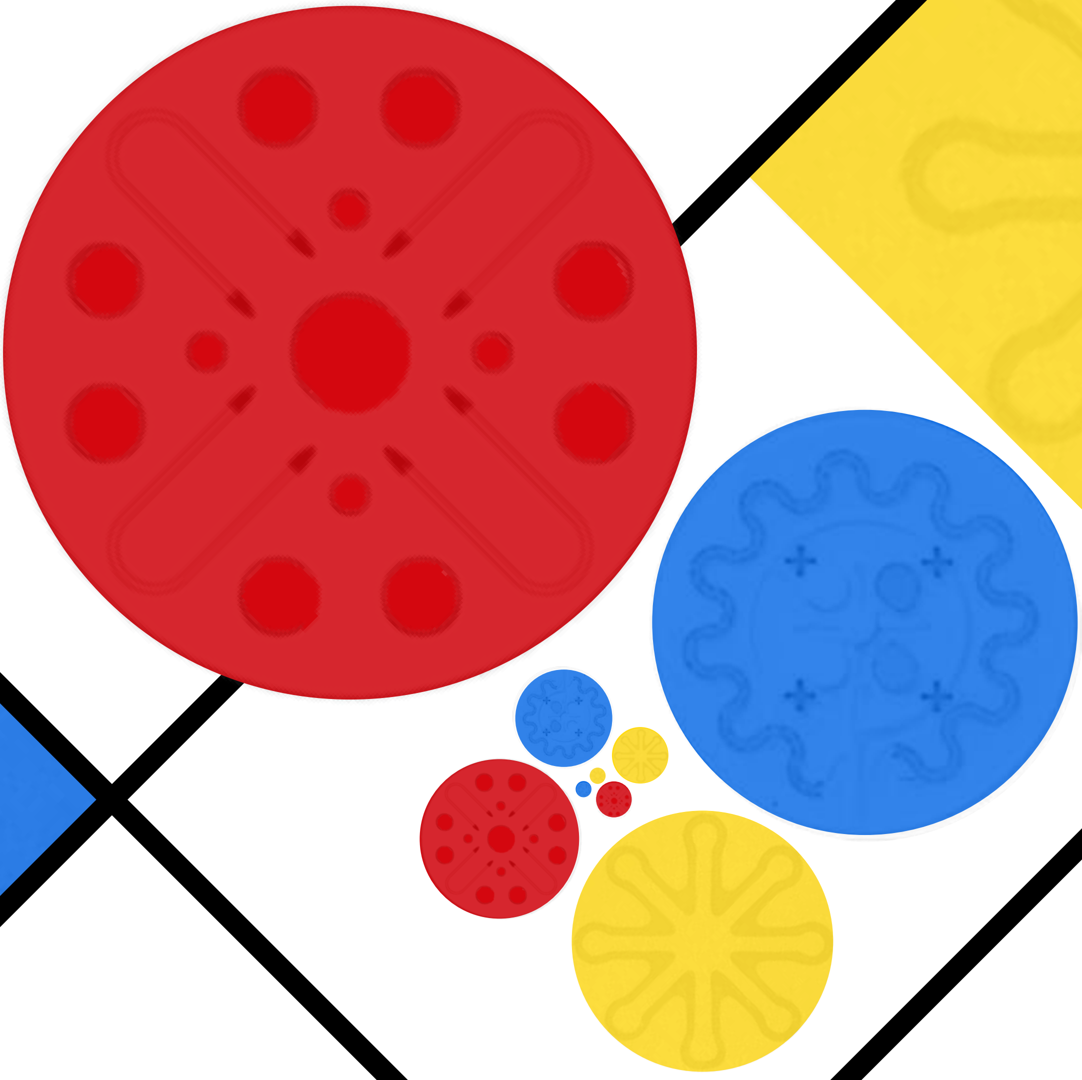
Life Cycle Assessment of microfluidic devices for point-of-care testing

A comparative analysis of PDMS, paper and PLA

Kristie Tjokro



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Life Cycle Assessment of microfluidic devices for point-of-care testing

A comparative analysis of PDMS, paper and PLA

by

Kristie Tjokro

in partial fulfilment of the requirements for the degree
of Master of Science in Industrial Ecology
at Leiden University and Delft University of Technology
to be defended publicly on 14 August 2023 at 11:00.

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Project Duration:	February 2023 - August 2023

This thesis and the supplementary information are available at `http://repository.tudelft.nl`.
Cover Image: Colourful composition of the microfluidic devices of Koh et al. [1], Gabriel et al. [2], and Tothill [3] by the author.

Preface

At 17 years old, I moved away from Suriname to the Netherlands in order to pursue a higher education. Like most people at that age, I had no clue what I wanted to do with my life. All I knew is that I wanted to study something STEM-related and I wanted it to be in Delft. I was determined to study at the Delft University of Technology, and was amazed by all it had to offer. I dabbled in computer science for a year, before deciding to get my bachelor's degree in applied physics. Once I achieved this, I felt like something was missing. While our findings could and would inevitably help to change the world for the better, I felt that the distance between applied physics and real-world applications was too large. I was also becoming more passionate about environmental sustainability, an aspect which was often only an afterthought within the field. I therefore decided to change lanes, and study industrial ecology for my master's degree.

In industrial ecology, I discovered systemic and holistic thinking. I learned about approaching complex issues from environmental, technological, and social perspectives. I was taught about various methods to solve these issues. I also found a wonderful community where I often gain hope for the future. After a project with the RIVM on improving sustainability in governmental laboratories, I became interested in sustainability in pharmaceutical and medical contexts. At the same time, my interest in life cycle assessment grew. Unravelling a product and translating its entire life cycle into environmental impacts is challenging, but incredibly satisfying. I therefore decided to do this thesis on microfluidics, per the suggestion of my supervisors Stefano and Justin.

After six months, the thesis has finally been completed. I would like to thank my supervisors Stefano, Alina, and Justin for their support and for their quick responses to my many questions. Additionally, I would like to thank Stefano and Justin for pushing me to submit the abstract for this thesis to the ISIE 2023 conference, and for attending the presentation when it got accepted.

I would like to thank my many wonderful friends, both old and new, who have made the tough times bearable. While there are too many to name, some deserve special recognition. Katha, who has been there since day one, and without whom I would have not gotten to this point. Roosa, who is the kindest person and whose words of support always arrive at the best time. Aïcha, who understands me like no other and makes me feel like I am back home. You are all beacons of light that deserve the world. I would also like to thank the IE key group: Jasmine, Hajar, and Quan. Our dinners fill me with love and I cannot wait for the next one. I would like to thank my boyfriend's family, who I consider to be my own. Thank you for giving me a second home, and providing me with endless comfort. My gratitude goes out to my parents for their unwavering support and the sacrifices they have made to allow me to study abroad. I often wish I had a teleportation machine, so I could visit you every weekend.

Lastly, Thomas, thank you for being there this whole time. Thank you for proofreading and helping me solve my coding errors. Thank you for making me laugh and guiding me out of the dark when necessary. I love you lots.

Kristie Tjokro
Delft, August 2023

Abstract

In microfluidics, typical laboratory processes can be condensed to a miniature device. This reduces analysis time and required volumes of samples and reagents, increases mobility and flexibility, and is cost effective. In this work, the environmental impacts of three microfluidic devices for glucose detection are assessed using a comparative life cycle assessment (LCA) from cradle-to-grave. The three devices are a polydimethylsiloxane (PDMS) device manufactured through soft lithography, a paper device manufactured through wax stamping, and a polylactic acid (PLA) device manufactured through 3D printing. The environmental impacts are determined for two manufacturing scenarios: on laboratory-scale and commercial-scale. The functional unit is 1 act of glucose detection performed on a human sample using 1 microfluidic glucose detection device.

Assuming laboratory-scale manufacturing, the paper device has the lowest environmental impacts, whereas the PLA device has the highest impact. The main contributing processes are those pertaining to the devices' manufacture. For the PDMS device, these are the processes for soft lithography, for the paper device it is the paraffin use, while for the PLA device it is the 3D printing. Assuming commercial-scale manufacturing, the PLA device has the lowest environmental impact, whereas the PDMS device has the highest impact. This scenario was modelled by improving efficiencies in the manufacturing of the PDMS and paper device, and substituting 3D printing for injection moulding for the PLA device.

To reduce the devices' environmental impacts, a general recommendation is to transition to an electricity mix based on renewables rather than fossil fuels. For the PDMS device, a recommendation is to redesign the device such that the user can apply reagents before use, thereby avoiding emissions by cutting out a need for refrigeration, which is present in the current design. For the paper device a recommendation is to minimise the waste of paraffin, as it is the main contributor to the device's environmental impacts. Lastly, for the paper and PLA device it is recommended to consider alternate manufacturing methods when upscaling production. Their current manufacturing methods are ideal for prototyping, but are inefficient on a commercial scale.

Some limitations are that several data points were estimated, cut off, or secondary. Data gaps were bridged through the use of proxies and stoichiometry for chemicals, which affected the accuracy of the model. Furthermore, recycling and chance of failure during manufacture are not accounted for. Lastly, as microfluidic devices are designed in many different ways, the results cannot be translated one-to-one to other devices. They can only provide a general idea of what the impacts for other devices might be.

A continuation of this work could simulate the synthesis of chemicals using process design software, for increased accuracy. Another opportunity for further study is to collect and implement primary data and assess how that affects the results. Future research could investigate fields of microfluidics other than diagnostics. Generally, more research is necessary to model a proper ex-ante LCA with various scenarios. With enough research, microfluidics might fully reach its potential, while being environmentally responsible.

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1

Introduction

Microfluidics is an area of research concerned with the behaviour of fluids flowing through micro-channels. Research also focuses on the fabrication of miniature devices comprised of micro-channels, which fluids can flow through, or be confined in. Microfluidics has its foundations in molecular analysis, molecular biology, microelectronics and national security, and stems from research into microelectronic technologies [4]. It is a multidisciplinary field where (bio)chemistry, nano- and biotechnology, engineering, and physics come together.

Microfluidics allows typical laboratory processes to be condensed so that they can be performed entirely on a microfluidic device alone. Processes like separations and detection of samples and reagents can be performed using much smaller quantities, without sacrificing resolution or sensitivity [4]. Due to miniaturisation, analyses become more cost-effective, while also shortening the time required for experiments. Their small size also means they allow for more flexibility, as the devices' portability greatly increases the number of possible applications. Now, analyses traditionally performed in a laboratory can also be applied in point-of-care situations. This could have a great effect on healthcare in remote areas that are far-removed from laboratories [5, 6].

Microfluidic devices are applicable in a variety of areas. The technology has contributed to the understanding of cell growth and cellular ageing [7], it is the foundation for inkjet printing [8], but also enables research into antibiotic drug-resistant bacteria, transport phenomena in blood, and chemical reaction kinetics [9]. Microfluidic devices also have applications in diagnostics, such as for cancer biomarkers or pathogens [10, 11].

Certain use cases for microfluidics are still in their infancy, but show great potential. These can often provide proof-of-concept, but experience barriers penetrating the market for large-scale commercialisation [12, 13]. Examples are microfluidics for personalised cancer treatment [14], wearable devices for biofluids diagnostics [15, 16], and on-demand pharmaceutical drug manufacturing [17].

Depending on the use case, microfluidic devices may be fabricated from various materials. Most common are microfluidic devices based on polydimethylsiloxane (PDMS), an optically transparent, soft elastomer. PDMS was introduced as a cheaper and more effective alternative to the commonly used materials at the time: glass and silicon [4]. In combination with the development of soft photolithography, microfluidic devices could be manufactured in less time and with fewer consumables per device [18]. PDMS has since become one of the most employed materials for the fabrication of microfluidic devices. Not only does PDMS facilitate rapid prototyping, its transparency enables real-time monitoring of the processes under study, while its biocompatibility, permeability and low autofluorescence are ideal for research in biotechnology and biomedical engineering.

PDMS does suffer from drawbacks. One of the most important is its absorption of small molecules, which is problematic for drug screening [19]. Another issue is its absorption of hydrocarbon solvents, which causes the material to swell [20]. This relegates PDMS to water-based chemistry, which eliminates it as a candidate for universal application. Lastly, PDMS is hydrophobic, which is problematic for biobased assays. This can be circumvented with a plasma treatment, but only for a short time [21]. Despite PDMS's shortcomings, it remains the preferred material for many researchers, who do not mind using mitigation strategies to overcome its limitations. However, these shortcomings prevent PDMS from becoming a suitable material for industrial scale microfluidic device production [22].

Alternatives to PDMS for the fabrication of microfluidic devices include materials like paper [23]; plastics, like acrylics, polystyrene, and polytetrafluoroethylene (PTFE); hydrogels [24]; and textiles [25]. Alongside these materials, alternative manufacturing methods have emerged, like the 3D printing of (bio)plastics and wax printing on paper. These alternatives often offer flexibility and cost savings over soft lithography using PDMS, which requires a master mould manufactured in a cleanroom.

1.1. Environmental impacts

Considerations of sustainability are slowly becoming more commonplace for microfluidic devices. This is highly necessary, as many of the manufacturing methods require large inputs of energy and resources, while the typically single-use devices generate waste upon their disposal. With laboratories generating large amounts of plastic waste annually [26], PDMS devices are only exacerbating the issue: cured PDMS is difficult to recycle, cannot be remoulded into a new part, and is not biodegradable [27].

Research on improving the sustainability of microfluidic devices has resulted in studies focusing on alternate materials to PDMS with lower environmental footprints. Examples include a device developed by Wan et al. based on recycled PMMA [28] and a device developed by Luecha et al. based on corn proteins [29]. However, the issue of environmental sustainability for microfluidics is multi-faceted and application-dependent. Additionally, the environmental impacts of a device may change drastically once its production is realised on an industrial scale.

1.2. Goal of the study

The sustainability of microfluidic devices has not yet been extensively researched. It is unclear what environmental impacts can be attributed to microfluidic devices, and how the environmental impacts differ between devices of different makes. Additionally, it is unclear what phase in the product life cycle of a microfluidic device makes the largest contribution to the associated impacts.

In order to bridge this research gap, this work performs a comparative life cycle assessment (LCA) of microfluidic devices. Given the many applications for microfluidic devices, the scope is limited to only assessing point-of-care devices. Specifically, focusing on glucose detecting devices. To understand the impact of material choice better, devices of three material types are assessed: PDMS, paper, and polylactic acid (PLA). The respective fabrication methods to be assessed are soft lithography, wax stamping, and 3D printing. The impacts associated with commercialising microfluidics, specifically the associated scaling up of fabrication, is assessed as well. The goal of the study is thus to answer the research question: *"For microfluidic devices based on soft photo-lithography PDMS, wax-stamped paper, and 3D printed PLA, what are the environmental impacts associated with the entire lifecycle of* *their respective product systems and where are the hotspots for environmental impacts?”*

As part of the MSc programme Industrial Ecology, this MSc thesis hopes to contribute to the efforts of solving sustainability issues in microfluidics by integrating technical and environmental aspects. The findings of this work are relevant to researchers developing microfluidic devices, those concerned with sustainability of laboratories and point-of-care environments, LCA practitioners, as well as those interested in the commercialisation of microfluidic devices.

The devices at the focus of the comparative LCA are explained in detail in Chapter 2. This chapter also includes an overview of relevant findings from literature. The methodology used to conduct the LCA is described in Chapter 3, while the goal and scope of the LCA are defined in Chapter 4. The inventory analysis, impact assessment and interpretation of the results are presented in Chapters 5, 6, and 7, respectively. The impacts of commercialisation are shown and discussed in Chapter 8. All findings are discussed in Chapter 10, while recommendations and concluding statements are given in Chapter 11 and 12 respectively.

2

Literature review

An overview is provided on existing literature on microfluidics and its environmental impacts. Additionally, the limitations to commercialising microfluidics are looked into. Lastly, ex-ante LCA methodologies are discussed.

2.1. Sustainability in microfluidics

So far, few studies have been published in which the environmental sustainability and impacts of microfluidics are assessed. However, these studies already provide some insight into what factors, scenarios, and alternatives should be considered. Firstly, the choice in material and manufacturing method will affect the results greatly and should be carefully considered [30]. Some methods require specialised equipment and cleanroom facilities, which is energy-intensive [31]. Additionally, some materials are based on fossils, such as thermoplastics, or involve dangerous toxins and chemicals during fabrication [30]. Furthermore, microfluidics are typically single-use, and are typically applied in a lab or healthcare setting. After use, this leads to (plastic) waste, which is typically incinerated. The incineration of plastics releases toxic pollutants, which affect air quality and negatively impact human health [9].

If material choice changes, these waste management strategies might be adjusted so that their impacts are less damaging. Ongaro et al. [30] discuss such solutions. These include researching more sustainable materials, improving waste management and waste treatment strategies, and changing practices to reduce unnecessary or inappropriate testing at point-of-care. The alternative materials discussed by Ongaro et al. include materials like recycled plastics, bio-derived and biodegradable plastics, and natural fibrous materials (such as paper). Notably, the authors recommend the usage of LCA to improve the design and environmental performance of microfluidic devices, and stress the power that stakeholders have in enacting change.

2.2. Previous LCA studies

Florez et al. [32] used cradle-to-grave LCA to assess the environmental sustainability of microfluidic devices called micromixers, which were manufactured by laser cutting polymethyl methacrylate (PMMA) [32]. These devices were used to synthesise Fe_3O_4 nanoparticles (NPs), which is conventionally done through batch co-precipitation. The comparative LCA was therefore between the micromixer-based method and the conventional co-precipitation method. The functional unit was defined as 0.5 g of the NPs produced per batch in each method [32]. They chose water and energy consumption as metrics to compare the devices. This approach found microfluidic devices to have a higher environmental impact. Key mitigating factors could be the use of recycled PMMA and to account for technological and economy-of-scale benefits which would accompany commercial production of microfluidic devices.

Crahay [33] designed a paper-based microfluidic sensor for water quality monitoring and conducted a comparative LCA between their paper sensor and a conventional PDMS sensor. The paper device could be fabricated with and without a polyester backing. For the LCA, the functional unit was "1000 microfluidic devices each one able to transport 30 µL of a liquid media in 90 s". This corresponded to 1000 strips of 1.0 cm x 3.5 cm nitrocellulose (paper) and 1000 microfluidic caps of about 1.0 cm^3 made from PDMS. The author compared the embodied energy and carbon footprint of the two microfluidic sensors. They found that the paper device had a significantly lower embodied energy and carbon footprint compared to the PDMS device. The inclusion of a polyester backing for the paper device became a big contributor to the environmental impacts of the device; the author recommends the use of bioplastics as a substitute for this backing instead.

2.3. Commercialisation

Despite the potential of microfluidics and the many devices developed in academic laboratories, only few products have been able to reach commercialisation [34]. Mostly, the technology has not yet been able to reach diffusion. This is due to several factors. Users of commercially available microfluidic devices may face issues synchronising their devices to corresponding hardware, like pumps or fluid control mechanisms [12]. Additionally, users may need to undergo training in order to use the device effectively, which might deter researchers from moving away from methods and instruments they are already familiar with. The incentive to use microfluidic devices in the laboratory or in the field is then reduced, which devalues microfluidics. Consumers may be convinced if the operational advantages or cost reductions are significant.

Some areas have been successful in marketing microfluidics, namely genomics and point-of-care diagnostics [12]. Here, devices are fabricated on industrial scale using cost-effective materials and fabrication methods. Additionally, companies were able to make their devices compatible with existing equipment, or alternatively were able to cut out the need for additional equipment. They achieved this by allowing the user to perform all steps on the analysis on a singular device. Most importantly, the operational and economic advantages were significant, easing customer acceptance.

There is a misalignment between academia and commercial industries. While extensive research is being done on microfluidic devices, topics like standardisation and integration are neglected [35]. This is barring microfluidics from reaching market diffusion. Lack of standardisation is resulting in the development of novel devices that cannot reasonably be manufactured from available technologies on the market, while lack of integration is resulting in devices that cannot easily be connected to additional equipment to perform analyses. The former keeps fabrication on an industrial scale from becoming reality, while the latter disincentivises consumers.

2.4. Ex-ante LCA

To understand how the environmental impacts associated with the microfluidic devices may change in future scenarios, such as in the case of commercialisation, an LCA that looks to the future is required. An ex-ante LCA is described by Cucurachi et al. as one that "explores the future by assessing a range of possible scenarios that define the space in which the technology may operate" [36]. The authors narrow the definition even further by describing ex-ante LCA studies as those that assess the upscaling of the emerging technology, or those that compare the emerging technology with an evolved incumbent technology at scale. In these studies, scenario modelling is a key feature. These are scenarios of possible future states of the technologies, all with different likelihoods.

There are several challenges to conducting ex-ante LCA studies, like scaling issues and a lack of data on novel processes and materials [37]. These all lead to a growing uncertainty. While LCA will always have a degree of uncertainty, too much uncertainty can render the study meaningless. These uncertainties must be reported on clearly and transparently, such that decision-makers are sufficiently informed. According to Villares et al., an ex-ante LCA cannot be relied on for accurate results, but it does provide a good foundation to build upon [38].

3

Method

To answer the main research question, the study will follow a quantitative approach in the form of an LCA. The approach and sub-research questions, which will help to formulate an answer to the research question, are described in Section 3.1. The LCA framework and modelling approach are explained in Section 3.2 and Section 3.3 respectively.

3.1. Approach

The approach consists of an LCA, conducted from cradle-to-grave. LCA is an analytical tool that can be used to assess the environmental impacts across a process, service, or product's lifecycle. In a cradle-to-grave analysis, this includes raw material extraction, production, distribution, use processes, and disposal. This is an advantage of LCA, as a cradle-to-grave LCA avoids shifting burdens between stages by considering the full life cycle, while other modelling methods might exclude certain stages. Through quantifying carbon emissions and other environmental impacts, an LCA offers insight into the product system. Additionally, the results of an LCA might be used to improve a product's design or manufacturing process in order to reduce its environmental impacts. An advantage of the approach itself is the specificity of the case study. Studying a generic microfluidic device would not provide the same insight as studying the particular activities associated with three different devices.

A limitation to this approach is that an LCA only provides insights into social and economic impacts to the extent that these are influenced by the chosen environmental impact categories. To garner more insight into the social and economic aspects, additional tools would be necessary. Additionally, the results of the case study might not be applicable to other microfluidic devices due to their high specificity. Other limitations are inherent to the LCA methodology. The results are heavily dependent on the assumptions and modelling choices made by the analyst [39]. The method of allocating environmental burdens between co-products, or the chosen functional flow on which to base the analysis, might change the conclusion of the LCA. The quality of the data that was used might also impact the results. Some data and models to calculate impact categories might be incomplete or unavailable, which introduces further uncertainties.

These limitations will be overcome by choosing high-quality data, carefully considering the choices for functional units, and carefully considering allocation methods. To evaluate the modelling choices, sensitivity analyses will be performed. Additionally, the results will be validated by performing completeness and consistency checks of the modelled alternatives. Lastly, while the results will be specific to the case study, a framework will be developed wherein the approach taken is generalised. This framework can offer guidance to future research.

A set of sub-research questions has been formulated which address different facets of the main research question. Together, they ensure completeness of the answer to the main question. In the sub-questions below, LCA will play a central role.

1. What contributions does each alternative make to global impact categories?
2. How are the environmental impacts affected by scaling up the production for each alternative?
3. How can the environmental impacts be reduced for each alternative?

3.2. LCA framework

As shown in Figure 3.1, an LCA is divided over four phases as defined by ISO 140140 and ISO 14044 standards [40, 41].

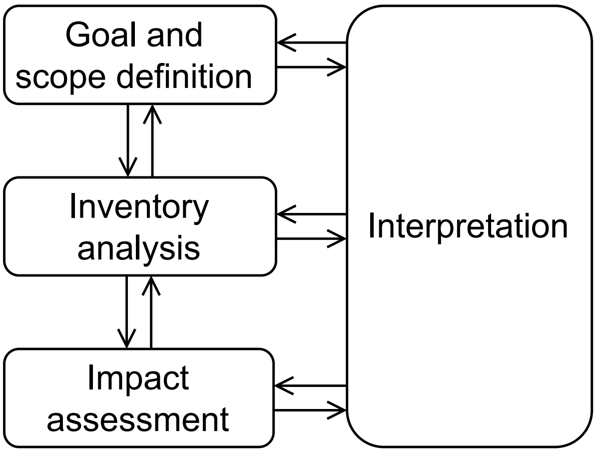


Figure 3.1: Framework for conducting a Life Cycle Assessment, based on ISO 14040 [41]. The bilateral arrows are used to indicate that conducting an LCA is an iterative process. It is possible to adjust a stage based on findings in other stages.

In the first phase, the goal and scope definition, the initial choices are made which will determine the direction and focus of the study. The goal is defined in terms of research question, intended audience, and application. In the scope, the geographical, temporal, and technological coverages are defined, and a minimum level of sophistication is set for the analysis. Lastly, the products that the study is centred around, are defined in terms of a function, functional unit, and reference flows. Both the goal and scope definitions are backed up by literature and the knowledge gaps that were found.

In the second phase, the inventory analysis, the system boundaries are defined. In this phase, the analyst will design flow diagrams to model each alternative after, collect data, resolve multifunctionality, perform allocation when necessary, and complete final calculations to achieve inventory results.

In the third phase, the impact assessment, the inventory results are processed to achieve characterisation and normalisation results. These are based on the impact categories chosen by the analyst in the goal and scope definition. In characterisation, each alternative's contribution to the environmental impact categories are quantified. In normalisation, this contribution is scaled to global totals.

In the fourth phase, the interpretation, the choices and assumptions made during modelling and the achieved results are evaluated. During this step, the analyst validates their work, by checking for completeness and consistency across alternatives. Conclusions are drawn based on contribution and sensitivity analyses, and these results are used to formulate recommendations for improvements.

As depicted by the bilateral arrows between the various phases, conducting an LCA is an iterative process. Performing an interpretation step between each phase – e.g., validating the choices made so far – is advantageous to the study. This also prohibits the propagation of errors made early in the study. Additionally, the analyst may choose to redefine their goal and scope after performing the inventory analysis, e.g., due to the quality and availability of data.

3.3. Modelling the LCA

LCA calculations will be performed using the Activity Browser, an open-source LCA software developed by Steubing et al. [42]. The Activity Browser is built on the Brightway2 framework for LCA, which allows for advanced calculations. Brightway2 and the Activity Browser are both based on the python programming language. The Activity Browser was chosen as modelling software in this study due to its open source nature, which is useful for the scenario-modelling and sensitivity-analysis steps. It also provides graphs and sankey diagrams upon calculations, which facilitates a detailed result analysis.

The microfluidic devices at the centre of this work all require a range of chemicals to detect glucose in samples. While some chemicals are available in the ecoinvent database, those that are not will be modelled based on literature or stoichiometry. This is based on the approach defined by Huber et al. [43], who provide a decision-tree for handling missing LCI data for chemicals. The stoichiometry-based modelling will be done according to the method described by Langhorst et al. [44], which is discussed in Section 5.3.

4

Goal and scope definition

First, the goal of the study is defined in Section 4.1. Then, an overview is provided of the microfluidic devices at the centre of this study. Their individual compositions, manufacturing methods and working principles are described in Section 4.2. Lastly, the scope of the LCA is defined in Section 4.3 by defining the system boundaries and the functional unit.

4.1. Goal definition

The goal of the LCA is firstly to compare the product systems of three different microfluidic devices based on their environmental performance. Secondly, the goal is to identify hot-spots within the chosen product systems and formulate recommendations such that their environmental performance may be improved. Thirdly, the goal is to understand how scaling up production for commercialisation would change the environmental performance, and how the impacts can be minimised.

Based on the identified areas of improvement, alongside the recommendations given, researchers can come to a better understanding of how microfluidics contribute to current climate issues. Additionally, the results can inform interested investors of the environmental impacts associated with scaling-up production of the chosen microfluidic devices.

This LCA does not aim at a public comparative assertion, and is conducted purely as academic research. The study is conducted as part of an MSc thesis at Leiden University. A complete steering committee cannot be appointed due to the scale and context of the study, but the LCA will be reviewed by the supervisors of the project, who are themselves familiar with LCA.

4.2. Chosen devices for case study

As mentioned in Chapter 1, the comparative LCA will assess the environmental performance of three microfluidic devices developed for glucose detection. The materials to be assessed are PDMS, paper, and PLA. The manufacturing methods are soft lithography, wax stamping, and 3D printing respectively. The detection sensitivity is described through the limit of detection (LOD), which indicates the minimum amount of a substance (in mol) that a device can detect per litre of sample.

4.2.1. PDMS microfluidic device

The PDMS device to be assessed is one developed by Koh et al. in 2016 [1]. The device is shown in Figure 4.1.

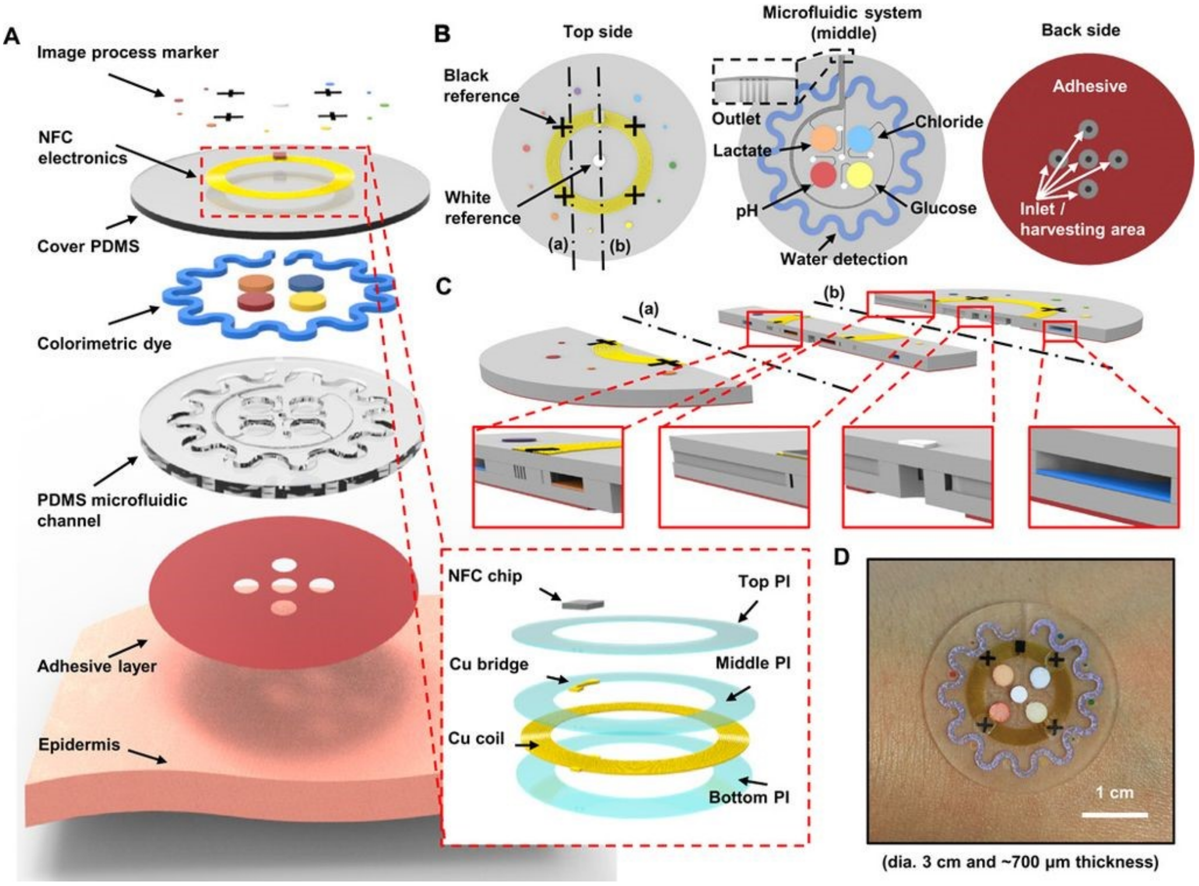


Figure 4.1: The PDMS microfluidic device. **(A)** Illustration of the PDMS device, broken down by its individual layers, as well as a zoomed in overview of the device's NFC electronics. The device measures biomarker levels in the wearer's sweat, entering the device through the epidermis. **(B)** Illustrations of the top, middle and bottom layers of the PDMS device. Black and white markers serve as reference points during the scanning process. **(C)** Illustration of the cross-sections of the device at the dashed lines (a) and (b) also shown in (B). **(D)** The PDMS device as fabricated, provided with dimensions. From "A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat," by Koh et al., 2016, *Science Translational Medicine*, *8*, p.366ra165 [1]. Copyright 2016 by the American Association for the Advancement of Science.

Composition and manufacture

The PDMS microfluidic device has the shape of a disk, with a diameter of 3 cm and a thickness of 700 μm. It consists of three layers. The top layer is a cover of PDMS and carries the NFC electronics of the device. The middle layer is a disk of PDMS containing the microfluidic channels of the device. The reagents and colorimetric dyes are injected into this layer. The bottom layer is a medical adhesive with which the device can be attached to the user's skin.

The manufacturing process for the PMDS device is shown in Figure 4.2. The middle layer of the microfluidic device is fabricated using soft lithography and replica moulding. Photolithography and deep reactive-ion etching (DRIE) generate channels with depths of 300 μm on a silicon wafer, which then serves as the mould. The middle layer of the device is then obtained using replica moulding. Here, PMMA is spin-cast onto the mould at 3000 rpm for 30 s to prevent adhesion of PDMS to Si-wafer. This is cured on a hotplate at 180 °C for 5 min. Then, the PDMS is spin-cast onto the mould at 200 rpm for

30 s, and subsequently cured on a hotplate at 70 °C for 4 h. Once cured, the PDMS is removed from the mould.

