Evaluating the Environmental Sustainability of the Cold-Chain Transportation and Storage of Different COVID-19 Vaccines by Life Cycle Analysis

Group 11-13

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Abstract

Although the COVID-19 vaccines are integral in facilitating society's return to a "new normal" amidst the pandemic, the cold-chain transportation and storage of these vaccines may cause irreversible damage to our environment. This is in large part due to their strict cold-chain transportation and storage requirements. Such cold-chain requirements will invariably result in a significant environmental footprint. We will thus be analysing and quantifying said environmental footprint through a life cycle analysis, and further cross-referencing these environmental impacts to the efficacy rates of the various vaccines, before evaluating which vaccine is the most environmentally-friendly whilst still maintaining a convincing efficacy rate. We take into account the transportation, storage as well as disposal of the vaccines and its related products, but will make some assumptions in place of data that is not available to the public, such as storage facilities or precise transportation details. Through an impact assessment, we are able to quantify the total environmental impacts of such vaccine cold chains on our environment, and conclude that the Moderna vaccine has the smallest environmental footprint. If we solely consider the cold-chain in Singapore (i.e., excluding shipping of vaccines to and from international production plants), however, then the AstraZeneca vaccine has the smallest environmental footprint.

Introduction

Millions have died due to the SARS-CoV-2 virus that has spread rampantly throughout the globe over the past year and a half. Recently, a number of biotech companies have managed to develop and mass produce vaccines for the virus, which will indubitably aid society in returning back to normal after this global pandemic. However, these vaccines have a variety of negative impacts on individuals, society and the environment alike. Such vaccines have various side-effects, ranging from mild fever to life-threatening blood clots. On top of these negative impacts on individuals, there are also various large-scale downsides that are generated from the development and production of these vaccines, namely the environmental impacts caused by the intensive

cold-chain transportation and storage required by the vaccines. Such cold-chain procedures will expend large amounts of energy and generate a large amount of environmental damage.

The vaccines have a wide range of cold-chain requirements, ranging from the Pfizer-BioNTech vaccine requiring between -80℃ and -60℃ to the Sinovac vaccine that can be stored at 37℃ for 28 days. Thus, we will be analysing the environmental impacts brought about by the cold-chain of the various vaccines. Of note, however, is that some vaccines have proven to be less effective than other vaccines; for example, the Sinovac vaccine demonstrated an efficacy rate of approximately 50.65% (when released in Brazil) compared to the Pfizer vaccine, which has shown a 95% efficacy rate. Thus, we will also take efficacy rates into account, as well as the various side effects of the vaccines in our research.

After considering different vaccine efficacy rates, we decided to focus mainly on the 3 vaccines (with the highest efficacy); namely, the Pfizer vaccine, the Moderna vaccine and the AstraZeneca vaccine. Reducing the environmental footprint of these vaccines without severely impacting their effectiveness is a challenge, as the cold-chain is what prevents the mRNA vaccines, which are incredibly fragile, from breaking down and thus becoming ineffective. Thus, the existing solutions can only reduce the environmental impacts on a very minute scale. One example is that of multiple transport companies utilising correx as lining for storage boxes instead of cardboard. This helps to reduce the environmental footprint of the vaccine as correx is fully recyclable and has a longer shelf life due to its Polyethylene lining. Another example is the use of Vacuum Insulated Panels instead of Expanded Polystyrene. This helps to reduce the environmental impacts as Vacuum Insulated Panels are more effective at reducing the amount of dry ice, which is used as phase change material, that escapes from the box. This reduces the amount of carbon dioxide produced by the transportation and storage procedure and reduces the impact on the environment.

