Assessing the Impact of Disposable Nitrile Gloves Used in UBC Labs

Providing recommendations for reducing the impact of single-use nitrile gloves following the identification of hotspots using a cradle-to-grave life cycle assessment and scenario-based analysis of nitrile gloves.

Prepared for:

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List of Abbreviations

CO_2 - Carbon Dioxide Emissions

GHG - Greenhouse Gas

GWP - Global Warming Potential

LCA - Life Cycle Assessment

kg CO_2e - Kilogram Carbon Dioxide equivalent

Executive Summary

Abstract

Single-use nitrile gloves play an important role in reducing the risk of contamination in various industrial sectors such as medical facilities, food manufacturing and processing factories, as well as research laboratories. A previous student research project reported that 7 million individual nitrile gloves are discarded each year across the University of British Columbia's (UBC) 400+ labs (Mikolay et al., 2020). This research project provides an analysis of the environmental impact of nitrile gloves across their entire life cycle through the form of a cradle-to-grave life cycle analysis (LCA). The first stage of this LCA study identified the production process as the most carbon-intensive process within the glove's entire life cycle. Meanwhile, the second stage of this study performed a series of scenario-based comparisons in order to generate recommendations for reducing the carbon intensity of nitrile gloves within the production stage. In recognition of the important role of single-use gloves as PPE in UBC labs, the results of this study can be used to inform and guide UBC labs to source its nitrile gloves from more sustainable glove manufacturers.

Key words: LCA; nitrile gloves; climate change; sustainability.

Graphical Abstract

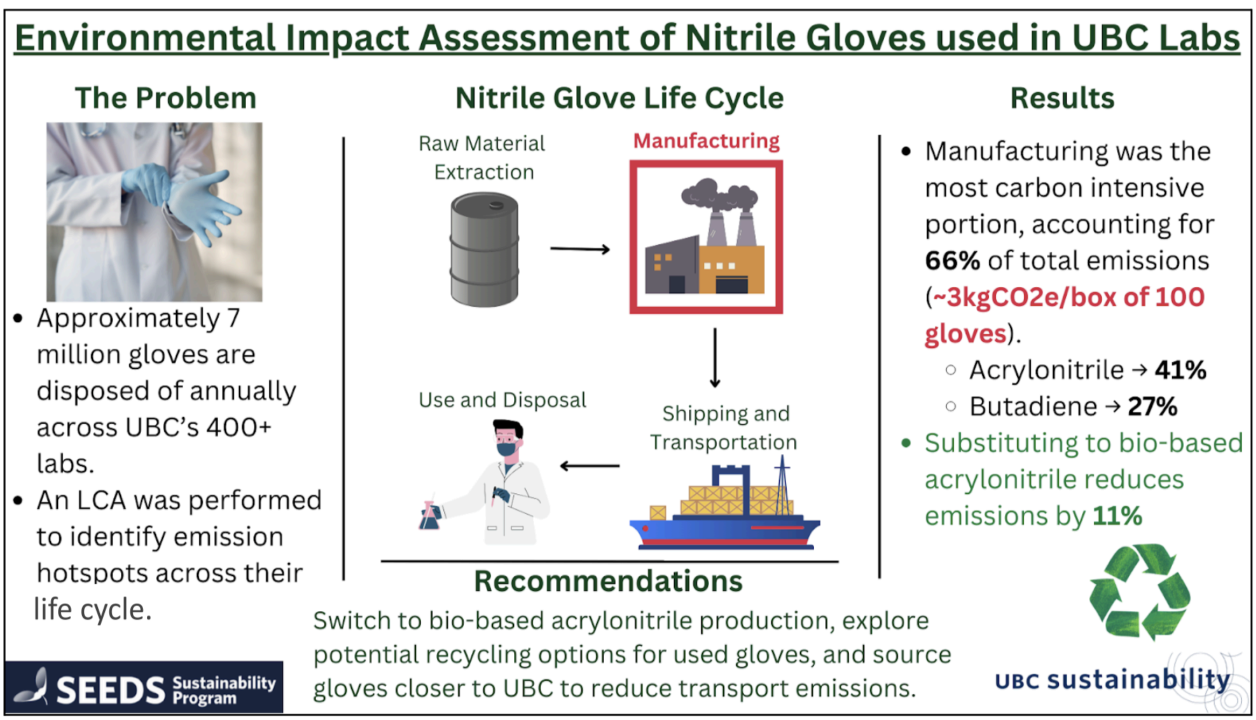

Figure 1. Graphical abstract of this LCA study.

1 Introduction

1.1 Project background

Nitrile gloves maintain personal hygiene, prevent contamination, and enable the wearer to work safely in a toxic/hazardous environment. As such, single-use nitrile gloves have become an essential component in laboratory settings. Although gloves continue to be manufactured using a variety of materials, nitrile gloves offer improved durability and protection in comparison to other materials, such as vinyl and latex (Rego & Roley, 1999). Nitrile gloves also display many other advantageous properties such as reduced allergic reactions to the user, resistance against toxic compounds such as gasoline or kerosene, good resistance against heat, low gas permeability, and lower production costs. These properties make nitrile gloves one of the most popular personal protective equipment (PPE) choices in research laboratories globally (Yew, et al., 2019). However, following a surge in demand for PPE amidst the COVID-19 pandemic, in 2020 an estimated 65 billion single-use gloves were consumed globally (Bosco & Mollea, 2021). The global demand of nitrile gloves for laboratories reached an estimated $2.3 billion in 2020, and is expected to grow steadily through 2027 (Anton Paar, n.d.). In light of this increased demand, consideration must be given to the environmental impact of nitrile gloves across each stage of their life cycle, from cradle-to-grave.

1.2 Literature review

The use of single-use nitrile gloves implicates environmental burdens spanning across the whole life cycle of each glove. In a previous cradle-to-grave life cycle assessment (LCA) studies of nitrile gloves, Rizan et al. (2021) determined that a single nitrile glove may account for ~26 g CO_2e (roughly six times its mass). In the same study, it was determined that eliminating disposable glove use would have omitted approximately 48,262 tonnes CO_2e over a six month study period in the UK (Rizan et al., 2021). Patrawoot et al. (2021) completed a cradle-to-gate LCA to compare the environmental impacts of natural rubber and nitrile rubber used to make medical examination gloves, accounting for material extraction, transportation, production, and disposal by total incineration. The results indicate that the glove production stage contributed more than 50% of the total environmental impact, primarily due to the use of coal and gas to generate heat for warming liquid latex, drying, and chlorination processes (Patrawoot et al., 2021). Similarly, Poh et al. (2019) draw the same conclusion that manufacturing synthetic gloves may cause adverse environmental impacts, including global warming, acidification, photochemical ozone formation, eutrophication, human toxicity, and increased water footprint, with the major contributor being energy consumption. By comparing various energy sources for electricity generation, they found that biodiesel had the greatest potential to reduce emissions, especially for acidification, up to 40.48% (Poh et al., 2019). Apart from production, transportation also had a large effect on environmental issues. According to Kumar et al. (2021), the environmental burden from transportation was considerable, with emissions amounting to 2.76 kg CO_2e, particularly for long-distance transport.