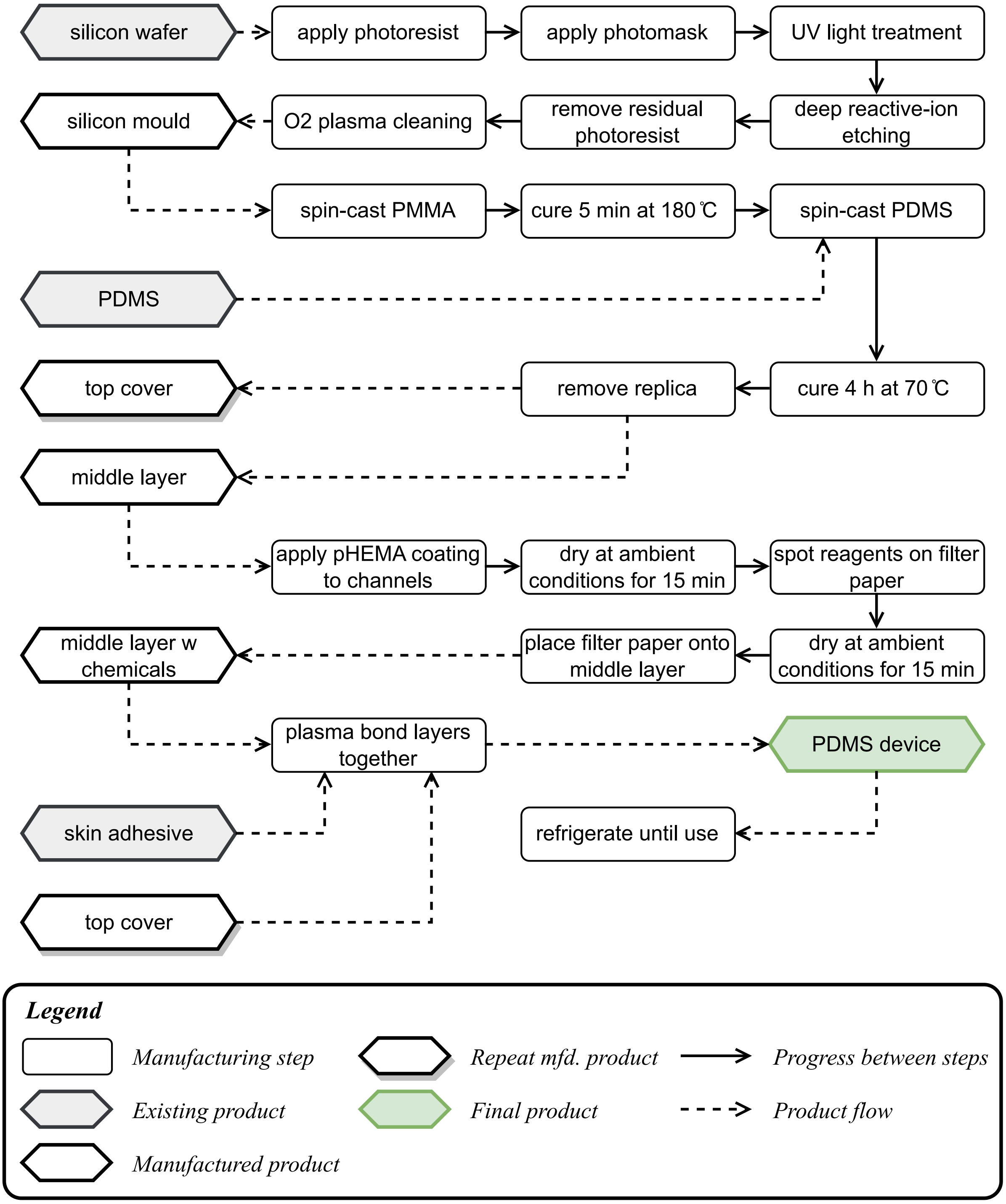


Figure 4.2: Process diagram of the manufacturing process for the PDMS device. The top cover and middle layer are manufactured using the same process, while the skin adhesive is purchased from a third party. Once the PDMS device has been completed, it must be refrigerated until use to preserve the inserted enzymes.

The colorimetric dyes are applied to the channels and reservoirs using fill-and-dry and drop-casting methods respectively. First, the channels are coated with a pHEMA hydrogel solution containing cobalt(II) chloride. The coatings are allowed to dry for 30 min. The colorimetric reagent for glucose consists of glucose oxidase (GOx), horseradish peroxidase (HRP), trehalose, and potassium iodide, which are dissolved into a sodium citrate buffer solution (pH = 6.0). The colorimetric reagents are applied to 4 mm diameter circles of filter paper, which are then left to dry. These are then inserted into their allocated spots on the device.

The device's individual layers are attached to each other through plasma bonding. Upon exposure to oxygen plasma, chemical reactions occur between -OH groups in the materials, which enable covalent bonding to the PDMS surface. The cover of PDMS is placed on top of the microfluidic channels to seal them off, while the adhesive is attached on the bottom. Upon finalisation, the device is refrigerated at $4\,^\circ$C until use. The refrigeration step is crucial for enzyme preservation.

Working principle

The PDMS device detects glucose, lactate, and chloride ions in sweat, and gives an indication of the pH of the sweat. For detecting glucose in human sweat, the obtained LOD was 0.2 mM.

The device is wearable, and sticks to the skin by means of an adhesive layer. Once the wearer starts perspiring, the perspiration flows through the micro-channels until it comes into contact with the assays. Upon reaction, the fluid changes colour, thereby giving a colorimetric indication of the glucose, lactate, chloride ions and pH levels of the wearer's sweat.

While the colorimetric results give indications of biomarker levels that are visible to the naked eye, the results can be quantified and analysed even further through the use of NFC electronics and a smartphone. Upon scanning the device, its NFC chip will launch a program for image processing on the user's smartphone. The software then provides the user with the RGB values that the device's colouring has taken on. Using these values, the biomarker levels can be quantified.

4.2.2. Paper microfluidic device

The paper-based microfluidic device is one developed by Gabriel et al., who developed paper-based colorimetric assays for glucose and uric acid, and showed that using chitosan – a sugar that is extracted from the outer skeletons of shellfish – improved the analytical performance of the paper device. The device is shown in Figure 4.3.

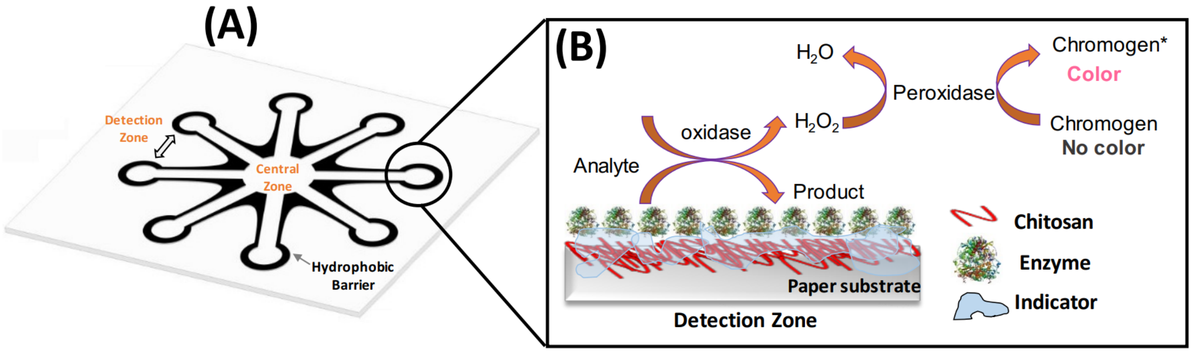


Figure 4.3: The paper-based microfluidic device. **(A)** Indication of the detection zones for colorimetric analysis, the central zone for sample deposition and the hydrophobic barriers to keep the sample and reagents within the designated area. **(B)** Working principle of the device, in which the analyte and glucose assay react, resulting in a colour change. The chitosan improves the paper's ability to act as a solid support for the adsorption of enzymes, which ensures a more uniform reaction throughout the entire detection zone. Image is adapted from Figure S1 in the Electronic Supplementary Information of "Highly sensitive colorimetric detection of glucose and uric acid in biological fluids using chitosan-modified paper microfluidic devices," by Gabriel et al., 2016, *Analyst*, *141*, p.4749-4756 [2]. Copyright 2016 by The Royal Society of Chemistry.

Composition and manufacture

The paper-based microfluidic device has a dimension of 45 mm by 45 mm, and is based on two sheets of filter paper joined together through handheld wax stamping [2]. The wax stamping method was developed in a paper published by de Tarso Garcia et al., and is the foundation for the paper device under assessment [45]. The stamping method utilises paraffin wax to form hydrophobic barriers in the filter paper, such that the sample does not leave the designated area for detection. The method also requires a stamp; in the case of this paper, the stamp is manufactured from stainless steel. The author reports using the stamp to fabricate 5000 µPADs without degradation and with great reproducability [45]. The manufacturing process for the paper device is shown in Figure 4.4.

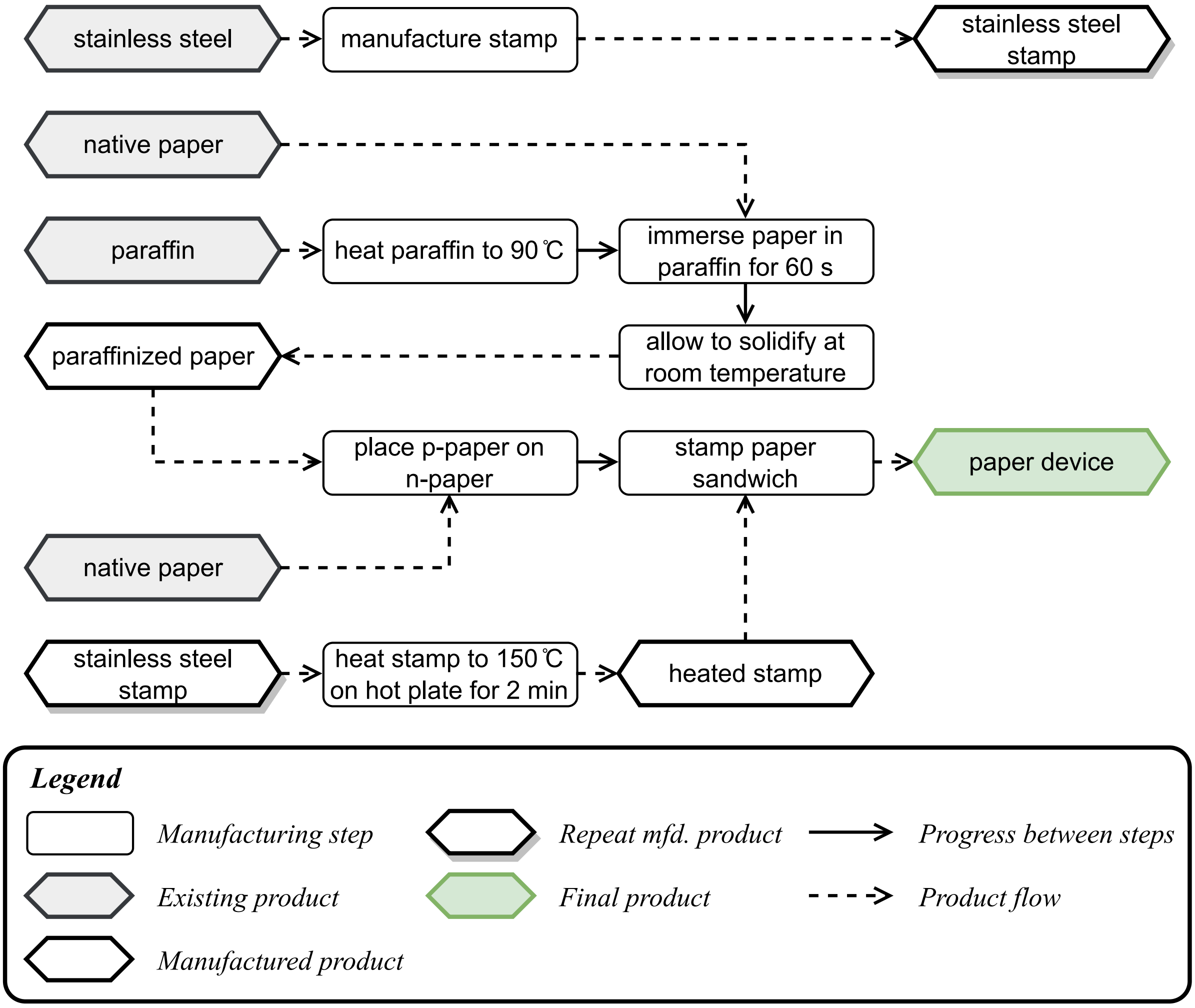


Figure 4.4: Process diagram of the manufacturing process for the paper device. By placing native paper on top of paraffin-impregnated paper, and stamping this with a hot stamp, hydrophobic wax barriers are formed.

The paper devices are fabricated as follows:

1. Preheat stainless steel stamp to 150 °C.
2. Impregnate sheet of filter paper with liquid paraffin wax and allow to dry.
3. Place native filter paper on top of impregnated paper.
4. Once stamp is hot, place stamp on layered paper.
5. Place pressure onto the stamp for 2 s to allow paraffin to melt onto the native paper and form hydrophobic barriers.

Once the barriers have formed in the paper, chitosan is applied to the detection zones and left to dry at room temperature. Once dry, the assay for glucose detection is applied to the detection zones as well. The glucose assay consists of parts GOx and HRP mixed into a phosphate buffer solution (PBS) (pH = 6.0). After the glucose assay is applied, it is allowed to dry for 15 min. Afterwards, the chromogenic agent is applied, which enables colorimetric analysis. The chromogenic agent is a mixture of 4-aminoantipyrine (4-AAP) and 3,5-dichloro-2-hydroxybenzenesulfonate (DHBS) dissolved in water. Finally, once the reagent has been left to dry for 15 min, the device is ready for use. Exact mixture compositions can be found in Appendix A.

Working principle

The device detects glucose in the sample and changes colour based on the glucose concentration. For detecting glucose in human tears, the obtained LOD was 23 μM.

Paper-based microfluidic devices for colorimetric detection often suffer from poor colour uniformity, which impairs the analytical reliability [2]. The quality of the colorimetric measurements can be improved through the use of chitosan, as shown by Gabriel et al. The chitosan application modifies the surface, and creates a micro-environment where direct electron transfer between enzyme and reagent can take place more effectively. Comparing the chitosan-enriched paper device to standard μPADs, there is a noticeable improvement in colour uniformity and pixel intensity in the detection zones.

The paper device is used for glucose detection by depositing a human sample onto the central zone – in the case of the paper by Gabriel et al. human tears are used. Once the sample is applied, the capillary forces present in the wet paper force the tears to flow into the detection zones, prevented by the wax from flowing outside of the barriers. Once the colour in the detection zone has changed, the paper device can be scanned and assigned RGB values. The intensity and gradient of the colour are then used to quantify glucose levels.

4.2.3. PLA microfluidic device

The third device to be assessed is a 3D printed device based on PLA, developed by Tothill in 2017 as part of the author's PhD thesis [3]. The device is shown in Figure 4.5.

Composition and manufacture

The device is 3D printed using PLA filament. The 3D printing machine used is consumer grade, and is based on fused deposition modelling. The device is disk shaped, has a 90 mm diameter, and has an inner spindle hole with a diameter of 15 mm. The device has a thickness of 2 mm. The manufacturing process for the PLA device is shown in Figure 4.6.

The device is printed at a speed of 10 mm s^{-1}, with a layer height of 0.06 mm. The total printing time is 8.5 h and about 14 g of PLA filament is required per device. After printing, the device is treated with heat to ensure channel water-tightness. This is done by placing the device into an electric convection oven at 60 °C for over 24 h. After its heat-treatment, the device is left to cool, upon which it is ready for use.

Working principle

For glucose detection, a blood sample is mixed with a glucose assay. The glucose assay consists of chromotropic acid, 4-aminoantipyrine, horseradish peroxidase, and glucose oxidase. Upon mixing, the sample-assay mixture is injected into the device's channels. The PLA device is placed onto an optical disk drive (ODD) for centrifugation to force blood separation. Once centrifugation is done, a distinct colour can be seen on the device where the plasma has reacted with the glucose assay. For detecting glucose in blood plasma, the obtained LOD was 0.6 mM.

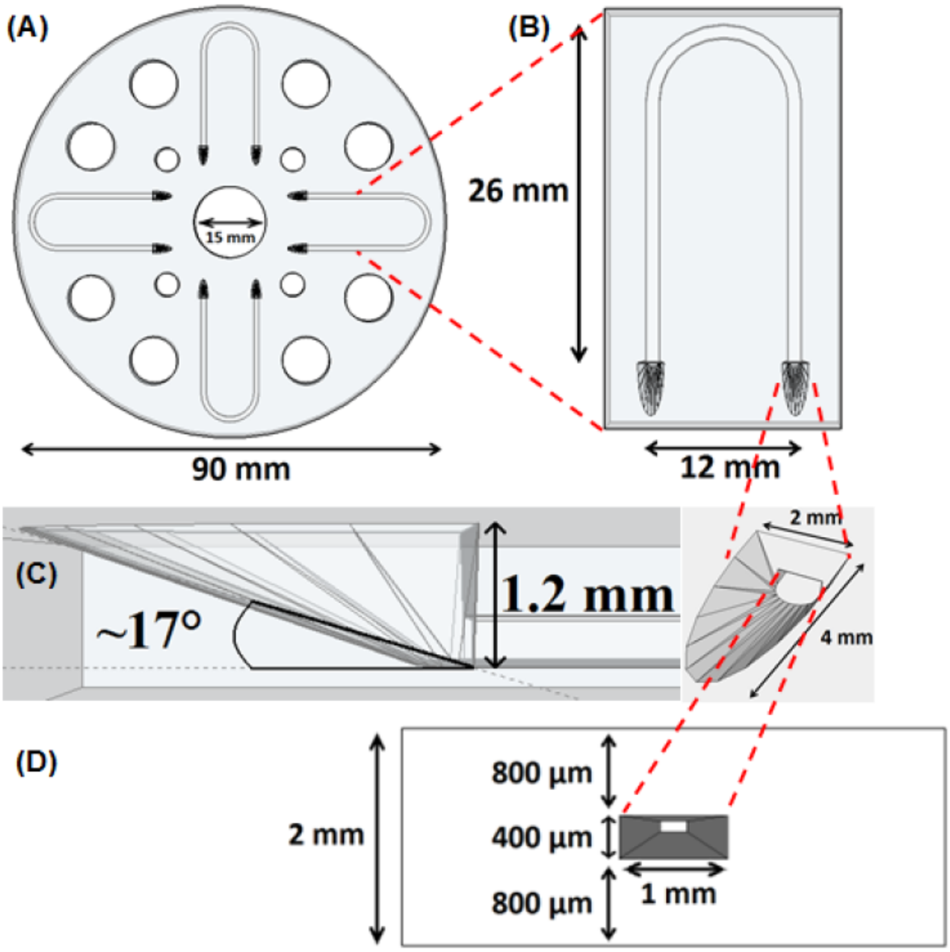


Figure 4.5: The PLA microfluidic device. **(A)** Design specifications of the device. **(B)** Zoomed-in view of the device's channels, and its specifications. **(C)** Geometry and specifications of the device's inlets. **(D)** Specifications of the channel's cross-section. From "Developing a proof of principle 3D-printed lab-on-a-disc assay platform," by Tothill, 2017 [3]. Copyright 2017 by Cranfield University.

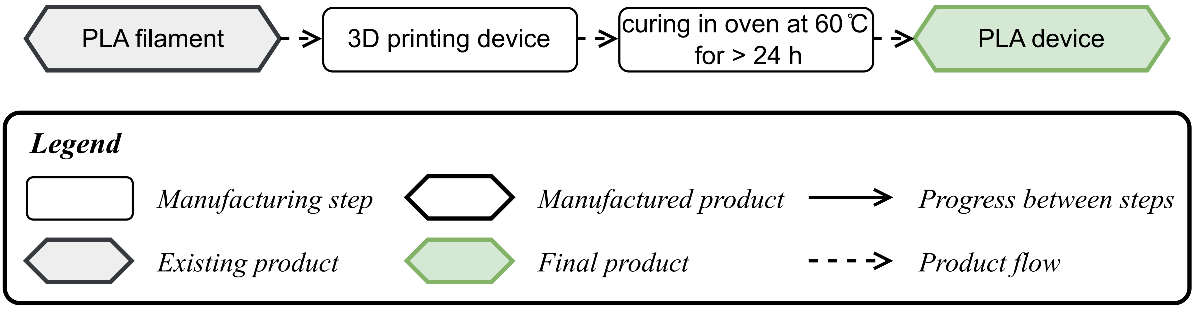


Figure 4.6: Process diagram of the manufacturing process for the PLA device. Using PLA filament, the device is 3D printed. To ensure the device is leakproof, it undergoes heat treatment in an electric convection oven for over 24 h.

4.2.4. Discussion on chosen devices

The devices at the centre of this work all employ glucose oxidase and a chromogenic agent for colorimetric detection of glucose in a biological sample. However, the type of sample differs between devices. The PDMS device detects glucose in human sweat, the paper device detects glucose in human tears, and the PLA device detects glucose in horse plasma. It is assumed that when using the PLA device on human plasma instead, the reagents used may need to be recalibrated, but that the device itself would still be functional. This difference does therefore not render the PLA device unsuitable for human glucose monitoring, and is thus used to represent the PLA device in the comparative LCA.

Given that different samples are used, it was logical that the sensitivity of the devices also varied. The most sensitive device is the paper device, while the least sensitive is the PLA device. For both the PDMS device and the PLA device, the authors indicate that further research and development of the reagent solution would be required to further lower the LOD.

Glucose concentrations also vary depending on the sample. Glucose concentrations in sweat vary, with levels around 0.06 mM to 0.2 mM [46, 47]. Conversely, glucose concentrations in human tears average around 0.2 mM for normal patients, while they average around 0.92 mM for diabetics [48]. Lastly, according to the World Health Organisation, normal values for glucose concentration in blood are around 3.9 mM to 5.6 mM [49]. For diabetics, this concentration is higher than 7 mM.

The devices are therefore clearly different in terms of sensitivity and what sample was used to provide proof-of-concept. However, it is assumed that the more sensitive devices will still be functional when using a different sample. Here, that would mean that the paper device should still be able to detect glucose in blood or sweat, if reagents are recalibrated. The same is true for the PDMS device. For the purposes of the study, it is therefore assumed that the devices are applied to detect glucose in 1 type of human sample. It is not specified which sample this would be, but it is assumed that it is a sample with glucose concentrations around or higher than the LOD of the PLA device.

Another difference between the devices is that the PDMS device requires refrigeration to preserve the applied enzymes. No such refrigeration step is specified for the two other devices. It is assumed that this is because these enzymes are only applied right before use in the cases of the paper device and the PLA device. Given that the enzymes are enclosed within the PDMS device during the bonding step, it is not possible for the user to apply these right before use. Hence, the PDMS device is the only device that requires cooling until use.

The chemistry the devices operate on is similar across devices. The glucose oxidase present in the assay reacts with glucose in the human sample, as well as with oxygen and water, to produce hydrogen peroxide. The peroxide subsequently oxides the chromogenic agent, causing its colour to change. The level of oxidation is then an indication for how much glucose was present in the sample.

The devices were chosen such that they could be compared as equally as possible. They were chosen based on the available information on their compositions and manufacturing methods, their similarities between each other, and their complexity relative to other glucose detection microfluidic devices. Considering the studies on the three devices were all published between 2016 and 2017, the devices are each other's contemporaries. This further facilitates comparability between devices.

4.3. Scope definition

The LCA was used to identify hot-spots and potential areas for improvements within the product systems of three microfluidic devices, for the European economic region. To define the scope of an LCA study clearly, several topics must be considered [40].

The study was conducted over the span of six months, starting from February 2023 and ending in August 2023. The LCA assumes that fabrication processes, use, and waste disposal occur in the European economic region. Transport is accounted for if processes occur in other continents. Other transport, such as between the sites for manufacturing and use, is neglected. It was assumed that the technology to be modelled was of current standards, widely available, and was the best available technology. The technology covered in the LCA was representative of the present state of technology in the EU.

The LCA represents the entire lifecycle of the product systems, from cradle to grave. These include processes for raw material extraction, manufacturing, use, as well as disposal processes. The environmental performance of the product systems was assessed based on their scores in environmental impact categories. The LCA was detailed, meaning that the involved processes were considered in depth, covered a large degree of the life cycle impacts, and that a full interpretation of the results was performed [40].

4.4. Functional unit

The function studied in the LCA is that of detecting glucose in a human sample. The functional unit has been defined as 1 act of glucose detection performed on a human sample using 1 microfluidic glucose detection device, assuming use and manufacture in the European economic region. The alternatives are:

- a PDMS microfluidic device, as manufactured through soft lithography;
- a paper microfluidic device, as manufactured through wax stamping;
- a PLA microfluidic device, as manufactured through 3D printing.

The respective reference flows are therefore:

- 1 act of glucose detection performed on a human sample, assuming use and manufacture in the European economic region, using 1 *PDMS* microfluidic device manufactured through soft lithography.
- 1 act of glucose detection performed on a human sample, assuming use and manufacture in the European economic region, using 1 *paper* microfluidic device manufactured through wax stamping.
- 1 act of glucose detection performed on a human sample, assuming use and manufacture in the European economic region, using 1 *PLA* microfluidic device manufactured through 3D printing.

5

Inventory analysis

5.1. Defining system boundaries

When conducting an LCA, boundaries are necessary to distinguish the system being studied from the rest of the world. The system under study is often called the product system. When conducting inventory analysis for LCA, there are three boundaries that need defining. These are described and defined below.

5.1.1. Economy-environment system boundary

In LCA terminology, an intervention is the disturbance of the environment due to human activity. This could be the extraction of natural resources, or the disposal of waste into nature without further human transformation. These flows cross the border between the economy system – or product system – and the environment system [40]. These flows are at times also called environmental flows or elementary flows.

Each economic flow, through a series of transformations, at some point came from the environment and at some point will return to it. However, where to draw this line between economy and environment is not always clear, for example when looking at agriculture, mining, and landfills. This has led to specific definitions being made for where to establish this boundary [40]. Since, in this study, the foreground system has no processes where the environment-economy boundary is blurry, no further consideration is given to this boundary. Instead, interventions emerge through connections to the background system, the ecoinvent database, using the conventions of this database to define the environment-economy boundary.

5.1.2. Cut-offs

Ideally, all unit processes involved in a product system are modelled accurately, taking into account all inputs and outputs, both economic and environmental. However, this level of detail and accuracy is often unachievable. This could be due to various constraints, like lack of time and resources, but especially due to data availability. To circumvent this issue, these flows must be quantitatively estimated instead. If a flow cannot reasonably be estimated, that flow must be cut off and, therefore, ignored.

In this study, certain economic flows are cut off due to aforementioned constraints. The material inputs for equipment are excluded from the product systems. Thus, equipment use – such as the use of hotplates and stirrers – is only represented by their electricity consumption, and not their material requirements. This can be cut off, as it is assumed that their contributions would be negligible. These machines are typically used for a very short time, which is only a small part of their total lifetime. Conversely, an exception here is equipment that is used for an extended time. Including their material requirements might have an impact on overall results, justifying their inclusion. Examples are a 3D printer used for 8 h, and a refrigerator used for 24 h.

Any economic flows for the acts of taking human samples are also cut off. It is assumed that the human sample used for testing is the same across devices, and would therefore require the same processes. Given their similarity, and the goal to compare the devices' performance, this part of the system can be ignored. Lastly, environmental interventions associated to foreground processes are cut-offs if this data is not available. Estimating these interventions would require time and resources, which are currently unavailable.

Lastly, refrigeration needs for chemicals are cut off. It is assumed that these chemicals would require refrigeration regardless of using microfluidic devices. The choice was therefore made to not attribute any of the related impacts to the product systems.

5.1.3. Multifunctionality and allocation

A unit process' environmental impacts are attributed to its functional flow. However, when a unit process has multiple functional flows, it becomes unclear how environmental impacts should be distributed. Resolving multifunctionality therefore becomes an important step. Additionally, the manner in which multifunctionality is solved is an important decision, as different resolution methods can potentially influence the results. The steps towards resolving multifunctionality in a product system are described below.

1. **Identify the good and waste flows of every unit process.** Here, a good has a positive economic value (> 0), while a waste has a negative economic value ($\leq €0$).
2. **Identify the functional flow(s) of every unit process.** The functional flow is the representation of the unit process' function. This can be the production (outflow) of a good, and/or the processing (inflow) of a waste.
3. **Identify the multifunctional unit processes.** Multifunctional processes can be:
    (a) Co-production: > 1 outflow of goods
    (b) Combined waste processing: > 1 inflow of wastes
    (c) Recycling: ≥ 1 outflow of goods, *and* ≥ 1 inflow of wastes
4. **Resolve multifunctionality.** Resolution can be achieved in a variety of ways. In this work, multifunctionality is solved using physical allocation, where functional flows are partitioned based on physical relationships.

Multifunctionality is most prevalent when modelling the unit processes for chitosan and chemical production. For modelling chemicals based on stoichiometry, the approach of Huber et al. [43] was followed. They recommend determining allocation factors based on mass if any by-products are produced. Here, it is important to note that if water is created as a byproduct, it is not considered in allocation. This is because this water could not reasonably be used in any further processes without further treatment [43]. In any other case, physical allocation was used to resolve multifunctionalty.

5.2. Flow diagrams

Simplified flow diagrams for the product systems of the PDMS, paper, and PLA device are shown in Figure 5.1, Figure 5.2, and Figure 5.3 respectively. More detailed versions are given in Figure B.1, Figure B.2, and Figure B.3 respectively.

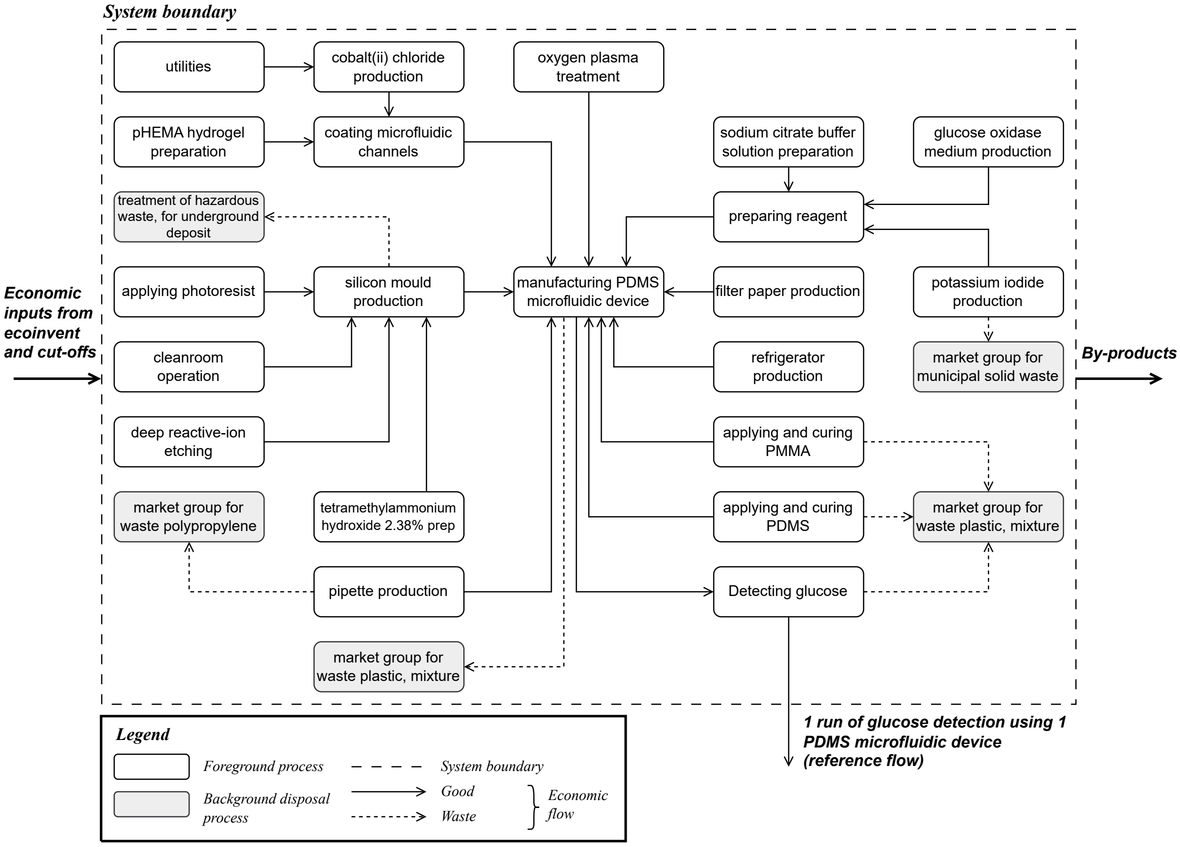


Figure 5.1: Flow diagram for the product system of the PDMS device. Soft lithography is at the center of its manufacturing process.

Some unit processes – like *utilities* and *glucose oxidase production* – occur multiple times within and between product systems. For *glucose oxidase production* a separate flowchart is provided in Figure B.5 to avoid repetition. For the systems of the PDMS and paper device, complex supporting systems are required, such as for the production of chitosan and household refrigerators. These systems are also illustrated in separate flowcharts, which can be found in Figure B.4 and Figure B.6 respectively.

The unit process *utilities* is based on Langhorst et al. [44]. In their work, they provide estimations for heat and electricity consumption for chemicals production. During this process, heat is recovered, which has not been reflected in the flowchart. This is because the process is considered to be a closed loop, where the recovered heat is used again for the preparation of the chemicals. This multifunctionality was resolved using substitution instead of physical allocation, based on the recommendations of Langhorst et al. [44]. However, due to the closed loop, this choice is not expected to have much of an effect on the results.

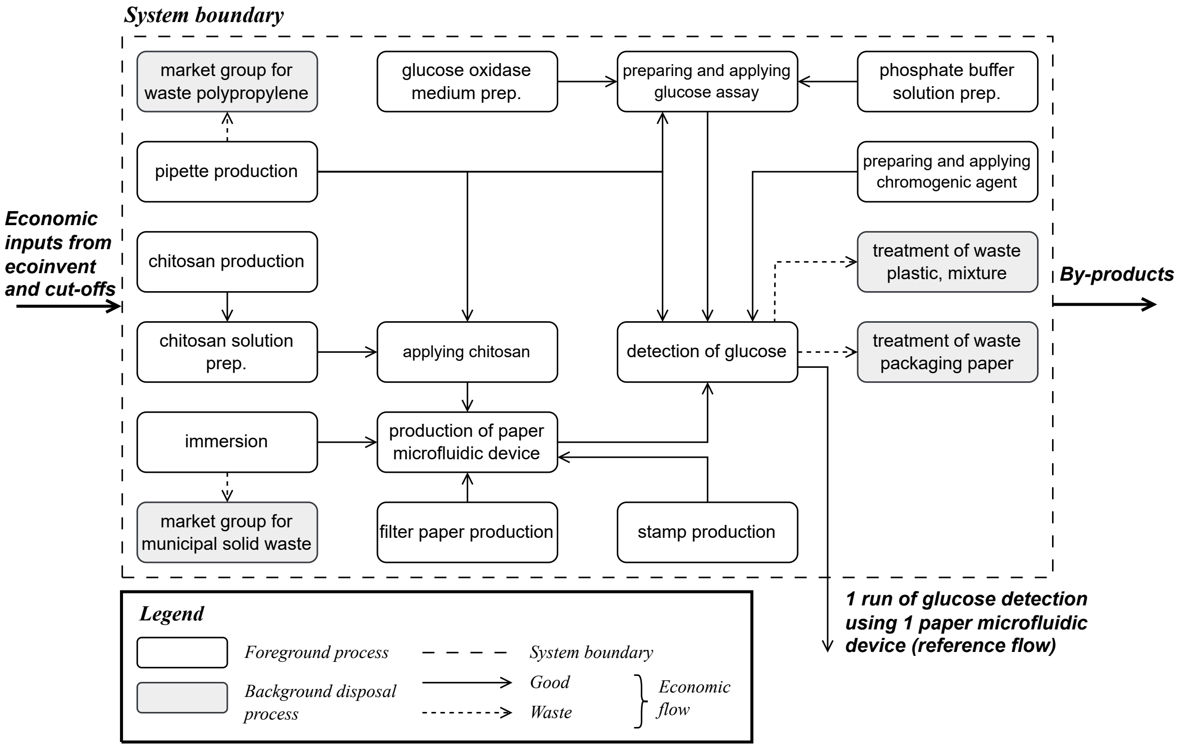


Figure 5.2: Flow diagram for the product system of the paper device. It is a relatively simple manufacturing method, where no specialised equipment is necessary.