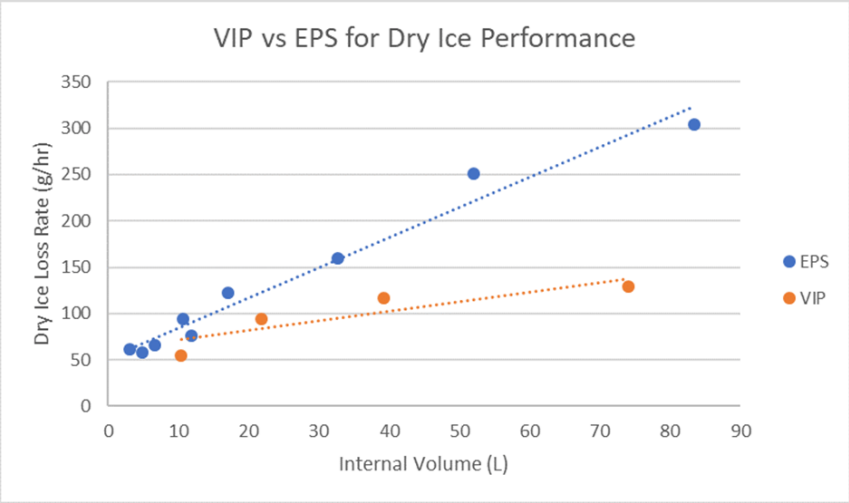

Fig 1.1 Graph of Dry Ice Loss against Internal Volume for VIPs and EPs

However, our project aims to identify the most environmentally friendly vaccine, by quantifying the environmental impacts generated by this vaccine, so as to increase public awareness of the environmental impacts of said vaccines, in the hopes of encouraging them to use the more environmentally friendly vaccine, in order to eventually reduce the amount of environmental impact generated by the vaccines.

Solution Design

We will be using OpenLCA (an open source Life Cycle Analysis software) for this project. Life Cycle Assessment (LCA) is a framework for evaluating the environmental impacts of a product system—the processes and material or energy flows associated with a commercial product or service—through the compilation of inputs (raw materials) and outputs (emissions) from the relevant product's "cradle to grave", i.e., throughout the resource extraction, manufacturing, storage and transportation, usage, and disposal phases of its life cycle.

The LCA framework we use has four main components: goal definition and scoping, life cycle inventory, life cycle impact assessment and (results) interpretation. An outline of each component is as follows:

Goal Definition and Scoping: During the goal-definition stage of LCA, it is necessary to define clearly and describe the product system under investigation. To do so, a functional unit must be ascribed to the product system. The functional unit is a measure of the performance of the system being studied, which provides a reference for inputs and outputs to be related; e.g., "1 kg of cheese leaving the gate of the dairy farm". As the reference point for relating (quantitatively) inputs with outputs, a functional unit must be defined with sufficient precision: for example, a relevant mass/volume must be specified (e.g., "1 kg of cheese" instead of "cheese"). The start and endpoints of the product system under investigation must likewise be specified. These would, most often, be the product's "cradle to grave", i.e., from resource extraction through to the product's disposal (or recycling), though alternative start and endpoints may be specified, such as "cradle to gate", which focuses solely on the resource extraction, manufacturing and transportation involved. In this case, our functional unit is one vial of vaccine.

During the scoping stage, it is also necessary to define system boundaries for the product system under investigation, i.e., the set of criteria specifying which unit processes are part of the product system studied. (A unit process, as defined in section 2, is the smallest element considered in the life cycle inventory analysis for which input and output data are quantified. Examples of unit processes include production, washing, packaging and usage of a product.) When scoping system boundaries, the following must be considered:

1. Boundaries between the product system and nature. Most often, the starting point for the product system is taken to be the point at which resources (e.g., raw materials) are extracted/acquired for production; environmental systems (e.g., conversion of dead matter into coal) are not accounted for. For fund resources (e.g., farmland, forests and animals), the harvest should be included, in addition to the activities needed to produce the harvest, such as ploughing, planting, fertilizing and use of pesticides; for flowing resources (e.g., solar radiation or running water), activities needed to bring the resources into the technological system should be included (Tillman et al., 1993).

II. Boundaries between the product system and other product systems, such as capital goods or technology involved in manufacturing of the product under investigation. The latter should be

included under LCI if the technology involved has a short life-span and high rate of breakage/spoilage.

III. Geographical boundaries. It is necessary to scope the relevant area for the product system under study as infrastructure (e.g., electricity production and waste management) varies across geographical regions, the various components of a product (e.g., plastic lids and paper cups) may be manufactured anywhere in the world, and the sensitivity of an environment to pollutants may vary across regions.

IV. Time horizon (temporal boundaries). Such boundaries include the life-spans of pollutants and technology involved in production. The time horizon of the inventory is usually restricted to the timespan during which the technology can be surveyed.

Life Cycle Inventory Analysis (LCI): During the LCI, inputs for all processes involved in the product system must be compiled under the system inventory. In general, data must be collected for the following:

1. Raw materials acquisition. Data collected under this subsystem includes all raw materials extracted and activities involved in acquisition, including transportation of raw materials to the manufacturing site, and all quantifiable effects of extraction, e.g., pesticide run-off and soil loss. Additional (non-quantifiable) impacts to the ecosystem are not compiled under the inventory but may be included under the impact assessment. In addition, it is necessary to collect data on energy acquisition, such as energy consumption and emissions due to extraction and refining.