In most available literature, the gloves were disposed of either by landfilling or incineration. Kumar et al. (2021) compared the environmental impacts of various kinds of PPE in both landfilling and ignition disposal methods. The results showed that the incineration of PPEs generated 1,487.37 kg CO_2e emissions, making the disposal stage the second-largest contributor to global warming potential (GWP) after the production stage, which accounted for 1,850 kg CO_2e. Among all the PPE, gloves were the second greatest contributor to the total GWP (Kumar et al., 2021). In order to further assess the environmental impact of nitrile glove disposal when subject to surface water runoff, Wang et al. (2022) studied the physicochemical behaviour of disposable glove waste in an aqueous environment. The results of this study indicated that nitrile gloves release leachable materials and pollutants with adverse effects on human and environmental health, including microplastics and heavy metal pollution. The amount of leachates released was found to be highest when exposed to high UV index and physical abrasion, demonstrating the effect of environmental degradation processes on accelerating leachate pollution (Wang et al., 2022). Another study similarly showed that nitrile gloves are enriched in leachable trace elements, a concerning source of environmental pollution that poses a high risk to both human and environmental health (Garçon et al., 2016).

Although the environmental consequences of single-use plastic waste are well-established, disposable gloves remain an important tool in reducing contamination and there is not a commercially available bio-based and biodegradable alternative that maintains adequate barrier properties necessary for use in high-risk applications (Rahman et al., 2020). Therefore, innovative recycling methods may present an immediate strategy for reducing the environmental impact of single-use glove waste until a more sustainable alternative is developed. Mishra et al. (2019) responded to this opportunity by studying the co-pyrolysis of neem seed (NM) with waste nitrile gloves to produce liquid fuel. This study demonstrated a synergistic effect that enhanced the yield of the pyrolysis reaction between biomass and nitrile gloves. Furthermore, the use of catalysts in co-pyrolytic oil was found to increase the heating value and lower viscosity relative to the NM pyrolytic oil, establishing a potential pathway for renewable fuel production from waste nitrile gloves (Mishra et al., 2019). In a subsequent study, Mishra & Mohanty (2020) demonstrated the effect of blending waste nitrile gloves with mahua seeds (MH) by enhancing the yield of co-pyrolytic liquid and value-added chemicals. Compared to the NM-nitrile glove pyrolytic oil previously studied, the MH-nitrile glove blend maintained a higher heating value, while reducing moisture content and viscosity, making it a more suitable fuel for transportation (Mishra & Mohanty, 2020).

As an alternative recycling solution to energy recovery, nitrile gloves may also be reused in various applications, with a specific emphasis on their role as an additive used to improve a material's mechanical properties. If successfully diverted from landfills, nitrile glove waste could be used to strengthen and stabilize the expansive clay subgrade, offering an important and cost-effective engineering strategy for improving the performance of expansive soil (Zhu et al., 2022). Similarly, the addition of 0.2% shredded nitrile gloves was found to increase the compressive strength of concrete by 22% (Kilmartin-Lynch et al., 2022). In both of these examples, the use of nitrile gloves as strengthening additives may play an important role in displacing carbon-intensive cement, which has been conventionally used for strengthening and stabilization purposes - despite accounting for 8% of global carbon dioxide emissions (Zhu et al., 2022). Used nitrile gloves can also be blended with natural rubber to produce a material with enhanced properties, notably high strength and thermal stability (Hayeemasae et al., 2019). These synergistic properties of a rubber waste blend make it suitable for numerous applications within construction and the rubber and plastic industries.

Although a growing number of studies have identified the environmental burden of nitrile gloves, studies conducting a life cycle assessment of nitrile gloves were few. Existing life cycle assessment (LCA) studies primarily focus on traditional disposal methods such as incineration and landfilling, while innovative recycling and reuse methods, including pyrolysis, reuse in construction, or blending with other materials, have been identified but not yet analyzed from an LCA perspective.

1.3 Nitrile Gloves at UBC

In alignment with the Zero Waste Action Plan, UBC has set a target to reduce waste disposal to landfill by 50% below 2019 levels by 2030, with a heavy focus on reducing waste from UBC labs (UBC, n.d.). A previous UBC student research project reported that 7 million individual nitrile gloves are discarded each year across the University of British Columbia's (UBC) 400+ labs (Mikolay et al., 2020). As such, further research on nitrile gloves is urgently needed to establish actionable strategies for UBC to reduce the environmental impact attached to the gloves used in the university's labs at every stage of their cradle-to-grave life cycle.

1.4 Research Questions

In recognition of the research gaps identified in the literature review, specifically with respect to considering the relative environmental impact of various end-of-life processes for nitrile gloves, this research study originally teamed up with UBC Green Labs, UBC SEEDS, as well as a third party recycling company in order to build a comparative LCA that would consider the relative impact of either disposing or recycling nitrile gloves generated from UBC labs. However, due to a lack of data, this research project had to shift its focus to consider a two-part research question.

1. This study aims to first evaluate the environmental impact of nitrile gloves across their entire cradle-to-grave life cycle in order to identify hotspot processes contributing heavily to the overall environmental profile of the nitrile gloves.
2. After identification of these hotspots, this study aimed to perform scenario-based comparisons to identify opportunities for emission reduction within that hotspot. In other words, how can UBC labs reduce the environmental impact of their gloves?

These research questions were translated into the following modelling questions:

1. What stages of the cradle-to-grave life cycle of 1 box (containing 100 medium-sized non-sterile nitrile gloves) have the highest contribution to the environmental impact profile?
2. Based on the highest-contributing stage of the life cycle of 1 box of nitrile gloves, what alternative-scenarios could reduce the impact of this process?

1.5 Life Cycle Analysis (LCA)

Life Cycle Assessment (LCA) has its origins in the 1960s, when environmental degradation and resource scarcity became growing concerns (Bjørn, et al., 2018). During the 1980s and 1990s, LCA saw significant methodological innovations, including the introduction of the life cycle impact assessment and life cycle costing models (Guinée et al., 2011).

The primary purpose of LCA is to provide a comprehensive assessment of the environmental impacts associated with all stages of a product's life cycle that are included in the study's system boundary (gate-to-gate, cradle-to-gate, or cradle-to-grave). A cradle-to-grave system boundary considers the entire life cycle of a product, including the extraction of raw materials, manufacturing, distribution, use, and disposal (Moutik et al., 2023). By quantifying the environmental impacts attached to a product, LCA helps to identify opportunities for reducing environmental impacts and supports decision-making in environmental management. It also serves as a tool for assessing the environmental impacts of products, technologies, materials, processes, and services.

LCA has since become a standardized methodology with international guidelines like the ISO 14040 and 14044, consisting of four main phases: defining the goal and scope, conducting inventory analysis of inputs and outputs, assessing environmental impacts, and interpreting results to support decision-making. LCA is an essential tool for environmental management and sustainable development, with applications between multiple sectors.

This project aims to quantify greenhouse gas emissions generated from disposable nitrile gloves according to ISO 14040 and 14044 standards. The ISO framework encompasses a four-phase approach as shown in Figure 2 and defined as follows:

1. Goal and Scope Definition:
    - Establishes the objectives and intended use of the LCA.
    - Delineates the product system, the functional unit, system boundaries, as well as any assumptions and limitations within the study.
2. Life Cycle Inventory Analysis (LCI):

- Collection of foreground and background data.

3. Life Cycle Impact Assessment (LCIA):
   - Impact assessments associate inventory data with specific environmental impacts, such as global warming potential, eutrophication, and acidification..
4. Life Cycle Interpretation:
   - Data analysis and interpretation.
   - Assessing the reliability and robustness of the results through a sensitivity analysis.
   - Providing a summary of findings and recommendations for the future.