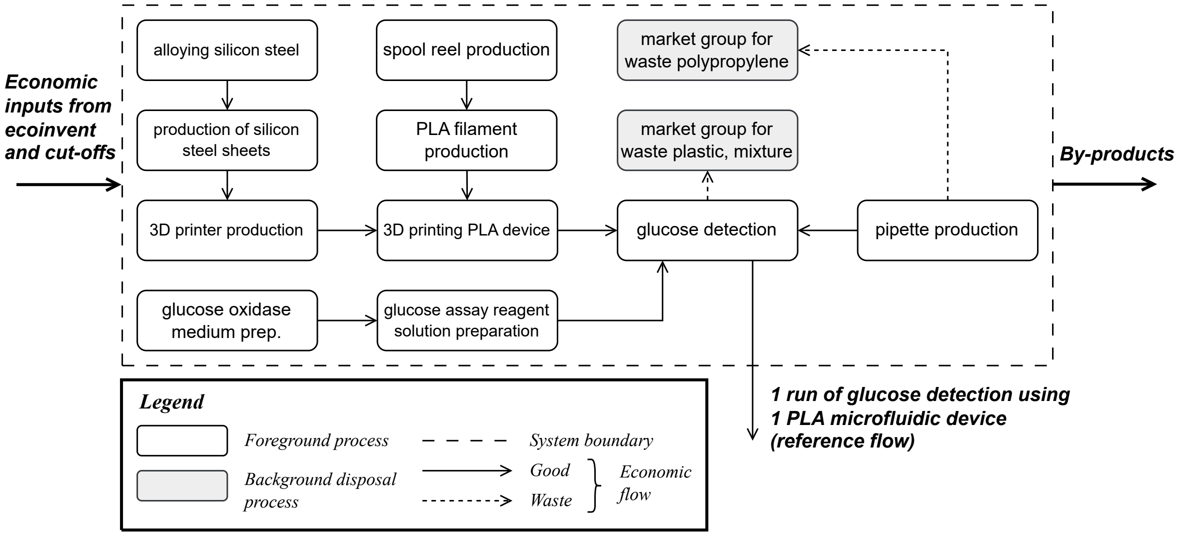


Figure 5.3: Flow diagram for the product system of the PLA device. Of the three alternatives, it is the least complex product system, in terms of number of unit processes.

5.3. Data collection

When data is unavailable in the ecoinvent database, it was sourced elsewhere. Data was collected from literature and patents, whereas the electricity consumption of laboratory equipment was sourced from retailer websites.

Other data collection methods were employed in case data was not available in literature. In the case of the production of silicon moulds for the PDMS device, an interview was conducted with an expert on soft lithography. From this interview, values were collected for the type and amount of materials used during the process.

In the case of missing LCI data for chemicals, the approach described by Huber et al. was used. The authors provide recommendations for which method to use depending on the situation [43]. When modelling the inventory data for a chemical that is unavailable in LCA datasets, a proxy can be found in a different chemical that is sufficiently similar. When there is no suitable proxy, the inventory data can be based on the stoichiometry, or chemical balance, for the synthesis of the chemical.

Langhorst et al. provide a method for stoichiometry-based estimation of chemical data [44]. Their method is based on the methods proposed by Parvatker and Eckelman [50], Roh et al. [51], Hischier et al. [52], Geisler, Hofstetter and Hungerbühler [53], and Kim and Overcash [54]. These models have different values for the yield, and have different assumptions regarding energy and water consumption of synthesis processes. By comparing models and aggregating the best aspects between them, Langhorst et al. propose a combined estimation method. Here, they chose the approach of Geisler, Hofstetter and Hungerbühler, who assume a yield of $87\,\%$ when there are no significant by-products (like water), and a yield of $77\,\%$ if by-products may occur. They also choose the approach of Kim and Overcash, who provide average values for the energy demands of the synthesis processes.

Primary data was collected for the electricity consumption of an electric convection oven. Given the cycles of heating and cooling an oven experiences during its operation, it would not be possible to ensure the accuracy of energy calculations without knowing the specifications of the cycles. While this cannot be ensured for any energy calculations, it was especially necessary for the oven, given that the oven is used for more than 24 h to cure the PLA device. Therefore, data was collected by measuring the electricity consumption of an oven in a soft lithography laboratory. The oven was kept at a constant temperature of 70 °C; it was measured over the span of a weekend, for more than 80 h.

Inventory data for the microfluidic devices is shown in Appendix C. The inventory for the PDMS, paper, and PLA device is shown in Table C.2, Table C.7 and Table C.10 respectively. Data for chemical preparation and supporting systems is also shown in Appendix C. References for unit processes are provided in the supplementary information.

5.4. LCI results

The inventory analysis results in a comprehensive inventory table of all elementary flows. From these results, some impacts can be identified. However, through the impact assessment, the results become clearer as they are aggregated in several impact categories. This is done in Chapter 6. The life cycle inventory results are provided in the supplementary information.

6

Impact assessment

In the impact assessment, the inventory results are translated into each alternative's contribution to various impact categories. This is done through classification and the use of characterisation factors. Between characterisation methods, classification (assigning elementary flows to categories) varies, and characterisation factors vary. Depending on the chosen method, the impact assessment results might therefore differ. The chosen characterisation method and impact categories are described and discussed in Section 6.1. The final characterisation results are shown in Section 6.3.

6.1. Characterisation method and choices

The Environmental Footprint (EF) family of impact categories was chosen for assessing the alternatives' performance, based on the European Commission's recommendation for LCAs conducted on products [55]. The EF family is based on the International Reference Life Cycle Data System (ILCD), a set of guidelines and standards for LCA developed by the European Commission. EF was proposed as a common way of measuring environmental performance, to simplify understanding and communication of the life cycle performance of products and organisations throughout the EU.

The impact categories were chosen according to the best available practice for impact assessment, as described by Guinée et al. [40]. These are mid-point indicators, which provide insight into environmental problems, rather than the total damage that is caused by the accumulation of individual environmental problems (end-point). The chosen categories are all common choices for most LCA studies [56]. No additional, study-specific categories were chosen, as the coverage was considered sufficient. The chosen impact categories are shown in Table 6.1.

6.2. Lacking characterisation factors

Regardless of characterisation method family, many elementary flows will be lacking characterisation factors. These have not yet been calculated, or are difficult to determine due to a lack of data or knowledge. Because of this, the characterisation results are not all-encompassing. Therefore, the characterisation results as they have been calculated using the present LCA model must be regarded with the notion that they are higher in actuality.

Given the applications that the studied microfluidic devices have in healthcare, it is necessary that their production and use do not contribute significantly to health-related impact categories. However, certain elementary flows that are dangerous to human health are not accounted for in the impact assessment due to their missing characterisation factors. Examples are emissions of ^{210}Pb and ^{210}Po to surface water. These substances are radioactive, and can therefore cause cancer.

Many other flows would contribute to the overall results if they had characterisation factors. These considerations will be taken into account during the impact assessment and interpretation phase. Flows lacking characterisation factors are provided in the supplementary information.

6.3. Characterisation results

The characterisation results are shown in Table 6.1 for the PDMS, paper, and PLA microfluidic device. Additionally, the results are shown relative to each other in Figure 6.1. Here, the results are normalised relative to the highest contribution for each category.

Table 6.1: Characterisation results for the three alternatives: PDMS, paper, and PLA.

Impact category	PDMS	Paper	PLA	Unit
climate change	2.26	$5.98e{-1}$	2.99	kg CO_2-Eq
acidification	$1.18e{-2}$	$3.37e{-3}$	$1.60e{-2}$	mol H+-Eq
ecotoxicity: freshwater	$5.42e{+1}$	$2.29e{+1}$	$5.63e{+1}$	CTUe
eutrophication: freshwater	$2.00e{-3}$	$1.29e{-4}$	$2.70e{-3}$	kg PO_4-Eq
eutrophication: marine	$2.14e{-3}$	$7.68e{-4}$	$2.97e{-3}$	kg N-Eq
eutrophication: terrestrial	$1.85e{-2}$	$6.44e{-3}$	$2.56e{-2}$	mol N-Eq
human toxicity: carcinogenic	$1.87e{-9}$	$3.67e{-10}$	$1.94e{-9}$	CTUh
human toxicity: non-carcinogenic	$2.82e{-8}$	$6.54e{-9}$	$4.67e{-8}$	CTUh
ionising radiation: human health	1.16	$4.16e{-2}$	1.47	kBq U_{235}-Eq
land use	7.03	1.58	9.82	dimensionless
material resources: metals/minerals	$9.00e{-6}$	$6.46e{-6}$	$4.94e{-5}$	kg Sb-Eq
ozone depletion	$8.28e{-6}$	$1.86e{-8}$	$1.49e{-7}$	kg CFC-11-Eq
particulate matter formation	$5.26e{-8}$	$3.82e{-8}$	$7.63e{-8}$	disease incidence
photochemical ozone formation	$5.14e{-3}$	$2.16e{-3}$	$7.21e{-3}$	kg NMVOC-Eq

From the results, it becomes clear that the paper device makes the lowest contributions in all impact categories. In most categories, the paper device performs significantly better compared to the other two alternatives. In other categories, the difference in performance between the paper and PDMS device is smaller, like in *material resources* and *particulate matter formation*.

The PLA device performs worst in almost all categories. The exception is that of *ozone depletion*, where PDMS makes the biggest contribution by far. In two categories, *ecotoxicity: freshwater* and *human toxicity: carcinogenic*, the contributions by the PDMS and PLA device are of similar magnitude. It is important to keep in mind that these results would have been different, if flows that are currently missing characterisation factors would have been included. Regardless, the conclusion that can be drawn from the results is clear. To determine the reasons for the significant difference in performance between devices, a contribution analysis is performed in Section 7.3.

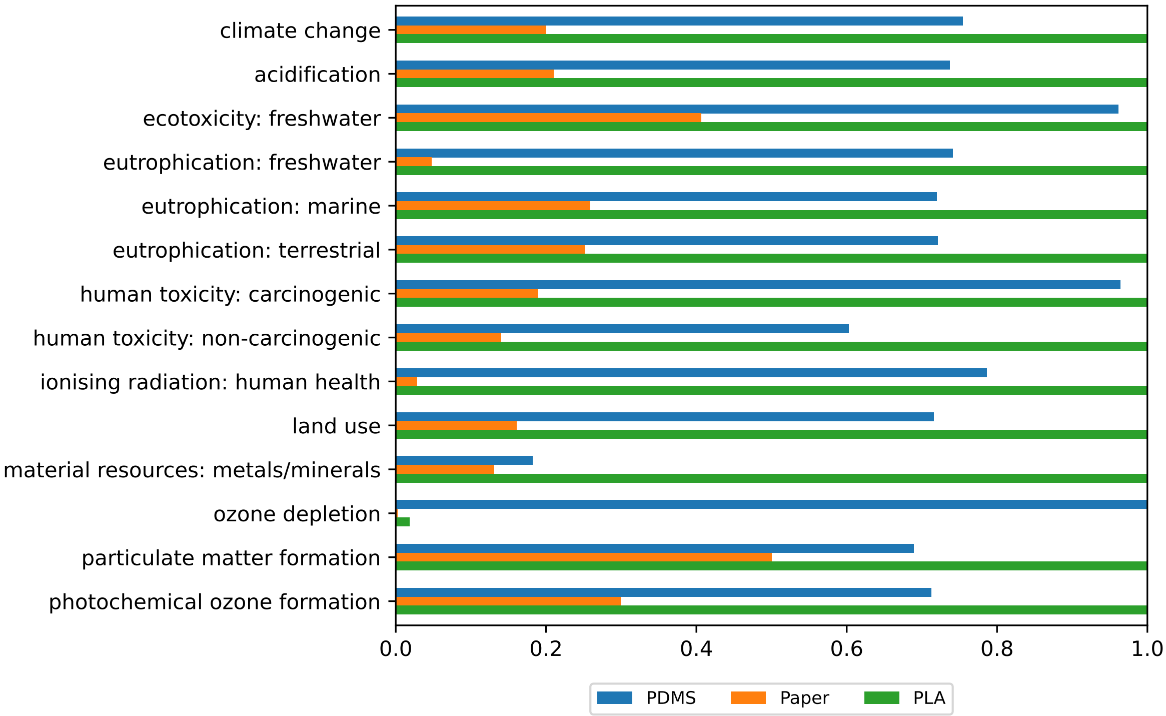


Figure 6.1: Characterisation results for the PDMS, paper, and PLA devices. Here, the results are shown in relative size to each other. For each category, the biggest respective value is used as the normalisation factor.

7

Interpretation

In the interpretation phase, the model is first reviewed for consistency and completeness to ensure that the results can be interpreted accordingly. If inconsistencies or errors are discovered, they can be resolved by reiterating previous steps, or by analysing their influence. Typically, these steps would include comparisons to previous studies on similar cases. However, for the PLA device no such previous study exists. This step will therefore be omitted for the PLA device.

Once consistency and completeness are ensured, the results are analysed in a contribution analysis. Additionally, modelling choices and assumptions are tested for robustness in a sensitivity analysis. Based on these results, recommendations are formulated and conclusions are drawn.

7.1. Consistency check

During the consistency check, an examination is performed to analyse whether the choices made – and thereby the assumptions, methods, models and data used as a result of those choices – are consistent with the defined goal and scope. This check is performed over each product's life cycle.

7.1.1. Methods

The LCA was conducted according to the scope defined in Chapter 4. The alternatives were assessed assuming manufacturing, use, and disposal in the European economic region. Additionally, each alternative was modelled assuming contemporary technology. If multi-functionality occurred in an alternative's product system, this was handled using allocation.

The LCA was always conducted from cradle-to-grave, as defined in the scope. The main processes were always included, and they always spanned over the product's entire life cycle. Those processes, necessary for raw material extraction, manufacturing, use and disposal, were modelled according to the flowcharts shown in Chapter 4. If transport needed to be included, as manufacturing of a product occurred in a continent other than Europe, then transport distance was calculated from the product's local port to the Port of Rotterdam, the largest port of Europe. Lastly, each alternative's impact assessment was conducted using the same family of impact categories.

7.1.2. Models

Each alternative is modelled using the ecoivent database for background processes, and otherwise data is sourced from scientific literature. Data gaps in the LCIs of chemicals, were always handled based on the approach of Huber et al. [43]. This way the greatest accuracy could be achieved across alternatives, based on available data in literature and patents. Using this approach, and that of Langhorst et al. [44], most chemicals were modelled based on their stoichiometry. In the case of two chemicals, they were modelled based on scientific literature, and one chemical was modelled by adjusting an ecoinvent process based on scientific literature. While the chemicals in the three product systems will not always be of similar accuracy, the same method was used to ensure that their accuracy was as high as possible.

In modelling each alternative, occasionally the manufacturing and material inputs for machinery were included. This was done in the case of the PLA device with the 3D printer, and in the case of the PDMS device the refrigerator. These were included given that these machines were used for more than 8 hours in the manufacturing of the devices. Their extended use indicates their significance to the manufacturing of the microfluidic devices. Therefore, their inclusion ensures the completeness of the LCA model, and ensures the adherence to the defined scope.

In the case of the PLA device, the device undergoes heat treatment in an electric oven for longer than 24 hours. Due to a lack of data on the life cycle inventory of an electric oven, the material inputs for its manufacture was omitted. This is inconsistent with how the other devices were modelled. However, the additional impact associated with the refrigerator and 3D printer will be investigated in the sensitivity analysis. Here, it will be determined whether their exclusion will change the overall results.

In the model, certain inputs were considered as cut-offs. This was consistent across alternatives. Manufacturing emissions for equipment used for less than 8 hours, such as hotplates and stirrers, were cut off. Additionally, any inputs from taking a human sample were cut off. In the case of the PDMS device, its electrical components were omitted such that the design might be more similar to that of the paper and PLA device.

7.1.3. Data

Data on the product life cycles were based on each alternative's respective scientific paper, detailing their manufacture, composition and use. The level of detail provided in these papers was not always equal, necessitating the use of assumptions to be able to model product systems. These assumptions are further elaborated on in Section 7.1.4. To close data gaps in the manufacture of the microfluidic devices, more research was done. For the PDMS device, this was achieved through interviewing an expert on soft lithography. For the paper device, this was achieved by consulting previous publications of the authors, Gabriel et al. [2], in which the manufacturing method was described in greater detail. The inconsistency was thereby reduced as much as possible.

As described in Section 7.1.1, the same method was used to determine chemical data. However, due to the availability of information on chemical synthesis, it can not be ensured that the modelled chemicals are consistently accurate. This is justified based on the fact that the method used to determine inputs was consistent, and that there was no better option for modelling the chemicals otherwise. If no synthesis information was available, chemicals were modelled using a proxy. Given that all 3 alternatives suffered from this lack of information at some point, the use of proxies across the alternatives is consistent.

7.1.4. Assumptions

It was assumed that each alternative would be used to detect glucose in a human biological sample; therefore, the sample collecting steps could be cut off. If any two alternatives required the same type of equipment, the resulting electricity consumption was calculated for both alternatives assuming the same brand and model for that equipment. For example, if two alternatives required a hotplate, it was assumed that they would both use a hotplate of the same brand and model. The type of equipment that electricity consumption is modelled after is therefore consistent across alternatives.

For disposal, it was assumed that used devices were thrown into the general waste. The chemicals used are not hazardous, and therefore it does not warrant the use of specialised waste disposal. The waste processing is therefore modelled as municipal solid waste for each alternative.

7.1.5. Comparison to previous studies

Crahay [33] designed a paper-based microfluidic sensor for water quality monitoring and conducted a comparative LCA between their paper sensor and a conventional PDMS sensor. For the LCA, the functional unit was chosen to be “1000 microfluidic devices each one able to transport 30 µL of a liquid media in 90 s”. This corresponded to 1000 strips of 1.0 cm x 3.5 cm nitrocellulose (paper) and 1000 microfluidic caps of about 1.0 cm^3 made from PDMS.

The author compared the embodied energy and carbon footprint of the two microfluidic sensors. They found that for 1000 units of the paper sensor, without a polyester backing, had a carbon footprint of about 0.46 kg CO_2-eq. For 1000 units of the paper sensor with a polyester backing, they found a carbon footprint of about 0.62 kg CO_2-eq. This value is significantly smaller than the carbon footprint found for the paper device in this study. If the functional unit is adjusted for comparability, the carbon footprint for 1000 runs of detecting glucose using a paper device is determined to be 13.43 kg CO_2-eq. There could be several reasons for this difference in results. Considering the devices have been designed for different purposes, it is only logical for their design to be different as well. When comparing the paper water quality monitoring sensor (WQMS) to the paper glucose detecting device (GDD), it has a smaller surface area ($A_{WQMS} = 3.5$ cm^2 $< A_{GDD} \approx 20.3$ cm^2), and is lighter as a result ($m_{WQMS} = 7.96 \times 10^{-5}$ kg $< m_{GDD} = 1.96 \times 10^{-3}$ kg). Additionally, the manufacturing method differs. Whereas the WQMS is prepared by applying the chemicals and reagents to a strip of nitrocellulose, the GDD undergoes wax immersion and a stamping process. These steps are energy intensive, resulting in the GDD having a larger carbon footprint than the WQMS. Lastly, Crahay does not include waste disposal within their LCA boundary, which would otherwise contribute to the carbon footprint calculations.

For 1000 units of the PDMS water quality monitoring sensor, Crahay found a carbon footprint of roughly 2.75×10^5 kg CO_2-eq. This value is significantly larger than the carbon footprint found for the PDMS glucose detection device studied here, which was determined to be 1.92×10^3 kg CO_2-eq for 1000 runs of detecting glucose using a PDMS device. Here, too, there are several reasons for why the device studied by Crahay has a larger environmental impact than the PDMS device studied here. Again, the design of the device is different. The PDMS WQMS can be described as a tube with a volume of 1.0 cm^3, and the PDMS GDD is a flat disk with much less volume. While the manufacturing steps are similar between the two PDMS devices, the manufacturing times show contrast as a result. Whereas the GDD requires 30 s of spin-coating PMMA onto the wafer, the WQMS requires 30 min. Additionally, instead of curing for 4 h, the WQMS requires curing for 12 h. Similarly, other manufacturing processes are more time-consuming for the WQMS, and therefore more energy intensive. Given the different geometry of the WQMS, and the longer manufacturing time, more material is required as well.

While the exact values for the carbon footprint of the water quality monitoring sensors do not align with the results found for the glucose detecting devices, the ranking between PDMS and paper is consistent. Crahay also found that the paper device performed drastically better in the carbon footprint category when compared to the PDMS device, albeit by a much larger margin than found in this work.

7.2. Completeness check

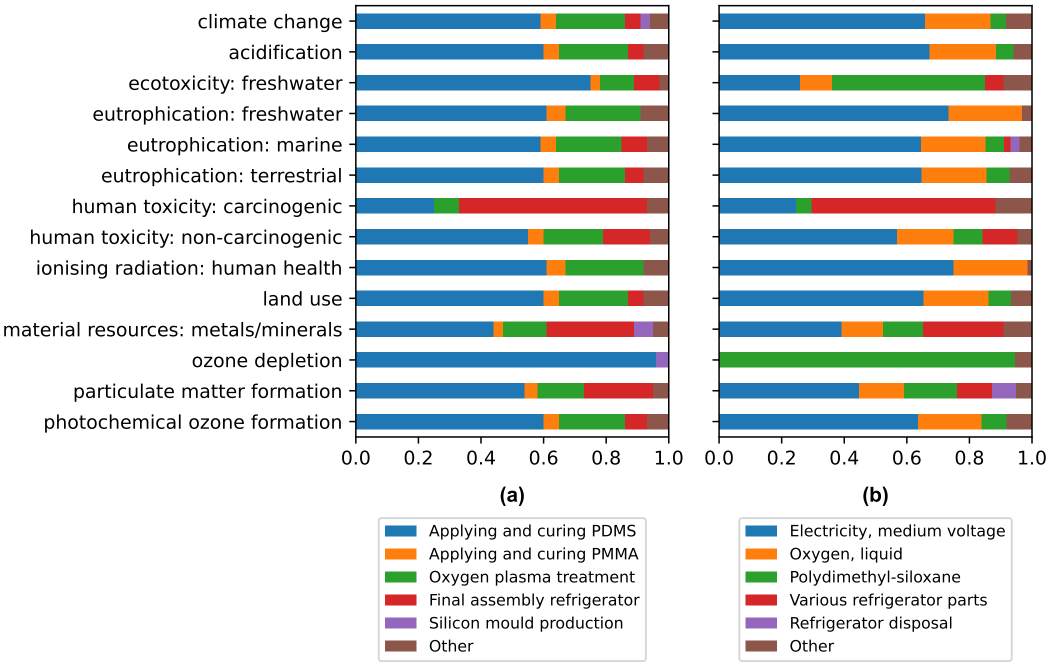
During the completeness check, an expert reviews the information and data and ensures that it is sufficiently complete to analyse the results. The reviewer would also check for false assumptions, model choices, and data. In this study, no expert reviewer was consulted for a completeness check. In lieu of a reviewer, special attention was paid to ensure all processes were included and that all assumptions can be justified and are valid.

7.3. Contribution analysis

For each alternative, it was analysed which unit processes and economic flows contributed most to each impact category. This was done by specifying a cut-off of $1.50\,\%$ in the Activity Browser, which generated sankey diagrams. These provided overviews of which unit processes and elementary flows contributed most to each impact category for each alternative. This cut-off was chosen to get a greater insight into the contributions, without becoming overwhelming. The biggest contributing unit processes and economic flows were reported on in Appendix D. Each alternative's contribution analysis is discussed and shown graphically in their respective subsection below.

7.3.1. PDMS

The results for the PDMS device are shown in Figure 7.1. Figure 7.1a shows that the processes responsible for a large share of the impacts are all related to the manufacturing process. As can be seen in Figure 7.1b, this is due to the electricity that these processes require.



(a)

(b)

Figure 7.1: Contribution analysis for the PDMS device. Contributions from unit processes are shown under (a); contributions from economic flows are shown under (b). The impacts can largely be attributed to manufacturing processes and electricity.

Electricity becomes an important aspect to consider, given the heavy fossil fuel dependency of the European electricity mix. This is also true for the second largest contributing economic flow: liquid oxygen. Again, electricity is necessary for its production, and it is the source for most of its impacts. The use of PDMS as a material is significant in all impact categories. It is the main contributor in the *ozone depletion* category, where the PDMS device performs significantly worse compared to the other devices. This is due to PDMS being based on dimethyldichlorosilane, an inorganic compound used in the synthesis of various silicones. During its production, many components require cooling. The refrigerants used during this cooling are responsible for the CFC emissions contributing to ozone depletion.

Lastly, for the PDMS device, its refrigeration step appears to have an especially large impact in the categories *human toxicity: carcinogenic* and *material resources: metals/minerals*. Its manufacture requires large amounts of metals, such as steel, the production of which is toxic to human health, and have been proven to increase cancer risk for steelworkers [57].

7.3.2. Paper

The results for the paper device are shown in Figure 7.2. Similarly to the PDMS device, Figure 7.2a shows that the processes mainly responsible for the paper device's overall performance are related to manufacturing. The main material that the device is based on, filter paper, makes small contributions in a few categories. The same can be said for the process *pipette production*, which is present during the use phase. Interestingly, the process for *chitosan production* does not make any significant contributions.

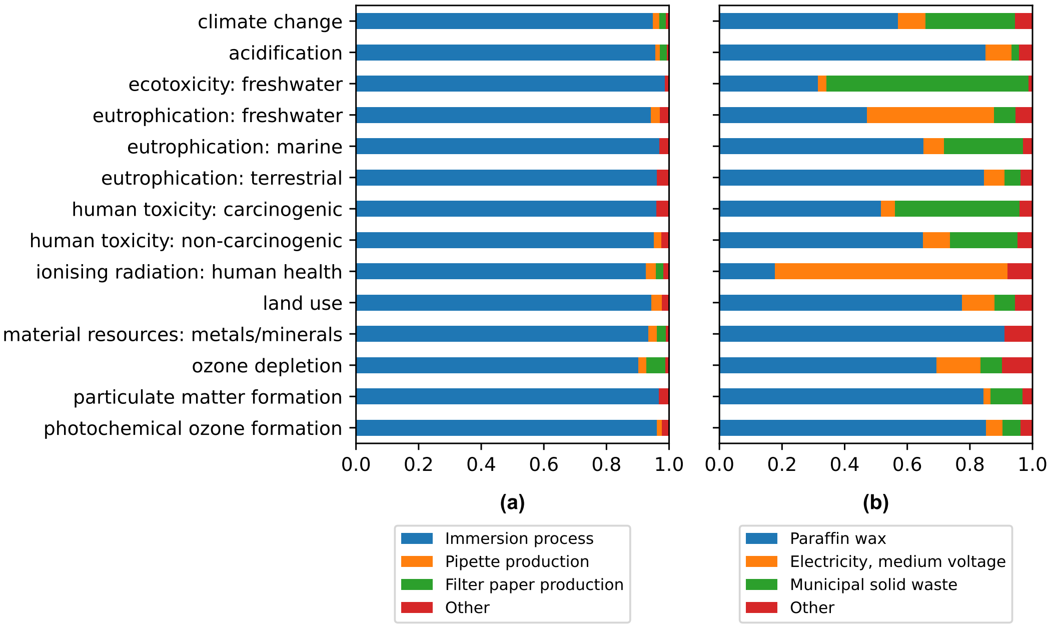


Figure 7.2: Contribution analysis for the paper device. Contributions from unit processes are shown under (a); contributions from economic flows are shown under (b). Again, electricity is a main contributor. However, the use of paraffin is also immensely influential to the results. The wasted paraffin, represented as the flow *municipal solid waste*, also makes significant contributions in many categories.

From Figure 7.2b it can be deduced that electricity plays a significant role, but compared to the PDMS device, its associated impacts are not as critical. For the paper device, the use of paraffin wax is more relevant. The production of paraffin is heat intensive, and therefore dependent on fossil inputs like hard coal. These results are undoubtedly also influenced by the amount of wax that is wasted during the manufacturing process. This is exemplified by the inclusion of the flow *municipal solid waste* in the contribution graph. This flow is used in the LCA model to indicate how much wax is discarded. The influence of wasted wax is investigated further in the sensitivity analysis.

7.3.3. PLA

The results for the PLA device are shown in Figure 7.3. From Figure 7.3a, it becomes clear that the main reason the PLA device's performs worst out of all alternatives is due to its main manufacturing method: 3D printing. The printing process taken about $8.5\,\mathrm{h}$, which requires large inputs of electricity. This can also be seen in Figure 7.3b, where electricity makes up a large part of each impact category.

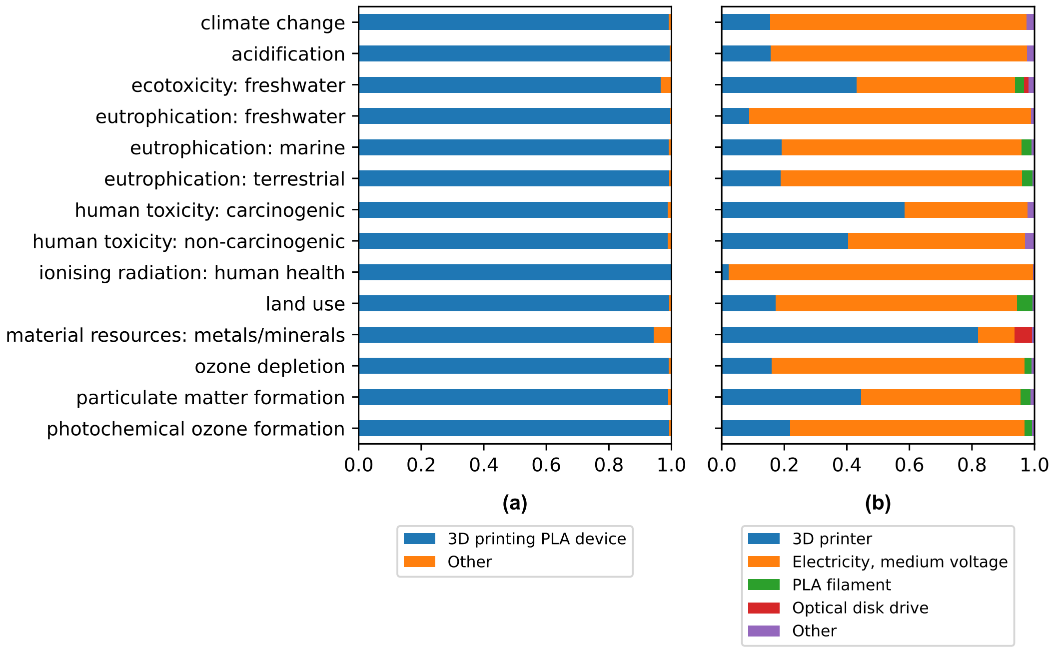


Figure 7.3: Contribution analysis for the PLA device. Contributions from unit processes are shown under (a); contributions from economic flows are shown under (b). The 3D printer, and its associated electricity consumption, are big contributors for this device. The PLA material and the optical disk drive make minimal contributions.

The 3D printer is the second biggest contributor to impact categories. Its various material requirements causes the 3D printer to play significant roles in many categories, making it the biggest contributor in the categories *material resources: metals/minerals* and *human toxicity: carcinogenic*. Other flows, like the *PLA filament* and the *optical disk driver*, are minor relevant contributors.

7.4. Sensitivity analysis

The robustness of the results is tested using a sensitivity analysis. Here, the influence of different choices and assumptions is investigated, to determine how they might affect the overall results.

Five sensitivities were analysed. First, the ReCiPe characterisation model was used to investigate the influence of differing characterisation factors. Secondly, a $100\,\%$ renewable electricity mix based on wind energy was implemented. Third, a different curing method was tested for the PDMS device, by curing the device in the oven rather than on a hotplate. Fourth, the inclusion of machinery in the form of the refrigerator and 3D printer was tested for influence, by excluding these flows. Fifth, the influence of wasting paraffin was investigated for the paper device. Lastly, a redesign for the PDMS device was implemented, wherein refrigeration would no longer be necessary after manufacture.

This sensitivity analysis is reported in-depth in Appendix E. A summary of the findings is provided here. The combined results for the PDMS, paper, and PLA device are shown in Figure 7.4, Figure 7.5, and Figure 7.6 respectively.

For the PDMS device, a transition to a renewable electricity mix would result in the biggest overall improvement. This is not true for all impact categories. In categories where electricity was previously not the biggest reason for a large impact, the PDMS device now experiences the least improvement. In categories where the refrigerator was the biggest contributor, the best improvement can be seen when refrigeration is excluded, either by cutting out the need for refrigeration entirely, or by not including its production in the scope.

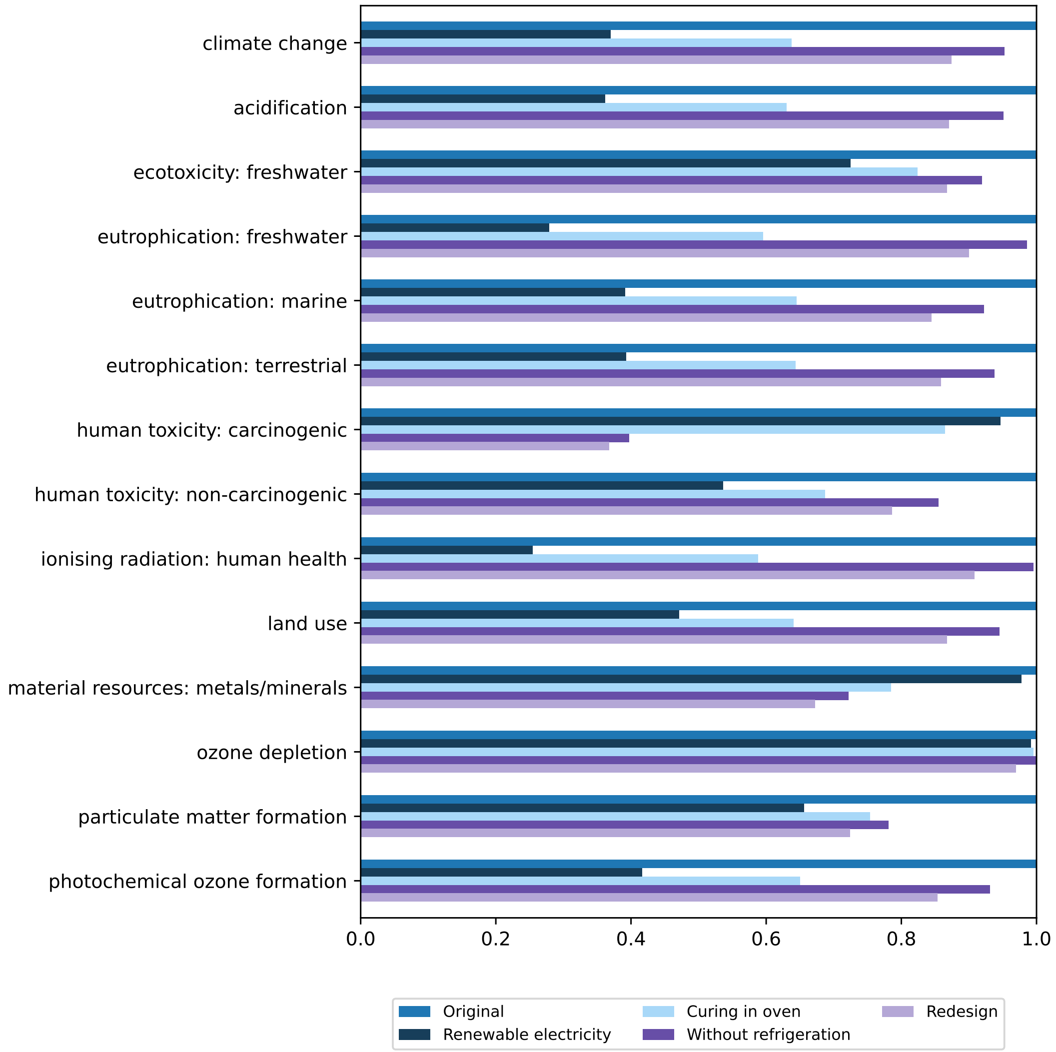


Figure 7.4: Results from the sensitivity analysis for the PDMS device. The biggest improvement compared to the original model can be seen when the PDMS device is produced using an electricity mix that is based on $100\,\%$ wind energy. Excluding the refrigerator from the model seems to make the smallest impact.