2. Manufacturing. Data collected under this subsystem includes all energy, water and material inputs and outputs of the manufacturing and fabrication process required to convert extracted raw materials into intermediate or end products. Co-products (products which are not inputs or outputs elsewhere in the system) may be generated during this process, and should be analysed under LCI until separated from the primary product under investigation. Differences in technology throughout the industry may require assumptions to be made at this stage of the LCA, e.g., with regards to facilities sizes or age of equipment involved.

The manufacturing and fabrication process is defined as the process by which extracted raw materials are converted into finished products ready for consumer purchase; therefore, it is also necessary to collect data on the inputs and outputs required for packaging of the product.

3. Transportation (distribution) of product. Data collected under this subsystem includes all transportation activities of the product, both from production facilities to intermediate storage (e.g., warehouses) and from storage facilities to consumers. Environmental controls (e.g., refrigeration at intermediate storage facilities) are also included as components of the distribution process.

4. Consumer use. Data collected under this subsystem includes all outputs generated through usage of the product under investigation. Additional considerations include life-span of product and frequency of repair. Maintenance and related inputs must also be included under LCI.

5. Disposal/recycling. Data collected under this subsystem includes inputs into waste management and outputs generated through disposal (e.g., landfill emissions).

Data quality (specificity and accuracy) is an important consideration under LCI. As per ISO14040 (2006), all materials and energy flows as well as associated environmental releases must be allocated to the different products according to clearly stated procedures, which must be documented and justified. The calculation of energy flow should also take into account different fuels and electricity sources used, the efficiency of conversion and distribution of energy flow, as well as the inputs and outputs associated with the generation and use of that energy flow. Data on resource acquisition may be collected from public databases; in general, data under the manufacturing and distribution subsystems should be collected from the production site, to ensure greater accuracy.

Life Cycle Impact Assessment (LCIA): During the LCIA, results of the LCI are evaluated, in order for the significance of the product system's environmental impacts to be assessed. Several impact categories (i.e., environmental issues of concern, such as ozone depletion potential) may

be formulated to assess the significance of LCI results, and characterisation factors or indicators may be ascribed to each category as quantitative units for assessment (e.g., disability adjusted life years (DALY) with respect to damage to human health per unit emission). Characterisation factors may also be classified as midpoint or endpoint indicators, where, broadly, midpoints are considered links in a cause-effect chain (environmental mechanism) and endpoints are broader categories at which characterization factors (indicators) can be derived to reflect the larger relative importance of emissions or extractions (Bare et al., 2000). Common impact categories modelled at the midpoint level include abiotic and biotic resources, land use, global warming (climate change), stratospheric ozone depletion, ecotoxicological impacts, human toxicological impacts, photochemical oxidant formation, acidification and eutrophication (Jensen et al., 1998). These may be further combined into endpoint categories, e.g., ecological impacts. Endpoint modeling may facilitate more structured and informed weighting, due to broader impact categories and aggregation of common parameters (for example, human health impacts associated with climate change can be compared with those of ozone depletion using a common basis such as DALYs). The use of endpoint modelling may involve additional assumptions, however, due to uncertainty in conversion of characterisation factors (e.g., carbon dioxide emission/kg to DALYs), and this should be accurately reflected in reporting to stakeholders.

It should further be noted that several outputs may contribute to different impact categories and therefore may be accounted for twice in LCIA. The resulting double counting is acceptable if the effects are independent of each other (e.g., eutrophication and ozone depletion potentials), whereas double counting of different effects in the same effect chain is not; double counting should also be reported to stakeholders as part of the LCIA.

Interpretation: During the interpretation stage of the LCA, identification of significant environmental issues, evaluation, and conclusions and recommendations should be carried out. The aim of interpretation is to facilitate a decision making process based on the LCA study and to ensure that results are consistent with the goals of the LCA, as well as to evaluate methodology (e.g., data quality and sourcing) and conclusions derived.

As far as possible in our LCA, we have sourced input data regarding vaccine safety and manufacturing from the relevant pharmaceutical companies themselves, or federal/international public health agencies (e.g., WHO, CDC). For generic processes, however, such as plane travel or refrigeration, values built into the OpenLCA software's EcoInvent database was used.

Results and Discussion

Basic Findings: Through our OpenLCA, we have found that the cold-chain of the vaccines had the most impact on the impact category "Global warming, Terrestrial ecosystems", measured in species.yr (species disappearing during one year), "Global warming, Human health", measured in Disability-Adjusted Life Years (DALY; years of life lost due to premature mortality, years of life lost due to time lived in states of less than full health, or years of life lost due to disability), and "Global Warming (GWP100a)", measured in kg CO2 equivalent. These impact categories accounted for almost 97% of the total impacts generated, thus we will be mostly considering these few impact categories when evaluating the environmental impacts of the different vaccines.