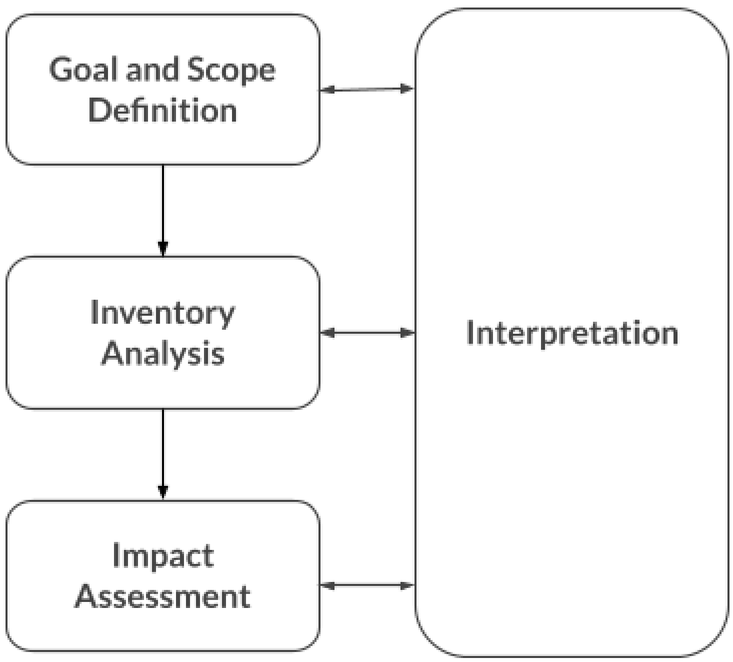

Figure 2. LCA framework

2 Goal and scope definition

2.1 Project goal

This research project initially aims to quantify the environmental impact of nitrile gloves across their entire life cycle in order to identify high-contributing stages to greenhouse gas emissions. In this study, environmental burden is characterized by the impact category: climate change (measured as kg CO_2e). Following the initial environmental impact assessment for a baseline scenario, the stages within the glove's life cycle that implicate the most significant environmental impacts, identified as hotspots, are further investigated to identify opportunities for emission reduction within that respective stage. Scenario-based comparisons were performed to evaluate opportunities for emission reduction and generate recommendations to reduce the impact of nitrile gloves used by UBC labs.

2.2 Product system

The product selected for analysis in this project is a generic non-powdered and non-sterile nitrile glove. A specific glove model was not studied due to a lack of available data from manufacturers. The specific data used to build the baseline product system model of the glove's extraction, manufacturing, distribution, use, and disposal were based on a previous study by Jamal et al. (2021) as they attempted to quantify and compare the LCA impact of sterile and non-sterile gloves. Figure 3 summarizes the product system of 1 box of nitrile gloves.

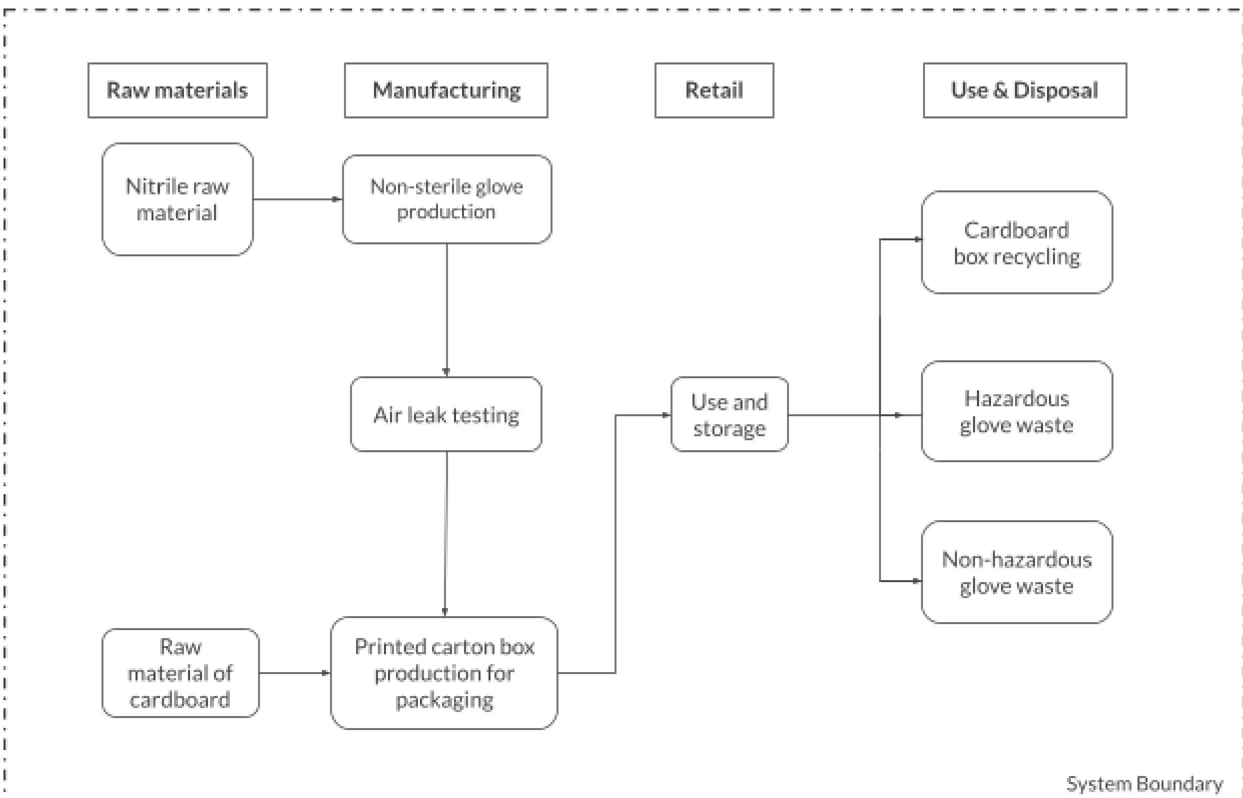

Figure 3. Product system of 1 box of nitrile gloves.

2.3 Functional unit

The functional unit used in this LCA is 1 box of non-powdered and non-sterile nitrile gloves (assuming that 1 box contains 100 individual medium-sized nitrile gloves). This functional unit was designed to reflect the impact of both the cardboard packaging and the nitrile gloves from raw material extraction to disposal. It was assumed in this case that 1 individual medium-sized nitrile glove weighs 3.44g while the cardboard box packaging weighs 1.0354g , for a total reference flow mass of 345.0354g for 1 box of 100 nitrile gloves.

2.4 System boundary

System boundaries are integral for defining the processes and stages of the life cycle that are considered in the LCA. This project assesses the impact of 1 box of nitrile gloves from cradle-to-grave, meaning that the system boundary includes activities from raw material extraction through processing, distribution, use and disposal or recycling - as previously shown in Figure 3.