From the results, it can be seen that minimising the waste of paraffin wax is conductive to minimising the impacts associated with the paper device. Similarly to the PDMS device, the paper device also experiences better performance in all impact categories when switching to a renewable electricity mix. The exception is the category *material resources: metals/minerals*, where electricity does not play a significant role. Lastly, as expected, minimising the amount of paraffin wasted is conductive to minimising the environmental impacts.

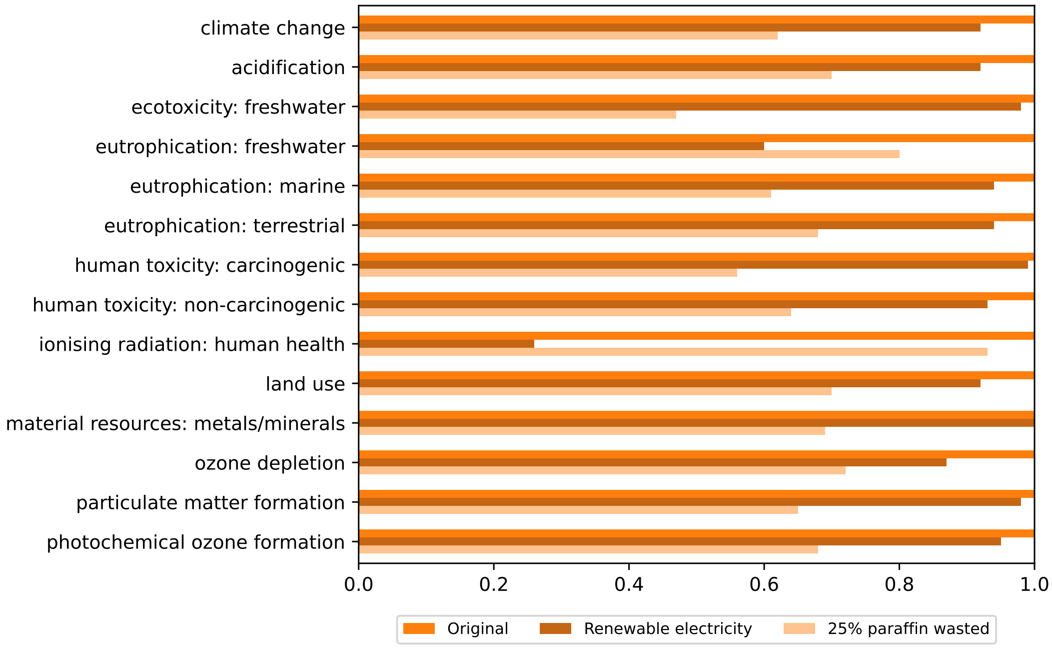


Figure 7.5: Results from the sensitivity analysis for the paper device. The biggest improvement is achieved when wasted paraffin is kept to a minimum. Compared to the other devices, the paper device experiences the least improvement from switching to renewables-based electricity.

When switching to an electricity mix based entirely on wind energy, the PLA device experiences significant performance improvements. However, the PLA device sees the biggest improvement in performance if the 3D printer is excluded from the scope of the LCA. The difference is significant, given that the machine was a big contributor. This indicates that the inclusion of the 3D printer was influential to the results, and the results must therefore be considered with great care.

Each alternative's best option is shown in relative magnitude to each other in Figure 7.7. The best option has been defined as the option where the impact is lowest in most impact categories. The results show that even if each alternative's best version is chosen, the paper device still has the lowest impact comparatively. However, the PDMS device now performs worse than the PLA device in certain categories. In other categories, this has not made much of a difference to the overall results. Regardless of the fact that the PLA device's performance has been improved, it still does not perform better than the other alternatives.

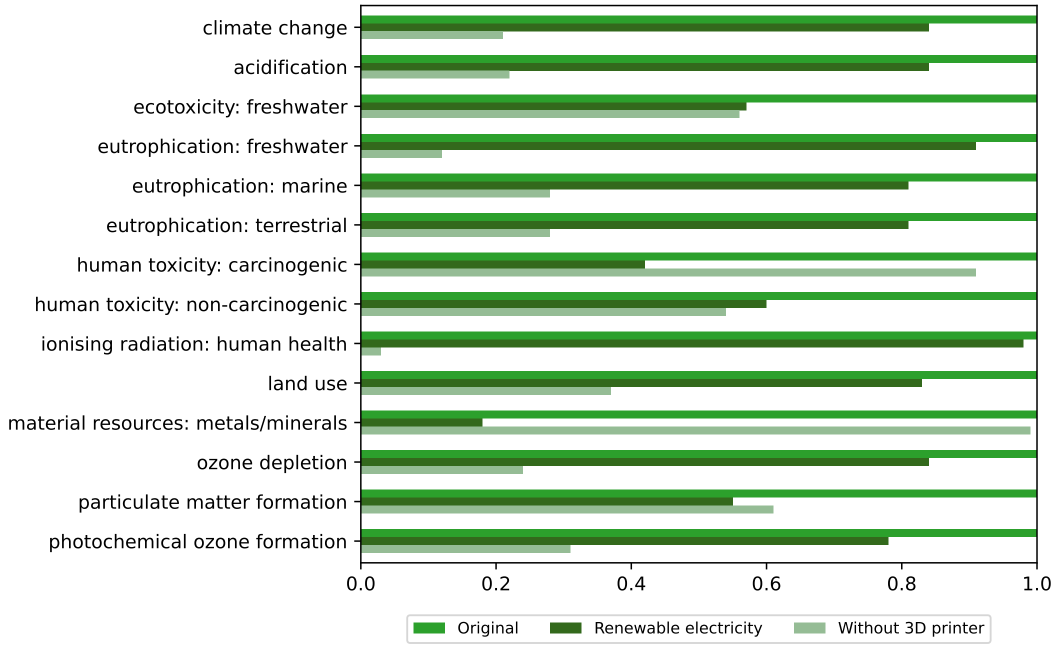


Figure 7.6: Results from the sensitivity analysis for the PLA device. Like the PDMS device, the PLA device experiences significant reductions in impacts when using a renewables-based electricity mix for its production. Excluding the 3D printer, a major contributor to the device's associated impacts, the environmental performance is logically improved significantly.

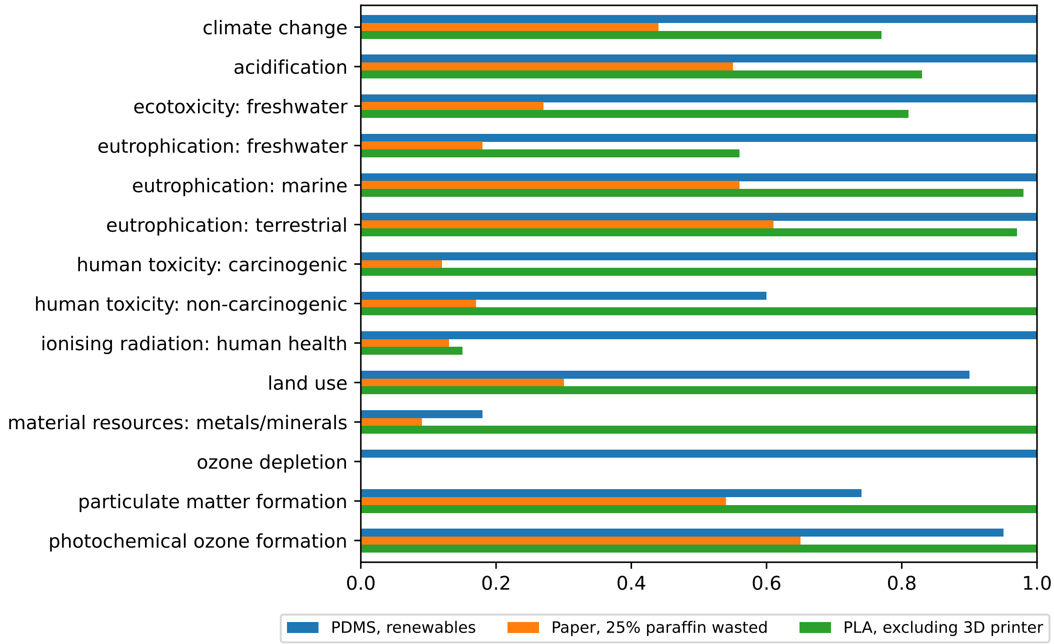


Figure 7.7: A comparison of the characterisation results from the sensitivity analysis. Here, the lowest impacts achieved in the sensitivity analysis are shown for each alternative. Even in this case, the paper device has the lowest environmental impacts overall.

8

Scaling up production

Challenges associated with commercialisation were discussed briefly in Section 2.3. In this chapter, the characterisation results are determined for the upscaling scenario.

8.1. Approach

In order to model commercial-scale production, the product systems of the alternatives were assessed for inefficiencies. The approach was then to investigate whether these inefficiencies would be reduced in large-scale production, and to what extent. If no potential for improvements could be identified, an alternative method for manufacturing was sought out. This approach is generalised to similar case studies in Chapter 9.

8.1.1. PDMS

From an industrial standpoint, manufacturing PDMS devices is expensive. There are a few examples of successful PDMS devices made through soft lithography, such as those sold by Fluidigm [58], but generally manufacturers prefer thermoplastics, glass, and silicon over PDMS. Taking Fluidigm as an example, the modelling of the commercial-scale LCA, little was changed to the manufacturing processes of the PDMS device. Improvements of efficiencies were achieved by reducing the space or electricity required per device produced. This was done by reducing the amount of cleanroom space required per mould produced. Another adjustment is that the curing of PDMS and PMMA is now performed in an electric oven, with space for 10 wafers to be cured simultaneously. This oven is modelled based on the oven used in the product system of the PLA device. The changes in economic flows between the models for laboratory-scale and commercial-scale are shown in Table 8.1.

8.1.2. Paper

As discussed by Akyazi, Basabe-Desmonts and Benito-Lopez [59], wax stamping is an inefficient manufacturing method that is unsuitable for mass production. While it is ideal for field research, and in low resource settings, the processes for heating the stamp and the immersion of the paper are slow and require too much manual labour. Nevertheless, the method was retained to model large-scale production.

Table 8.1: Differences in magnitudes of economic flows between scenarios for the PDMS device.

Flow name	Laboratory	Commercial	Unit
[A1.2] *Cleanroom operations*			
Economic inputs			
electricity, medium voltage	6.73	1.68	kilowatt hour
[A1.7] *Applying and curing PDMS*			
Economic inputs			
electricity, medium voltage	2.40	$7.69e{-2}$	kilowatt hour
[A1.6] *Applying and curing PMMA*			
Economic inputs			
electricity, medium voltage	$1.53e{-1}$	$4.81e{-2}$	kilowatt hour

In the model, the amount of paraffin wax that is wasted is reduced significantly. As more pieces of paper can be immersed, less is expected to be wasted. Additionally, to automate the process, a stamping machine is put into use instead. This is done using the ecoinvent process *deep drawing, steel, 650 kN press, single stroke* as a proxy. The changes in flows are shown in Table 8.2.

Table 8.2: Differences in magnitudes of economic flows between scenarios for the paper device.

Flow name	Laboratory	Commercial	Unit
[A2.2] *Immersion process for 1 paper device*			
Economic inputs			
paraffin	$4.66e{-1}$	$2.59e{-1}$	kilogram
Economic outputs			
municipal solid waste	$2.33e{-1}$	$2.59e{-2}$	kilogram
[A2.5] *Manufacturing paper microfluidic device*			
Economic inputs			
electricity, medium voltage	$1.30e{-3}$	0.00	unit
stamp	$2.00e{-4}$	0.00	kilowatt hour
deep drawing, steel, 650 kN press, single stroke	0.00	$1.96e{-3}$	kilowatt hour

8.1.3. PLA

In the case of the PLA device, it is unreasonable to 3D print many devices simultaneously, as the printing time takes so long. It can be argued that the advantages that are associated with 3D printing are the main reason to choose for 3D printing, and not any other method. These advantages include low cost and rapid prototyping. However, in this scenario the production is modelled for the commercial scale, where these initial advantages are no longer relevant. While other commercialisation strategies that retain these advantages might exist, they are out of the scope of this study.

Therefore, in this model, the mass production of the PLA device is modelled using a different manufacturing method. Injection moulding still allows the use of the same material, and the same level of detail can be achieved as in the original design. Modelling large-scale production of the PLA device is therefore modelled by replacing the 3D printing processes for injection moulding, which is included in the ecoinvent database as a service per kilogram of material. It is assumed that the same amount of material is needed per device in this scenario. The changes in flows are shown in Table 8.3.

Table 8.3: Differences in magnitudes of economic flows between scenarios for the PLA device.

Flow name	Laboratory	Commercial	Unit
[A3.6] *3D printing PLA microfluidic device*			
Economic inputs			
electricity, medium voltage, from scenario	6.32	0.00	kilowatt hour
PLA filament	$1.40e{-2}$	0.00	kilogram
3D printer	$4.10e{-4}$	0.00	unit
polylactide, granulate	0.00	$1.40e{-2}$	kilogram
injection moulding	0.00	$1.40e{-2}$	unit

8.2. Results

The characterisation results for the microfluidic devices in the case of commercial-scale production are provided in Table 8.4. These results are shown relative to each other in Figure 8.2. Additionally, they are shown compared to the results retrieved when modelling on laboratory-scale in Figure 8.1.

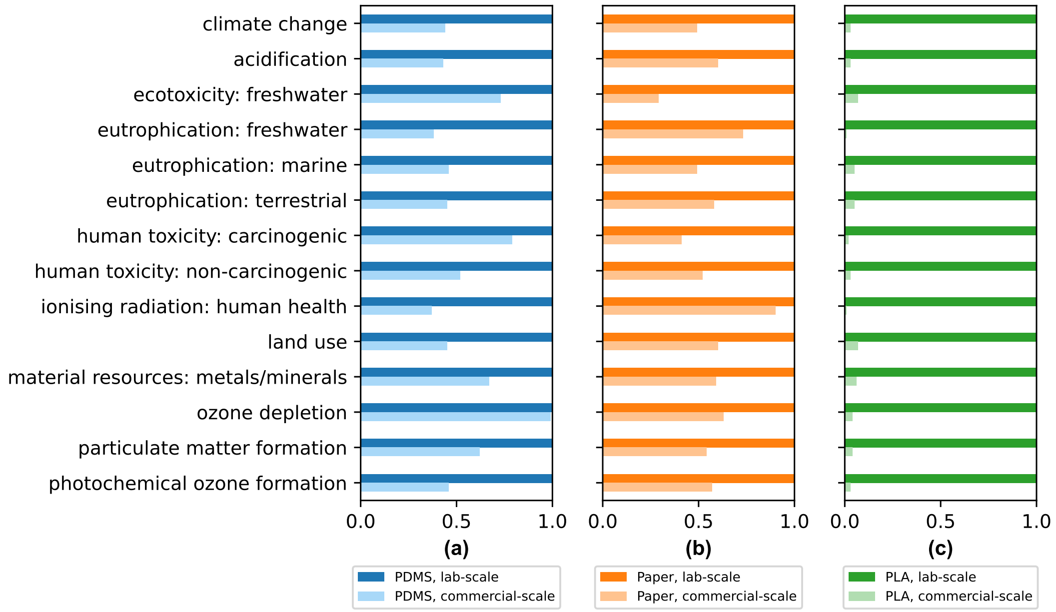


Figure 8.1: Characterisation results shown for each alternative. A comparison is made between the two scales of production, where L = laboratory-scale production, and C = commercial-scale production. In the case of commercialisation, all alternatives experience a reduction in impacts for each impact categories. The biggest difference is experienced by the PLA device.

From the results, it appears that commercialisation not only reduces the total environmental impacts per functional unit, it also changes how the devices perform compared to each other. In this scenario, the paper device is no longer the device with the lowest impact in every category. Instead, the PLA device now has the best performance overall. The paraffin use associated with the paper device's manufacturing is still the reason for most of the device's impacts, even though efficiency has been improved. Conversely, the main polluting process for the PLA device has been removed by switching to injection moulding. The PDMS device has experienced the fewest improvements compared to the other alternatives. It therefore retains its poor environmental performance.

Table 8.4: Characterisation results for the PDMS, paper, and PLA device for the case that they are manufactured on a large scale, such as for commercialisation.

Impact category	PDMS	Paper	PLA	Unit
climate change	1.00	$2.94e{-1}$	$7.98e{-2}$	kg CO_2-Eq
acidification	$5.11e{-3}$	$2.03e{-3}$	$4.42e{-4}$	mol H+-Eq
ecotoxicity: freshwater	$3.96e{+1}$	6.60	3.76	CTUe
eutrophication: freshwater	$7.62e{-4}$	$9.40e{-5}$	$3.63e{-5}$	kg PO_4-Eq
eutrophication: marine	$9.75e{-4}$	$3.73e{-4}$	$1.44e{-4}$	kg N-Eq
eutrophication: terrestrial	$8.38e{-3}$	$3.74e{-3}$	$1.18e{-3}$	mol N-Eq
human toxicity: carcinogenic	$1.48e{-9}$	$1.51e{-10}$	$4.69e{-11}$	CTUh
human toxicity: non-carcinogenic	$1.47e{-8}$	$3.40e{-9}$	$1.56e{-9}$	CTUh
ionising radiation: human health	$4.26e{-1}$	$3.76e{-2}$	$9.88e{-3}$	kBq U_{235}-Eq
land use	3.16	$9.52e{-1}$	$6.54e{-1}$	dimensionless
material resources: metals/minerals	$6.03e{-6}$	$3.82e{-6}$	$3.18e{-6}$	kg Sb-Eq
ozone depletion	$8.22e{-6}$	$1.18e{-8}$	$6.33e{-9}$	kg CFC-11-Eq
particulate matter formation	$3.27e{-8}$	$2.04e{-8}$	$3.41e{-9}$	disease incidence
photochemical ozone formation	$2.38e{-3}$	$1.23e{-3}$	$2.49e{-4}$	kg NMVOC-Eq

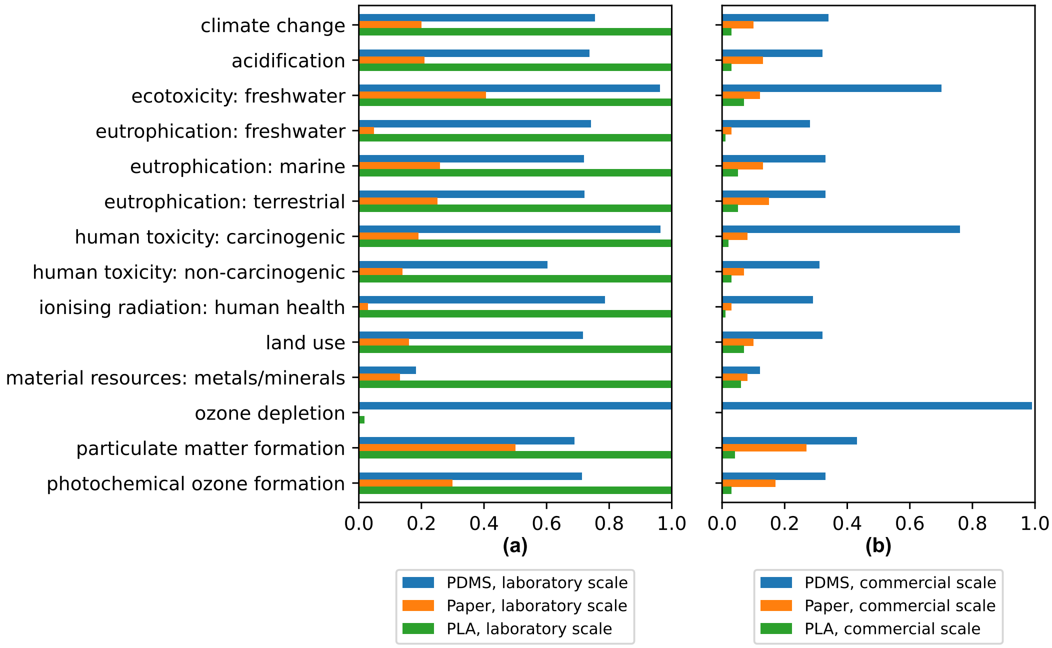


Figure 8.2: Characterisation results for the three alternatives. The scenarios are compared, where (a) shows manufacturing on a laboratory scale, while (b) shows manufacturing on a commercial scale. The characterisation results in (b) are scaled to the highest value in (a) for the given impact category. Contrary to the results achieved in Chapter 6 for laboratory-scale manufacturing, the PDMS device has the worst performance overall in the scenario for commercial-scale production, whereas the PLA device has the best impact.

9

Generalising the approach

A framework was created in which this study's approach was generalised, such that the lessons learnt during this work can be applied to future research. The purpose of the framework is to offer guidance to those who wish to conduct an ex-ante LCA of an emerging technology, the context of which may be similar to the case of microfluidic devices studied here. Here, mass production was modelled, despite small-scale manufacturing methods being unsuitable for large-scale production.

Given that in this work the scope encompassed both an LCA of the product system on laboratory scale and commercial scale, and given the limited time availability, no great depth could be achieved on the commercial-scale model. Combined with the lack of data, conducting an ex-ante LCA according to the recommended guidelines would have been difficult. Technology readiness analyses, scenario testing, monte carlo simulations of uncertainties, etc. were therefore out of scope for this work [36, 60]. However, to still gain some insight into how mass production would impact each alternative's associated environmental impacts, the LCA was conducted using certain assumptions and modelling choices.

This approach has been divided into 4 phases, and is summarised in Figure 9.1. In phase 1, the emerging technology is modelled on a laboratory scale, assuming a manufacturing method that is suitable for that scale, or assuming the manufacturing method that is described by the literature the LCA is based on. In this work, modelling the PLA device as made through 3D printing would fall within the phase.

Phase 2 is the identification phase, where possibilities for scale-up are identified. Here, two paths can be taken. Based on research findings and data availability, one may choose to move between path 1 and path 2. To illustrate this, bilateral arrows were included.

In path 1 (the upper arrow between phase 1 and 2), the analyst tries to identify conventional manufacturing technologies with which the emerging technology could be fabricated on commercial scale. By substituting the laboratory-scale manufacturing method, those inefficiencies inherent to the method are avoided. By identifying conventional technologies, the barrier to commercial production may be lower than expected. For example, in the case of the PLA device, it was found that injection moulding might be a fitting substitute for 3D printing, which circumvents the impacts associated with 3D printing.

Path 2 in phase 2 (the lower arrow) encompasses identifying inefficiencies within the current manufacturing method. This may be the preferred path if the analyst would like to retain the current manufacturing method. Once these have been identified, the next step comprises identifying whether inefficiencies can be reduced in the case of mass production. For example, in the case of the PDMS device, it was found that on a commercial scale, the area of cleanroom per silicon mould would be lower, and thus more efficient.

In Phase 3, the emerging technology is modelled on a commercial scale. Here, the path taken earlier dictates how modelling is performed. In path 1, the large-scale manufacture of the product is modelled assuming the use of a conventional manufacturing method. Conversely, in path 2, the large-scale manufacture of the product is modelled assuming improved efficiencies, while using the same manufacturing method used on laboratory scale.

Finally, in phase 4 the interpretation step is performed as usual in any LCA. Considering LCA is an iterative process, so too is this approach. Between phase 4 and phase 2, the analyst may want to validate their results, consider other options, perform a sensitivity analysis, etc. To illustrate this iterative process, bilateral arrows were included between phase 4 and phase 2.

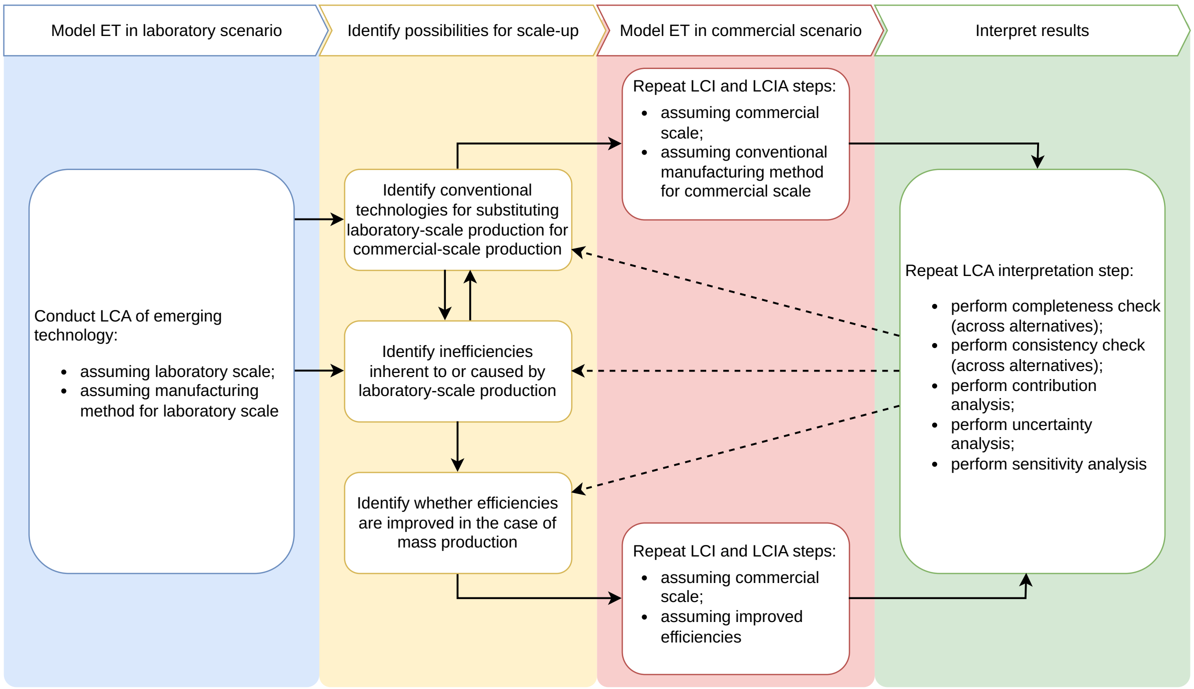


Figure 9.1: Framework for the approach taken in this study to model an emerging technology on commercial scale. ET: emerging technology; LCA: life cycle assessment; LCI: life cycle inventory; LCIA: life cycle impact assessment.

In this work, there were several data gaps for necessary chemicals. A framework has been created based on the approach taken in this study and based on the work of Huber et al. [43]. This approach is shown in Figure 9.2. The approach is structured through yes-no questions, where the higher in the decision tree an option is, the higher its (relative) accuracy is expected to be.

When aiming to model a chemical, the first step is to check whether this chemical is available in the ecoinvent database, or in the database of an equivalent. Ideally, the answer is yes, but if not, the next option is to use data from scientific literature. This could be an LCA published in a peer-reviewed paper, or similar. If this is also not available, the analyst may choose to use a proxy. If no suitable proxy is available, according to the standards and range set by the analyst, then the chemical's production must be modelled manually.

If preparation information can be found in patents or scientific literature, then the chemical can be modelled. If not, then the search for a suitable proxy must be broadened and a generic product must be chosen instead. If preparation information is available, however, the required chemicals must be identified. Ideally, those required chemicals and substances for the original chemical's preparation will be available in the chosen database. If they are not, the process starts again for the modelling of these substances. Once inventories for all required chemicals are established, the original chemical can be modelled through stoichiometry.

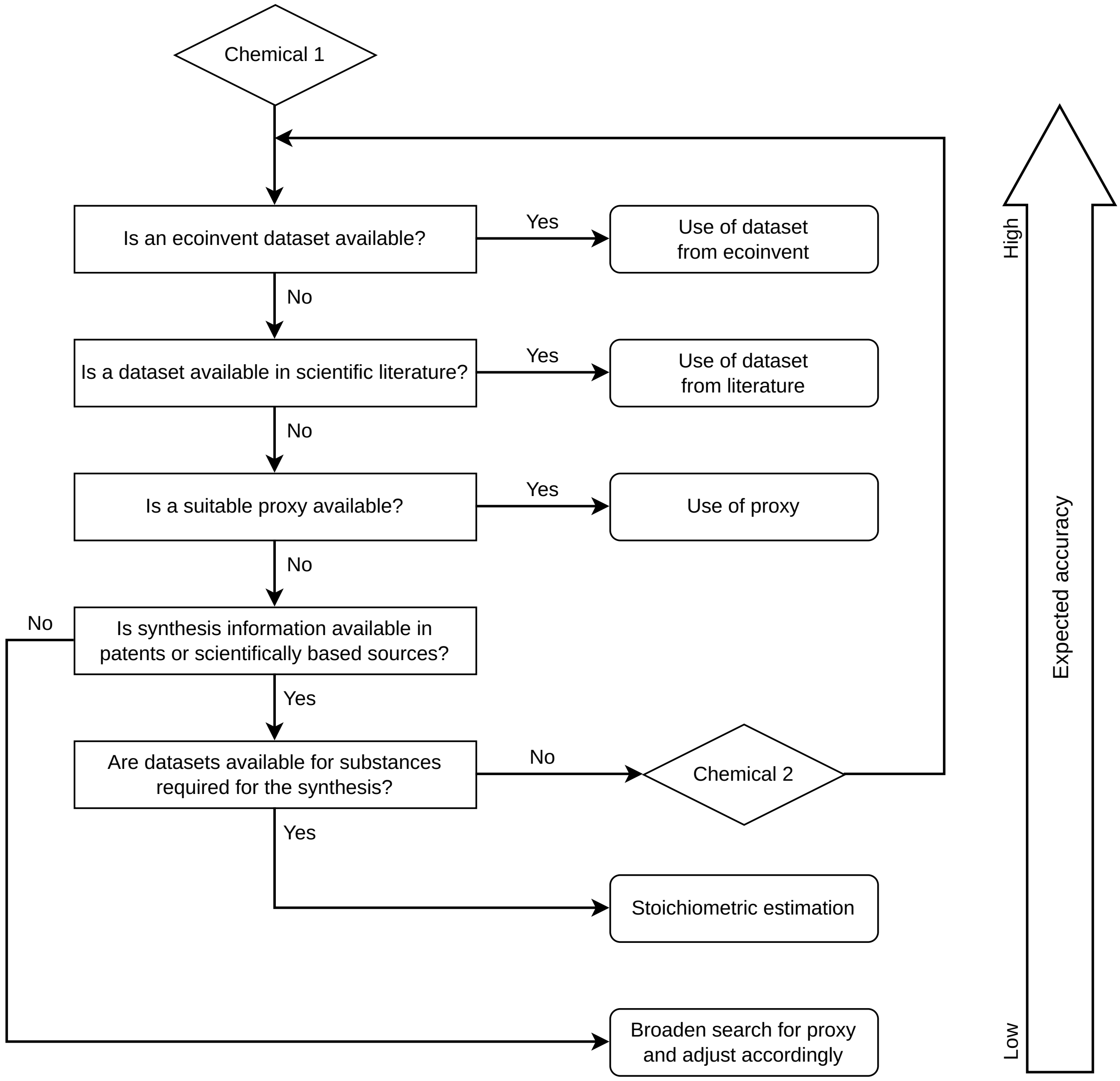


Figure 9.2: Framework for handling data gaps in the life cycle inventory of chemicals. Based on the framework created by Huber et al. [43].

10

Discussion

In this chapter, the limitations of the study are reviewed. Then, the approach and modelling choices are discussed. Additionally, a comparison is made between the results achieved on laboratory scale and commercial scale.

10.1. Limitations

This study was not without its limitations, caused by assumptions and necessary data cut-offs. These limitations are discussed below.

10.1.1. Data estimations

There was no opportunity for the collection of primary data, except for the interview with an expert and the electricity consumption of an electric convection oven. Therefore, a part of the model required estimations. Certain values were estimated based on an interview with an expert, specifically for the manufacture of the silicon mould for the PDMS device. Other values, such as those for equipment use, were based on technical specifications provided in user manuals. For material use, values were back calculated from the expected end product, while accounting for any expected waste.

Electricity consumption was based on equipment power ratings. However, in a few cases the provided power rating was for the maximum power consumption. Examples are equipment with duty cycles, like an oven, or equipment with varying intensity settings, like plasma cleaners or spin coating machines. While upper limits are provided for the power consumption, the exact power rating for the various settings is not provided. Therefore, electricity consumption was determined using the provided power rating, regardless of whether this was only the upper limit. Therefore, the real values for electricity consumption could be much lower than those calculated using the power ratings. This is corroborated by the calculations done for the electricity consumption of the oven. This was determined using the standard equation for determining the energy consumption $E = P \cdot t$, where P is the power rating in watts and t is the time the device is in operation in hours. Assuming a duty cycle of $40\,\%$ and $P = 1.27$ kW, the electricity consumption of the oven for $t = 24.0$ h was calculated to be $E = 12.2$ kWh. To compare, the electricity consumption was measured over a weekend, when the oven would not be in use and therefore heat escaping the oven from frequent opening and closing would be kept to a minimum. The electricity consumption was measured to be $E = 4.62$ kWh for $t = 24$ h. Therefore, it was shown that due to uncertainties surrounding duty cycles, the true electricity consumption was lower than the calculated value; thus, the true characterisation results will be lower. Alternatives where electricity consumption forms a large contribution, such as was the case for the 3D printer, are impacted more than others. This should be kept in mind. However, when combined with the sensitivity analysis using a renewable electricity mix, it can be inferred that this overestimation is not expected to change the relative rankings of the alternatives.

10.1.2. Data gaps

Data gaps could not always be closed. Material inputs for various equipment are therefore excluded from the LCA boundary. By including these materials, the overall impacts would increase, especially for the categories surrounding resource extraction. Additionally, inputs for the taking of human samples has been cut off. These processes are often resource-intensive, due to the common use of gloves, tubes, pipettes, and cotton swabs. However, since all alternatives would require a human sample, it can be assumed that the same amount of environmental impacts are being excluded across the three alternatives. It does mean that the real impact, if the human sample is included, is higher.

Missing chemicals data was handled through the use of proxies and stoichiometry. The latter was done using values for the yield and utilities based on Langhorst et al. [44]. This approach gives a good indication of what the necessary basic inputs are, but does not account for any additional materials. Given that this approach was only used when exact data is unavailable, it was the best method available. In the current model, no chemicals appeared to contribute above the chosen threshold. It is unclear whether this is due to the missing inputs, or whether they are simply inconsequential.

10.1.3. Exclusion of recycling

In this model, waste disposal was modelled using the available processes in the ecoinvent database. However, there are opportunities for recycling for the paper and PLA device [30, 61]. Due to recycling being outside of the scope, this has remained unexplored in this work. For both devices, their respective materials did contribute to the impacts above the threshold, albeit in small amounts. This LCA was generally approached in an attributional way, meaning that end-of-life recycling would at most reduce end-of-life impacts, which are already minor.

10.1.4. Basic ex-ante model

The approach discussed in Chapter 9 has lead to the characterisation results for the microfluidic devices, both on laboratory scale and commercial scale. As discussed there, the model for commercial-scale production is very different to typical ex-ante LCA models. When conducting an ex-ante LCA, one would usually do scenario modelling for future technology readiness levels, and analyse uncertainties using Monte Carlo simulations [36, 60]. However, this was out of scope for this work. More certainty could be achieved with a more in-depth ex-ante LCA approach.

10.1.5. Results are not all-encompassing

Due to the fact that the field of microfluidics is constantly evolving, few microfluidic devices will be similar. The results achieved in this work are therefore not applicable to all microfluidic devices in existence. The results here are highly dependent on the composition and manufacture as they were described by their designers. A PDMS device that is thicker, and therefore requires a longer curing time, would have different impacts. If a paper device were to be studied that used no paraffin at all, and was based on a different working, the results might have been entirely different as well. Similarly, a PLA device that does not require a long printing time might be better than the one studied here. The results can therefore not be directly generalised to other glucose-detecting microfluidic devices.