We have done our Life Cycle Analysis on the following processes.

- 6 months cold chain
- Disposal of syringe and vial
- Transport of Vial from production to administration site

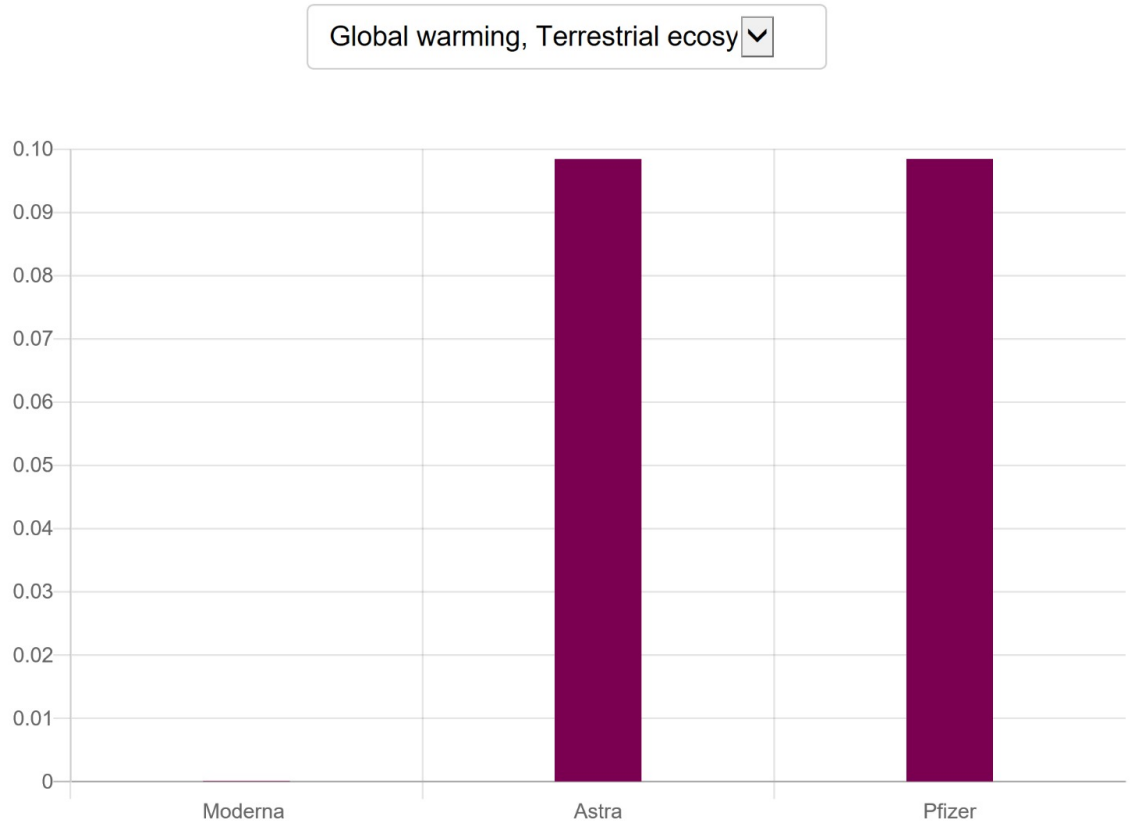

Fig 2.1 Comparison of the environmental impacts on terrestrial ecosystems generated by the different vaccines, Overseas Inclusion

"Global Warming, Terrestrial Ecosystems": After running the processes of transportation, storage, and waste disposal through the OpenLCA software, we found that it terms of 'Global Warming, Terrestrial Ecosystems", the Moderna vaccine generated the least impacts out of the three vaccines. Based on Fig 2.1 we can observe the large disparity between the environmental impacts generated by the Moderna vaccine compared to the other two vaccines. Moderna's impacts on terrestrial ecosystems was quantified as 1.03e-4 species.yr, whilst that of AstraZeneca and Pfizer were extremely similar at approximately 9.84e-2 species.yr. The impacts generated by the Moderna vaccine was almost equal to the environmental impacts generated by a palm oil plantation, whilst that of Pfizer and AstraZeneca are almost 1000 times that of a palm oil plantation (Obaideen et al., 2019). Compared to 1 Pet Bottle being produced, the impacts

generated by the Moderna vaccine are 5 times larger in magnitude, while impacts of Pfizer and AstraZeneca are 7 times larger in magnitude These results are interesting, as Moderna and Pfizer have extremely similar cold-chains, whilst AstraZeneca's cold-chain is in general less intensive than that of the mRNA vaccines. However, the likely cause of this result is the presence of a Moderna vaccine manufacturing facility in Singapore, the Lonza Biologics facility at Tuas. This removes the need for vaccines to be transported via plane and thus reduces a lot of carbon emissions generated. However, these results might not be completely accurate as the Singapore facility might not be able to keep up with Singapore's vaccine demands and vaccines will likely still have to be imported from overseas. Thus, we have done another impact assessment that assesses that case.