3 Methods of data collection and analysis

3.1 Data collection

3.1.1 Overview

All of the data used to build a life-cycle inventory for 1 box of nitrile gloves was obtained through secondary-sources due to limited primary data availability. A previous LCA study by Jamal et al. (2021) attempted to quantify and compare the impact of sterile and non-sterile gloves. Since Jamal et al. (2021) used a functional unit of one pair of medium-sized nitrile non-sterile gloves, this research project adjusted all the inventory values to reflect this research study's functional unit of 1 box of 100 nitrile gloves. Therefore, an assumption was made that the inputs and outputs associated with one pair of medium-sized nitrile gloves scaled linearly to reflect the inputs and outputs associated with 50 pairs of medium-sized nitrile gloves (1 box of 100 individual gloves).[1]

3.1.2 Manufacturing, Testing, and Packaging

This research project maintained Jamal et al.'s (2021) initial assumption that the gloves were manufactured in China; the choice of providers for the electricity mix for the production, testing, and packaging processes reflected this assumption.

In their analysis, Jamal et al. (2021) assumed that the only material input to produce 6.88g nitrile gloves (in their case, the weight of 1 pair of gloves/their functional unit) was 6.88g of acrylonitrile. However, this project's literature review suggested that nitrile rubber, the material used to manufacture nitrile gloves, is a co-polymer of 1,3-butadiene and acrylonitrile. Although exact values could not be found to reflect the specific ratio of 1,3-butadiene to acrylonitrile used to produce nitrile rubber, reasonable estimates could be found to suggest a 50:50 mix for higher medical-grade disposable nitrile gloves due to an association between better chemical resistance with increasing acrylonitrile-content (Phalen et al., 2006; Wahalathantrige, 2014). In the context of this study, with a functional unit of 1 box of 100 nitrile gloves (344 g worth of gloves) and assuming a 1:1 ratio of acrylonitrile-butadiene input to nitrile rubber glove output, it is assumed that 172g of 1,3-butadiene and 172g of acrylonitrile are used to produce 344g worth of nitrile gloves.

[1] Functional unit adjustment calculations listed in the Appendix.

Due to the fact that Jamal et al. (2021) assumed that the gloves would be distributed to the United Kingdom, they based the glove testing specifications on the European Standard (EN 455-1), which requires that four non-sterile gloves to be tested per batch of (estimated ~ 0.02%) (Jamal et al., 2021). Meanwhile, Canadian standards require medical disposable gloves to be ISO 11193-1 or ASTM D3578 compliant (Government of Canada, n.d.). However, since a glove that is compliant to EN 455 standards also meets the Canadian required standard, the reference study's testing standard assumptions and data were maintained in this project.

As per the functional unit, it was assumed that the nitrile gloves were packaged in an offset-printed cardboard box containing 100 individual medium-sized non-sterile and powder-free gloves.

3.1.3 Transport and Retail

The transportation of the packaged gloves from the manufacturer to UBC was broken down into three separate transport routes. In each case, the route taken was assumed to be the shortest and most direct route via land or sea, measured in kg·km.[2] The distance for road transport between the Chinese manufacturer and Qingdao port was provided by Jamal et al. (2021), while the distance for sea transport from the Chinese port to - what was assumed to be the Vancouver port - was estimated using Google Maps. The final distance for road transport from the Vancouver port to UBC was also estimated using Google Maps. All road transport was assumed to be via lorry road transport while sea transport was assumed to be via container ship.

After arriving at UBC, the use and retail stage of the box of nitrile gloves was not considered beyond mention given a negligible impact for the use-phase of disposable gloves.

3.1.4 Recycling and Disposal

After use within UBC labs, it was assumed that the cardboard box was recycled as paperboard waste. Meanwhile, all nitrile gloves were landfilled as either hazardous or non-hazardous waste - depending on their respective use. After reaching out to several UBC labs, as well as considering previous estimates by similar studies (Mikolay et al., 2020), the breakdown of non-hazardous to hazardous waste was estimated as 9:1 (i.e., 90% of glove waste is assumed to be non-hazardous).

3.2 Model creation and revision

3.2.1 LCA creation

The model was created on openLCA v2.2.0, a free and open source software used to calculate the life cycle impact of a product, in conjunction with the ecoinvent v3.10 database. As shown in Figure 4, this model was split into five main processes: (i) production of 100 nitrile gloves, (ii) quality testing of 100 nitrile gloves, (iii) packaging of 1 box of 100 nitrile gloves, (iv) transportation

[2] Kilogram-kilometer is a common unit of freight and is used in this context to reflect the movement of one kilogram of packaged gloves over a distance of one kilometer.

of 1 box of 100 nitrile gloves, and (v) use and disposal of 1 box of 100 nitrile gloves. Use and disposal were combined as a fifth and final step due to the single-use nature of these gloves, meaning that there is very little environmental impact attached to the use-phase of nitrile gloves and they are almost immediately disposed of upon arrival and use at UBC labs.

Direct emission factors are not modelled for any processes within this model as no estimates could be found for the nitrile gloves' various stages of the life cycle. Although the assumption is that there are no direct emissions throughout the gloves' life cycle, it is expected that these emissions are negligible within the production, testing, packaging, and use phases. There are also virtually no emissions associated with landfilling the nitrile gloves as they decompose over a 100-year period, which is a far greater timeframe than the scope of this research project. However, it would have been ideal to consider the direct emissions from transportation if better estimates could have been found and remains a blindspot in this current model.

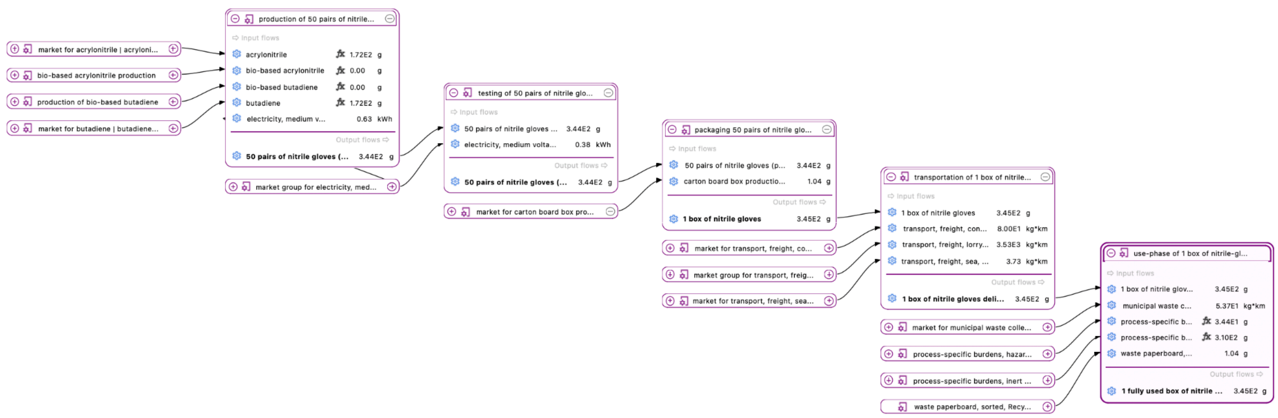

Figure 4. Model graph of the cradle-to-grave life cycle of 1 box of nitrile gloves.

3.2.2 Bio-based butadiene and acrylonitrile production

After reviewing the LCA model to identify impact hotspots within the nitrile gloves' life cycle, it was determined that the manufacturing of nitrile gloves accounted for over half of the entire life cycle global warming impact, a similar finding to previous LCA studies (Patrawoot et al., 2021; Poh et al., 2019). Acrylonitrile and butadiene production were identified as the major contributors to the emission-intensity of the nitrile glove production phase. These results will be discussed further in Sections 4 and 5, but this result required the model to be revised to include alternative scenarios to evaluate opportunities for emission reduction as part of the second research objective.