10.1.6. Exclusion of chance of failure

There is always a chance of failure when producing prototypes of new products. In the case of the PDMS device, the replica can break during the removal from the mould. 3D printers can sometimes make mistakes, causing projects to print incorrectly. This forces the user to start the printing process from the beginning. In this study, the losses that occur due to these failures are not accounted for, as it was not possible to set a failure rate for such processes in this case. The LCA was therefore conducted for product systems that do not experience any such failures. This does not reflect reality.

10.2. Approach and modelling choices

As discussed in Section 10.1.4, the model for commercial-scale production of the microfluidic device was very simple, compared to more extensive ex-ante LCAs that can be found in literature. However, the model and its results are still valuable. They provide insight into how the alternatives might be scaled up, and whether scale-up is even feasible. If it was not feasible, alternative manufacturing methods were identified, which provides insight into how the devices may be produced differently, without losing any of their physical characteristics. This is especially valuable given the many challenges that microfluidics encounters when attempting to reach technological diffusion. While the model is basic, and the results are not of the greatest accuracy, these results still provide some insights that would not otherwise be gained from the results on laboratory scale alone.

Additionally, certain modelling choices were made which should be kept in mind when regarding the characterisation results. The effect that some of these choices have had could previously be seen in the sensitivity analysis in Section 7.4. There it was seen that choosing a different curing method, or excluding machinery, would reduce the impacts. However, it still held true that the paper device made the least impacts overall.

10.3. Reviewing results

The results showed that electricity consumption was a big reason for the alternatives' environmental performance. By switching to renewables, the impacts were reduced for all three alternatives on laboratory scale. The results and analyses also showed that redesign will be necessary to reduce the impacts associated with the devices further.

10.3.1. Laboratory scale

Based on the results provided in Chapter 6 and the analyses conducted in Chapter 7, it can be deduced that the paper device is associated with a low environmental impact. Even when the main reason for the PLA device's large environmental impact – the 3D printer – is excluded, the paper device performs better.

The main reason for the paper device's impact is the use of paraffin wax to create hydrophobic barriers. The use of paraffin is common in wax-based paper microfluidic devices [62, 63]. A substitute for paraffin would be normal wax [64], but it is unclear whether this would significantly reduce the impacts. To replace paraffin in favour of a different wax or material with a lower environmental impact would require additional research, which would be challenging. Such a material might not yet exist.

For the PDMS device, there are many avenues that would lead to reduced impacts. All sensitivity analyses conducted resulted in an improved environmental performance. The need for refrigeration is currently an issue, which can be circumvented by redesigning the device such that enzymes and reagents are only applied before use. Similarly, curing the devices in an oven rather than on a hotplate would further reduce the impacts. However, with the PDMS device, a main polluting process is the PDMS material itself. Its application process is energy-intensive, while the elastomer exacerbates ozone depletion. Redesigning the device to use a wholly different material would therefore result in large impact reductions.

Lastly, the extremely long printing time of the PLA device has caused it to have the worst performance compared to the other two devices. Again, electricity consumption is a big reason, but the material inputs to produce a 3D printer are also significant. Unlike with the PDMs device, the PLA material rarely contributes to impact categories above the threshold. However, compared to the other devices, the PLA device performs significantly worse in the category *material resources: metals/minerals*. To redesign the PLA device such that no centrifugation is necessary would help to reduce the device's impacts in this category. However, while the main contributors are not handled, this will not make much of a difference.

10.3.2. Commercial scale

On commercial scale, the PDMS device has the highest environmental impact in all impact categories. Few areas for improvement could be identified, causing the difference between scenarios to be minimal for this alternative. To realise reductions, an alternative design and/or material would need to be used such that more widely available production methods can be employed.

By switching production method, the PLA device could realise a large reduction in impacts. While 3D printing has its advantages for rapid prototyping, it cannot realistically be scaled for mass production. Similarly, injection moulding would be difficult to implement into a laboratory setting. For the paper device, it appeared that the stamping method was unsuitable for mass production. However, impact reductions were achieved by reducing the paraffin wax that was wasted. In this scenario, the PLA device has the lowest environmental impact in all impact categories.

10.4. Recommendations for future research

To circumvent the limitations discussed in Section 10.1.2, one option for closing the gap on chemical life cycle inventory data would be to use a process modelling software to simulate the synthesis of chemicals. The combination of process modelling and LCA has been done in similar studies where chemical data was necessary [65, 66]. In this work, the use of this software was omitted due to the added complexity it would entail. The restricted time allowance made this unfeasible. It was therefore decided that this was outside of the scope of this study.

Due to limitations of the study, opportunity for future research is abundant. More research is needed to fully understand the environmental impacts of various microfluidic devices. Not only for glucose detection, but also for, e.g., droplet generation and drug delivery. Further research is required to understand the effects of the cut-offs made here. This includes the human sample and refrigeration of chemicals.

It might also be interesting to investigate how further design changes influence the lab-scale and scaled-up results. Generally, more research is necessary to model a proper ex-ante LCA with various scenarios.

11

Recommendations

From the contribution analysis, it became clear that most impacts are due to manufacturing processes. A set of recommendations has been formulated, which are all related to the manufacturing in some way. These recommendations are informed by the results, the limitations of the study, the sensitivity analysis, and the discussion in Chapter 10. They would be especially useful for researchers who are investigating how they might reduce the impacts of their laboratories, or for microfluidic product designers who are looking to improve the environmental performance of their devices or are interested in what a scaled production might look like.

11.1. Transition to renewable energy

This is a general recommendation. All alternatives experienced improvements in their environmental impacts in the scenario where they were manufactured using electricity based entirely on wind energy. While such an electricity mix is not realistic, the results are clear. By cutting out electricity that is dependent on fossil fuels, large emissions are avoided.

Therefore, a transition should be made to green energy wherever possible. The equipment necessary to produce the devices all run on electricity, so initial electrification would not be necessary. Transitioning to renewable energy sources could be achieved by installing solar panels, or by switching to a supplier for renewables-based electricity. This might not always be feasible, as the electricity mix of the country that is being operated in might not have the suitable infrastructure for such a transition. It is then the responsibility of policymakers to invest in renewable energy projects, which will not only reduce impacts of the microfluidic devices, but also reduce impacts in other sectors.

11.2. Redesign the PDMS device

The manufacturing of the PDMS device currently involves refrigerating the device, including the applied glucose assay, until the device is used. This ensures that the enzymes in the reagents are preserved. Due to the PDMS device's design, the reagents cannot be applied before use, as the receiving filter paper is sealed off in the manufacturing process. By redesigning the device such that the filter paper is not enclosed, the user can apply the assay right before use. For the other alternatives, refrigeration was not attributed to the product systems. One can therefore expect a reduction in impacts, although the full scope of this is unclear.

In this redesign, additional design aspects would be necessary. For example, it should be ensured that the user applies the right amount of reagent such that the working of the device is not altered. By implementing a calibration bar, the user could receive an indication once the right concentration is reached. To fully flesh out such a redesign, further research would be necessary, but the reduction in impacts would be worth the additional effort.

11.3. Minimise paraffin waste during paper immersion

The amount of paraffin that is used and wasted is a big reason for the paper device's environmental performance. While it may not be possible to reduce the amount of paraffin that is used, the amount of paraffin that is wasted should be kept to a minimum. By minimising contamination of the paraffin, it should be possible to achieve very little paraffin waste.

11.4. Choose alternate manufacturing method for paper device

The stamping method is not perfectly suitable for mass production, but its implementation is not entirely impossible. Through the use of specialised machinery, it is not unreasonable to think that the processes of immersing and stamping could be automated.

However, the paper device could also be manufactured through the use of wax printing. This method has been researched extensively, and is generally a well-known method to produce hydrophobic barriers on filter paper using wax [63, 64]. Wax printing is based on the use of solid ink printers, which are currently no longer available commercially. While these machines can be purchased secondhand, this would make prototyping difficult. However, once the design has been finalised, the printing process can be scaled to mass production using roll-to-roll manufacturing [67, 68]. There is therefore great potential for using this method.

11.5. Choose alternate manufacturing method for PLA device

When scaling up production of the PLA device, and if the goal is to achieve commercialisation of the device itself, the main manufacturing method should not be through 3D printing. Due to the long printing time, it is unsuitable for mass production; the cumulative environmental impact of such an operation would also be immense.

Instead, an alternative method should be considered, such as injection moulding. The use of PLA for injection moulding to replace 3D printing has been studied before, and PLA has been proven to be suitable [69, 70]. Given that injection moulding is a well-researched and widely used technology, it has had the chance to evolve to a point where using this method for mass production is cost effective.

12

Conclusion

In microfluidics, typical laboratory processes can be condensed to a miniature device, thereby reducing analysis time, reducing the required quantities of reagents and samples, increasing mobility and flexibility, while being cost effective. In this work, three microfluidic devices for glucose detection were reviewed for their environmental impacts. This was done through a comparative LCA, which was conducted from cradle-to-grave, assuming manufacture, use, and disposal in the European economic region. The functional unit was 1 act of glucose detection performed on a human sample using 1 microfluidic glucose detection device.

The three devices at the centre of this study were different in both material and manufacturing method. These devices are a PDMS device manufactured through soft lithography, a paper device manufactured through wax stamping, and a PLA device manufactured through 3D printing. The research question is: *"For microfluidic devices based on soft photo-lithography PDMS, wax-stamped paper, and 3D printed PLA, what are the environmental impacts associated with the entire lifecycle of their respective product systems and where are the hotspots for environmental impacts?"*

To answer this question, three sub-questions were formulated. The first asked what contributions each alternative would make to global impact categories. This was determined through the characterisation results. Amongst the three alternatives, it showed that the paper device had the lowest impact on the environment, whereas the PLA device had the highest impact. Through the contribution analysis, it was shown that the main contributing processes are those pertaining to the devices' manufacture. For the PDMS device, it was the electricity consumption due to the energy-intensive DRIE processes, as well as the curing of the materials. For the paper device, this was the use of paraffin, while for the PLA device it was the 3D printer and its associated electricity consumption.

The second sub-question pertained to how these environmental impacts would be influenced in the case of mass production. The results showed that the environmental impact per functional unit is overall decreased on this scale. When comparing the three alternatives in this scenario, the PLA device now has the lowest environmental impact, whereas the PDMS device has the highest impact. This is because the main polluting process was removed for the PLA device by switching from 3D printing to injection moulding. Comparatively, the PDMS and paper device did not experience drastic changes in their manufacturing processes between scenarios.

The last sub-question asked how the environmental impacts might be reduced for the three devices.

Through conducting a series of sensitivity analyses, and by analysing the results, a set of recommendations was formulated. Generally, by relying on an electricity mix that is overwhelmingly based on renewable energy sources rather than fossil fuels, the environmental impacts of all three devices can be reduced. A recommendation is therefore to transition to renewable energy as much as possible. Additionally, a recommendation is to alter the design of the PDMS device, such that the user can apply reagents before use. In the current design, reagents are added during manufacture, necessitating the need for a refrigerator until the device is used. For the paper device a recommendation is to minimise the waste of paraffin, as it is the main reason for the magnitude of its impacts. Lastly, for the paper and PLA device it is recommended to consider alternate manufacturing methods when scaling up production. Their current manufacturing methods are ideal for prototyping, but would become too slow on commercial scale.

This work has certain limitations which must be kept in mind. Many data points were estimated due to a lack of available data, or cut off completely if no estimations were possible. Data gaps were bridged through the use of proxies and stoichiometry for chemicals, further reducing the overall accuracy of the model. The study does not account for recycling, or the chance that the production of devices might fail during the manufacture process. Lastly, due to the highly specific design of the devices, the results cannot be generalised to all glucose detection microfluidic devices. They can only provide a general idea of what the impacts for other devices might be.

Further research can model chemical production processes to ensure a more complete life cycle inventory. Furthermore, ex-ante LCA can be a valuable tool in evaluating possible design changes. In the end, only a proper understanding of the technology, its environmental impacts, as well as a well-structured commercialisation strategy, will help microfluidics to finally reach its potential, while being environmentally responsible.

References

[1] A. Koh, D. Kang, Y. Xue, S. Lee, R. M. Pielak, J. Kim, T. Hwang, S. Min, A. Banks, P. Bastien et al. “A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat”. In: *Science Translational Medicine* 8.366 (2016), p. 366ra165. DOI: `10.1126/scitranslmed.aaf2593`.

[2] E. F. M. Gabriel, P. T. Garcia, T. M. G. Cardoso, F. M. Lopes, F. T. Martins and W. K. T. Coltro. “Highly sensitive colorimetric detection of glucose and uric acid in biological fluids using chitosan-modified paper microfluidic devices”. In: *Analyst* 141 (15 2016), pages 4749–4756. DOI: `10.1039/C6AN00430J`.

[3] A. M. Tothill. “Developing a proof of principle 3D-printed lab-on-a-disc assay platform”. PhD thesis. Cranfield University, 2017. URL: `https://dspace.lib.cranfield.ac.uk/handle/1826/13496`.

[4] G. Whitesides. “The origins and the future of microfluidics”. In: *Nature* 442 (7101 2006), pages 368–373. DOI: `10.1038/nature05058`.

[5] W. G. Lee, Y.-G. Kim, B. G. Chung, U. Demirci and A. Khademhosseini. “Nano/Microfluidics for diagnosis of infectious diseases in developing countries”. In: *Advanced Drug Delivery Reviews* 62.4-5 (2010), pages 449–457. DOI: `10.1016/j.addr.2009.11.016`.

[6] S. Sharma, J. Zapatero-Rodríguez, P. Estrela and R. O’Kennedy. “Point-of-care diagnostics in low resource settings: present status and future role of microfluidics”. In: *Biosensors* 5.3 (2015), pages 577–601. DOI: `10.3390/bios5030577`.

[7] P. Wang, L. Robert, J. Pelletier, W. L. Dang, F. Taddei, A. Wright and S. Jun. “Robust Growth of Escherichia coli”. In: *Current Biology* 20.12 (2010), pages 1099–1103. DOI: `10.1016/j.cub.2010.04.045`.

[8] D. Lohse. “Fundamental Fluid Dynamics Challenges in Inkjet Printing”. In: *Annual Review of Fluid Mechanics* 54.1 (2022), pages 349–382. DOI: `10.1146/annurev-fluid-022321-114001`.

[9] R. Verma, K. Vinoda, M. Papireddy and A. Gowda. “Toxic Pollutants from Plastic Waste- A Review”. In: *Procedia Environmental Sciences* 35 (2016), pages 701–708. DOI: `10.1016/J.PROENV.2016.07.069`.

[10] C. Rivet, H. Lee, A. Hirsch, S. Hamilton and H. Lu. “Microfluidics for medical diagnostics and biosensors”. In: *Chemical Engineering Science* 66.7 (2011), pages 1490–1507. DOI: `10.1002/biot.201700047`.

[11] C. M. Pandey, S. Augustine, S. Kumar, S. Kumar, S. Nara, S. Srivastava and B. D. Malhotra. “Microfluidics based point-of-care diagnostics”. In: *Biotechnology Journal* 13.1 (2018), page 1700047. DOI: `10.1016/j.ces.2010.08.015`.

[12] L. Volpatti and A. Yetisen. “Commercialization of microfluidic devices”. In: *Trends in Biotechnology* 32 (7 2014), pages 347–350. DOI: `10.1016/j.tibtech.2014.04.010`.

[13] A. Bohr, S. Colombo and H. Jensen. “Chapter 15 - Future of microfluidics in research and in the market”. In: *Microfluidics for Pharmaceutical Applications*. Edited by H. A. Santos, D. Liu and H. Zhang. Micro and Nano Technologies. William Andrew Publishing, 2019, pages 425–465. ISBN: 978-0-12-812659-2. DOI: `10.1016/B978-0-12-812659-2.00016-8`.

[14] I. Hajji, M. Serra, L. Geremie, I. Ferrante, R. Renault, J.-L. Viovy, S. Descroix and D. Ferraro. “Droplet microfluidic platform for fast and continuous-flow RT-qPCR analysis devoted to cancer diagnosis application”. In: *Sensors and Actuators B: Chemical* 303 (2020), page 127171. DOI: `10.1016/j.snb.2019.127171`.

[15] W. Gao, S. Emaminejad, H. Y. Y. Nyein, S. Challa, K. Chen, A. Peck, H. M. Fahad, H. Ota, H. Shiraki, D. Kiriya et al. “Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis”. In: *Nature* 529.7587 (2016), pages 509–514. DOI: `10.1038/nature16521`.

[16] J. C. Yeo and C. T. Lim. “Emergence of microfluidic wearable technologies”. In: *Lab on a Chip* 16.21 (2016), pages 4082–4090. DOI: `10.1039/C6LC00926C`.

[17] I. Lewin John J., E. J. Choi and G. Ling. “Pharmacy on demand: New technologies to enable miniaturized and mobile drug manufacturing”. In: *American Journal of Health-System Pharmacy* 73.2 (2016), pages 45–54. DOI: `10.2146/ajhp150639`.

[18] K. Raj M and S. Chakraborty. “PDMS microfluidics: A mini review”. In: *Journal of Applied Polymer Science* 137.27 (2020), page 48958. DOI: `10.1002/app.48958`.

[19] M. W. Toepke and D. J. Beebe. “PDMS absorption of small molecules and consequences in microfluidic applications”. In: *Lab Chip* 6 (12 2006), pages 1484–1486. DOI: `10.1039/B612140C`.

[20] J. N. Lee, C. Park and G. M. Whitesides. “Solvent Compatibility of Poly-(dimethylsiloxane)-Based Microfluidic Devices”. In: *Analytical Chemistry* 75.23 (2003), pages 6544–6554. DOI: `10.1021/ac0346712`.

[21] R. Mukhopadhyay. *When PDMS isn’t the best*. 2007. DOI: `10.1021/ac071903e`.

[22] S. Battat, D. A. Weitz and G. M. Whitesides. “An outlook on microfluidics: the promise and the challenge”. In: *Lab on a Chip* 22.3 (2022), pages 530–536. DOI: `10.1039/D1LC00731A`.

[23] D. M. Cate, J. A. Adkins, J. Mettakoonpitak and C. S. Henry. “Recent Developments in Paper-Based Microfluidic Devices”. In: *Analytical Chemistry* 87.1 (2015), pages 19–41. DOI: `10.1021/ac503968p`.

[24] X. Hou, Y. S. Zhang, G. T.-d. Santiago, M. M. Alvarez, J. Ribas, S. J. Jonas, P. S. Weiss, A. M. Andrews, J. Aizenberg and A. Khademhosseini. “Interplay between materials and microfluidics”. In: *Nature Reviews Materials* 2.5 (2017), pages 1–15. DOI: `10.1038/natrevmats.2017.16`.

[25] A. Nilghaz, D. R. Ballerini and W. Shen. “Exploration of microfluidic devices based on multi-filament threads and textiles: A review”. In: *Biomicrofluidics* 7.5 (2013). DOI: `10.1063/1.4820413`.

[26] R. S. of Chemistry. *Sustainable laboratories: a community-wide movement toward sustainable laboratory practices*. Royal Society of Chemistry, 2022. URL: `www.rsc.org/new-perspectives`.

[27] H. El Itawi, S. Fadlallah, P. Perré and F. Allais. “Microfluidics for Polymer Microparticles: Opinion on Sustainability and Scalability”. In: *Sustainable Chemistry* 4.2 (2023), pages 171–183. DOI: `10.3390/suschem4020013`.

[28] A. M. Wan, D. Devadas and E. W. Young. “Recycled polymethylmethacrylate (PMMA) microfluidic devices”. In: *Sensors and Actuators B: Chemical* 253 (2017), pages 738–744. DOI: `10.1016/j.snb.2017.07.011`.

[29] J. Luecha, A. Hsiao, S. Brodsky, G. L. Liu and J. L. Kokini. “Green microfluidic devices made of corn proteins”. In: *Lab on a Chip* 11.20 (2011), pages 3419–3425. DOI: `10.1039/C1LC20726A`.

[30] A. Ongaro, Z. Ndlovu, E. Sollier, C. Otieno, P. Ondoa, A. Street and M. Kersaudy-Kerhoas. “Engineering a sustainable future for point-of-care diagnostics and single-use microfluidic devices”. In: *Lab on a Chip* 22 (17 2022), pages 3122–3137. DOI: `10.1039/D2LC00380E`.

[31] K. Kircher, X. Shi, S. Patil and K. Zhang. “Cleanroom energy efficiency strategies: Modeling and simulation”. In: *Energy and Buildings* 42 (3 2010), pages 282–289. DOI: `10.1016/j.enbuild.2009.09.004`.

[32] S. Florez, A. Campaña, M. Noguera, V. Quezada, O. Fuentes, J. Cruz and J. Osma. “CFD Analysis and Life Cycle Assessment of Continuous Synthesis of Magnetite Nanoparticles Using 2D and 3D Micromixers”. In: *Micromachines* 13 (6 2022). DOI: `10.3390/MI13060970`.

[33] O. Crahay. “Towards the design of a paper-based microfluidic sensor for water quality monitoring and comparative life cycle assessment”. Master’s thesis. Ecole polytechnique de Louvain, Université catholique de Louvain, 2020. URL: `http://hdl.handle.net/2078.1/thesis:25150`.

[34] N. Blow. “Microfluidics: the great divide”. In: *Nature methods* 6.9 (2009), pages 683–686. DOI: `10.1038/nmeth0909-683`.

[35] M. I. Mohammed, S. Haswell and I. Gibson. “Lab-on-a-chip or Chip-in-a-lab: Challenges of Commercialization Lost in Translation”. In: *Procedia Technology* 20 (2015). Proceedings of The 1st International Design Technology Conference, DESTECH2015, Geelong, pages 54–59. DOI: `10.1016/j.protcy.2015.07.010`.

[36] S. Cucurachi, C. van der Giesen and J. Guinée. “Ex-ante LCA of Emerging Technologies”. In: *Procedia CIRP* 69 (2018). 25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark, pages 463–468. DOI: `10.1016/j.procir.2017.11.005`.

[37] A. C. Hetherington, A. L. Borrion, O. G. Griffiths and M. C. McManus. “Use of LCA as a development tool within early research: challenges and issues across different sectors”. In: *The International Journal of Life Cycle Assessment* 19 (2014), pages 130–143. DOI: `10.1007/s11367-013-0627-8`.

[38] M. Villares, A. Işıldar, C. Van Der Giesen and J. B. Guinée. “Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste”. In: *Int J Life Cycle Assess* 22.10 (2017), pages 1618–1633. DOI: `10.1007/s11367-017-1270-6`.

[39] M. Curran. “Strengths and Limitations of Life Cycle Assessment”. In: *Background and Future Prospects in Life Cycle Assessment*. Edited by W. Klöpffer. Dordrecht: Springer Netherlands, 2014, pages 189–206. ISBN: 978-94-017-8697-3. DOI: `10.1007/978-94-017-8697-3_6`.

[40] J. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. W. Sleeswijk, S. Suh, H. U. de Haes, J. de Bruijn, R. van Duin and M. Huijbregts. “Handbook on life cycle assessment: operational guide to the ISO standards.” In: edited by J. B. Guinée. Volume 7. Springer Netherlands, 2002. ISBN: 978-1-4020-0228-1. DOI: `10.1007/0-306-48055-7`.

[41] International Organization for Standardization. *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. Retrieved from: `https://www.iso.org/standard/37456.html`.

[42] B. Steubing, D. de Koning, A. Haas and C. L. Mutel. “The Activity Browser — An open source LCA software building on top of the brightway framework”. In: *Software Impacts* 3 (2020), page 100012. DOI: `10.1016/j.simpa.2019.100012`.

[43] E. Huber, V. Bach, P. Holzapfel, D. Blizniukova and M. Finkbeiner. “An Approach to Determine Missing Life Cycle Inventory Data for Chemicals (RREM)”. In: *Sustainability* 14.6 (2022). DOI: `10.3390/su14063161`.

[44] T. Langhorst, B. Winter, D. Roskosch and A. Bardow. “Stoichiometry-Based Estimation of Climate Impacts of Emerging Chemical Processes: Method Benchmarking and Recommendations”. In: *ACS Sustainable Chemistry & Engineering* 11.17 (2023), pages 6600–6609. DOI: `10.1021/acssuschemeng.2c07624`.

[45] P. de Tarso Garcia, T. M. Garcia Cardoso, C. D. Garcia, E. Carrilho and W. K. Tomazelli Coltro. “A handheld stamping process to fabricate microfluidic paper-based analytical devices with chemically modified surface for clinical assays”. In: *RSC Adv.* 4 (71 2014), pages 37637–37644. DOI: `10.1039/C4RA07112C`.

[46] J. D. Moyer, D. A. Wilson, I. V. Finkelshtein, B. D. Wong and R. O. Potts. “Correlation Between Sweat Glucose and Blood Glucose in Subjects with Diabetes”. In: *Diabetes Technology & Therapeutics* 14.5 (May 2012), pages 398–402. DOI: `10.1089/dia.2011.0262`. URL: `https://doi.org/10.1089/dia.2011.0262`.

[47] H. Zafar, A. Channa, V. Jeoti and G. Stojanović. “Comprehensive Review on Wearable Sweat-Glucose Sensors for Continuous Glucose Monitoring”. In: *Sensors* 22.2 (Jan. 2022), page 638. DOI: `10.3390/s22020638`.

[48] D. Sen and G. Sarin. “Tear glucose levels in normal people and in diabetic patients.” In: *British Journal of Ophthalmology* 64.9 (Sept. 1980), pages 693–695. DOI: `10.1136/bjo.64.9.693`.

[49] W. H. Organization. *Mean fasting blood glucose*. URL: `https://www.who.int/data/gho/indicator-metadata-registry/imr-details/2380#:~:text=The%20expected%20values%20for%20normal,(5.6%20mmol%2FL)`. (visited on 11th July 2023).

[50] A. G. Parvatker and M. J. Eckelman. “Comparative evaluation of chemical life cycle inventory generation methods and implications for life cycle assessment results”. In: *ACS Sustainable Chemistry & Engineering* 7.1 (2018), pages 350–367. DOI: `10.1021/acssuschemeng.8b03656`.

[51] K. Roh, A. Bardow, D. Bongartz, J. Burre, W. Chung, S. Deutz, D. Han, M. Heßelmann, Y. Kohlhaas, A. König et al. “Early-stage evaluation of emerging CO 2 utilization technologies at low technology readiness levels”. In: *Green Chemistry* 22.12 (2020), pages 3842–3859. DOI: `10.1039/C9GC04440J`.

[52] R. Hischier, S. Hellweg, C. Capello and A. Primas. “Establishing life cycle inventories of chemicals based on differing data availability (9 pp)”. In: *The International Journal of Life Cycle Assessment* 10 (2005), pages 59–67. DOI: `10.1065/lca2004.10.181.7`.

[53] G. Geisler, T. B. Hofstetter and K. Hungerbühler. “Production of fine and speciality chemicals: procedure for the estimation of LCIs”. In: *The International Journal of Life Cycle Assessment* 9 (2004), pages 101–113. DOI: `10.1007/BF02978569`.

[54] S. Kim and M. Overcash. “Energy in chemical manufacturing processes: gate-to-gate information for life cycle assessment”. In: *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology* 78.9 (2003), pages 995–1005. DOI: `10.1002/jctb.821`.

[55] The European Commission. *Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. 2015.

[56] E. C. J. R. Center. *ILCD Handbook: Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment*. European Commission Joint Research Centre, 2010.

[57] W. J. Blot, L. M. BROWN, L. M. POTTERN, B. Stone and J. F. FRAUMENI JR. “Lung cancer among long-term steel workers”. In: *American Journal of epidemiology* 117.6 (1983), pages 706–716.

[58] A. Shakeri, S. Khan and T. F. Didar. “Conventional and emerging strategies for the fabrication and functionalization of PDMS-based microfluidic devices”. In: *Lab on a Chip* 21.16 (2021), pages 3053–3075. DOI: `10.1039/d1lc00288k`.

[59] T. Akyazi, L. Basabe-Desmonts and F. Benito-Lopez. “Review on microfluidic paper-based analytical devices towards commercialisation”. In: *Analytica Chimica Acta* 1001 (2018), pages 1–17. DOI: `https://doi.org/10.1016/j.aca.2017.11.010`.

[60] N. Tsoy, B. Steubing, C. van der Giesen and J. Guinée. “Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review”. In: *The International Journal of Life Cycle Assessment* 25 (2020), pages 1680–1692. DOI: `10.1007/s11367-020-01796-8`.

[61] J. Sasse, L. Pelzer, M. Schön, T. Ghaddar and C. Hopmann. “Investigation of Recycled and Coextruded PLA Filament for Additive Manufacturing”. In: *Polymers* 14.12 (2022). DOI: `10.3390/polym14122407`.

[62] Y. Lu, W. Shi, L. Jiang, J. Qin and B. Lin. “Rapid prototyping of paper-based microfluidics with wax for low-cost, portable bioassay”. In: *Electrophoresis* 30.9 (2009), pages 1497–1500. DOI: `10.1002/elps.200800563`.

[63] E. Carrilho, A. W. Martinez and G. M. Whitesides. “Understanding Wax Printing: A Simple Micropatterning Process for Paper-Based Microfluidics”. In: *Analytical Chemistry* 81.16 (2009), pages 7091–7095. DOI: `10.1021/ac901071p`.

[64] S. Altundemir, A. Uguz and K. Ulgen. “A review on wax printed microfluidic paper-based devices for international health”. In: *Biomicrofluidics* 11.4 (2017), page 041501.

[65] Y. Mery, L. Tiruta-Barna, E. Benetto and I. Baudin. “An integrated “process modelling-life cycle assessment” tool for the assessment and design of water treatment processes”. In: *The International Journal of Life Cycle Assessment* 18.5 (2013), pages 1062–1070. DOI: `10.1007/s11367-012-0541-5`.

[66] P. Arora, A. Hoadley, S. M. Mahajani and A. Ganesh. *Multi-level Modelling of Sustainable Chemical Production: from CFD to LCA*. Elsevier BV, 2016, pages 499–504. DOI: `10.1016/b978-0-444-63428-3.50088-6`.

[67] J. Olkkonen, K. Lehtinen and T. Erho. “Flexographically Printed Fluidic Structures in Paper”. In: *Analytical Chemistry* 82.24 (2010), pages 10246–10250. DOI: `10.1021/ac1027066`.

[68] R. M. Roller and M. Lieberman. “Beyond wax printing: The future of paper analytical device fabrication”. In: *Sensors and Actuators B: Chemical* 392 (2023), page 134059. DOI: `https://doi.org/10.1016/j.snb.2023.134059`.

[69] T. Tábi, A. Z. Égerházi, P. Tamás, T. Czigány and J. G. Kovács. “Investigation of injection moulded poly(lactic acid) reinforced with long basalt fibres”. In: *Composites Part A: Applied Science and Manufacturing* 64 (2014), pages 99–106. DOI: `https://doi.org/10.1016/j.compositesa.2014.05.001`.

[70] B. Freeland, E. McCarthy, R. Balakrishnan, S. Fahy, A. Boland, K. D. Rochfort, M. Dabros, R. Marti, S. M. Kelleher and J. Gaughran. “A Review of Polylactic Acid as a Replacement Material for Single-Use Laboratory Components”. In: *Materials* 15.9 (2022). DOI: `10.3390/ma15092989`.

[71] R. Van Baak, E. Bol, X. Cui, A. Denkova, R. Gielen, J. Haaring, M. Van der Hoeven, M. Regenbogen, R. Roestenberg and M. Steenbakker. *The production of epsom salt from magnesium hydroxide, sulphuric acid and waste magnesium sulphate*. Delft University of Technology, 2001.

[72] J. Gong, S. B. Darling and F. You. “Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts”. In: *Energy & Environmental Science* 8 (7 2015), pages 1953–1968. DOI: `10.1039/C5EE00615E`.

[73] M. Seeger, W. Otto, W. Flick, F. Bickelhaupt and O. S. Akkerman. “Magnesium Compounds”. In: *Ullmann’s Encyclopedia of Industrial Chemistry*. John Wiley & Sons, Ltd, 2011, pages 41–77. ISBN: 9783527306732. DOI: `10.1002/14356007.a15_595.pub2`.

[74] A. Riofrio, T. Alcivar and H. Baykara. “Environmental and Economic Viability of Chitosan Production in Guayas-Ecuador: A Robust Investment and Life Cycle Analysis”. In: *ACS Omega* 6.36 (2021), pages 23038–23051. DOI: `10.1021/acsomega.1c01672`.

[75] J. Rogalski, J. Fiedurek, J. Szczordrak, K. Kapusta and A. Leonowicz. “Optimization of glucose oxidase synthesis in submerged cultures of Aspergillus niger G-13 mutant”. In: *Enzyme and Microbial Technology* 10.8 (1988), pages 508–511. DOI: `10.1016/0141-0229(88)90030-0`.

[76] R. Xiao, Y. Zhang, X. Liu and Z. Yuan. “A life-cycle assessment of household refrigerators in China”. In: *Journal of Cleaner Production* 95 (2015), pages 301–310. DOI: `https://doi.org/10.1016/j.jclepro.2015.02.031`.

[77] Laurell Technologies. *WS-650 Series spin processor operation manual*. 2011. URL: `http://microfluidics.cnsi.ucsb.edu/wiki/lib/exe/fetch.php?media=tools:spincoater:ws_650_operation_manual.pdf` (visited on 14th Apr. 2023).

[78] Harrick Plasma. *Oxygen Service Vacuum Pumps*. 2021. URL: `https://harrickplasma.com/vacuum-pumps/oxygen-service-vacuum-pumps/` (visited on 20th Apr. 2023).

[79] Harrick Plasma. *Basic Plasma Cleaner*. 2022. URL: `https://harrickplasma.com/plasma-cleaners/basic-plasma-cleaner/` (visited on 20th Apr. 2023).

[80] T. F. Scientific. *RT2 Basic Hotplate Stirrer*. URL: `https://www.thermofisher.com/order/catalog/product/88880003` (visited on 14th Apr. 2023).

[81] National Center for Biotechnology Information. *PubChem Compound Summary for CID 7355, Glycol Dimethacrylate.* 2023.

[82] S. A. Torosyan, Y. N. Biglova, V. B. Mikheev, Z. T. Khalitova, F. A. Gimalova and M. S. Miftakhov. “Synthesis of fullerene-containing methacrylates”. In: *Mendeleev Communications* 22.4 (2012), pages 199–200. DOI: `10.1016/j.mencom.2012.06.009`.

[83] W. Otto. *US3220960A - Cross-linked hydrophilic polymers and articles made therefrom - Google Patents*. 1960. URL: `https://patents.google.com/patent/US3220960A/en`.

[84] S. A. Shafiee, J. Aarons and H. A. Hamzah. “Review—Electroreduction of Peroxodisulfate: A Review of a Complicated Reaction”. In: *Journal of The Electrochemical Society* 165.13 (2018), H785–H798. DOI: `10.1149/2.1161811jes`.

[85] N. Greenwood and A. Earnshaw. *Chemistry of the Elements*. 2nd edition. Butterworth-Heinemann, 1997.

[86] V. A. Ettel. *EP0052444A1 - A process of producing cobalt (II) chloride - Google Patents*. 1980. URL: `https://patents.google.com/patent/EP0052444A1/en`.

[87] P. Roose. “Methylamines”. In: *Ullmann’s Encyclopedia of Industrial Chemistry* (2015), pages 1–10. DOI: `10.1002/14356007.a16\\{_}535.pub4`.

[88] J. J. Walker and J. M. Johnston. “C.—Tetramethylammonium hydroxide”. In: *Journal of the Chemical Society* 87.0 (1905), pages 955–961. DOI: `10.1039/ct9058700955`.