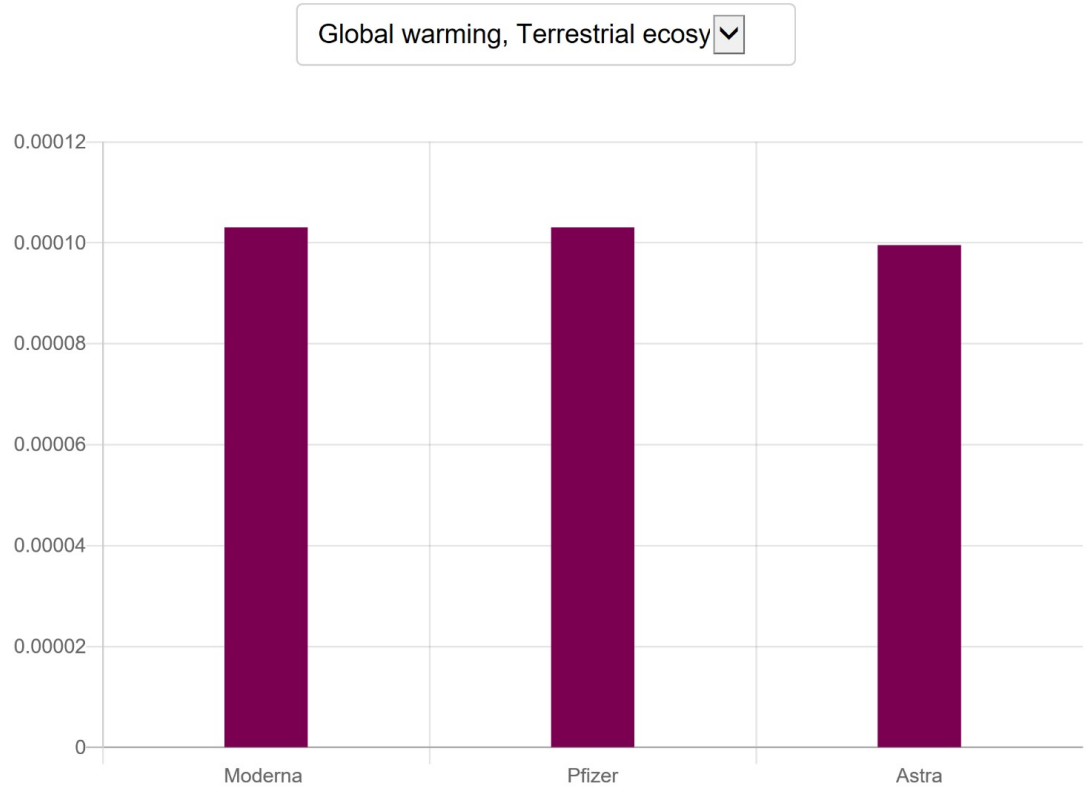

Fig 2.2 Comparison of the environmental impacts on terrestrial ecosystems generated by the different vaccines, Singapore only

Without considering the plane journey in our LCA, the 3 vaccines all display similar results. Thus, we can see that the plane journey contributes massively to the environmental impacts of the vaccines. However, the AstraZeneca vaccine has the smallest impact with 9.95e-5 species.yr,

and both Moderna and Pfizer have the same impacts with 1.03e-4 species.yr. This is due to the AstraZeneca vaccine's different cold chain requirements, with it only needing 2-8 degrees celsius of long term storage, while since both Moderna and Pfizer have similar cold-chain requirements, they have the same environmental impacts.