Given the fact that both acrylonitrile and butadiene are synthetic, petroleum-based chemicals, this study identified their bio-based counterparts as alternative production inputs as a strategy to reduce the emission intensity of the production process. As an alternative to the Sohio process for petroleum-based acrylonitrile production, a bio-based acrylonitrile production was modelled based on data provided by Musse Neto et al., (2023). Meanwhile, the bio-based butadiene production model was based on inventory tables provided by Cabrera Camacho et al. (2022). Using these studies' data as proxies for bio-based acrylonitrile and butadiene production within our model, the production phase of the model was revised to include bio-based acrylonitrile and butadiene inputs, in addition to the petroleum-based acrylonitrile and butadiene already modelled (Figure 5). Input parameters were implemented for the petroleum-based acrylonitrile and butadiene and dependent parameters were implemented for bio-based acrylonitrile and butadiene, thereby allowing this study to perform a scenario-based analysis by changing the relative input contribution of petroleum-based and bio-based acrylonitrile/butadiene and observing the associated impact of increasing amounts of bio-based acrylonitrile and butadiene on the emission-intensity of the production phase.

Flow	Category	Amount ^	Unit
bio-based acrylonitrile	Nitrile Gloves	biobased_acrylonitrile	g
bio-based butadiene	Nitrile Gloves	biobased_butadiene	g
electricity, medium voltage	D:Electricity, ga	0.63350	kWh
acrylonitrile	C:Manufacturin	petrobased_acrylonitrile	g
butadiene	C:Manufacturin	petrobased_butadiene	g

Figure 5. Revised production input table for nitrile glove production.

3.3 Data analysis

3.3.1 Impact assessment

The environmental impact profile for the life cycle of 1 box of nitrile gloves was determined by performing an impact assessment using ReCiPe H Midpoint 2016. This midpoint impact assessment method generates various indicators that reveal the immediate environmental effects attached to the life cycle of 1 box of nitrile gloves. This study focuses on climate change as the main impact category to determine the highest-contributing stages of the life cycle of 1 box of nitrile gloves, as well as to compare the relative environmental impact of different ratios of petroleum-based to bio-based acrylonitrile and butadiene in the scenario-based analysis.

3.3.2 Project creation: Scenario-based analysis

This study compared 10 scenarios in total for the same product system, but with differing ratios of petroleum-based to bio-based acrylonitrile/butadiene. This study separately considered 5 scenarios of differing ratios of petroleum-based acrylonitrile to bio-based acrylonitrile, as well as another 5 scenarios assessing the impact of increasing contributions of bio-based butadiene. These scenarios were separated in order to assess the individual impact of both bio-based acrylonitrile and butadiene. The ratios of petroleum-based to bio-based acrylonitrile/butadiene considered for each set of 5 scenarios were the same (100:0, 75:25, 50:50, 25:75, 0:100).[3]

[3] Inputs of acrylonitrile/butadiene must total to 172g. Therefore, inputs of petroleum-based acrylonitrile/butadiene must be $\leq$ 172g (input parameter), with bio-based acrylonitrile/butadiene being a function of 172g minus petroleum-based acrylonitrile/butadiene input (dependent parameter).

4 Results

4.1 Impact hotspot identification

In order to respond to the first research question, which aimed to identify the highest contributing stage of the life cycle to the environmental impact profile of 1 box of nitrile gloves, an impact assessment was generated for the baseline scenario (100% petroleum-based acrylonitrile and butadiene inputs). Figure 6 depicts the Sankey diagram generated for this baseline product system, providing a graphical illustration of the impacts of different processes within the cradle-to-grave life cycle of 1 box of nitrile gloves to climate change (measured as kg CO_2e). As shown in this Sankey diagram, the production phase of nitrile gloves emerged as the highest contributing process within the product system, accounting for 66.2% of the total greenhouse gas emissions generated from 1 box of nitrile gloves over their entire life cycle (from cradle-to-grave). Within the production phase, acrylonitrile accounted for 41% of production-related emissions and butadiene accounted for another 27% of production-related emissions.

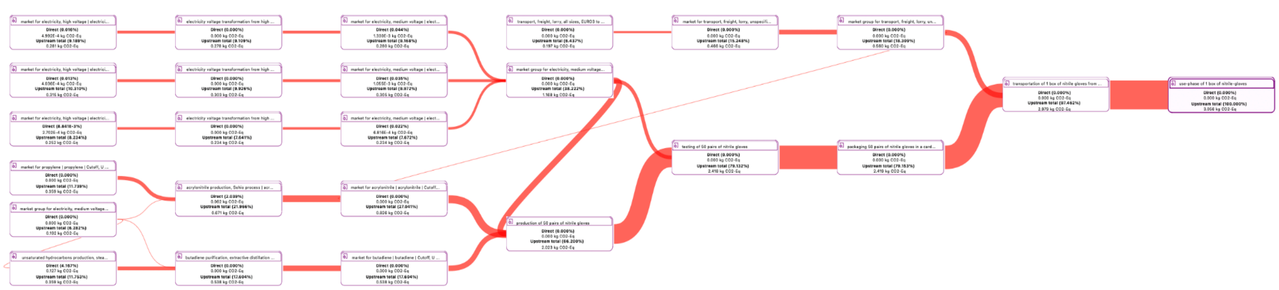

Figure 6. Sankey diagram for the entire cradle-to-grave life cycle of 1 box of nitrile gloves.

4.2 Scenario-based analysis

After identifying the production phase as a major hotspot within the life cycle of 1 box of nitrile gloves, with particular emphasis on the production of acrylonitrile and butadiene as accounting for the majority of production-related emissions, this study shifted its focus to answer the second research question by considering opportunities to reduce the emission-intensity of the production-phase. Figure 7 illustrates the relative climate change impact, measured as kg CO_2e, for different ratios of petroleum-based to bio-based acrylonitrile, meanwhile Figure 8 illustrates the relative climate change impact for different ratios of petroleum-based to bio-based butadiene.

As shown in Figure 7, it was demonstrated that an increasing proportion of bio-based acrylonitrile as inputs into nitrile glove production led to a reduction in greenhouse gas emissions. However, Figure 8 demonstrates the opposite trend, with an increasing proportion of bio-based butadiene as inputs into nitrile glove production leading to an overall increase in greenhouse gas emissions.

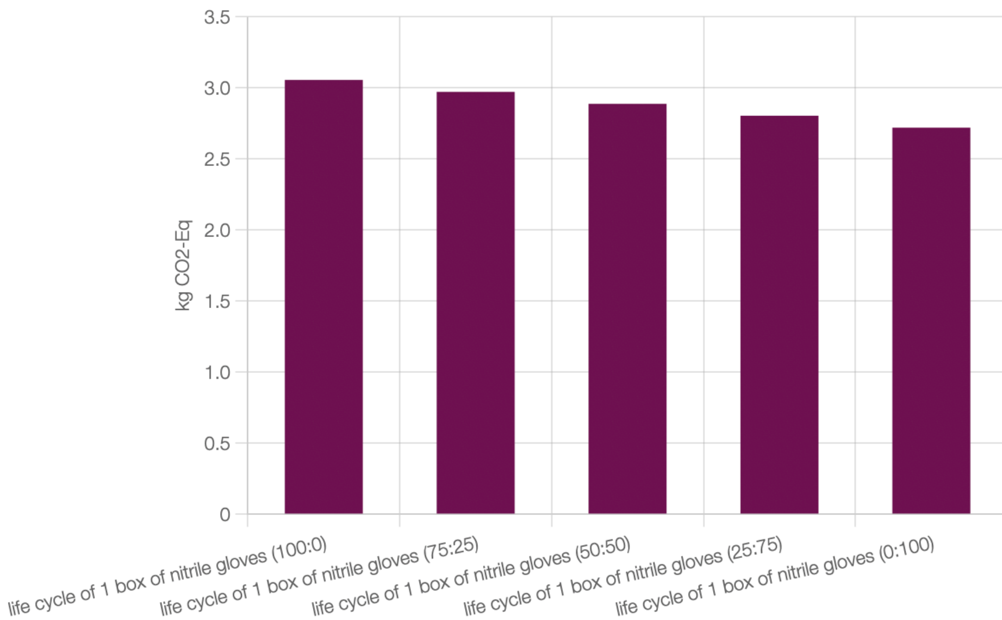

Figure 7. Emissions from different ratios of petroleum-based to bio-based acrylonitrile inputs.