[89] J. Yao, B. Zhu and J. Yao. *CN104478704A - Preparation method of anhydrous trisodium citrate - Google Patents*. 2014. URL: `https://patents.google.com/patent/CN104478704A/en`.

[90] T. Phillips. *How to Make Sodium Citrate Buffer*. 2019. URL: `https://www.thoughtco.com/how-to-make-sodium-citrate-buffer-375494` (visited on 6th May 2023).

[91] S. Havelange, N. Lierde, A. Germeau, E. Martins, T. Theys, M. Sonveaux, C. C. Toussaint, K. Schrödter, G. Bettermann, T. Staffel, F. M. Wahl, T. W. Klein and T. Hofmann. “Phosphoric Acid and Phosphates”. In: *Ullmann’s Encyclopedia of Industrial Chemistry* (2022), pages 1–55. DOI: `10.1002/14356007.a19\\{_}465.pub4`.

[92] K. M. DeAngelis. *Phosphate buffer*. 2007. URL: `https://www.unl.edu/cahoonlab/phosphate%5C%20buffer.pdf` (visited on 15th May 2023).

[93] F. Cerdas, M. Juraschek, S. Thiede and C. Herrmann. “Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System”. In: *Journal of Industrial Ecology* 21.S1 (2017), S80–S93. DOI: `10.1111/jiec.12618`.

[94] S. Lundmark and A.-M. Tillman. “A scalable life cycle inventory of an electrical automotive traction machine—Part II: manufacturing processes”. In: *The International Journal of Life Cycle Assessment* 23.2 (2017), pages 295–313. DOI: `10.1007/s11367-017-1309-8`.

[95] J. Faludi, C. Bayley, S. Bhogal and M. Iribarne. “Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment”. In: *Rapid Prototyping Journal* 21.1 (2015), pages 14–33. DOI: `10.1108/rpj-07-2013-0067`.

[96] Microlit. *How are pipette tips manufactured? - Microlit USA*. 2022. URL: `https://www.microlit.us/faqs/how-are-pipette-tips-manufactured/` (visited on 20th May 2023).

[97] M. Huijbregts, Z. Steinmann, P. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander and R. van Zelm. “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level”. In: *The International Journal of Life Cycle Assessment* 22 (2017), pages 138–147. DOI: `10.1007/s11367-016-1246-y`.

[98] Bosch en van Rijn. *WindStats*. 2023. URL: `https://windstats.nl/statistieken/#data_results` (visited on 1st June 2023).

[99] Rijksoverheid. *Windenergie op zee*. 2023. URL: `https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee` (visited on 1st June 2023).

A

Stoichiometry for chemicals

The microfluidic devices at the centre of this study require various chemicals to function. Some of these could be found in the ecoinvent database, while others were unavailable. This latter group of chemicals was therefore modelled manually based on data from literature. A distinction is made between chemicals that were modelled based on stoichiometry alone (listed in Table A.1), and those that were modelled based on similar studies.

Table A.1: An overview of chemicals modelled based on stoichiometry, following the approach of Langhorst et al. [44].

Chemical name	Chemical formula	Chemical equation
ammonium persulfate	$(NH_4)_2S_2O_8$	Equation A.1
cobalt(ii)chloride	$CoCl_2$	Equation A.2
dipotassium monophosphate	K_2HPO_4	Equation A.3
ethylene glycol dimethacrylate	$C_{10}H_{14}O_4$	Equation A.4
ethylene glycol monomethacrylate	$C_6H_{10}O_3$	Equation A.5
monopotassium diphosphate	KH_2PO_4	Equation A.6
sodium thiosulfate	$Na_2S_2O_3$	Equation A.7
tetramethylammonium chloride	$C_4H_{12}NCl$	Equation A.8
tetramethylammonium hydroxide	$C_4H_{13}NO$	Equation A.9
trisodium citrate	$Na_3C_6H_5O7$	Equation A.10

Chemical inventory data was modelled based on stoichiometry, or chemical balances. This was done according to the approach proposed by Langhorst et al. [44]. This method provides estimates for utilities and estimates for the yield: $87\,\%$ if there are no expected byproducts, and $77\,\%$ if byproducts may occur. The inventory data for these chemicals are shown in Appendix C. In the case that water is a byproduct, it is disregarded, following the approach of Huber et al. [43]. Since this water cannot be used for any further processes without treatment, it is not taken into account.

Two chemicals were modelled based on reported inputs in studies with similar contexts to the LCA conducted here. The first is magnesium sulfate, or Epsom salt, which is based on the report by Van Baak et al. [71]. Here, process streams are provided for Epsom salt production. The second chemical is potassium iodide, which is modelled based on Gong, Darling and You [72], who conducted an LCA of perovskite photovoltaics and provided detailed unit process data.

Lastly, one chemical does not fit either category: magnesium hydroxide. Its production was modelled after the ecoinvent process “salt production from seawater, evaporation pond”, and was expanded on by using information provided by Seeger et al. [73]. Here, the authors describe the process of precipitating magnesium hydroxide from seawater, which was considered to be sufficiently similar to the ecoinvent process.

$$\begin{gathered}\text{Ammonium sulfate} + \text{Sulfuric acid} \longrightarrow \text{Ammonium persulfate} + \text{hydrogen gas} \\ (\mathrm{NH_4})_2\mathrm{SO_4} + \mathrm{H_2SO_4} \longrightarrow (\mathrm{NH_4})_2\mathrm{S_2O_8} + \mathrm{H_2}\end{gathered} \tag{A.1}$$

$$\begin{gathered}\text{Cobalt hydroxide} + \text{Hydrochloric acid} \longrightarrow \text{Cobalt(ii) chloride} \\ \mathrm{Co(OH)_2} + 2\,\mathrm{HCl} \longrightarrow \mathrm{CoCl_2}\end{gathered} \tag{A.2}$$

$$\begin{gathered}\text{Phosphoric acid} + \text{Potassium hydroxide} \longrightarrow \text{Dipotassium monophosphate} \\ \mathrm{H_3PO_4} + 2\,\mathrm{KOH} \longrightarrow \mathrm{K_2HPO_4}\end{gathered} \tag{A.3}$$

$$\begin{gathered}\text{Methacrylic acid} + \text{Ethylene glycol} \longrightarrow \text{Ethylene glycol dimethacrylate} \\ 2\,\mathrm{C_5H_8O_2} + \mathrm{C_2H_6O_2} \longrightarrow \mathrm{C_{10}H_{14}O_4}\end{gathered} \tag{A.4}$$

$$\begin{gathered}\text{Ethylene glycol} + \text{Methacrylic acid} \longrightarrow \text{ethylene glycol monomethacrylate} \\ 10\,\mathrm{C_2H_6O_2} + 4\,\mathrm{C_4H_6O_2} \longrightarrow 4\,\mathrm{C_6H_{10}O_3}\end{gathered} \tag{A.5}$$

$$\begin{gathered}\text{Phosphoric acid} + \text{Potassium chloride} \longrightarrow \text{Monopotassium diphosphate} + \text{Hydrochloric acid} \\ \mathrm{H_3PO_4} + \mathrm{KCl} \longrightarrow \mathrm{KH_2PO_4} + \mathrm{HCl}\end{gathered} \tag{A.6}$$

$$\begin{gathered}\text{Sodium sulfide} + \text{Sulfur} \longrightarrow \text{Sodium thiosulfate} \\ \mathrm{Na_2SO_3} + \mathrm{S} \longrightarrow \mathrm{Na_2S_2O_3}\end{gathered} \tag{A.7}$$

$$\begin{gathered}\text{Trimethylamine} + \text{Methylchloride} \longrightarrow \text{Tetramethylammonium chloride} \\ \mathrm{C_3H_9N} + \mathrm{CH_3Cl} \longrightarrow \mathrm{C_4H_{12}NCl}\end{gathered} \tag{A.8}$$

$$\begin{aligned}&\text{Tetramethylammonium chloride} + \text{Potassium hydroxide} \\ &\qquad\longrightarrow \text{Tetramethylammonium hydroxide} + \text{Potassium chloride} \\ &\mathrm{C_4H_{12}NCl} + \mathrm{KOH} \longrightarrow \mathrm{C_4H_{13}NO} + \mathrm{KCl}\end{aligned} \tag{A.9}$$

$$\begin{gathered}\text{Citric acid} + \text{Sodium hydroxide} \longrightarrow \text{Trisodium citrate} \\ \mathrm{C_6H_8O_7} + 3\,\mathrm{NaOH} \longrightarrow \mathrm{Na_3C_6H_5O_7}\end{gathered} \tag{A.10}$$

B

Product system flowcharts

For the flowcharts, some processes have been omitted for clarity. In the case of the preparation of chemical solutions in water, the intermediate step of diluting the chemical in water has been left out. Instead, the addition of water is added to the main chemical production step, which then continues directly to the unit process the solution is used in. For example, in the PDMS flowchart, when a sodium thiosulfate solution is required, the input of water occurs in the unit process for the production of sodium thiosulfate. The output then flows directly to pHEMA hydrogel preparation, instead of an intermediate process called “sodium thiosulfate solution preparation”.

This is inconsistent with the LCA model, where these intermittent steps were modelled separately for ease of calculation. However, in the flowchart, adding these processes would only clutter the diagram, while not contributing to making the system more understandable. This must be taken into consideration when assessing the flowchart and comparing it to the inventory data tables in Appendix C.

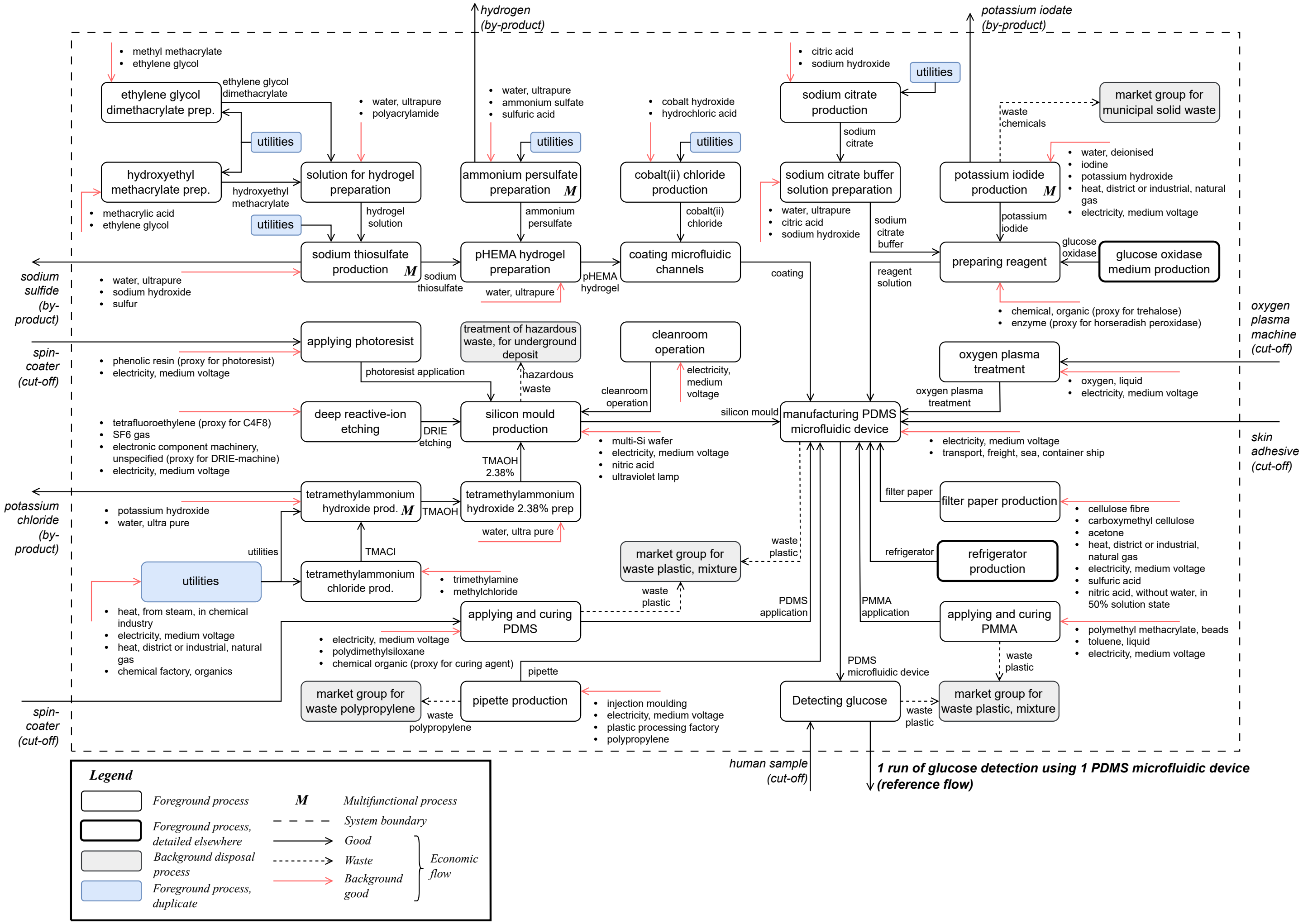


Figure B.1: Flowchart illustrating the product system of the PDMS microfluidic device designed by Koh et al. [1]. This diagram has been created based on additional information from personal communication with an expert of soft lithography.

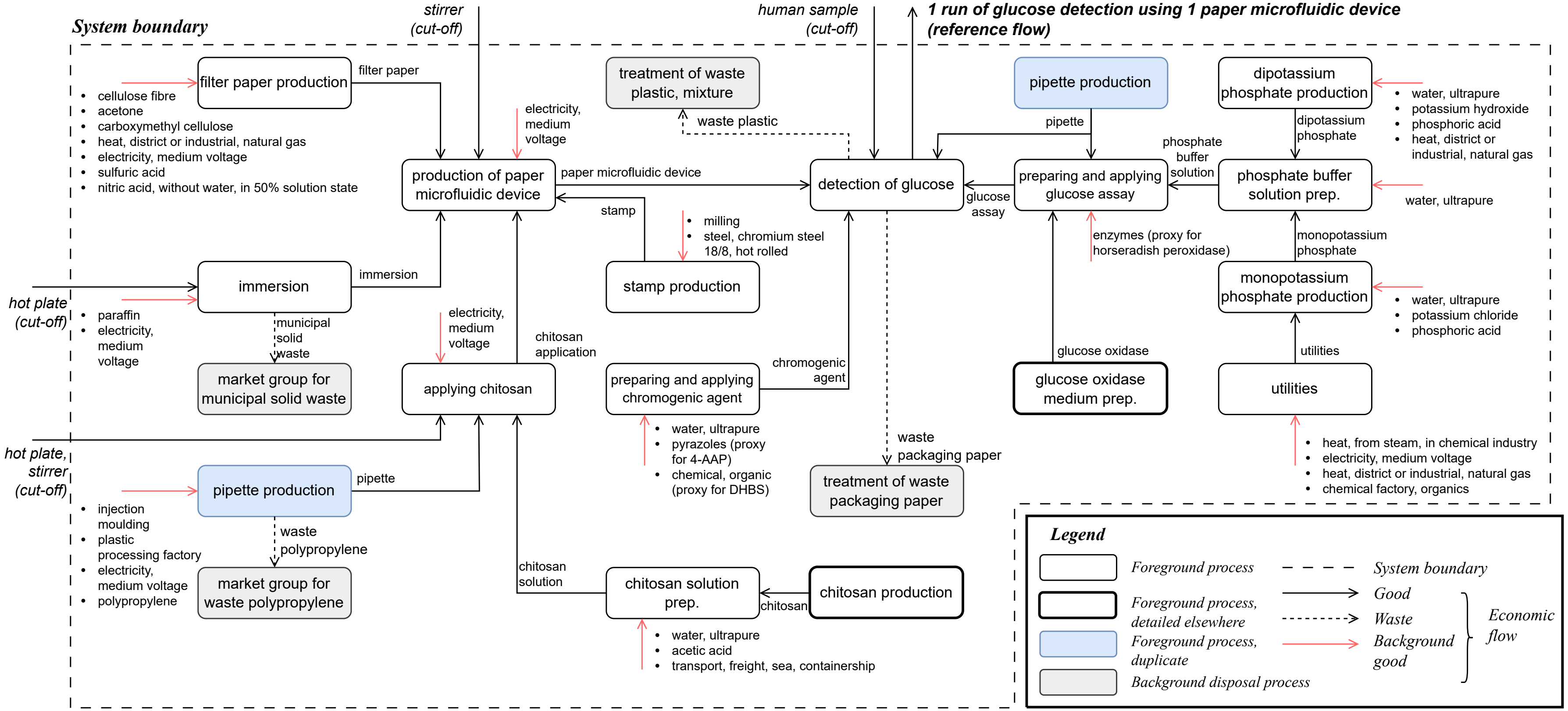


Figure B.2: Flowchart illustrating the product system of the paper microfluidic device designed by Gabriel et al. [2].

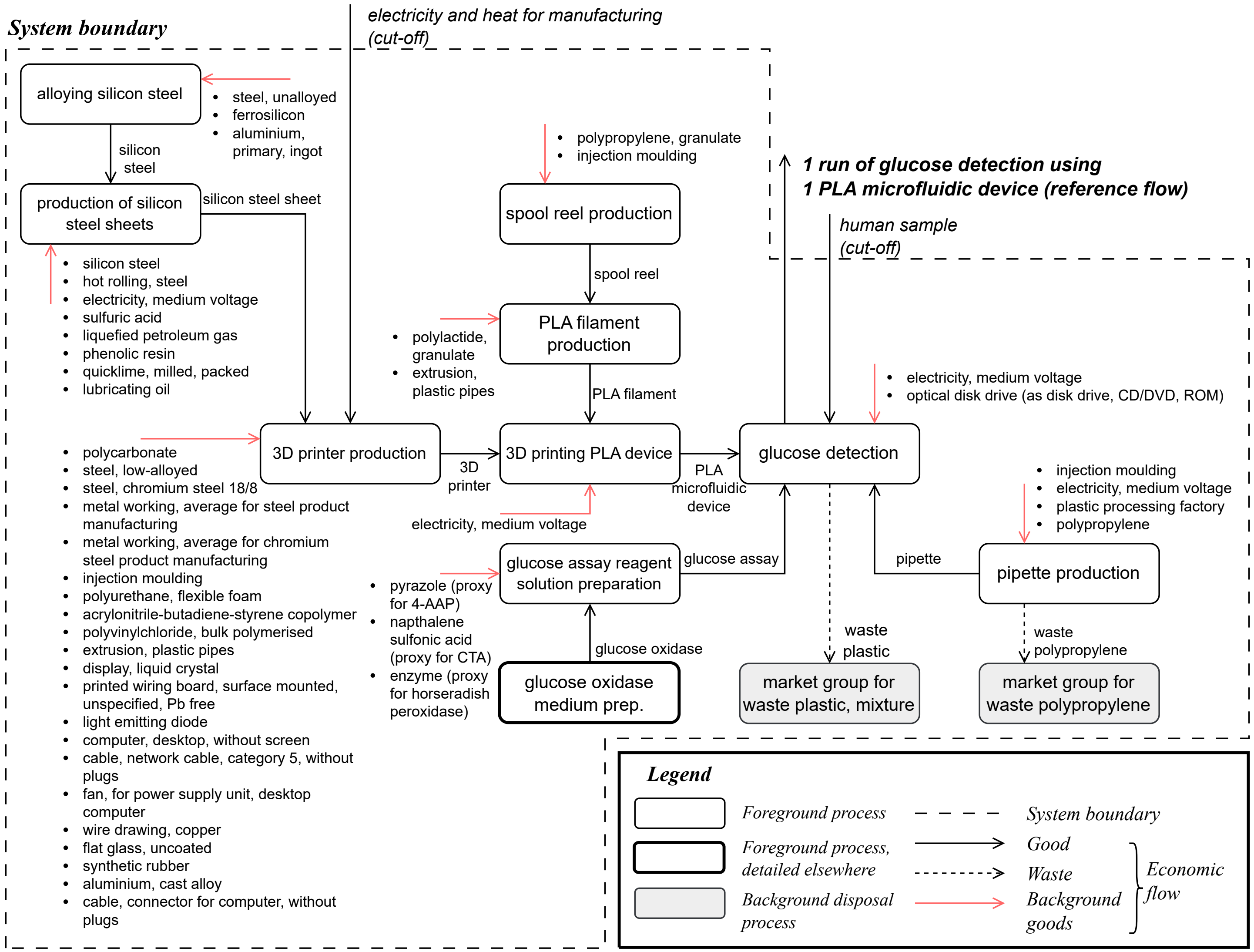


Figure B.3: Flowchart illustrating the product system of the PLA microfluidic device designed by Tothill [3].

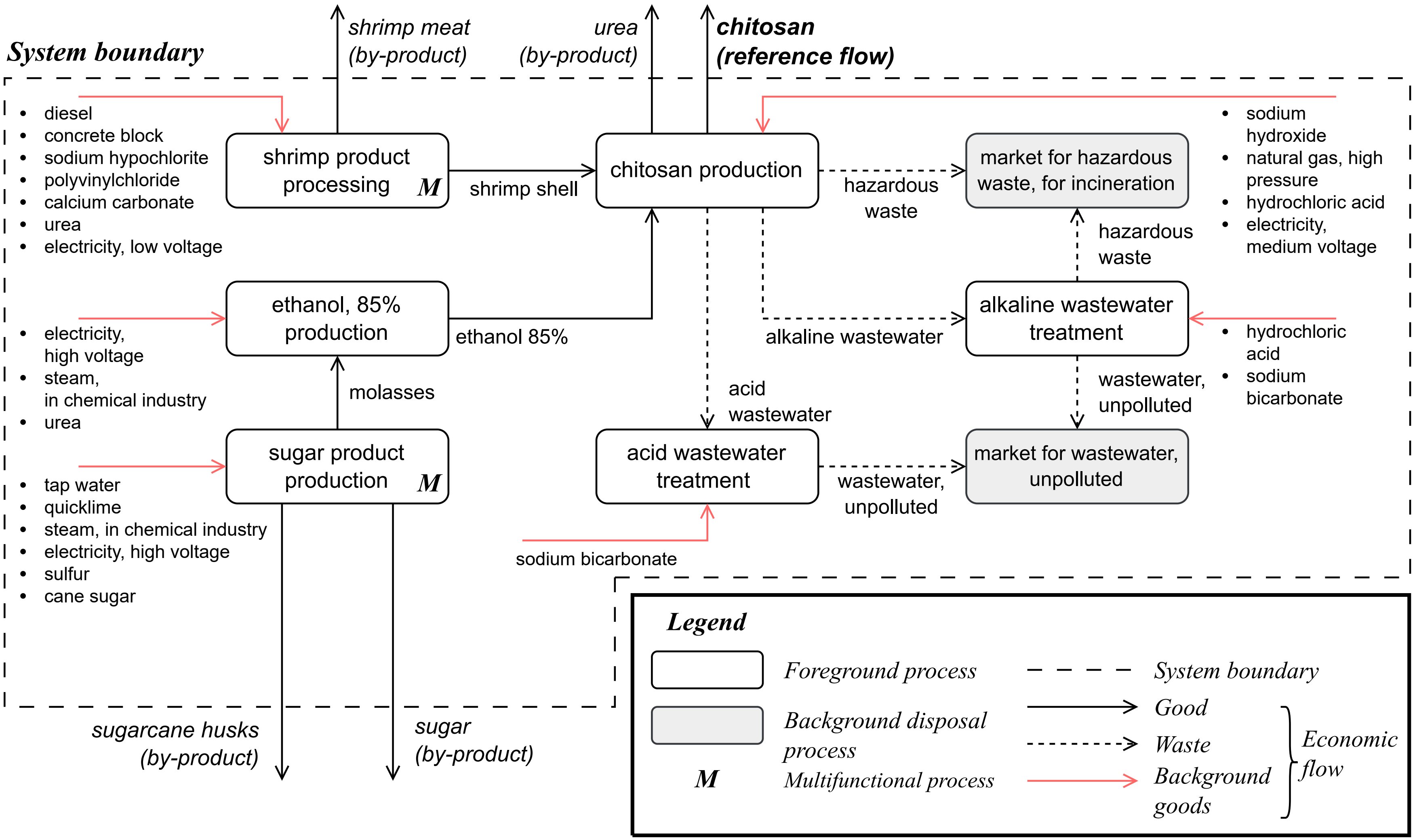


Figure B.4: Flowchart illustrating the product system of chitosan. This diagram is based on the work of Riofrio, Alcivar and Baykara [74].

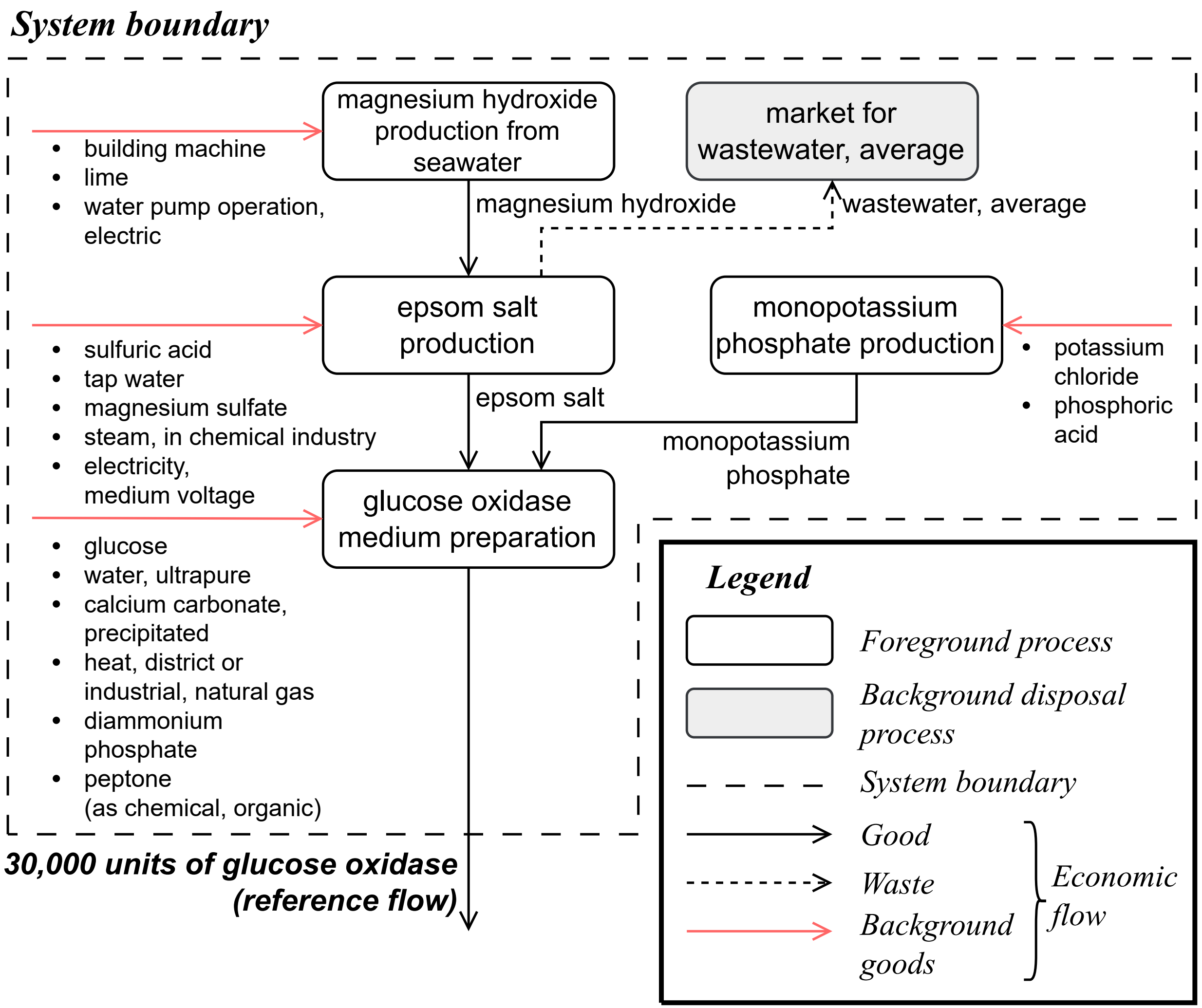


Figure B.5: Flowchart illustrating the product system of a medium containing 30000 units of glucose oxidase, according to Rogalski et al. [75].

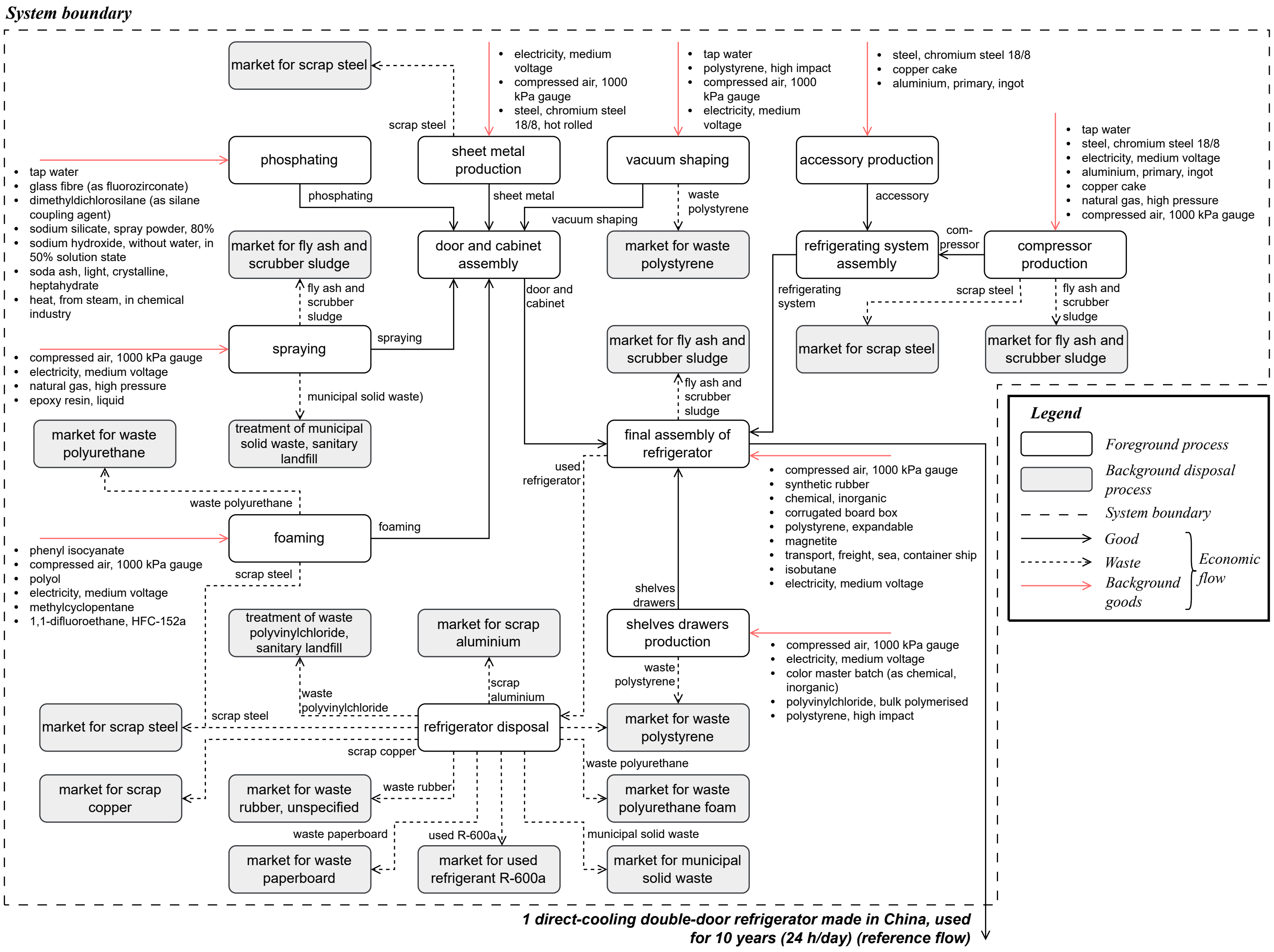


Figure B.6: Flowchart illustrating the product system of a household refrigerator. This diagram is based on the work of Xiao et al. [76].

C

Life cycle inventory data

An overview of the inventory tables provided in this appendix is given in Table C.1. More information on the unit processes is provided in the supplementary Excel sheet.

Table C.1: An overview of the inventory tables. Chemical data is given under the alternative they are predominantly used for.

System	Inventory table number
PDMS alternative	Table C.2
Chemicals for coating PDMS microchannels	Table C.3
Chemicals for manufacturing PDMS mould	Table C.4
Chemicals for reagent, PDMS	Table C.5
Refrigerator	Table C.6
Paper alternative	Table C.7
Chemicals for glucose assay, paper	Table C.8
Chitosan	Table C.9
PLA alternative	Table C.10
Glucose oxidase	Table C.12
Duplicate processes	Table C.11

Table C.2: Inventory data for the product system of the PDMS microfluidic device.

Flow name	Quantity	Unit
[A1.1] *Applying photoresist*, based on [1, 77].		
Economic inputs		
electricity, medium voltage	$1.50e{-2}$	kilowatt hour
phenolic resin (proxy for photoresist)	$1.41e{-2}$	kilogram
Economic outputs		
photoresist application	1.00	unit
[A1.2] *Cleanroom operations*, based on yet unpublished data.		
Economic inputs		
electricity, medium voltage	6.73	kilowatt hour
Economic outputs		
cleanroom operations	1.00	unit
[A1.3] *Deep reactive-ion etching*, based on personal communication and [1].		
Economic inputs		
electricity, medium voltage	1.67	kilowatt hour
sulfur hexafluoride, liquid	$7.51e{-2}$	kilogram
tetrafluoroethylene (proxy for C4F8)	$2.36e{-2}$	kilogram
Economic outputs		
deep-reactive ion etching	1.00	unit
[A1.4] *Silicon mould production*, based on personal communication and [1].		
Economic inputs		
photoresist application	1.00	unit
deep-reactive ion etching	1.00	unit
cleanroom operations	1.00	unit
tetramethylammonium hydroxide 2.38% soln[1]	$4.00e{-1}$	liter
multi-Si wafer	$7.85e{-3}$	square meter
nitric acid, without water, in 50% soln state	$6.04e{-4}$	kilogram
electricity, medium voltage	$6.67e{-5}$	kilowatt hour
electronic component machinery, unspecified	$1.60e{-5}$	unit
ultraviolet lamp	$9.26e{-7}$	unit
Economic outputs		
silicon mould	1.00	unit
hazardous waste, for underground deposit	$3.99e{-1}$	kilogram
[A1.5] *Oxygen plasma treatment*, based on [1, 78, 79].		
Economic inputs		
oxygen, liquid	$8.57e{-1}$	kilogram
electricity, medium voltage	$3.75e{-2}$	kilowatt hour
Economic outputs		
oxygen plasma treatment	1.00	unit
[A1.6] *Applying and curing PMMA*, based on [1, 77, 80].		
Economic inputs		
electricity, medium voltage	$1.53e{-1}$	kilowatt hour
toluene, liquid	$2.30e{-7}$	kilogram
polymethyl methacrylate, beads	$5.75e{-9}$	kilogram
Economic outputs		
PMMA application	1.00	unit
waste plastic, mixture	$2.10e{-7}$	kilogram

Table C.2: Inventory data for the product system of the PDMS microfluidic device. - continued from previous page

Flow name	Quantity	Unit
[A1.7] *Applying and curing PDMS*, based on [1, 77, 80].		
Economic inputs		
electricity, medium voltage	2.40	kilowatt hour
polydimethylsiloxane	$5.31e{-3}$	kilogram
chemical, organic (proxy for curing agent)	$1.54e{-5}$	kilogram
Economic outputs		
PDMS application	1.00	unit
waste plastic, mixture	$4.83e{-3}$	kilogram
[A1.8] *Coating microfluidic channels*, based on [1].		
Economic inputs		
pHEMA hydrogel[2]	1.00	liter
cobalt(ii) chloride[2]	$1.00e{-1}$	kilogram
Economic outputs		
coating for microfluidic channels	1.00	liter
[A1.9] *Preparing reagent for PDMS device*, based on [1].		
Economic inputs		
glucose oxidase[3]	$1.20e{+5}$	unit
sodium citrate buffer solution[4]	1.00	liter
chemical, organic[4]	$1.02e{-1}$	kilogram
potassium iodide[4]	$9.96e{-2}$	kilogram
enzymes	$1.20e{-4}$	kilogram
Economic outputs		
reagent for PDMS device	1.00	liter
[A1.10] *Manufacturing PDMS microfluidic device*, based on [1].		
Economic inputs		
PMMA application	2.00	unit
PDMS application	1.29	unit
oxygen plasma treatment	1.00	unit
electricity, medium voltage	$3.50e{-1}$	kilowatt hour
transport, freight, sea, container ship	$3.25e{-2}$	ton kilometer
silicon mould	$4.00e{-3}$	unit
pipette[5]	$2.20e{-3}$	kilogram
household refrigerator[6]	$2.74e{-4}$	unit
coating for microfluidic channels	$5.00e{-5}$	liter
reagent for PDMS device	$5.00e{-6}$	liter
filter paper	$1.01e{-6}$	kilogram
Economic outputs		
PDMS microfluidic device	1.00	unit
waste plastic, mixture	$1.38e{-3}$	kilogram
[A1.11] *Detecting glucose using PDMS device*, based on [1].		
Economic inputs		
PDMS microfluidic device	1.00	unit
Economic outputs		
run of detecting glucose using PDMS device	1.00	unit
waste plastic, mixture	$6.18e{-4}$	kilogram

[1] Inventory data shown in Table C.4 for chemicals for PDMS.