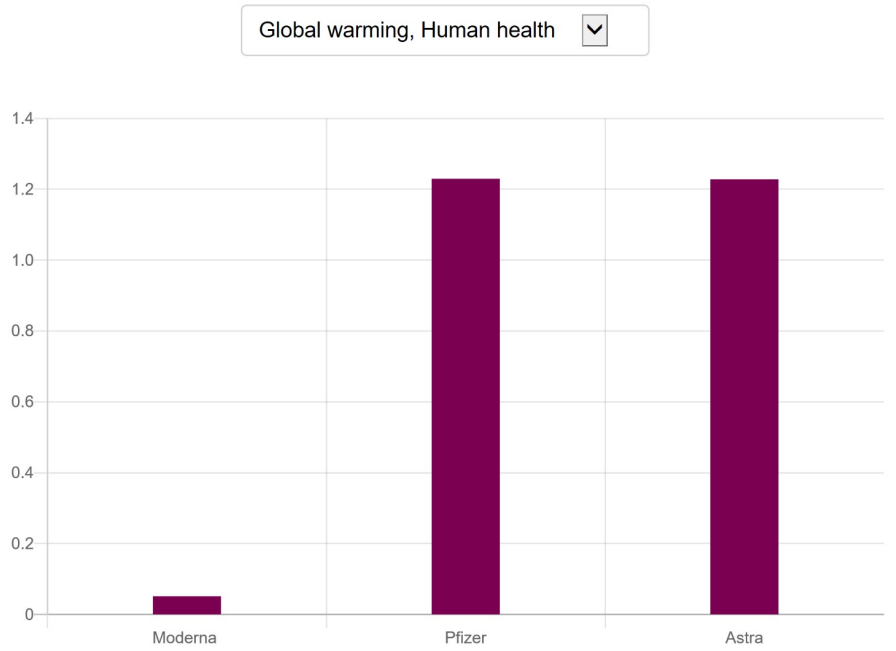

Fig 3.1 Comparison of the environmental impacts on human health generated by the different vaccines, Overseas Inclusion

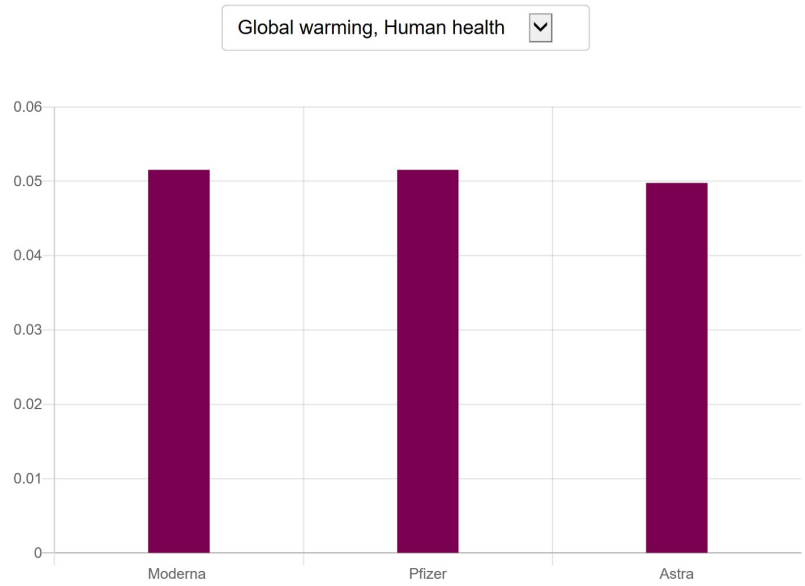

Fig 3.2 Comparison of the environmental impacts on human health generated by the different vaccines, Singapore only

"Global Warming, Human Health": Fig 3.1 and Fig 3.2 show similar trends to that of the environmental impacts generated by the environmental vaccines. Before plane travel is taken into account, the Moderna and Pfizer vaccines generate similar impacts on human health, quantified at 5.15e-2 DALY, whilst that of AstraZeneca is slightly lower, at 4.98e-2 DALY. However, when plane travel is taken into account, the impacts of human health generated by the Pfizer and AstraZeneca vaccines skyrocket to approximately 4.92e+1 DALY, whilst that of Moderna remains at 5.15e-2 DALY. This means that the transport of just one vial of vaccine will cause one person to live 49 years with a disability or die 49 years prematurely just because of the vaccines, more than 3000 times of the impacts generated by palm oil plantation (Obaideen et al., 2019). Such vaccines work to protect people from the coronavirus, but also causes knock-on effects that could damage another's life. The causes of these observations are once again similar to that of the impacts on terrestrial ecosystems, with the less intensive cold-chain of AstraZeneca and the presence of a Moderna manufacturing facility in Singapore removing the need for long-distance plane transport.