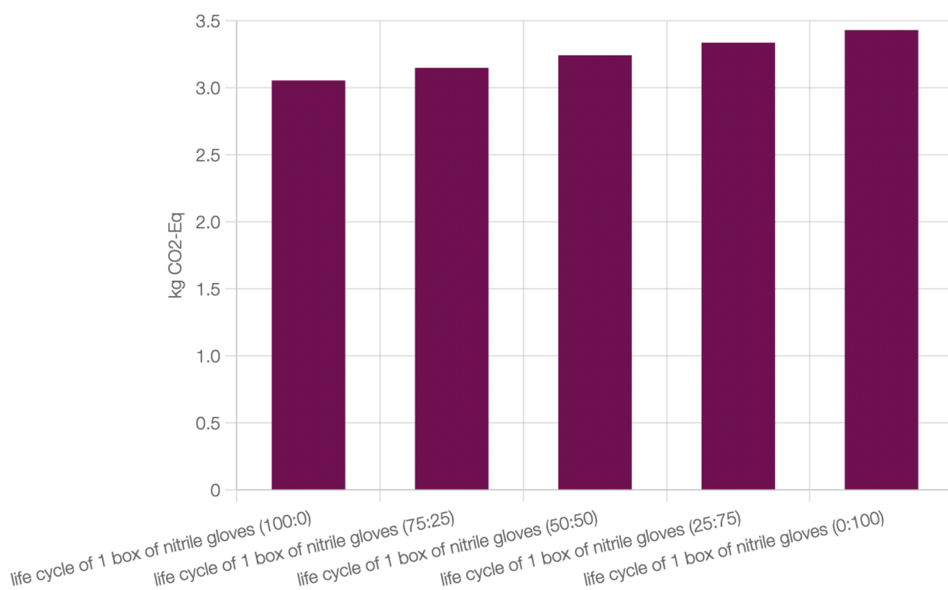

Figure 8. Emissions from different ratios of petroleum-based to bio-based butadiene inputs.

5 Discussion

5.1 Interpretation

The results of this LCA demonstrate that the production-phase of nitrile gloves' cradle-to-grave life cycle is the single-biggest contributor to the box of nitrile gloves' overall contribution to climate change, measured as kg CO_2e (Figure 6). Scenario-based analyses considered the impact of replacing petroleum-based acrylonitrile and butadiene with bio-based acrylonitrile and butadiene. The results of this scenario-based analysis demonstrated that replacing petroleum-based acrylonitrile with bio-based acrylonitrile reduced greenhouse gas emissions. In a conventional scenario with an input of 100% petroleum-based acrylonitrile, the total emissions generated from the life cycle of 1 box of nitrile gloves amounted to 3.056 kg CO_2e. However, in an alternative scenario where the petroleum–based acrylonitrile was replaced 100% with bio-based acrylonitrile, the total emissions generated from the life cycle of 1 box of nitrile gloves was 2.721 kg CO_2e. However, when modelling the same scenario comparison with substituting petroleum-based butadiene with bio-based butadiene, emissions generated from the entire life cycle of 1 box of nitrile gloves increased from 3.056 kg CO_2e (100% petroleum-based butadiene input) to 3.423 kg CO_2e (100% bio-based butadiene input).

While the observed impact of replacing petroleum-based butadiene with bio-based butadiene were not the expected or intended results, given that this study aims to identify strategies for emission reduction, the contrasting impact between bio-based acrylonitrile and butadiene reveals an important consideration for relying on biomass feedstocks, as well as the subsequent impact of provider selection. Based on the data provided by Musse Neto et al. (2023), it was assumed that the glycerine used for bio-based acrylonitrile production was obtained from waste biomass. Meanwhile, the data provided by Cabrera Camacho et al. (2022) assumed that bio-based butadiene was obtained from ethanol sourced from a mix of fermentation of sugar cane, sugar beet (molasses), maize, grass, rye, potatoes, wood, whey and sweet sorghum. The difference in selections of providers for inputs to produce bio-based acrylonitrile and butadiene, speaking to the reliance on either waste or dedicated biomass feedstocks, has important implications for whether the environmental implications of direct or indirect land use change is considered.

Figures 9 and 10 respectively demonstrate the land use impact from an increasing share of bio-based acrylonitrile/butadiene as inputs into nitrile glove production. As these figures illustrate, bio-based acrylonitrile's reliance on waste feedstocks implicates negative land use, while bio-based butadiene engenders direct and indirect land use change for the production of dedicated biomass feedstocks. This difference in assumptions rationalizes the contradictory impact of replacing petroleum-based acrylonitrile/butadiene with their bio-based counterparts.

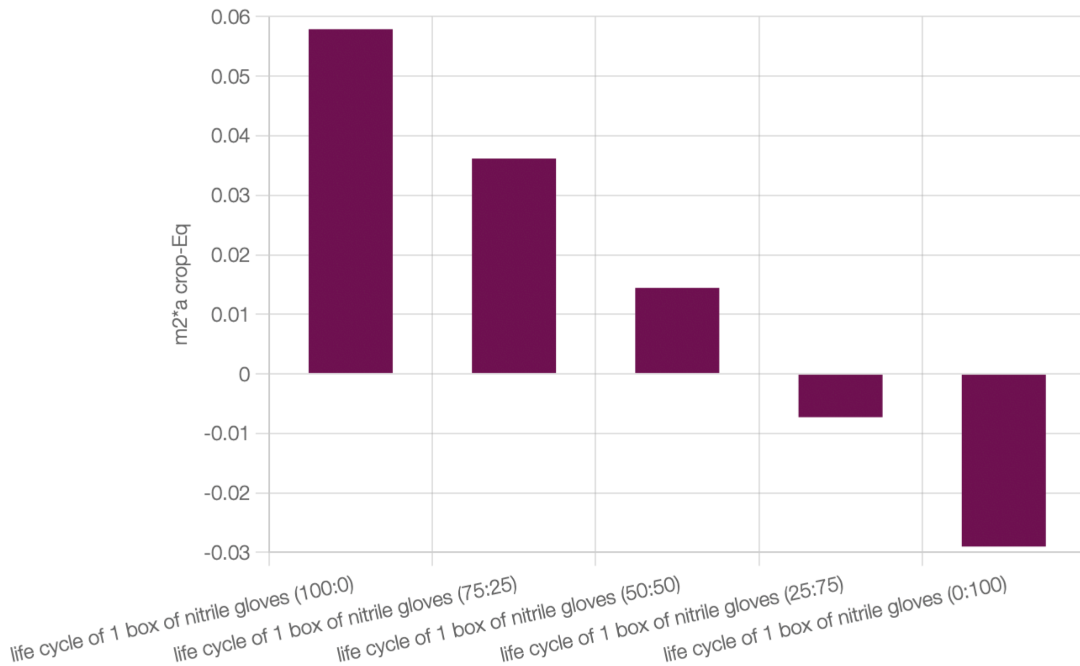

Figure 9. Land use from different ratios of petroleum-based to bio-based acrylonitrile inputs.

