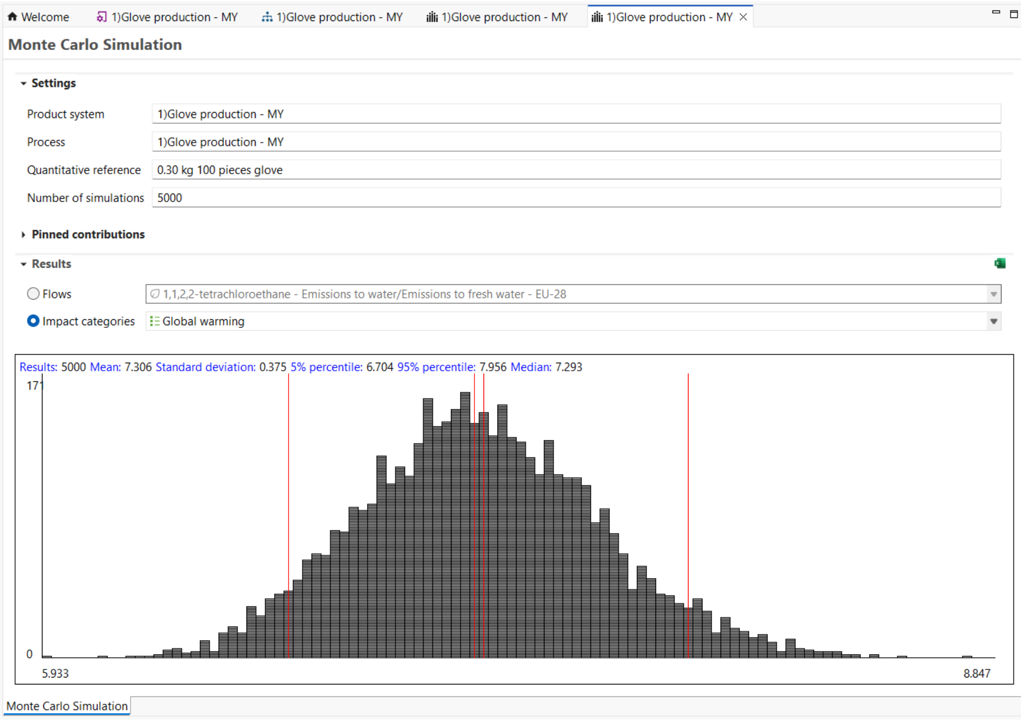
Average monthly production: 40,000 (per 100 pieces)
Annual production: 480,000 (per 100 pieces)

Impact category	Average monthly impact value	Annual impact value	Normalisation reference from recipe	Normalised annual impact (per 100 pcs)
FRS	2.72482	1307912.64	980.392157	1334
MEcotox	0.00146	701.76	1.031992	680
TEcotox	1.23434	592482.24	1036.26943	572
GW	6.83646	3281501.76	7987.220447	411
HNCT	0.08526	40926.72	149.031297	275
TA	0.02153	10332.48	40.983607	252
OFTE	0.00942	4521.60	17.761989	255
FWEutrof	0.00034	162.24	0.649351	250
OFHH	0.00916	4394.88	20.576132	214
HCT	0.00104	501.12	2.770083	181
WC	0.08797	42223.68	266.666667	158
FPMF	0.00646	3101.76	25.575448	121
FWEcotox	0.00030	143.04	1.226994	117
IR	0.03677	17647.68	480.769231	37
MEutrof	0.00020	96.96	4.608295	21
SOD	0.00000	0.16	0.05988	3
LU	0.00044	212.16	6172.839506	0
MRS	0.00134	643.20	120048.0192	0

APPENDIX F-NORMALISED IMPACT VALUES ACCORDING TO LIFE CYCLE STAGES

Impact category	Usage	End of life	Distribution	Production
FRS	0.00903	0.00347	0.00014	0.00125
TEcotox	0.00358	0.00012	0.00006	0.00221
MEtocox	0.00481	0.00227	0.00000	0.00000
HNCT	0.00116	0.00000	0.00160	0.00015
GW	0.00227	0.00146	0.00000	0.00056
TA	0.00053	0.00212	0.00212	0.00212
OFTE	0.00042	0.00185	0.00185	0.00185
OFHH	0.00033	0.00141	0.00141	0.00141
FPMF	0.00026	0.001	0.001	0.001
FWEutrof	0.00025	0.00344	0.00344	0.00344
WC	0.00022	0.00217	0.00217	0.00217
IR	8.57E-05	0.00417	0.00417	0.01908
LU	8.67E-08	1.26E-06	1.26E-06	1.26E-06
MRS	1.14E-08	1.58E-07	1.58E-07	1.58E-07
FWEcotox	-1.06E-05	0.0182	0.0182	0.0182
MEutrof	-2.52E-05	-0.00016	-0.00016	-0.00016
SOD	-6.30E-04	-0.0051	-0.0051	-0.0051
HCT	0.00073	0.01236	0.01236	0.01236

APPENDIX G- DISTRIBUTION OF MONTE CARLO SIMULATION



APPENDIX H- MONTE CARLO SIMULATION RESULT OF 5TH PERCENTILE AND 95TH PERCENTILE

Impact category	Reference unit	Mean	Standard deviation	Minimum	Maximum	Median	5% Percentile	95% Percentile
OFTE	kg NOx eq	0.01028	0.00051	0.00853	0.01220	0.01027	0.00945	0.01116
WC	m3	0.09153	0.00569	0.07060	0.11574	0.09134	0.08253	0.10134
GW	kg CO2 eq	7.30602	0.37478	5.93270	8.84742	7.29301	6.70437	7.95635
FPMF	kg PM2.5 eq	0.00732	0.00039	0.00618	0.00866	0.00731	0.00668	0.00797
HCT	kg 1,4-DCB	0.00120	0.00007	0.00100	0.00149	0.00120	0.00109	0.00131
MEcotox	kg 1,4-DCB	0.00177	0.00012	0.00139	0.00226	0.00176	0.00157	0.00197
OFHH	kg NOx eq	0.01001	0.00050	0.00832	0.01186	0.00999	0.00921	0.01086
FWEutrof	kg P eq	0.00034	0.00002	0.00025	0.00044	0.00034	0.00030	0.00038
TA	kg SO2 eq	0.02433	0.00129	0.02059	0.02876	0.02430	0.02222	0.02651
IR	kBq Co-60 eq	0.04127	0.00210	0.03468	0.05089	0.04123	0.03795	0.04484
SOD	kg CFC11 eq	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LU	m2a crop eq	0.00054	0.00004	0.00041	0.00070	0.00054	0.00047	0.00060
FRS	kg oil eq	2.85072	0.16275	2.24483	3.54784	2.84456	2.59039	3.12984
MRS	kg Cu eq	0.00136	0.00009	0.00104	0.00175	0.00136	0.00122	0.00152
TEcotox	kg 1,4-DCB	1.48924	0.10374	1.17081	1.90462	1.48642	1.32234	1.66263
MEutrof	kg N eq	0.00021	0.00001	0.00016	0.00026	0.00021	0.00019	0.00023
HNCT	kg 1,4-DCB	0.10099	0.00640	0.08133	0.12596	0.10090	0.09059	0.11159
FWEcotox	kg 1,4-DCB	0.00033	0.00002	0.00028	0.00039	0.00033	0.00030	0.00036