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HEALTHCARE

Comparative life cycle assessment and implementation of disposable, biodegradable, and reusable absorbent mats in healthcare

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Abstract

Purpose Absorbent mats are widely used in healthcare, with around 23 million consumed annually in the Netherlands. These single-use products are typically discarded after use, making them non-circular. As healthcare transitions towards more sustainable practices, understanding the environmental impact of these mats and evaluating reusable alternatives is essential. This study aimed to compare the life cycle environmental impact of disposable and reusable absorbent mats to identify the most sustainable option for healthcare use.

Methods A comparative life cycle assessment (LCA) was conducted for three disposable absorbent mats (A, B, C) and one reusable mat (Reusable A), covering all stages from raw material extraction to end-of-life. The analysis included 18 environmental impact categories, such as climate change, land use, and material resource use, following ISO 14,040/44 standards. Inventory data were derived from (i) Ecoinvent database, (ii) industry data, (iii) measurement data, and (iv) literature. The sensitivity analysis tested the main assumptions, and two scenarios were assessed: a best-case and a worst-case scenario, defined by the parameter values identified in the sensitivity analysis for each absorbent mat.

Results and discussion Reusable A had the lowest environmental impact in 14 out of 18 categories, including climate change, where its footprint was 87 kg CO_2-equivalents, compared to 266, 202, and 150 kg CO_2-eq. for Disposable A, B, and C, respectively. The reduced impact of the reusable mat was mainly due to lower material requirements per functional unit, despite additional water and energy use for laundering. Sensitivity analysis confirmed that Reusable A remained the lowest-impact option in terms of carbon footprint across varying conditions. Scenario analysis showed potential further reductions of 29% in optimal washing conditions, while the worst-case scenario still resulted in a lower carbon footprint than the disposable option.

Conclusions The reusable absorbent mat demonstrated superior environmental performance compared to disposable alternatives, even under less favourable conditions. Transitioning from single-use to reusable mats could substantially reduce the environmental footprint of healthcare facilities.

Recommendations Hospitals should consider implementing reusable absorbent mats within broader circular procurement strategies.

Synopsis Absorbent mats in healthcare generate significant waste due to single-use designs. This study shows reusable mats have substantially lower environmental impacts, supporting sustainable transitions in healthcare product use.

Keywords Life cycle assessment · Absorbent mats · Environmental impact · Healthcare · Reusable · Circularity

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1 Introduction

Healthcare is essential for human well-being, yet it comes with a considerable environmental cost (Lenzen et al. 2020). In our efforts to care for patients, we inadvertently drive environmental changes on a global scale. Climate change, along with other forms of environmental degradation, such as air and water pollution, paradoxically exacerbates health risks for populations worldwide (Frumkin and Haines 2019, Agache et al. 2022). These impacts extend beyond humans, threatening biodiversity and the well-being of ecosystems across the planet (Weiskopf et al. 2020, Sintayehu 2018).

To address this issue and prioritise planetary health, significant changes are needed in the healthcare sector. One key step is transitioning towards a circular healthcare system (D'Alessandro et al. 2024). According to the R-ladder of circularity, the initial focus should be on 'refusing' and 'reducing' the use of materials before moving on to reuse (Cramer 2014). Implementing these two strategies alone could already lead to a significant reduction in the excessive material consumption seen in healthcare. The next step involves prioritising the reuse of materials. However, in past decades, there has been a notable shift from reusable to disposable medical products. This trend has been largely driven by industry narratives emphasising the perceived benefits of disposables, such as convenience, short-term cost savings, and reduced infection risks. However, these claims were not always grounded in robust scientific evidence. At the same time, the long-term environmental consequences of disposable products were largely overlooked. Recent research increasingly highlights that reusable alternatives often have a lower environmental impact. For instance, reusable steel instruments like specula and scissors have been shown to be more environmentally friendly than their disposable counterparts (Donahue et al. 2020, Ibbotson et al. 2013). Similarly, reusable textiles, such as isolation gowns and sterile surgical gowns, have demonstrated substantial environmental advantages (Vozzola et al. 2018, Vozzola et al. 2020).