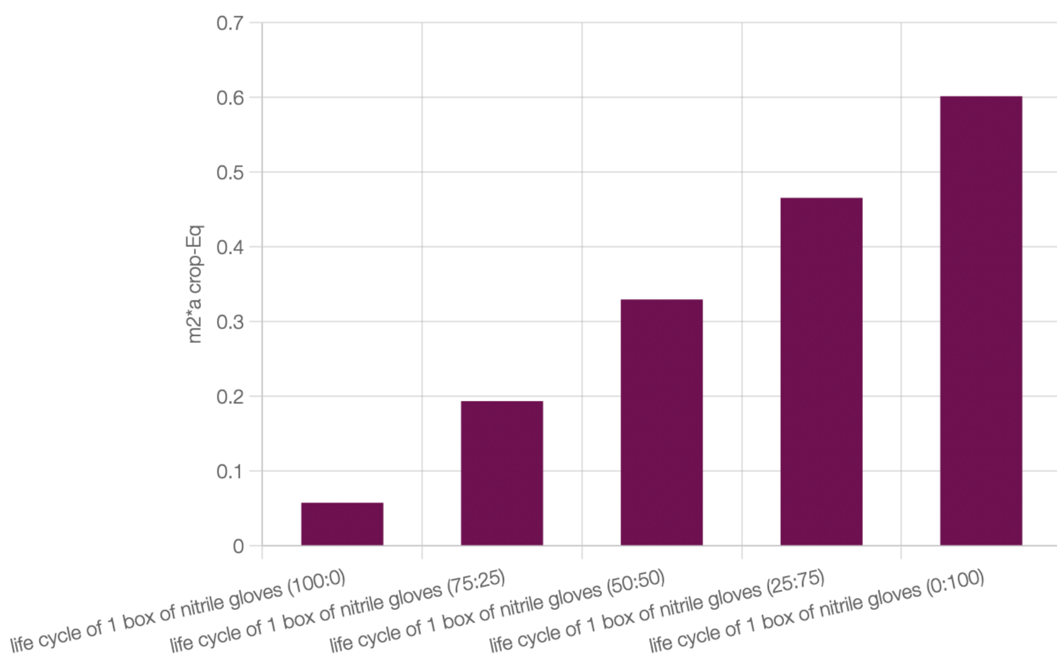

Figure 10. Land use from different ratios of petroleum-based to bio-based butadiene inputs.

5.2 Limitations

There are several limitations of this study and its findings, all of which can largely be attributed to this study's reliance on secondary data collected throughout the literature review. By relying on specific studies as data proxies for building the product system, the reliability and certainty of this study's results were reduced. This study's embedded overreliance on a select few studies reflects the current lack of data available for the life cycle processes (manufacturing, transportation, use, & disposal) of nitrile gloves. Similarly, embedded assumptions within the product system may heavily influence the results of the LCA. The sensitivity to assumption is well exemplified by the choice of provider for the production of bio-based chemicals, as the impact of increasing amounts of bio-based acrylonitrile/butadiene inputs were contradictory; this was explained by bio-based acrylonitrile's assumed reliance on glycerine from waste feedstocks compared to bio-based butadiene's assumed reliance on ethanol from primary biomass feedstocks. The overall reliability of this study could be drastically improved if primary data for the production, transportation, and disposal-processes was obtained for the specific nitrile gloves used by UBC labs.

5.3 FAIR Principle

In order to align with the FAIR principle, a set of guidelines established to improve the overall **F**indability, **A**ccessibility, **I**nteroperability, and **R**euse of digital media and assets, both the raw data used to build the LCA model and its results are included in the Appendix of this report.

6 Recommendations

Based on the results of this LCA, this study provides a series of recommendations for actionable steps to be taken by UBC, as well as to identify opportunities for further research. Based on the results of the scenario-based analysis, it is recommended that UBC labs attempt to source its gloves from nitrile glove manufacturers using bio-based acrylonitrile. However, attention should be given to whether the glycerine used for acrylonitrile is sourced from primary or secondary biomass feedstocks (i.e., waste residues) in order to ensure that bio-based chemical inputs remain a strategy for emission reduction. Furthermore, as the emission-intensity of the production phase decreases through careful substitution of input chemicals, UBC should also attempt to source its nitrile gloves from manufacturers that are both closer in proximity in order to reduce transportation emissions, as well as to prioritize glove manufacturers using cleaner power sources in order to cut emissions from electricity use in the production phase. However, in recognition of the fact that UBC has limited control over the upstream emissions generated from nitrile gloves, this study recommends that UBC should support future research to consider the relative impact of recycling nitrile gloves compared to conventional disposal methods, as this study initially intended. Recycling nitrile gloves into pellets that can be used as inputs into nitrile glove production may be an especially promising strategy for reducing the demand of biomass feedstocks for acrylonitrile and butadiene production, while still offsetting the use of conventional petroleum-based acrylonitrile and butadiene.

7 Conclusion

This study responded to two research questions by identifying the nitrile glove production process as the single-biggest contributor to the environmental impact profile of 1 box of nitrile gloves, with a specific emphasis on the impact of petroleum-based acrylonitrile and butadiene inputs. Upon identification of the production process as a significant hotspot within the life cycle of 1 box of nitrile gloves, this study performed a scenario-based analysis in an attempt to identify opportunities for emission reduction by substituting petroleum-based acrylonitrile and butadiene with their bio-based counterparts. However, replacing petroleum-based chemicals with bio-based chemicals has variable impacts on the emissions generated from nitrile gloves depending on whether the bio-based chemicals are sourced from waste or dedicated biomass feedstocks. In light of this feedstock-sensitivity, this study recommends that UBC should use this LCA as a base model in order to conduct further research to identify other opportunities for emission reduction. Particularly, UBC should support future research to consider the relative impact of recycling nitrile gloves compared to conventional disposal methods.

8 Contribution Statement

Our group, consisting of Aijun Wang, Constantine Bousalis, Lizzie Woodley, & Raul de Leon Rabago, collectively take responsibility for the work presented in this report. Raul & Aijun wrote the majority of Section 1, with a specific focus on researching and writing the literature review. Lizzie built the LCA model, with the support of her group members (openLCA does not make collaboration easy on different computers), and took the lead in writing Sections 2 through 7, as well as compiling data for the Appendix. Constantine prepared the graphical abstract and took the lead in formatting the report in APA style.

9 Appendix

9.1 Data

Life Cycle Inventory Table with Calculations: Nitrile Glove LCA Data. This document includes 3 tables with the raw data used to build the LCA model. These models are separated as (i) life cycle inventory data for the baseline model (assuming 100% petroleum-based acrylonitrile and butadiene production), (ii) bio-based acrylonitrile production data, and (iii) bio-based butadiene production data.