[2] Inventory data shown in Table C.3 for chemicals for PDMS channel coating production and preparation.

[3] Inventory data shown in Table C.12 for glucose oxidase production.

[4] Inventory data shown in Table C.5 for chemicals for PDMS reagent preparation.

[5] Inventory data shown in Table C.11 for pipette production (duplicate process).

[6] Inventory data shown in Table C.6 for a household refrigerator.

Table C.3: Inventory data for chemicals required for the preparation of hydrogel for microchannel coating, for the PDMS device.

Flow name	Quantity	Unit
[A1.C1.1] *Ethylene glycol dimethacrylate production*, based on [81].		
Economic inputs		
utilities[1]	1.00	unit
methacrylic acid	$9.98e{-1}$	kilogram
ethylene glycol	$3.60e{-1}$	kilogram
Economic outputs		
ethylene glycol dimethacrylate	1.00	kilogram
[A1.C1.2] *Hydroxyethyl methacrylate production*, based on [82].		
Economic inputs		
ethylene glycol	1.37	kilogram
utilities[1]	1.00	unit
methacrylic acid	$1.90e{-1}$	kilogram
Economic outputs		
hydroxyethyl methacrylate	1.00	kilogram
[A1.C1.3] *Solution for hydrogel preparation*, based on [83].		
Economic inputs		
water, ultrapure	$7.67e{-1}$	kilogram
polyacrylamide	$1.54e{-1}$	kilogram
hydroxyethyl methacrylate	$1.02e{-1}$	kilogram
ethylene glycol dimethacrylate	$1.03e{-3}$	kilogram
Economic outputs		
solution for hydrogel	1.00	liter
[A1.C1.4] *Ammonium persulfate production*, based on [84].		
Economic inputs		
utilities[1]	1.00	unit
ammonium sulfate	$7.52e{-1}$	kilogram
sulfuric acid	$5.58e{-1}$	kilogram
Economic outputs		
ammonium persulfate	1.00	kilogram
hydrogen	$8.84e{-3}$	kilogram
[A1.C1.5] *Ammonium persulfate solution production*, based on [1].		
Economic inputs		
water, ultrapure	$9.80e{-1}$	kilogram
ammonium persulfate	$2.00e{-2}$	kilogram
Economic outputs		
ammonium persulfate solution	1.00	liter
[A1.C1.6] *Sodium thiosulfate production*, based on [85].		
Economic inputs		
utilities[1]	1.00	unit
sodium sulfite	$9.16e{-1}$	kilogram
sulfur	$2.33e{-1}$	kilogram
Economic outputs		
sodium thiosulfate	1.00	kilogram
[A1.C1.7] *Sodium thiosulfate solution production*, based on [1].		
Economic inputs		
water, ultrapure	$9.98e{-1}$	kilogram
pHEMA	$2.00e{-3}$	kilogram
Economic outputs		
pHEMA hydrogel	1.00	liter

Table C.3: Inventory data for chemicals required for the preparation of hydrogel for microchannel coating. - continued from previous page

Flow name	Quantity	Unit
[A1.C1.8] *pHEMA production*, based on [83].		
Economic inputs		
solution for hydrogel	4.11	liter
ammonium persulfate solution	$6.16e{-2}$	liter
sodium thiosulfate solution	$4.11e{-2}$	liter
Economic outputs		
pHEMA	1.00	kilogram
[A1.C1.9] *pHEMA hydrogel production*, based on [83].		
Economic inputs		
water, ultrapure	$9.98e{-1}$	kilogram
pHEMA	$2.00e{-3}$	kilogram
Economic outputs		
pHEMA hydrogel	1.00	kilogram
[A1.C1.10] *Cobalt(ii) chloride production*, based on [86].		
Economic inputs		
utilities[1]	1.00	unit
cobalt hydroxide	$8.23e{-1}$	kilogram
hydrochloric acid, w/o water, in 30% soln state	$6.46e{-1}$	kilogram
Economic outputs		
cobalt(ii) chloride	1.00	kilogram

[1] Inventory data shown in Table C.11 for utilities (duplicate process).

Table C.4: Inventory data for chemicals required for the manufacture of the mould for the PDMS device.

Flow name	Quantity	Unit
[A1.C2.1] *Tetramethylammonium chloride production*, based on [87].		
Economic inputs		
utilities[1]	1.00	unit
trimethylamine	$6.20e{-1}$	kilogram
methylchloride	$5.30e{-1}$	kilogram
Economic outputs		
tetramethylammonium chloride	1.00	kilogram
[A1.C2.2] *Tetramethylammonium hydroxide production*, based on [88].		
Economic inputs		
tetramethylammonium chloride	1.56	kilogram
utilities[1]	1.00	unit
potassium hydroxide	$7.99e{-1}$	kilogram
Economic outputs		
tetramethylammonium hydroxide	1.00	kilogram
potassium chloride	$8.18e{-1}$	kilogram
[A1.C2.3] *Tetramethylammonium hydroxide 2.38% preparation*, based on [1].		
Economic inputs		
water, ultrapure	$9.73e{-1}$	kilogram
tetramethylammonium hydroxide	$2.37e{-2}$	kilogram
Economic outputs		
tetramethylammonium hydroxide 2.38% soln	1.00	liter

[1] Inventory data shown in Table C.11 for utilities (duplicate process).

Table C.5: Inventory data for chemicals required for the reagent preparation for the PDMS microfluidic device.

Flow name	Quantity	Unit
[A1.C3.1] *Sodium citrate production*, based on [89].		
Economic inputs		
utilities[1]	1.00	unit
citric acid	$8.56e{-1}$	kilogram
sodium hydroxide, w/o water, in 50% soln state	$5.34e{-1}$	kilogram
Economic outputs		
sodium citrate	1.00	kilogram
[A1.C3.2] *Sodium citrate solution preparation*, based on [1].		
Economic inputs		
water, ultrapure	1.00	kilogram
sodium citrate	$2.94e{-2}$	kilogram
Economic outputs		
sodium citrate solution	1.00	kilogram
[A1.C3.3] *Citric acid solution preparation*, based on [1].		
Economic inputs		
water, ultrapure	$9.97e{-1}$	kilogram
citric acid	$2.10e{-2}$	kilogram
Economic outputs		
citric acid solution	1.00	liter
[A1.C3.4] *Sodium hydroxide 1 M preparation*, based on [1].		
Economic inputs		
water, ultrapure	1.00	kilogram
sodium hydroxide, w/o water, in 50% soln state	$4.00e{-2}$	kilogram
Economic outputs		
sodium hydroxide 1M	1.00	liter
[A1.C3.5] *Sodium citrate buffer solution production*, based on [90].		
Economic inputs		
water, ultrapure	$8.90e{-1}$	kilogram
citric acid solution	$8.20e{-2}$	liter
sodium citrate solution	$1.80e{-2}$	liter
sodium hydroxide 1M	$1.00e{-2}$	liter
Economic outputs		
sodium citrate buffer solution	1.00	liter
[A1.C3.6] *Potassium iodide production*, based on [72].		
Economic inputs		
heat, district or industrial, natural gas	1.72	megajoule
iodine	$9.33e{-1}$	kilogram
water, deionised	$8.00e{-1}$	kilogram
potassium hydroxide	$4.05e{-1}$	kilogram
electricity, medium voltage	$1.19e{-2}$	kilowatt hour
Economic outputs		
potassium iodide	1.00	kilogram
potassium iodate	$1.88e{-1}$	kilogram
municipal solid waste	$1.35e{-2}$	kilogram

[1] Inventory data shown in Table C.11 for utilities (duplicate process).

Table C.6: Inventory data for the production of a household refrigerator. Based on the work of Xiao et al. [76].

Flow name	Quantity	Unit
[R.1] *Foaming door process*		
Economic inputs		
phenyl isocyanate	1.33	kilogram
compressed air, 1000 kPa gauge	1.15	cubic meter
polyol	9.88e−1	kilogram
electricity, medium voltage	5.11e−1	kilowatt hour
methylcyclopentane	9.88e−2	kilogram
1,1-difluoroethane, HFC-152a	0.049 424	kilogram
Economic outputs		
foaming door	1.00	unit
scrap steel	2.79e−3	kilogram
waste polyurethane	5.42e−3	kilogram
Environmental outputs		
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	7.41e−4	kilogram
[R.2] *Foaming cabinet process*		
Economic inputs		
phenyl isocyanate	5.15	kilogram
compressed air, 1000 kPa gauge	4.43	cubic meter
polyol	3.81	kilogram
electricity, medium voltage	1.97	kilowatt hour
methylcyclopentane	3.81e−1	kilogram
1,1-difluoroethane, HFC-152a	0.190 575	kilogram
Economic outputs		
foaming cabinet	1.00	unit
scrap steel	1.90e−2	kilogram
waste polyurethane	1.06e−2	kilogram
Environmental outputs		
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	2.86e−3	kilogram
[R.3] *Door sheet metal production*		
Economic inputs		
steel, chromium steel 18/8, hot rolled	1.92	kilogram
compressed air, 1000 kPa gauge	1.15e−1	cubic meter
electricity, medium voltage	5.10e−2	kilowatt hour
Economic outputs		
door sheet metal	1.00	unit
scrap steel	2.14e−2	kilogram
[R.4] *Cabinet sheet metal production*		
Economic inputs		
steel, chromium steel 18/8, hot rolled	1.31e+1	kilogram
compressed air, 1000 kPa gauge	7.84e−1	cubic meter
electricity, medium voltage	3.48e−1	kilowatt hour
Economic outputs		
cabinet sheet metal	1.00	unit
scrap steel	1.45e−1	kilogram
[R.5] *Phosphating door process*		
Economic inputs		
heat, from steam, in chemical industry	1.60	megajoule
tap water	1.00	kilogram
sodium silicate, spray powder, 80%	9.15e−4	kilogram

Table C.6: Inventory data for the production of a household refrigerator. - continued from previous page

Flow name	Quantity	Unit
soda ash, light, crystalline, heptahydrate	$6.86e{-4}$	kilogram
dimethyldichlorosilane	$6.86e{-4}$	kilogram
glass fibre	$6.86e{-4}$	kilogram
sodium hydroxide, w/o water, in 50% soln state	$2.28e{-4}$	kilogram
Economic outputs		
phosphating door sheet metal	1.00	unit
Environmental outputs		
to water:		
COD, Chemical Oxygen Demand	$7.13e{-4}$	kilogram
Suspended solids, unspecified	$3.45e{-4}$	kilogram
Ammonium, ion	$2.25e{-5}$	kilogram
Nitrogen	$2.25e{-5}$	kilogram
Oils, unspecified	$1.10e{-5}$	kilogram
[R.6] *Phosphating cabinet process*		
Economic inputs		
heat, from steam, in chemical industry	6.18	megajoule
tap water	5.00	kilogram
sodium silicate, spray powder, 80%	$3.53e{-3}$	kilogram
soda ash, light, crystalline, heptahydrate	$2.65e{-3}$	kilogram
dimethyldichlorosilane	$2.65e{-3}$	kilogram
glass fibre	$2.65e{-3}$	kilogram
sodium hydroxide, w/o water, in 50% soln state	$8.82e{-4}$	kilogram
Economic outputs		
phosphating cabinet sheet metal	1.00	unit
Environmental outputs		
to water:		
COD, Chemical Oxygen Demand	$2.75e{-3}$	kilogram
Suspended solids, unspecified	$1.33e{-3}$	kilogram
Oils, unspecified	$4.30e{-5}$	kilogram
Ammonium, ion	$8.75e{-5}$	kilogram
Nitrogen	$8.75e{-5}$	kilogram
[R.7] *Spraying door process*		
Economic inputs		
compressed air, 1000 kPa gauge	$1.95e{-1}$	cubic meter
electricity, medium voltage	$8.70e{-2}$	kilowatt hour
natural gas, high pressure	$4.60e{-2}$	cubic meter
epoxy resin, liquid	$2.29e{-2}$	kilogram
Economic outputs		
spraying door	1.00	unit
fly ash and scrubber sludge	$2.20e{-5}$	kilogram
municipal solid waste	$6.86e{-4}$	kilogram
Environmental outputs		
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	$1.94e{-4}$	kilogram
Nitrogen oxides	$8.00e{-5}$	kilogram
Sulfur dioxide	$9.00e{-6}$	kilogram
[R.8] *Spraying cabinet process*		
Economic inputs		
compressed air, 1000 kPa gauge	$7.52e{-1}$	cubic meter
electricity, medium voltage	$3.34e{-1}$	kilowatt hour
natural gas, high pressure	$1.76e{-1}$	cubic meter
epoxy resin, liquid	$8.82e{-2}$	kilogram

Table C.6: Inventory data for the production of a household refrigerator. - continued from previous page

Flow name	Quantity	Unit
Economic outputs		
spraying cabinet	1.00	unit
fly ash and scrubber sludge	$8.60e{-5}$	kilogram
municipal solid waste	$2.65e{-3}$	kilogram
Environmental outputs		
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	$7.49e{-4}$	kilogram
Nitrogen oxides	$3.11e{-4}$	kilogram
Sulfur dioxide	$3.50e{-5}$	kilogram
[R.9] *Vacuum forming door process*		
Economic inputs		
tap water	4.00	kilogram
polystyrene, high impact	2.73	kilogram
compressed air, 1000 kPa gauge	2.12	cubic meter
electricity, medium voltage	$9.44e{-1}$	kilowatt hour
Economic outputs		
vacuum forming door	1.00	unit
waste polystyrene	$3.03e{-3}$	kilogram
Environmental outputs		
to water:		
COD, Chemical Oxygen Demand	$1.18e{-3}$	kilogram
Suspended solids, unspecified	$5.72e{-4}$	kilogram
Nitrogen	$3.75e{-5}$	kilogram
Ammonium, ion	$3.75e{-5}$	kilogram
Oils, unspecified	$1.80e{-5}$	kilogram
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	$6.10e{-5}$	kilogram
[R.10] *Vacuum forming cabinet process*		
Economic inputs		
tap water	$1.20e{+1}$	kilogram
polystyrene, high impact	7.27	kilogram
compressed air, 1000 kPa gauge	5.66	cubic meter
electricity, medium voltage	2.52	kilowatt hour
Economic outputs		
vacuum forming cabinet	1.00	unit
waste polystyrene	$8.08e{-3}$	kilogram
Environmental outputs		
to water:		
COD, Chemical Oxygen Demand	$3.15e{-3}$	kilogram
Suspended solids, unspecified	$1.53e{-3}$	kilogram
Ammonium, ion	$1.00e{-4}$	kilogram
Nitrogen	$1.00e{-4}$	kilogram
Oils, unspecified	$4.90e{-5}$	kilogram
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	$1.62e{-4}$	kilogram
[R.11] *Refrigerator door production*		
Economic inputs		
door sheet metal	1.00	unit
foaming door	1.00	unit
phosphating door sheet metal	1.00	unit
spraying door	1.00	unit
vacuum forming door	1.00	unit

Table C.6: Inventory data for the production of a household refrigerator. - continued from previous page

Flow name	Quantity	Unit
Economic outputs		
refrigerator door	1.00	unit
[R.12] *Refrigerator cabinet production*		
Economic inputs		
cabinet sheet metal	1.00	unit
foaming cabinet	1.00	unit
phosphating cabinet sheet metal	1.00	unit
spraying cabinet	1.00	unit
vacuum forming cabinet	1.00	unit
Economic outputs		
refrigerator cabinet	1.00	unit
[R.13] *Injection moulding shelves drawers*		
Economic inputs		
compressed air, 1000 kPa gauge	1.20	cubic meter
electricity, medium voltage	$5.34e{-1}$	kilowatt hour
chemical, inorganic	$5.00e{-1}$	kilogram
polyvinylchloride, bulk polymerised	$4.67e{-1}$	kilogram
polystyrene, high impact	$2.22e{-1}$	kilogram
Economic outputs		
injection moulding shelves drawers	1.00	unit
waste polystyrene	$7.17e{-3}$	kilogram
[R.14] *Compressor production*		
Economic inputs		
tap water	$3.30e{+1}$	kilogram
steel, chromium steel 18/8	$1.49e{+1}$	kilogram
electricity, medium voltage	2.52	kilowatt hour
aluminium, primary, ingot	1.58	kilogram
copper cake	1.26	kilogram
natural gas, high pressure	$4.80e{-2}$	cubic meter
compressed air, 1000 kPa gauge	$4.80e{-2}$	cubic meter
Economic outputs		
compressor	1.00	unit
fly ash and scrubber sludge	$2.09e{-3}$	kilogram
scrap steel	$7.41e{-3}$	kilogram
Environmental outputs		
to water:		
COD, Chemical Oxygen Demand	$5.53e{-3}$	kilogram
Suspended solids, unspecified	$2.21e{-3}$	kilogram
Oils, unspecified	$1.76e{-4}$	kilogram
Nitrogen	$1.11e{-4}$	kilogram
Ammonium, ion	$1.11e{-4}$	kilogram
to air:		
Nitrogen oxides (to air)	$2.20e{-5}$	kilogram
Hydrocarbons, aliphatic, alkanes, unspecified (to air)	$1.21e{-3}$	kilogram
[R.15] *Refrigerating accessory production*		
Economic inputs		
steel, chromium steel 18/8	2.17	kilogram
aluminium, primary, ingot	$6.08e{-1}$	kilogram
copper cake	$5.00e{-2}$	kilogram
Economic outputs		
refrigerating accessory	1.00	unit

Table C.6: Inventory data for the production of a household refrigerator. - continued from previous page

Flow name	Quantity	Unit
[R.16] *Final assembly refrigerator*		
Economic inputs		
corrugated board box	3.92	kilogram
compressed air, 1000 kPa gauge	2.55	cubic meter
polystyrene, expandable	1.70	kilogram
electricity, medium voltage	1.13	kilowatt hour
refrigerator door	1.00	unit
refrigerator cabinet	1.00	unit
injection moulding shelves drawers	1.00	unit
compressor	1.00	unit
refrigerating accessory	1.00	unit
magnetite	$4.79e{-1}$	kilogram
chemical, inorganic	$3.51e{-1}$	kilogram
synthetic rubber	$2.87e{-1}$	kilogram
isobutane	$5.00e{-2}$	kilogram
Economic outputs		
household refrigerator	1.00	unit
disposal process refrigerator	1.00	unit
fly ash and scrubber sludge	$5.40e{-5}$	kilogram
Environmental outputs		
to air:		
Hydrocarbons, aliphatic, alkanes, unspecified	$1.00e{-3}$	kilogram
[R.17] *Disposal process refrigerator*		
Economic inputs		
disposal process refrigerator	1.00	unit
Economic outputs		
used refrigerant R-600a	$5.00e{-2}$	kilogram
waste rubber, unspecified	$2.87e{-1}$	kilogram
waste polyvinylchloride	$4.67e{-1}$	kilogram
scrap copper	1.31	kilogram
municipal solid waste	1.44	kilogram
scrap aluminium	2.19	kilogram
waste paperboard	3.92	kilogram
waste polystyrene	$1.19e{+1}$	kilogram
waste polyurethane foam	$1.20e{+1}$	kilogram
scrap steel	$1.61e{+1}$	kilogram

Table C.7: Inventory data for the product system of the paper microfluidic device.

Flow name	Quantity	Unit
[A2.1] *Stamp production*, based on [45].		
Economic inputs		
steel, chromium steel 18/8, hot rolled	$7.18e-2$	kilogram
chromium steel removed by milling, small parts	$2.15e-2$	kilogram
Economic outputs		
stamp	1.00	unit
[A2.2] *Immersion process for 1 paper device*, based on [45, 80].		
Economic inputs		
paraffin	$4.66e-1$	kilogram
electricity, medium voltage	$1.35e-1$	kilogram
Economic outputs		
immersion for 1 paper device	1.00	unit
municipal solid waste	$2.33e-1$	kilogram
[A2.3] *Chitosan in acetic acid solution preparation*, based on [2, 80].		
Economic inputs		
water, ultrapure	$9.77e-1$	kilogram
electricity, medium voltage	$3.00e-1$	kilowatt hour
transport, freight, sea, container ship	$7.11e-2$	ton kilometre
acetic acid, without water, in 98% solution state	$2.10e-2$	kilogram
chitosan [1]	$5.00e-3$	kilogram
Economic outputs		
chitosan solution	1.00	litre
[A2.4] *Applying chitosan solution*, based on [2].		
Economic inputs		
pipette[2]	$1.10e-3$	kilogram
chitosan solution	$3.00e-6$	litre
Economic outputs		
chitosan application for 1 paper device	1.00	unit
[A2.5] *Manufacturing paper microfluidic device*, based on [2, 45, 80].		
Economic inputs		
immersion	1.00	unit
chitosan application	1.00	unit
filter paper	$1.96e-3$	kilogram
electricity, medium voltage	$1.30e-3$	unit
stamp	$2.00e-4$	kilowatt hour
Economic outputs		
paper microfluidic device	1.00	unit
[A2.6] *Preparing reagent for paper device*, based on [2].		
Economic inputs		
water, ultrapure	1.00	kilogram
chemical, organic (proxy for DHBS)	$2.12e-3$	kilogram
pyrazole (proxy for 4-AAP)	$8.13e-4$	kilogram
Economic outputs		
reagent solution for paper device	1.00	liter

Table C.7: Inventory data for the product system of the paper microfluidic device. - continued from previous page

Flow name	Quantity	Unit
[A2.7] *Preparing glucose assay for paper device*, based on [2].		
Economic inputs		
glucose oxidase[3]	$1.20e{+}5$	unit
pipette[2]	1.10	kilogram
phosphate buffer solution 0.1M pH6.0[4]	1.00	liter
enzymes (proxy for horseradish peroxidase)	$1.20e{-}4$	kilogram
Economic outputs		
glucose assay solution for paper device	1.00	liter
[A2.8] *Detecting glucose using paper device*, based on [2].		
Economic inputs		
paper microfluidic device	1.00	unit
pipette[2]	$3.30e{-}3$	kilogram
reagent solution for paper device	$1.00e{-}6$	liter
glucose assay for paper device	$1.00e{-}6$	liter
Economic outputs		
run of detecting glucose using paper device	1.00	unit
waste plastic, mixture	$3.30e{-}3$	kilogram
waste packaging paper	$3.62e{-}4$	kilogram

[1] Inventory data shown in Table C.9 for chitosan.

[2] Inventory data shown in Table C.11 for pipette production (duplicate process).

[3] Inventory data shown in Table C.12 for glucose oxidase production (duplicate process).

[4] Inventory data shown in Table C.8 for chemicals required in the paper microfluidic device product system.

Table C.8: Inventory data for chemicals required in the product system of the paper microfluidic device.

Flow name	Quantity	Unit
[A2.C.1] *Monopotassium diphosphate production*, based on [91].		
Economic inputs		
utilities[1]	1.00	unit
phosphoric acid, industrial grade, w/o water, in 85% soln state	$9.35e{-}1$	kilogram
potassium chloride	$7.11e{-}1$	kilogram
Economic outputs		
monopotassium diphosphate	1.00	kilogram
hydrochloric acid	$2.68e{-}1$	kilogram
[A2.C.2] *Monopotassium phosphate, 1 M solution preparation*, based on [2].		
Economic inputs		
water, ultrapure	$9.98e{-}1$	kilogram
monopotassium diphosphate	$1.36e{-}1$	kilogram
Economic outputs		
monopotassium phosphate, 1 M solution	1.00	liter
[A2.C.3] *Dipotassium phosphate production*, based on [91].		
Economic inputs		
potassium hydroxide	$7.40e{-}1$	kilogram
phosphoric acid, industrial grade, w/o water, in 85% soln state	$6.47e{-}1$	kilogram
Economic outputs		
dipotassium phosphate	1.00	kilogram

Table C.8: Inventory data for chemicals required for the paper device. - continued from previous page

Flow name	Quantity	Unit
[A2.C.4] *Dipotassium phosphate, 1 M solution preparation*, based on [2].		
Economic inputs		
water, ultrapure	$9.98e{-1}$	kilogram
dipotassium phosphate	$1.74e{-1}$	kilogram
Economic outputs		
dipotassium phosphate, 1 M solution	1.00	liter
[A2.C.5] *Phosphate buffer solution production 0.1 M ph6.0*, based on [2, 92].		
Economic inputs		
water, ultrapure	$8.97e{-1}$	kilogram
monopotassium phosphate, 1 M solution	$8.68e{-2}$	liter
dipotassium phosphate, 1 M solution	$1.32e{-2}$	liter
Economic outputs		
phosphate buffer solution 0.1 M pH 6.0	1.00	liter

[1] Inventory data shown in Table C.11 for utilities (duplicate process).

Table C.9: Inventory data for chitosan production, required in the product system of the paper microfluidic device. Based on the work of Riofrio, Alcivar and Baykara [74].

Flow name	Quantity	Unit
[CS.1] *Cane sugar production*		
Economic inputs		
electricity, high voltage	$3.46e{-2}$	kilowatt hour
urea	$3.06e{-3}$	kilogram
diammonium phosphate	$1.43e{-3}$	kilogram
diesel, low-sulfur	$4.03e{-4}$	kilogram
Economic outputs		
cane sugar	1.00	kilogram
bagasse, from sugarcane (by-product)	$1.50e{-1}$	kilogram
Environmental inputs		
from natural resources, in water:		
Water, river	$2.99e{-1}$	cubic meter
from natural resources, land:		
Transformation, to permanent crop	$1.25e{-1}$	square meter
Environmental outputs		
to air (low population density, long-term):		
Carbon dioxide, fossil	$6.88e{-2}$	kilogram
[CS.2] *Molasses production*		
Economic inputs		
cane sugar	$4.32e{+1}$	kilogram
steam, in chemical industry	8.68	kilogram
electricity, high voltage	$5.07e{-1}$	kilowatt hour
quicklime, in pieces, loose	$3.43e{-2}$	kilogram
sulfur	$1.10e{-2}$	kilogram
tap water	$6.60e{-3}$	kilogram
Economic outputs		
molasses	1.00	kilogram
husks (by-product)	1.83	kilogram
sugar (by-product)	2.50	kilogram
Environmental outputs		
to air:		
Carbon dioxide, fossil	$2.06e{+2}$	kilogram

Table C.9: Inventory data for chitosan. - continued from previous page

Flow name	Quantity	Unit
[CS.3] *Ethanol, 85% production*		
Economic inputs		
molasses	2.93	kilogram
steam, in chemical industry	1.76	kilogram
electricity, high voltage	9.17e−1	kilowatt hour
urea	5.20e−4	kilogram
Economic outputs		
ethanol, 85%	1.00	kilogram
Environmental inputs		
from natural resources, in water:		
Water, river	1.04e−2	cubic meter
[CS.4] *Shrimp farming*		
Economic inputs		
calcium carbonate, precipitated	3.03	kilogram
electricity, low voltage	1.83	kilowatt hour
sodium hypochlorite, w/o water, in 15% soln state	3.43e−1	kilogram
urea	7.07e−2	kilogram
diesel	2.36e−2	kilogram
concrete block	4.73e−3	kilogram
polyvinylchloride, emulsion polymerised	4.33e−3	kilogram
Economic outputs		
shrimp shell	1.00	kilogram
shrimp meat (by-product)	2.33	kilogram
Environmental inputs		
from natural resources, in water:		
Water, unspecified natural origin	7.00e−3	cubic meter
Water, salt, ocean	4.33e−2	cubic meter
Environmental outputs		
to water:		
Nitrogen	1.27e−1	kilogram
BOD5, Biological Oxygen Demand	7.00e−2	kilogram
Phosphorus	1.33e−2	kilogram
Ammonium, ion	−6.33e−5	kilogram
Suspended solids, unspecified	−2.73e−2	kilogram
[CS.5] *Chitosan production*		
Economic inputs		
shrimp shell	1.58e+1	kilogram
sodium hydroxide, w/o water, in 50% soln state	5.13	kilogram
ethanol, 85%	1.92	kilogram
hydrochloric acid, w/o water, in 30% soln state	1.40	kilogram
natural gas, high pressure	9.01e−1	cubic meter
electricity, medium voltage	3.15e−2	kilowatt hour
Economic outputs		
chitosan	1.00	kilogram
hazardous waste, for incineration	4.05e−2	kilogram
alkaline wastewater	3.92e+1	kilogram
acid wastewater	4.23e+1	kilogram
Environmental inputs		
from natural resources, land:		
Occupation, industrial area	3.96e−2	square meter-year
from natural resources, in ground:		
Water, unspecified natural origin	2.07e−1	cubic meter

Table C.9: Inventory data for chitosan. - continued from previous page

Flow name	Quantity	Unit
Environmental outputs		
to air (low population density, long-term):		
Carbon dioxide, fossil	$9.01e{-1}$	kilogram
Carbon dioxide, non-fossil	$-7.39e{-1}$	kilogram
to water:		
Ethanol	$3.83e{-2}$	kilogram
[CS.6] *Acid wastewater treatment*		
Economic inputs		
acid wastewater	1.00	kilogram
sodium bicarbonate	$3.18e{-2}$	kilogram
Economic outputs		
wastewater, unpolluted	$9.46e{-4}$	cubic meter
Environmental outputs		
to air (low population density, long-term):		
Carbon dioxide, fossil	$9.36e{-4}$	kilogram
[CS.7] *Alkaline wastewater treatment*		
Economic inputs		
alkaline wastewater	1.00	kilogram
sodium bicarbonate	$7.84e{-4}$	kilogram
hydrochloric acid, w/o water, in 30% soln state	$3.36e{-4}$	kilogram
Economic outputs		
hazardous waste, for incineration	$1.64e{-2}$	kilogram
wastewater, unpolluted	$9.75e{-4}$	cubic meter
Environmental outputs		
inventory indicator - waste:		
Non-hazardous waste disposed	$3.43e{-2}$	kilogram
to air (low population density, long-term):		
Carbon dioxide, non-fossil	$1.93e{-2}$	kilogram
Carbon dioxide, fossil	$4.48e{-4}$	kilogram
Ammonia	$3.43e{-4}$	kilogram
Nitrogen oxides	$1.64e{-4}$	kilogram
Dinitrogen monoxide	$1.57e{-5}$	kilogram

Table C.10: Inventory data for the product system of the PLA microfluidic device.

Flow name	Quantity	Unit
[A3.4] *Spool reel production*, based on [93].		
Economic inputs		
polypropylene, granulate	1.00	kilogram
injection moulding	1.00	kilogram
Economic outputs		
spool reel	1.00	kilogram
[A3.5] *PLA filament production*, based on [93].		
Economic inputs		
extrusion, plastic pipes	$7.53e{-1}$	kilogram
polylactide, granulate	$7.53e{-1}$	kilogram
spool reel	$2.50e{-1}$	kilogram
Economic outputs		
PLA filament	1.00	kilogram

Table C.10: Inventory data for the product system of the PLA microfluidic device. - continued from previous page

Flow name	Quantity	Unit
[A3.1] *Alloying silicon steel*, based on [94].		
Economic inputs		
steel, unalloyed	$9.79e{-1}$	kilogram
ferrosilicon	$2.70e{-2}$	kilogram
aluminium, primary, ingot	$4.00e{-3}$	kilogram
Economic outputs		
silicon steel	1.00	kilogram
[A3.2] *Silicon steel sheet production*, based on [94].		
Economic inputs		
silicon steel	1.14	kilogram
hot rolling, steel	1.14	kilogram
electricity, medium voltage	$6.30e{-1}$	kilowatt hour
sulfuric acid	$1.90e{-2}$	kilogram
liquefied petroleum gas	$1.20e{-2}$	kilogram
phenolic resin	$1.00e{-3}$	kilogram
quicklime, milled, packed	$8.00e{-4}$	kilogram
lubricating oil	$4.00e{-4}$	kilogram
Economic outputs		
silicon steel sheet	1.00	kilogram
scrap steel	$1.14e{-4}$	kilogram
hazardous waste, for incineration	$3.30e{-3}$	kilogram
Environmental outputs		
to air:		
Carbon dioxide, fossil	$3.60e{-2}$	kilogram
Nitrogen oxides	$1.00e{-4}$	kilogram
Sulfur dioxide	$6.00e{-5}$	kilogram
[A3.3] *3D printer production*, based on [95].		
Economic inputs		
metal working, average for steel product mfg.	$9.41e{+1}$	kilogram
steel, low-alloyed	$8.95e{+1}$	kilogram
injection moulding	$3.27e{+1}$	kilogram
polycarbonate	$3.27e{+1}$	kilogram
wire drawing, copper	8.35	kilogram
cable, network cable, category 5, without plugs	6.00	meter
silicon steel sheet	4.60	kilogram
flat glass, uncoated	3.11	kilogram
polyurethane, flexible foam	2.30	kilogram
fan, for power supply unit, desktop computer	2.22	kilogram
cable, connector for computer, without plugs	2.00	meter
extrusion, plastic pipes	1.73	kilogram
polyvinylchloride, bulk polymerised	1.68	kilogram
computer, desktop, without screen	1.00	unit
metal working, avg for chromium steel product mfg.	$4.53e{-1}$	kilogram
steel, chromium steel 18/8	$4.53e{-1}$	kilogram
display, liquid crystal, 17 inches	$2.00e{-1}$	unit
light emitting diode	$2.00e{-1}$	kilogram
aluminium, cast alloy	$1.39e{-1}$	kilogram
synthetic rubber	$7.70e{-2}$	kilogram
acrylonitrile-butadiene-styrene copolymer	$5.10e{-2}$	kilogram
printed wiring board, SMT, unspecified, Pb free	$9.00e{-3}$	kilogram
Economic outputs		
3D printer	1.00	unit

Table C.10: Inventory data for the product system of the PLA microfluidic device. - continued from previous page

Flow name	Quantity	Unit
[A3.6] *3D printing PLA microfluidic device*, based on [3] and primary data.		
Economic inputs		
electricity, medium voltage, from scenario	6.32	kilowatt hour
PLA filament	$1.40e{-2}$	kilogram
3D printer	$4.10e{-4}$	unit
Economic outputs		
PLA microfluidic device	1.00	unit
[A3.7] *Preparing glucose assay reagent solution for PLA device, based on [3].*		
Economic inputs		
glucose oxidase[1]	$2.00e{+4}$	unit
naphthalene sulfonic acid (proxy for CTA)	$1.28e{-2}$	kilogram
pyrazole (proxy for 4-AAP)	$4.06e{-3}$	kilogram
enzyme (proxy for horseradish peroxidase)	$2.40e{-5}$	kilogram
Economic outputs		
glucose assay reagent solution for PLA device	1.00	litre
[A3.8] *Detecting glucose using PLA device*, based on [3].		
Economic inputs		
PLA microfluidic device	1.00	unit
pipette[2]	$1.10e{-3}$	kilogram
electricity, medium voltage, from scenario	$3.83e{-4}$	kilowatt hour
disk drive, CD/DVD, ROM, for desktop computer	$3.70e{-4}$	unit
glucose assay reagent solution for PLA device	$9.20e{-5}$	litre
Economic outputs		
run of detecting glucose using PLA device	1.00	unit
municipal solid waste	$1.51e{-2}$	kilogram

[1] Inventory data shown in Table C.12 for glucose oxidase production.