A commonly used medical product in healthcare is the disposable absorbent cellulose mat. These mats were introduced to absorb fluids in various situations, such as managing urinary incontinence in beds, capture blood loss during surgery, or amniotic fluid and blood during childbirth. In the Netherlands alone, approximately 23 million of these mats are used annually, not only in hospitals but also in nursing homes (Geene et al. 2023). At our tertiary hospital, the Leiden University Medical Centre (LUMC) in Leiden, around 250,000 of these mats are used each year. Major contributors to this usage include the obstetrics ward, intensive care units, the gastroenterology department, and the operating rooms (ORs). Given the widespread use of this product throughout the healthcare sector, exploring more environmentally friendly alternatives presents a valuable opportunity.

The environmental impact of incontinence underpads (IUPs) has been studied previously using life cycle assessment (LCA) (Griffing and Overcash 2023). However, these IUPs serve a different purpose and are significantly smaller compared to the absorbent cellulose mat. Beyond the disposable absorbent cellulose mat, alternatives such as a biodegradable absorbent mat and a reusable absorbent mat has been developed. Our aim is to compare the environmental impact of disposable and reusable mats, and gather information about the practical usage of the most environmentally friendly alternative. The goal is to provide the healthcare sector with advice on selecting the alternative that offers the greatest environmental benefits.

2 Materials and methods

In 2022, we launched a reduction campaign in the obstetric ward of a university hospital, the LUMC, focusing on the disposable absorbent cellulose mat and targeting the initial steps of the circularity ladder: 'refuse' and 'reduce'. In 2023, we conducted an LCA to compare the environmental impact of the current disposable cellulose mat with that of a newly developed reusable absorbent mat and to identify environmental hotspots. Finally, in 2024, after comparing the environmental impacts of the different options, we implemented the mat with the overall lowest environmental impact in clinical practice and collected data on its use.

2.1 Life cycle assessment

The conducted LCA followed the established framework of the methodological standards ISO 14,040 and ISO 14,044, and the Handbook on Life Cycle Assessment (ISO 1997, ISO 2006, Guinee 2001). The systematic and standardised LCA framework comprises four stages: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation.

2.1.1 Goal and scope definition

The goal of the LCA was to compare the cradle-to-grave environmental impact of three types of disposable absorbent mats, and a reusable absorbent mat (each approximately 60 × 60 cm). The intended application is to support decision-making on environmentally sustainable absorbent mat selection in healthcare, since detailed information on environmental impact is lacking. We carried out an attributional LCA at the Obstetric ward in a tertiary hospital, the LUMC, in the Netherlands.

Table 1 Suppliers and key properties of the studied absorbent mats

Name	Type	Used in the LUMC	Absorption capacity*	Weight of the mat	Dimensions	Biodegradable	Supplier identifier
Disposable A	Disposable	Yes	570 g	40 g	60 × 60 cm	No	TZMO
Disposable B	Disposable	Yes	327 g	28 g	60 × 60 cm	No	TZMO
Disposable C	Disposable	No	127 g	16 g	50 × 48 cm	Yes	Green it out
Reusable A	Reusable	Yes	695 g	186 g	60 × 60 cm	No	Cleanlease

Legend: *Data on absorption capacity was measured following the instructions of ISO 20158:2018 (Textiles-Determination of water absorption time and water absorption capacity of textile fabrics) and can be found in the supporting information (Appendix 1)

Table 2 Key product characteristics per absorbent mat

Parameter	Disposable A	Disposable B	Disposable C	Reusable A
Total mass (g)	40	28	16	186
Main absorbent material	Softwood pulp	Softwood pulp	Viscose fibre	80% polyester/20% viscose
Polymer layers	PP + LLDPE	PP + LLDPE	PLA	Polyester + PU
Adhesive	PU	PU	PU	PU
Manufacturing data source	No industry data	No industry data	Industry data	Industry data

Legend: Polypropylene (PP), Linear low-density polyethylene (LLDPE), Polyactic acid film (PLA), Polyurethane (PU)

While absorption capacity differed slightly between mat types (see Table 1), the function of the system was defined as collecting bodily fluids to maintain surface dryness and patient comfort during clinical care.