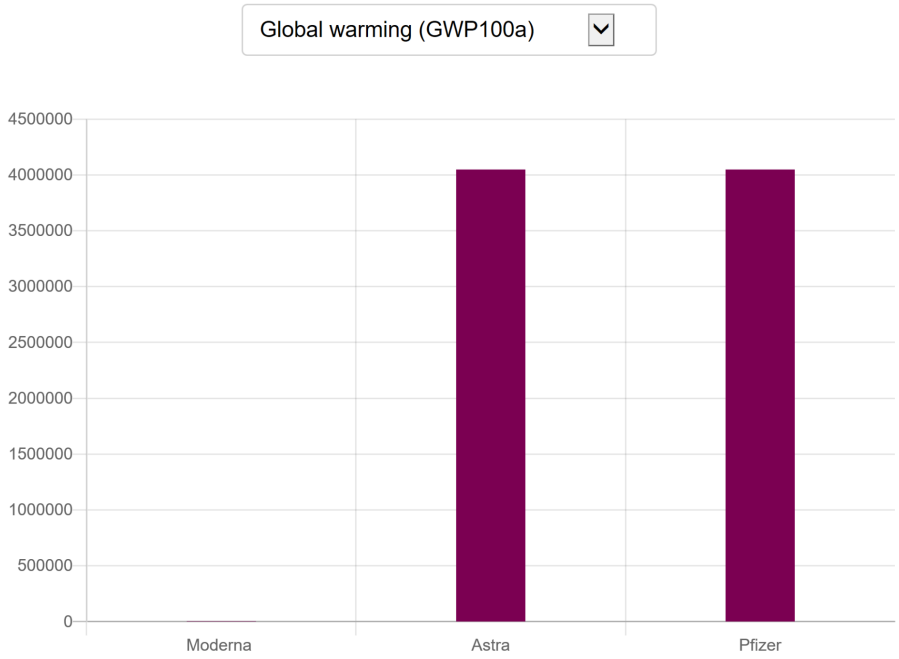

Fig 4.1 Comparison of the environmental impacts on human health generated by the different vaccines, Overseas Inclusion

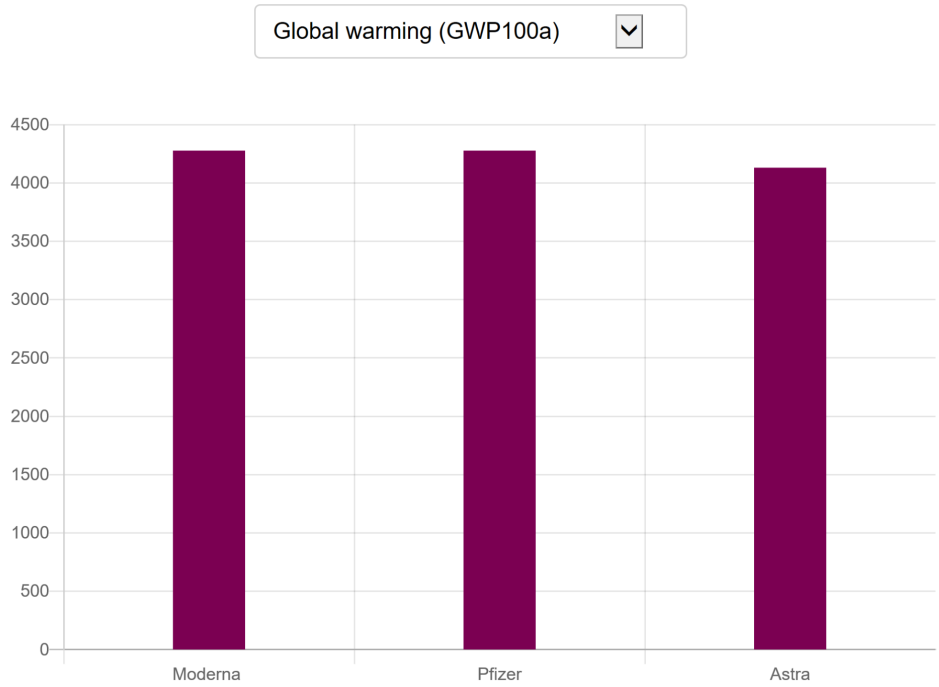

Fig 4.2 Comparison of the environmental impacts on human health generated by the different vaccines, Singapore Only

"**Global warming (GWP100a**)" This impact assessment quantifies the emissions, over 100 years. It is measured in kg CO2 equivalent, which is the weight of the CO2 equivalent in terms of carbon emissions. With the inclusion of the Plane journey, Pfizer has 4.05e+5, AstraZeneca has 4.05e+5, and Moderna has 4.28e+3 of kg CO2 equivalent, with AstraZeneca having slightly less emissions at its 6th decimal place compared to Pfizer. Without the plane journey, Moderna and Pfizer both have 4.28e+3, while AstraZeneca has 4.13e+3. As such, we can see that the cold-chain generates quite a lot of carbon emissions. As a comparison, a typical passenger car releases 4.6 kg of carbon dioxide a year, and when put against the emissions caused by the vaccine cold-chain and storage, the emissions caused by the vaccine cold-chain and storage are tantamount to 30 years of carbon dioxide emissions by the passenger car.