[2] Inventory data shown in Table C.11 for pipette production (duplicate process).

Table C.11: Inventory data for unit processes required in multiple product systems.

Flow name	Quantity	Unit
[D.1] *Filter paper production*, based on [33].		
Economic inputs		
heat, district or industrial, natural gas	$5.00e{+1}$	megajoule
sulfuric acid	1.27	kilogram
cellulose fibre	$9.47e{-1}$	kilogram
acetone, liquid	$7.85e{-1}$	kilogram
nitric acid, w/o water, in 50% soln state	$6.36e{-1}$	kilogram
electricity, medium voltage	$1.51e{-1}$	kilowatt hour
carboxymethyl cellulose, powder	$6.98e{-3}$	kilogram
Economic outputs		
filter paper	1.00	kilogram
[D.2] *Pipette production*, based on [96].		
Economic inputs		
polypropylene, granulate	1.01	kilogram
injection moulding	1.01	kilogram
electricity, medium voltage	$4.26e{-1}$	kilowatt hour
plastic processing factory	$7.40e{-10}$	unit
Economic outputs		
pipette	1.00	kilogram
waste polypropylene	$5.68e{-3}$	kilogram

Table C.11: Inventory data for unit processes required in multiple product systems. - continued from previous page

Flow name	Quantity	
[D.3] *Utilities*, based on [44].		
Economic inputs		
heat, from steam, in chemical industry	7.70	megajoule
electricity, medium voltage	1.67e−1	kilowatt hour
heat, district or industrial, natural gas	1.50e−1	megajoule
chemical factory, organics	4.00e−10	unit
Economic outputs		
utilities	1.00	unit
heat, from steam, in chemical industry	1.60	megajoule

Table C.12: Inventory data for glucose oxidase production, which is required in multiple product systems.

Flow name	Quantity	Unit
[G.1] *Magnesium hydroxide production from seawater*		
Economic inputs		
lime	1.27	kilogram
water pump operation, electric	1.00e−3	megajoule
building machine	1.00e−8	unit
Economic outputs		
magnesium hydroxide	1.00	kilogram
Environmental inputs		
Occupation, seabed, unspecified (natural resource - land)	7.32e+4	square meter-year
Water, salt, sole (natural resource - in water)	3.20e+3	cubic meter
Environmental outputs		
Calcium, ion (to water)	6.87e−1	kilogram
[G.2] *Epsom salt production*		
Economic inputs		
electricity, medium voltage	1.31e+1	kilowatt hour
steam, in chemical industry	7.48	kilogram
tap water	1.00	kilogram
magnesium hydroxide	4.00e−1	kilogram
sulfuric acid	3.70e−1	kilogram
magnesium sulfate	9.00e−2	kilogram
Economic outputs		
epsom salt production	1.00	kilogram
wastewater, average	1.17e−3	cubic meter
Environmental outputs		
Water, unspecified natural origin (to water)	5.78e−2	cubic meter
[G.3] *Glucose oxidase medium production*		
Economic inputs		
water, ultrapure	1.00	kilogram
glucose	8.00e−2	kilogram
heat, district or industrial, natural gas	5.40e−2	megajoule
calcium carbonate, precipitated	3.50e−2	kilogram
chemical, organic	3.00e−2	kilogram
diammonium phosphate	3.88e−4	kilogram
monopotassium diphosphate	1.88e−4	kilogram
epsom salt production	1.56e−4	kilogram
Economic outputs		
glucose oxidase	3.00e+4	unit

D

Contribution analysis

The numerical values for the contribution analysis discussed in Section 7.3 are provided here. These results are split up between the most contributing unit processes and economic flows. Those for the PDMS device are shown in Table D.1 and Table D.2 respectively. For the paper device, the analysis results are shown in Table D.3 and Table D.4 respectively, while for the PLA device they are shown in Table D.5 and Table D.6 respectively.

Table D.1: Contribution analysis for the PDMS device, based on the unit processes of the product system.

Impact category	Applying and curing PDMS	Applying and curing PMMA	Oxygen plasma treatment	Final assembly refrigerator	Silicon mould production	Other
climate change	58.60%	5.25%	21.60%	4.76%	3.22%	6.57%
acidification	60.00%	5.37%	22.10%	4.91%		7.62%
ecotoxicity: freshwater	74.80%	2.55%	10.60%	8.07%		3.98%
eutrophication: freshwater	60.80%	5.87%	24.10%			9.23%
eutrophication: marine	58.50%	5.15%	21.10%	7.75%		7.50%
eutrophication: terrestrial	59.80%	5.17%	21.30%	6.23%		7.50%
human toxicity: carcinogenic	25.20%		8.29%	60.20%		6.31%
human toxicity: non-carcinogenic	55.30%	4.54%	18.80%	14.50%		6.86%
ionising radiation: human health	61.20%	5.98%	24.60%			8.22%
land use	60.20%	5.21%	21.50%	5.47%		7.62%
material resources: metals/minerals	44.40%	3.12%	13.80%	27.80%	5.63%	5.25%
ozone depletion	95.50%				4.03%	0.47%
particulate matter formation	53.70%	3.58%	14.80%	21.90%		6.02%
photochemical ozone formation	59.60%	5.08%	20.90%	6.90%		7.52%

Table D.2: Contribution analysis for the PDMS device based on the economic flows in the product system.

Impact category	Electricity, medium voltage	Oxygen, liquid	PDMS	Various refrigerator parts	Refrigerator disposal	Other
climate change	65.80%	21.00%	4.98%			8.22%
acidification	67.20%	21.40%	5.59%			5.81%
ecotoxicity: freshwater	25.90%	10.20%	48.90%	5.91%		9.09%
eutrophication: freshwater	73.40%	23.40%				3.20%
eutrophication: marine	64.50%	20.60%	5.95%	2.03%	3.00%	3.92%
eutrophication: terrestrial	64.80%	20.70%	7.33%			7.17%
human toxicity: carcinogenic	24.60%		4.99%	58.77%		11.64%
human toxicity: non-carcinogenic	56.80%	18.20%	9.16%	11.33%		4.51%
ionising radiation: human health	74.90%	23.80%				1.30%
land use	65.30%	20.90%	7.24%			6.56%
material resources: metals/minerals	39.10%	13.40%	12.70%	25.78%		9.02%
ozone depletion			94.70%			5.30%
particulate matter formation	44.80%	14.30%	17.00%	11.22%	7.65%	5.03%
photochemical ozone formation	63.60%	20.30%	7.97%			8.13%

Table D.3: Contribution analysis for the paper device, based on the unit processes of the product system.

Impact category	Immersion process	Pipette production	Filter paper production	Other
climate change	94.90%	1.98%	2.04%	1.08%
acidification	95.60%	1.56%	2.15%	0.69%
ecotoxicity: freshwater	98.60%			1.40%
eutrophication: freshwater	94.20%	2.78%		3.02%
eutrophication: marine	96.90%			3.10%
eutrophication: terrestrial	96.10%			3.90%
human toxicity: carcinogenic	95.90%			4.10%
human toxicity: non-carcinogenic	95.20%	2.38%		2.42%
ionising radiation: human health	92.60%	3.25%	2.33%	1.82%
land use	94.40%	3.26%		2.34%
material resources: metals/minerals	93.40%	2.72%	2.89%	0.99%
ozone depletion	90.10%	2.71%	6.02%	1.17%
particulate matter formation	96.70%			3.30%
photochemical ozone formation	96.10%	1.63%		2.27%

Table D.4: Contribution analysis for the paper device, based on the economic flows in the product system.

Impact category	Paraffin wax	Electricity, medium voltage	Municipal solid waste	Other
climate change	57.00%	8.86%	28.70%	5.44%
acidification	85.00%	8.40%	2.32%	4.28%
ecotoxicity: freshwater	31.50%	2.69%	64.60%	1.21%
eutrophication: freshwater	47.10%	40.58%	6.96%	5.36%
eutrophication: marine	65.30%	6.41%	25.30%	2.99%
eutrophication: terrestrial	84.50%	6.63%	5.04%	3.83%
human toxicity: carcinogenic	51.60%	4.47%	39.90%	4.03%
human toxicity: non-carcinogenic	65.00%	8.74%	21.60%	4.66%
ionising radiation: human health	17.80%	74.30%		7.90%
land use	77.50%	10.39%	6.67%	5.44%
material resources: metals/minerals	91.10%			8.90%
ozone depletion	69.30%	14.13%	6.88%	9.69%
particulate matter formation	84.40%	2.20%	10.20%	3.20%
photochemical ozone formation	85.10%	5.40%	5.70%	3.80%

Table D.5: Contribution analysis for the PLA device, based on the unit processes of the product system.

Impact category	3D Printing PLA device	Other
climate change	99.20%	0.80%
acidification	99.50%	0.50%
ecotoxicity: freshwater	96.60%	3.40%
eutrophication: freshwater	99.60%	0.40%
eutrophication: marine	99.10%	0.90%
eutrophication: terrestrial	99.30%	0.70%
human toxicity: carcinogenic	98.80%	1.20%
human toxicity: non-carcinogenic	98.80%	1.20%
ionising radiation: human health	99.90%	0.10%
land use	99.30%	0.70%
material resources: metals/minerals	94.40%	5.60%
ozone depletion	99.10%	0.90%
particulate matter formation	98.90%	1.10%
photochemical ozone formation	99.30%	0.70%

Table D.6: Contribution analysis for the PLA device based on the economic flows in the product system.

Impact category	3D printer	Electricity, medium voltage	PLA filament	Optical disk drive	Other
climate change	15.50%	82.00%			2.50%
acidification	15.70%	81.90%			2.40%
ecotoxicity: freshwater	43.10%	50.80%	2.76%	1.56%	1.78%
eutrophication: freshwater	8.88%	90.00%			1.12%
eutrophication: marine	19.10%	76.80%	3.21%		0.89%
eutrophication: terrestrial	18.80%	77.30%	3.29%		0.61%
human toxicity: carcinogenic	58.50%	39.30%			2.20%
human toxicity: non-carcinogenic	40.40%	56.70%			2.90%
ionising radiation: human health	2.22%	97.40%			0.38%
land use	17.20%	77.30%	4.86%		0.64%
material resources: metals/minerals	81.90%	11.80%		5.50%	0.80%
ozone depletion	15.90%	81.00%	2.16%		0.94%
particulate matter formation	44.60%	51.00%	3.26%		1.14%
photochemical ozone formation	21.90%	75.00%	2.44%		0.66%

E

Sensitivity analysis

The robustness of the results is tested using a sensitivity analysis. Here, the influence of different modelling choices and assumptions is investigated, to determine whether a different set of circumstances will drastically change the overall results.

E.1. Different characterisation factors

To check whether the results are independent of the characterisation models and factors, a different family of impact categories is used. Here, the investigation is concerned with whether the alternatives' performance is still ranked similarly in the chosen impact categories.

The LCIA was initially performed using the EF family of impact categories, which was deliberated on in Chapter 4. For the sensitivity analysis, the impact assessment will be conducted using the ReCiPe family instead. The ReCiPe method was first developed in 2008 in a collaboration between the RIVM (the Dutch National Institute for Public Health and the Environment), Radboud University Neimegen, Leiden University, and Pré Consultants [97]. In 2016, the method was updated such that it would be in accordance with the most recent scientific knowledge. The ReCiPe method provides estimates for environmental impacts using midpoint indicators – where the focus is on single environmental issues, like climate change – and endpoint indicators – where the focus is on an aggregated area, like damage to ecosystems. Here, the sensitivity analysis is performed using the midpoint indicator over a 100 year timeline. This was chosen to ensure comparability between the EF results and the ReCiPe results.

The characterisation results determined by using the ReCiPe family are shown in Figure E.1. ReCiPe impact categories were chosen based on their similarity to the EF impact categories. The overall results are similar to those generated with the EF characterisation model. The paper device performs best in all categories, whereas the PLA device has the most impact in all categories, except for *ozone depletion*, where the PDMS device performs the worst.

The results can not always be compared based on their values, given that ReCiPe uses other units. Values for impact categories that can be compared based on their units are shown in Table E.1. For these six categories, it seems some characterisation factors are similar between the two impact assessment methods, with *climate change, marine eutrophication* and *ozone depletion* being the exception.

The largest difference in characterisation values is seen in the category *ozone depletion*. This difference can be explained by the fact that the two methods have different characterisation factors

Table E.1: Comparison between characterisation results for the EF and ReCiPe characterisation methods, for impact categories with the same unit.

Impact category	Unit	PDMS	Paper	PLA
Environmental Footprint				
climate change	kg CO2-Eq	2.26	$5.98e{-1}$	2.99
eutrophication: freshwater	P	$2.00e{-3}$	$1.29e{-4}$	$2.70e{-3}$
eutrophication: marine	kg N-Eq	$2.14e{-3}$	$7.68e{-4}$	$2.97e{-3}$
ionising radiation: human health	kBq U235-Eq	1.16	$4.16e{-2}$	1.47
ozone depletion	kg CFC-11-Eq	$8.28e{-6}$	$1.86e{-8}$	$1.49e{-7}$
photochemical ozone formation	kg NMVOC-Eq	$5.14e{-3}$	$2.16e{-3}$	$7.21e{-3}$
ReCiPe				
climate change	kg CO2-Eq	2.20	$5.53e{-1}$	2.91
freshwater eutrophication	kg P-Eq	$2.01e{-3}$	$1.33e{-4}$	$2.71e{-3}$
marine eutrophication	kg N-Eq	$2.26e{-3}$	$9.28e{-4}$	$2.99e{-3}$
ionising radiation	kg U235-Eq	1.16	$4.17e{-2}$	1.47
ozone depletion	kg CFC-11-Eq	$1.10e{-5}$	$1.59e{-8}$	$1.66e{-7}$
photochemical oxidant formation	kg NMVOC	$5.15e{-3}$	$2.17e{-3}$	$7.23e{-3}$

for the elementary flows. Additionally, the ReCiPe method has assigned characterisation factors to certain elementary flows, while the EF method has not. This can be seen in *ozone depletion* with the flow ‘chlorinated hydrocarbons’ for urbain air close to the ground. ReCiPe calculates the PDMS device’s impact, taking into account this flow, resulting in a higher value for *ozone depletion*. Similar explanations are true for the categories *climate change* and *marine eutrophication*.

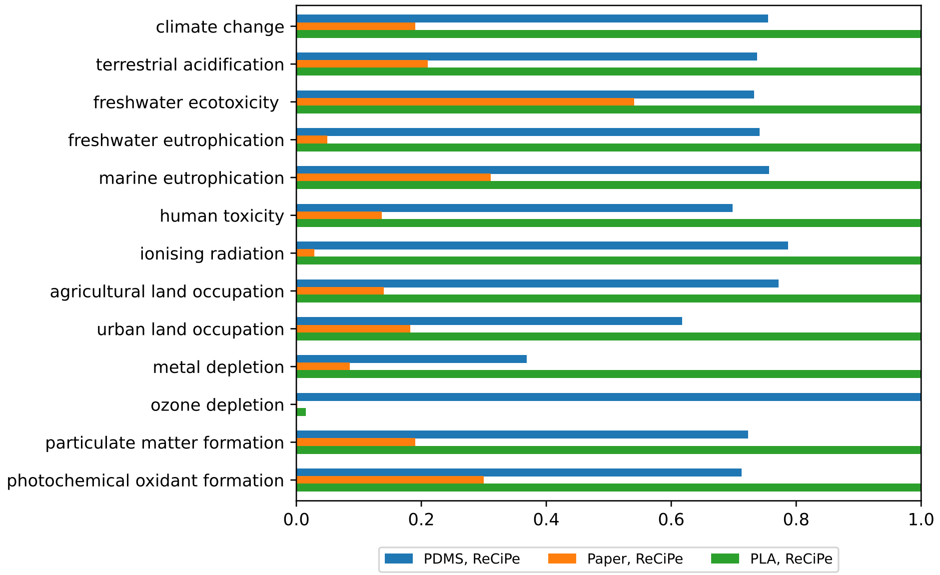


Figure E.1: Characterisation results for the PDMS, paper, and PLA device. These are shown relative to each impact category’s largest value. Different from the results calculated in Chapter 6, which used the EF characterisation model, these results were calculated based on the ReCiPe method.

E.2. Different electricity mix

The manufacturing processes for the microfluidic devices are energy intensive. As can be seen in Section 7.3, their environmental performance is highly dependent on electricity and its associated emissions. Given that the average electricity mix in Europe is largely made up out of fossil fuels, this sensitivity analysis investigates how the environmental performance of the devices may be improved if the electricity mix was $100\,\%$ renewable. This will be modelled by making the electricity mix fully based on wind energy. While this is not a realistic scenario, as an electricity mix based on renewables would reasonably also include other sources, the purpose of this sensitivity analysis is to investigate how much fossil fuel-based emissions contribute to the results.

This scenario is modelled based on the ecoinvent process “market for electricity, high voltage” in the Netherlands, using its values for transmission networks and conversions between high and medium voltage. In this scenario, it is assumed that $40\,\%$ is generated through offshore wind, while the rest is onshore. This is based on the current mix of installed capacity of wind power – where $27.97\,\%$ of the total is offshore [98] – and the Dutch target to construct more offshore wind parks until 2030 [99].

The results are shown in Figure E.2, where it can be seen that an electricity mix based entirely on wind would have a significant impact. For impact categories where electricity contributed to a large share of a device’s impacts, environmental performance has improved. The PDMS, paper, and PLA device all experience improved performance. This is especially noticeable for the PLA device, whose performance was initially drastically worse than the other alternatives. The paper device experiences the least improvement, with many impact values remaining relatively unchanged.

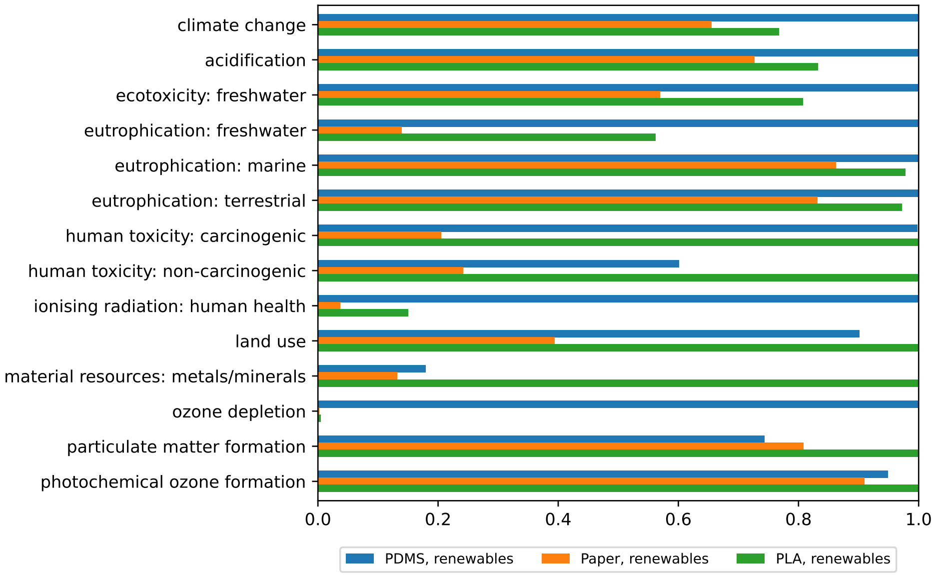


Figure E.2: Characterisation results for the PDMS, paper, and PLA device in the case that electricity is based entirely on wind energy, and therefore $100\,\%$ renewable. In this scenario, this change only pertains to electricity used during the manufacturing processes.

The PLA device’s now claims the number two position in the categories *climate change, acidification, freshwater ecotoxicity, freshwater eutrophication, marine eutrophication, terrestrial eutrophication*, and *ionising radiation*. Despite the improved performance, the PLA device still performs worst in the remaining categories. These are the categories where electricity was not the main contributor. In three categories, the difference in impact between the PDMS and PLA device is now very small.

The improvement is also clear for the PDMS device. The difference in magnitude of impacts between alternatives is generally smaller in several categories, with values being much closer to that of the paper device. This is true for the categories *climate change, acidification, marine eutrophication, terrestrial eutrophication, particulate matter formation*, and *photochemical ozone formation*. Meanwhile, the paper device is no longer always the best performer, as the PDMS device becomes favoured in the *particulate matter formation* category. In *photochemical ozone formation*, the paper device is only the best performer by a small margin.

Even when changing the electricity mix to one that is $100\,\%$ renewable, the paper device is favoured overall. However, it is not as clear-cut anymore how to rank the remaining two devices. It is certain environmental performance would be improved significantly for all devices, but the PLA device no longer consistently shoots out over the rest.

E.3. Different curing method for PDMS device

In this study, due to lack of detail in the reference paper, it was assumed that the PDMS was cured on a hotplate. Alternatively, PDMS can be cured in an oven. The potential difference in impacts between curing methods is investigated in this analysis.

Based on the electricity consumption of these two curing methods, it is immediately clear that choosing one or the other will have an impact on the total results. The electricity consumption of a 600 W hotplate used for 4 h was calculated to be $E_h = 2.4$ kW h. Conversely, the electricity consumption of an electric oven for the same amount of time was measured to be $E_o = 0.77$ kW h.

Implementing this change improves the environmental performance of the PDMS device significantly, which can be seen in Figure E.3. In some impact categories, the reduction in impact is as big as $41\,\%$. All impact categories see an improvement from implementing this change, except for ozone depletion. As was seen in the contribution analysis, the PDMS device's large impact in ozone depletion can mostly be attributed to the PDMS material itself.

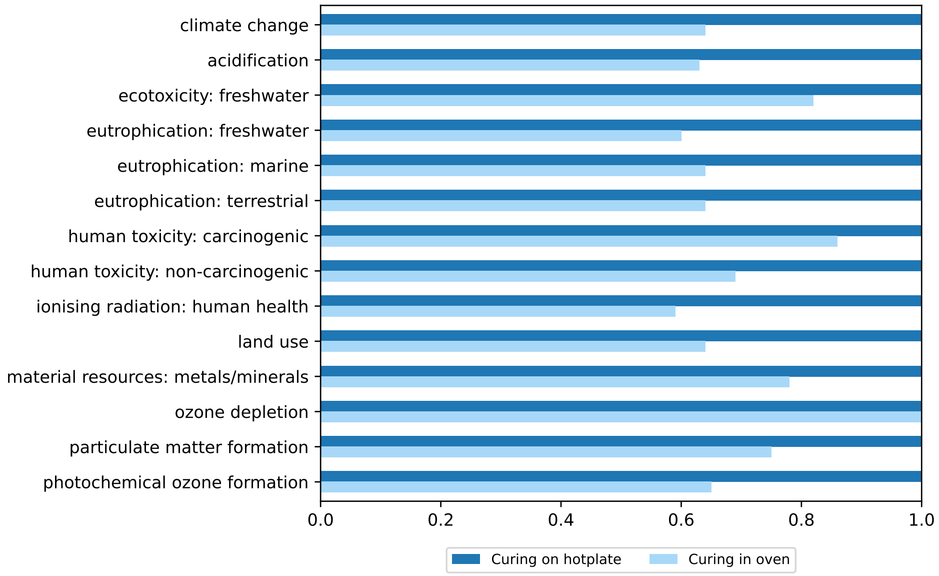


Figure E.3: Characterisation results for the PDMS device, where the equipment for curing is varied. In the original model, a hotplate is used. Here, the use of a hotplate is compared to the use of an oven.

While implementing this change improves the overall environmental performance of the PDMS device, it does not change the overall results of the comparative LCA. This can be seen in Figure E.4

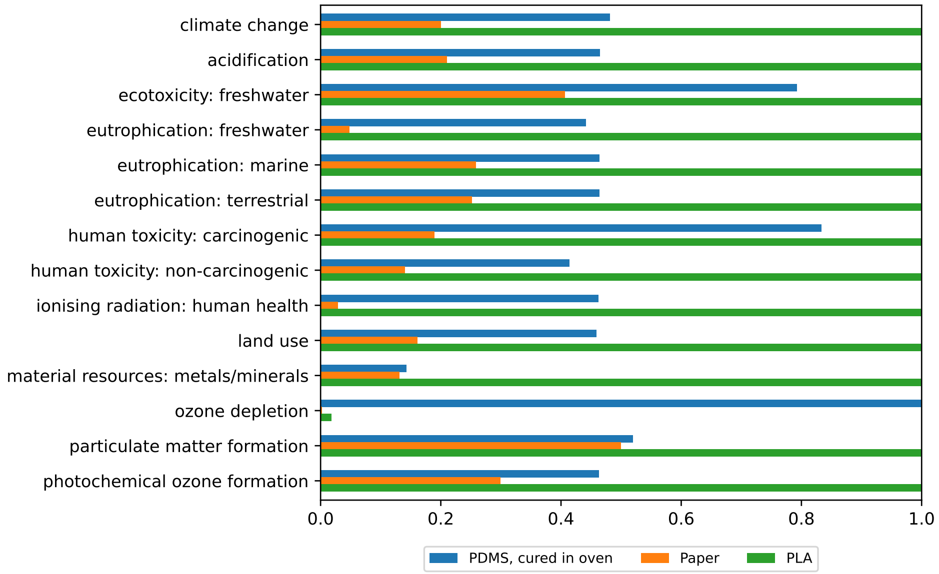


Figure E.4: Characterisation results for the PDMS, paper, and PLA device. Here, the PDMS device is cured using an oven rather than a hotplate, whereas no changes are made to the paper and PLA device.

E.4. Exclusion of material for machinery

Considering no LCI data was available for an oven, its material requirements were not included in the LCA model for the PLA device. This sensitivity analysis investigates to what degree the inclusion of material inputs for the 3D printer and refrigerator was influential to the overall results. For the paper device, no changes have been made, considering no big machinery is necessary for its manufacture. The characterisation results are shown in Figure E.5.

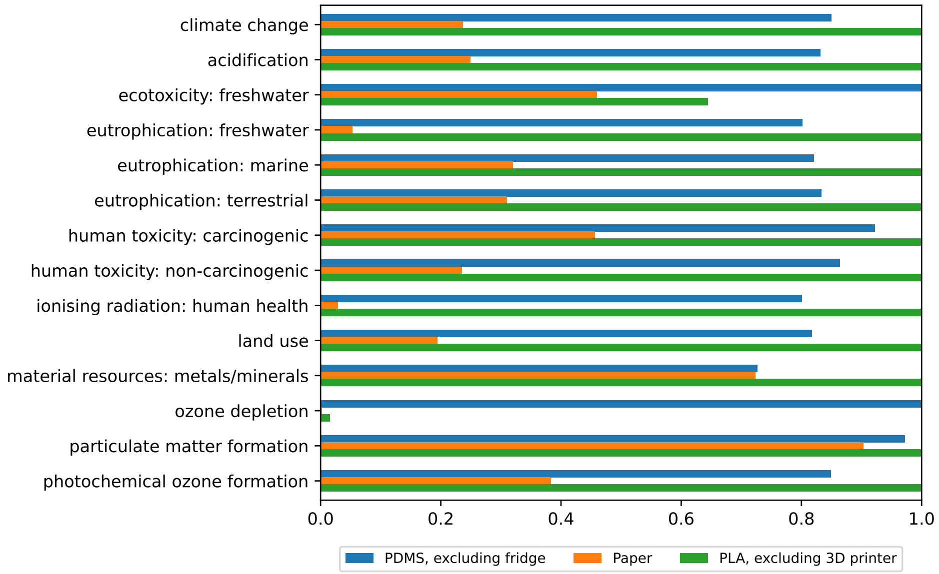


Figure E.5: Characterisation results for the PDMS, paper, and PLA device. Here, machinery like the refrigerator and the 3D printer are excluded. These changes affect the PDMS and PLA device. The paper device has undergone no changes.

Excluding the material input has logically decreased the impacts in all categories for the PDMS and PLA device. Where the PLA device used to be the worst performer in all categories except ozone depletion, it now becomes second best in the category *ecotoxicity: freshwater*. Here, the PDMS device becomes the worst performer.

This can be explained through the contribution analysis, which was also discussed in Section 7.3. Whereas the fridge contributed $8.69\,\%$ to freshwater ecotoxicity for the PDMS device, for the PLA device $43.1\,\%$ of impacts can be attributed to the 3D printer. For the PDMS device, the bulk of impacts is due to the PDMS material itself, which is unaffected by the exclusion of the refrigerator. It can then be stipulated that if the material inputs for an electric oven would have been included in the LCA model, it would only strengthen the position of the PLA device as the worst environmentally performing device.

E.5. Less paraffin wax wasted

Given the large contributions of paraffin wax to the impact categories for the paper device, it was investigated how wasting less might reduce the paper device's total impacts. The results are shown in Figure E.6. As expected, reducing how much wax is wasted also reduces the impacts.

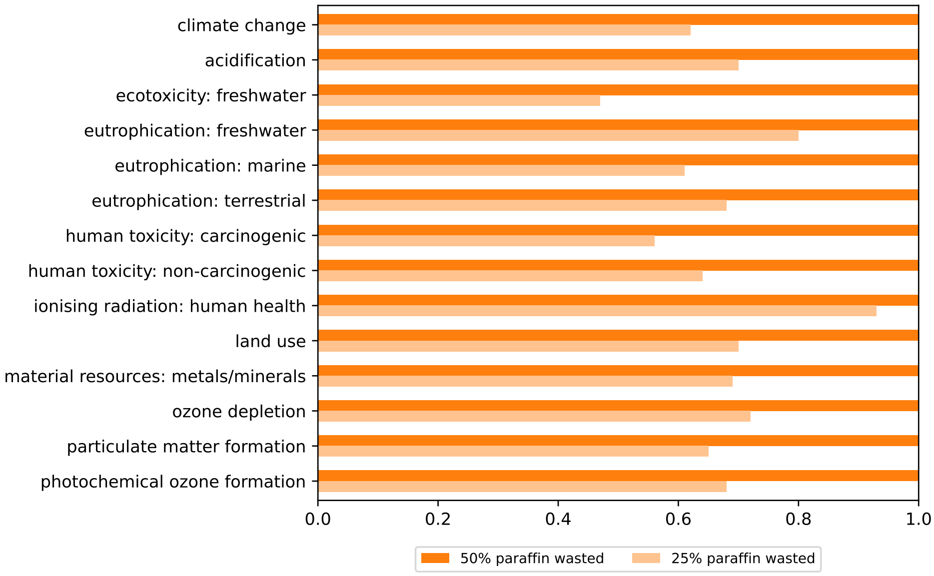


Figure E.6: Characterisation results for the paper device, shown for the case where 50% and 25% of paraffin is wasted. As expected, less waste results in a reduction of impacts across all categories.

E.6. Different design for PDMS device

The manufacturing of the PDMS device currently involves refrigerating the device, including the applied glucose assay, until the device is used. This to ensure that the enzymes in the reagents are preserved. Due to the PDMS device's design, the reagents cannot be applied before use, as the receiving filter paper is sealed off in the manufacturing process. In this analysis a different design is proposed, which would allow users to apply the reagents shortly before use. This would cut out the need for cooling, and any emissions that can be attributed to refrigeration.

The proposed design includes an individual, circular piece of filter paper, replacing the five pieces of filter paper in the current design. Additionally, by leaving an opening in the PDMS cover, such that the filter paper is exposed, a user would be able to apply reagents themselves right before use, rendering refrigeration unnecessary. In this design, additional calibration bars would need to be inserted such that the user applies the correct amount of reagent. However, for simplicity these bars will not be taken into account for the sensitivity analysis.

The results shown in Figure E.7 prove that cutting out refrigeration and associated processes – like transport and electricity consumption – reduces the environmental impact of the PDMS device. This reduction is clear in all impact categories, except for ozone depletion, where the PDMS material is the biggest contributor. The biggest improvement can be seen in the category human toxicity: carcinogenic, where the steel requirement for the refrigerator was the biggest contributor. In the remaining impact categories, other processes, like the PDMS application and oxygen plasma treatment, still rule.

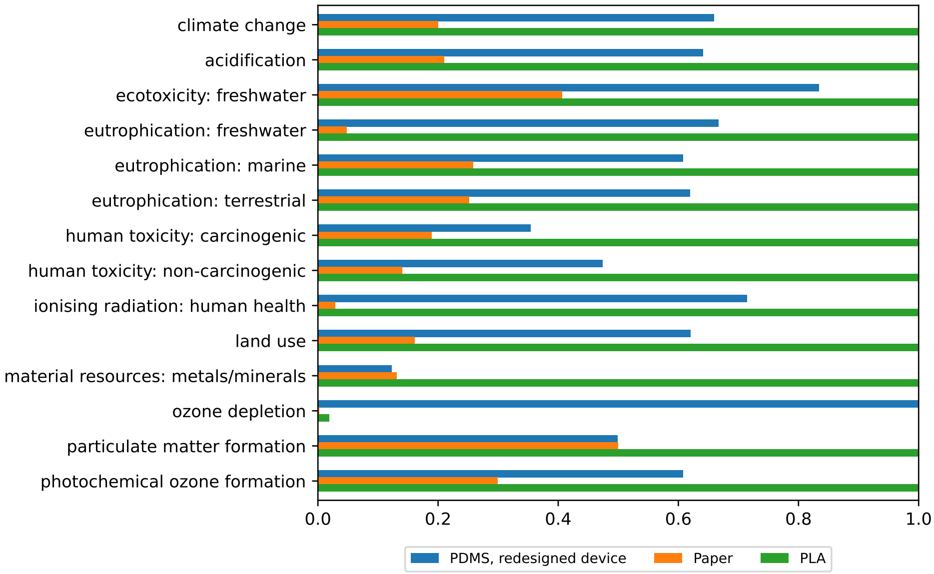


Figure E.7: Characterisation results for the PDMS, paper, and PLA device. Here, the PDMS device has been redesigned such that it does not require refrigeration before use. No other changes have been made to the paper and PLA device.

When comparing the new design of the PDMS device to the paper and PLA devices, there are few changes. PDMS is still the second best in most impact categories. However, in the category material resources: metals/minerals, the PDMS now beats the paper device by a small margin. There is also a small margin between the two devices in the category particulate matter formation. Changing the design of the PDMS device may improve its environmental performance, but not sufficiently to convincingly outperform the paper device.