The functional unit (FU) was defined as 1,000 absorbent mat uses in clinical practice. A usage-based FU was selected rather than defining the FU in terms of absorption of a specified fluid volume. In practice, mats are typically replaced before reaching their maximum absorption capacity, based on clinical judgement and hygiene considerations. Additionally, mats may be used for purposes other than fluid absorption (e.g., temporary neonatal warming or positioning, surface cleaning, or protective packaging). As replacement is therefore not solely driven by absorption capacity, absorption performance was not used as a differentiating quality parameter in the FU definition. Clinical performance was assumed to be equivalent between reusable and disposable mats within the defined system boundaries.

The reference flow was defined as the quantity of products and associated processes required to fulfil 1,000 mat uses. For disposable mats, this corresponds to 1,000 single-use mats. For reusable mats, assuming a technical lifetime of 100 uses per mat, the reference flow corresponds to 10 reusable mats, including all associated washing, drying, and transport processes required to deliver 1,000 total uses.

In this study, four different absorbent mats from various suppliers were evaluated. Disposable mats A (Seni Soft Super) and B (Seni Soft HE) were supplied by Toruńskie Zakłady Materiałów Opatrunkowych S.A. (TZMO S.A.), based in Toruń, Poland (ul. Żółkiewskiego 20/26, 87–100 Toruń, Poland). Disposable mat C was provided by the Dutch company Green it out B.V., registered at the Dutch Chamber of Commerce (KvK) under number 75915758, Buitendijks 63, 3356 LX Papendrecht. The reusable mat (Reusable A) was produced by a Dutch company HeboVanDijk B.V., registered under number KvK: 16021292, De Dintel 7, 5684 PS Best, The Netherlands, and is supplied and laundered by CleanLease B.V., a Dutch textile service provider (KvK number 28062071, Hoogewaard 191, 2396AR Koudekerk aan den Rijn). Table 1 provides an overview of the mats, including specific product characteristics. Detailed information about the characteristics, flow diagrams and material identification can be found in appendix 1–3.

2.1.2 Inventory analysis

The inventory analysis took place in 2023. The system boundary included the (i) Material extraction and production, (ii) Manufacturing, (iii) Use, (iv) End of life, (v) Transport, and (vi) Packaging. Four separate product systems were modelled, one for each absorbent mat alternative, using harmonised system boundaries to ensure comparability between the alternatives. A summary of the key product characteristics per mat type is presented in Table 2 to facilitate interpretation of material differences between alternatives. Detailed material and transport inventory data per functional unit are provided in Appendix 4 (Table S23). The following unit processes were cut-off from the system: Capital goods of foreground processes (i.e., machines, process equipment, factory buildings), workforce burdens (i.e., commuting to work), and packaging of semi-finished products. Capital goods were cut-off due to lack of data, their use outside the product system and their use over a prolonged period of time; workforce burdens due to difficulty in allocation, drawing boundaries, and obtaining data; and lastly packaging of semi-finished products due to the lack of data. Further details on the modelling choices and assumptions underlying the inventory analysis are provided in Appendix 4.