Evaluation/interpretation: Through our Life Cycle Analysis, we have found that throughout the life cycle the Moderna vaccine has the smallest environmental impact when considering cross-country transport via plane. However, when we remove this process, we find that AstraZeneca is the most environmentally friendly vaccine. When we cross-refer these environmental impacts to the efficacy rates and various side-effects uncovered by various researchers and vaccine test runs, we can see that the Moderna vaccine has a slightly higher efficacy rate at 94.5% (Moderna, 2020), compared to AstraZeneca's 90% (AstraZeneca, 2020). Furthermore, it has been found that, though rare, one of the side effects of the AstraZeneca vaccine is life-threatening blood clots that can occur in around one in every 50,000 people and often affects young and healthy adults and has an extremely high mortality rate (Pavord, 2021). The blood clots killed 23% of cases analysed, with risk of death increasing to about 73% for patients with low platelet counts and brain bleeds after blood clots in the brain (Hunt, 2021). Thus, the AstraZeneca vaccine does have extremely severe side-effects to the unlucky number of people to be affected by it. The Moderna vaccine does not have side-effects with such a high mortality rate and is relatively safer. Thus, when considering our Life Cycle Analysis, along with the side-effects and efficacy rates, it can be seen that the Moderna vaccine is the most

environmentally friendly vaccine that includes little tradeoffs regarding the patient's health and safety.

	Pfizer	Moderna	AstraZeneca
Efficacy	95%	94.5%	90%
Maximum storage length	Before mixing, vaccine may be stored between -80℃ and -60℃, between -25℃ and -15℃ for up to 2 weeks, or between 2℃ and 8℃ for up to 5 days.Once mixed, vaccine may be stored between 2℃ and 25℃ for up to 6 hours.	Vaccine may be stored between -25℃ and -15℃, and at between 2℃ and 8℃ for up to 30 days before vials are punctured.	Vaccine may be stored between 2℃ and 8℃ for up to 6 months.
Place of Manufacture	Belgium	Singapore	Belgium
Terrestrial Ecosystems (With Plane)/species.yr	1.03e-4	9.84e-2	9.84e-2
Human Health (With Plane)/DALY	5.15e-2	4.92e+1	4.92e+1
Global Warming (With Plane)/kg CO2 eq	4.28e+3	4.05e+5	4.05e+5
Terrestrial Ecosystems (No Plane)/species.yr	1.03e-4	1.03e-4	9.95e-5
Human Health (No Plane)/DALY	5.15e-2	5.15e-2	4.98e-2
Global Warming (No Plane)/kg CO2 eq	4.28e+3	4.28e+3	4.13e+3

Future Recommendations

An additional avenue for research is how different energy mixes (e.g., involving renewable energy) would affect the sustainability of the COVID-19 vaccine cold chain. It has been suggested, for example, that use of solar technology could assist in vaccine roll-outs in developing countries, on account of the higher efficiency and reliability of solar-powered refrigerators (The Conversation, 2021). This would also affect the net emissions produced in the course of transportation and storage of the vaccines.

Another avenue for research would be to consider the ingredients used in the vaccines and the biological impacts on the environment. Since several of the COVID-19 vaccines (e.g., Moderna; Pfizer) are made using mRNA, along with a mixture of other substances, a possible avenue for research would be to try to quantify the environmental impacts of the ingredients used to make the different vaccines (for the purposes of this LCA, we have not considered this segment of the manufacturing process).

Conclusion

Through this project, we have managed to quantify the environmental impacts of the different covid vaccines. As seen in our results, though it only shows the impacts of one vial of vaccine, when magnified by the large vaccination effort in Singapore with its 5.7 million populace, the environmental impacts of cold-chain storage and transportation of the COVID-19 vaccines are tremendous. We also are able to construct an environmental damage to efficacy graph, with each vaccine having different trade-offs. Thus, when considering which vaccine to use, considerations must be undertaken to consider vaccine efficacy compared to its environmental impact. A better choice might be to opt for a vaccine with slightly less efficacy, but with less environmental impacts. However, one limitation of our study that we did not consider was the efficacy of the vaccines against different variants of COVID-19, another major impact factor in selecting vaccines. Based on an overall consideration of the vaccines, we would recommend the Moderna vaccine, since it is the most environmentally friendly vaccine that includes little tradeoffs regarding the patient's health and safety.

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