9.2 Results

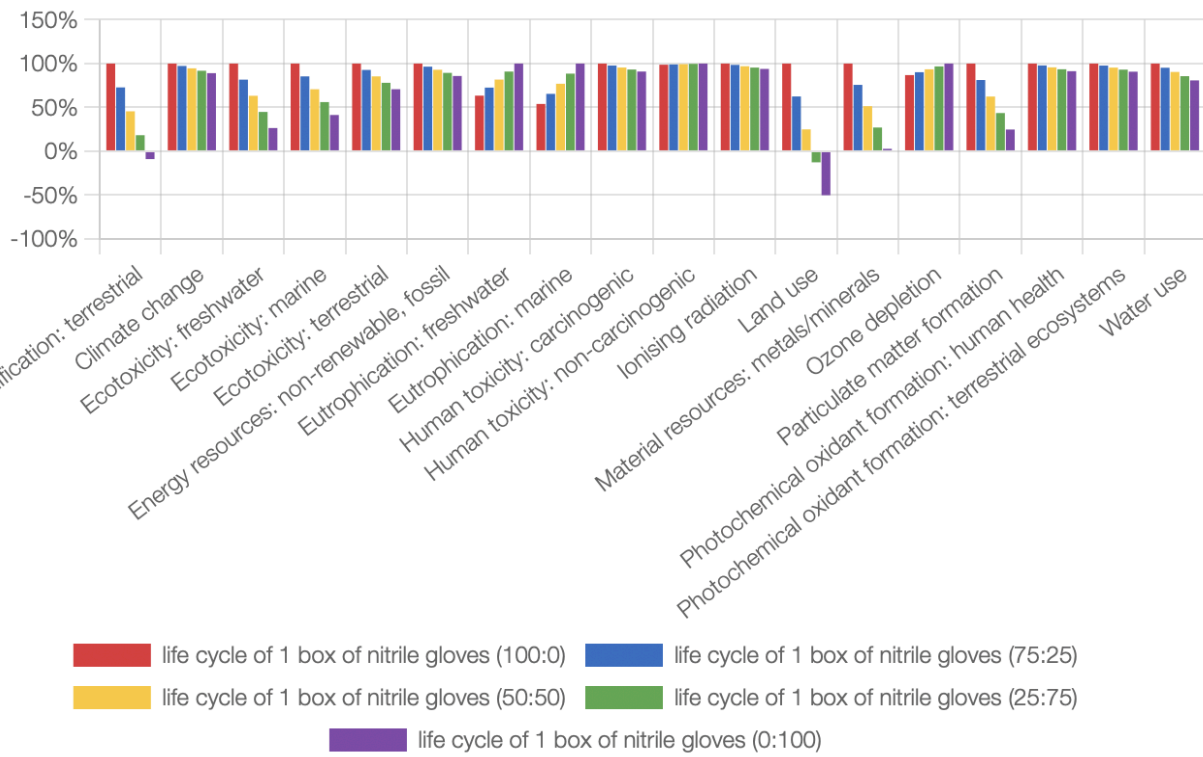

Figure 11. Full impact assessment results of the scenario-based analysis comparing different ratios of petroleum-based to bio-based acrylonitrile.

Figure 11 demonstrates the trend that increasing the amount of bio-based acrylonitrile input (from 0g bio-based acrylonitrile in the 100:0 ratio to 172g bio-based acrylonitrile in the 0:100 ratio) mainly resulted in a reduction in the environmental impact for different categories, such as acidification: terrestrial, climate change, ecotoxicity: marine and terrestrial, etc. Environmental impact only increased in three categories, including eutrophication: freshwater and marine, as well as ozone depletion.

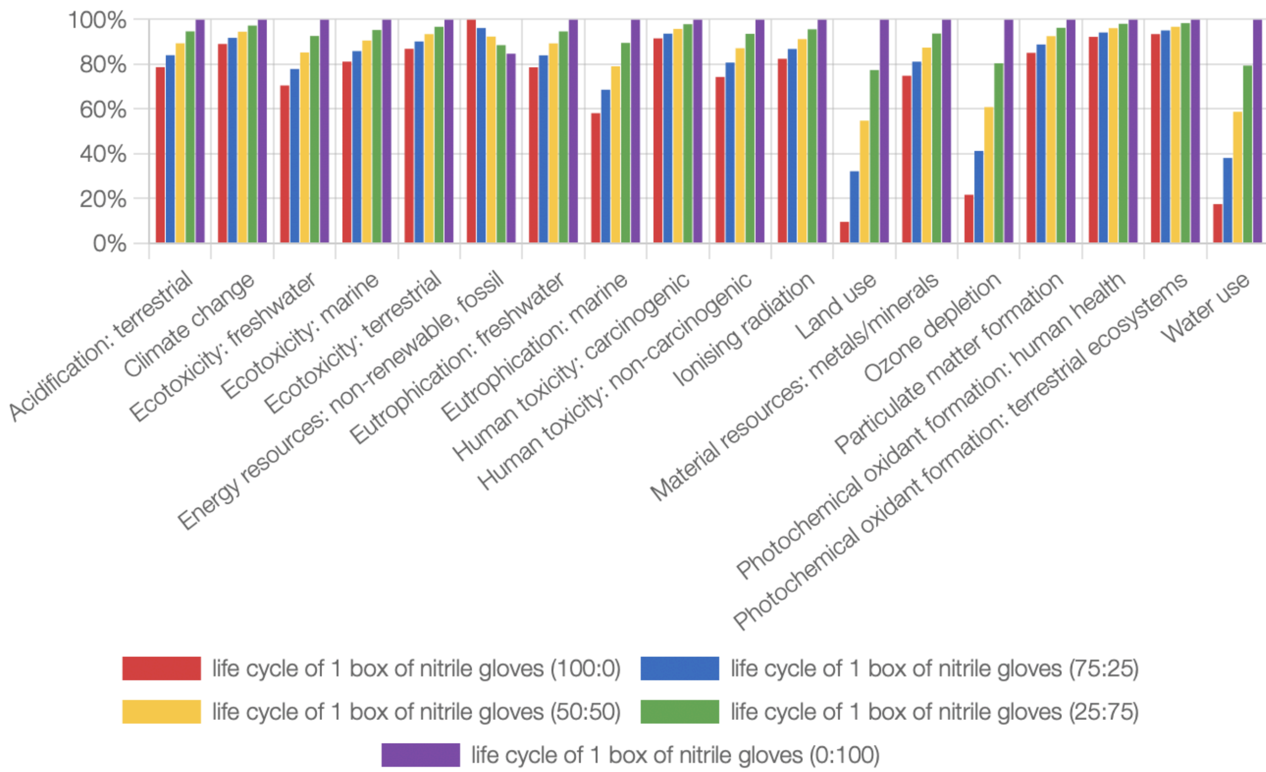

Figure 12. Full impact assessment results of the scenario-based analysis comparing different ratios of petroleum-based to bio-based butadiene.

Figure 12 demonstrates the trend that increasing the amount of bio-based butadiene input (from 0g bio-based butadiene in the 100:0 ratio to 172g bio-based butadiene in the 0:100 ratio) mainly resulted in an amplification of the environmental impact for different categories, such as acidification: terrestrial, climate change, ecotoxicity: marine and terrestrial, etc. Environmental impact only decreased in one category: energy resources: non-renewable, fossil.

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