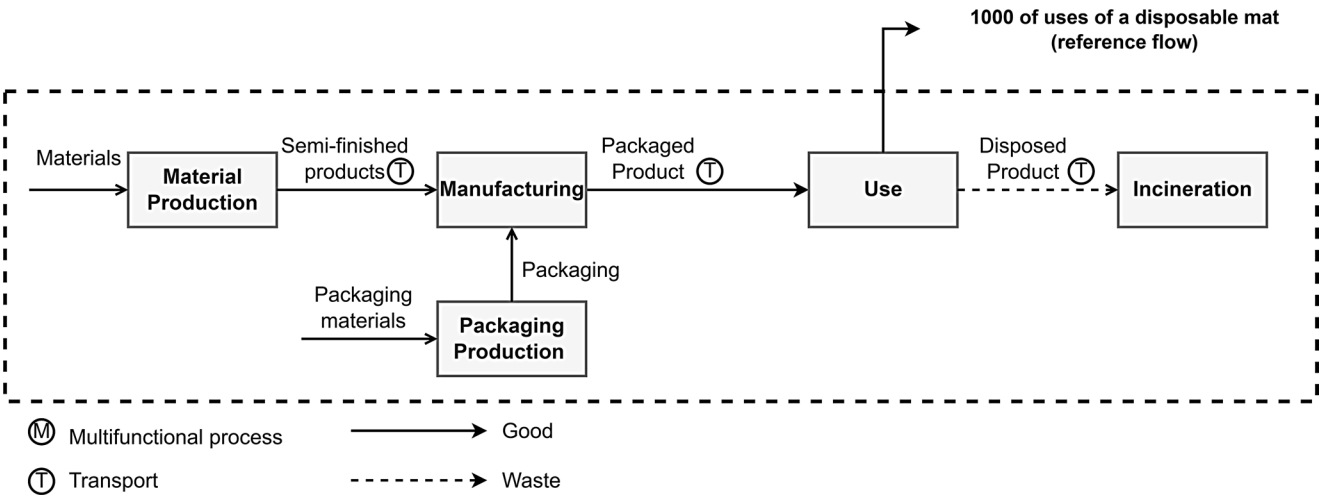


Fig. 1 Life cycle flow diagram disposable A, B, and C

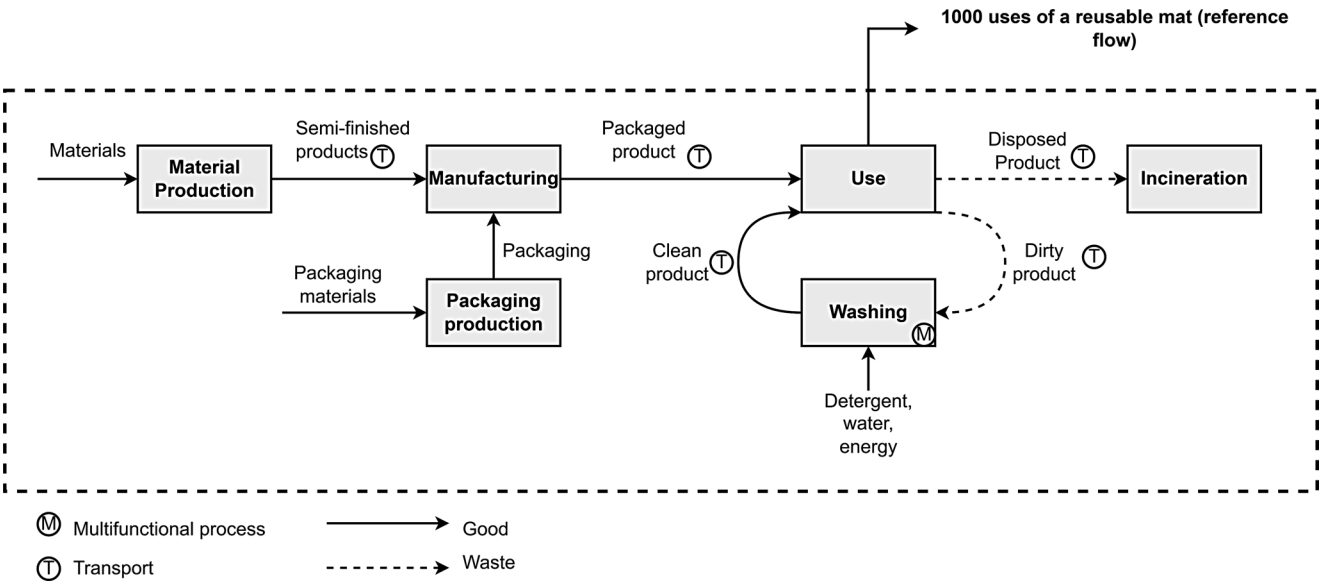


Fig. 2 Life cycle flow diagram reusable A

For each absorbent mat, a flow diagram was developed to provide an overview of the main unit processes included within the system boundaries (Figs. 1 and 2). These diagrams illustrate the overall structure and comparability of the systems assessed. While the diagrams are presented at a general level to aid readability, each absorbent mat was modelled using its own material-specific processes. Differences in material composition and quantities between alternatives are summarised in Table 2, while the full inventory of processes and flows per functional unit is provided in Appendix 5, which contains the unit process data for each mat type.

Data were gathered from the following sources: (i) Ecoinvent database (allocation, cut-off by classification, Version 3.9.1), (ii) industry data, (iii) measurement data, and (iv) literature. For Disposable C, the supplier provided manufacturing data (assembly of the semi-finished products). For Reusable A, the manufacturer supplied data on the production of semi-finished products and manufacturing (assembly of the semi-finished products), while the supplier provided washing data. For all mats, material type was determined through Fourier Transform Infrared Reflectance (FTIR) spectroscopy. For Reusable A, the manufacturer also provided material specifications, which were consistent with the FTIR results. For Disposable A and B, no industry data were available despite repeated requests; therefore, material type and quantity were determined through FTIR spectroscopy and mass measurements. Details on material analysis experiments can be found in the supporting information (Appendix 3). A consistent methodology was

applied, prioritising data sources in this order: (1) industry data, (2) measured or calculated data, (3) literature data, (4) estimation based on similar processes, (5) assumptions, and (6) missing data.

Several assumptions were made for the life cycle of absorbent mats. Bleaching was assumed for all mats due to their white colour. Due to the lack of data on the specific adhesive type, polyurethane adhesive was assumed based on literature (Cordella et al. 2015). For manufacturing, high-voltage electricity and high-pressure gas were assumed. Additionally, for manufacturing, it was assumed that 4.25% waste was generated for each input material for disposable absorbent mats (Cordella et al. 2015). For Reusable A, the supplier specified 7% waste generation during manufacturing. It was assumed that waste was not recycled or reused.

Environmental impact of the use stage of the disposable absorbent mats A, B, and C was assumed to be negligible (Bijleveld and Uijttewaal 2022). For Reusable A, an average technical lifetime of 100 uses per mat was assumed based on supplier information. Washing was modelled using industry-provided data, assuming full-capacity industrial laundering. Scaled to the functional unit of 1,000 mat uses, the washing process included water consumption of 0.97 m^3, electricity use of 25.85 kWh, natural gas use of 19.16 m^3, and surfactant use of 6.9 kg. The use of washing detergent in the literature differed from the provided data. For this reason, we used the provided data and included the literature data in the sensitivity analysis. For all mats, the fluid absorbed during use was assumed to have a negligible impact on the overall life cycle environmental impact.

It was assumed that packaging of semi-finished products was negligible, so only the packaging of the finished product was included. Based on FTIR analysis of Disposable A, it was assumed that all plastic packaging material consisted of High Density Poly Ethylene (HDPE).

Packaging mass for transportation was assumed negligible, and transport was included in each unit process. Based on Reusable A industry data, all road transport was assumed to use a 7.5–16 metric ton, EURO5 lorry. Semi-finished products were assumed to be produced at a different location than manufacturing, and their transport was included in each unit process. Finished products were assumed to be directly transported to the LUMC. If the manufacturing location was unknown, the brand's headquarters was used. Distances were determined via Google Maps for land and Searates for sea, rounding to the nearest 10 km (Google Maps 2023, World DP Searates 2023).

Based on standard waste treatment at the LUMC, disposable absorbent mats were assumed to be incinerated after one use. Since industry partners for Reusable A provided no end-of-life data, European Union (EU) textile waste literature was used, assuming 87% incineration and only 1% recycling (Milieuagentschap 2024). However, since Reusable A is composed of multiple materials which complicate recycling, for the purpose of this study it was assumed that 100% of reusable mats are incinerated at end-of-life. For all absorbent mat materials, specific waste treatments for the Netherlands (97% incineration) were applied. If material-specific treatments were unavailable, generic treatments (e.g., plastic mixture for polyester) were used.

Specific assumptions were made for each absorbent mat, with the main ones used in the sensitivity analysis listed in Table 3. Detailed assumptions are provided in Appendix 4.

In LCA methodology, multifunctionality typically refers to situations in which a process yields multiple functions, requiring allocation procedures or system expansion in accordance with ISO 14,044. There are three types of multifunctional processes:

- Co production: more than one GOOD as output.
- Multi waste treatment: more than one WASTE as input.
- Recycling: a WASTE as input and a GOOD as output.

A good has a positive economic value (the producer gets paid to deliver the product). A waste has a negative economic value (the producer needs to pay to get rid of the waste). In our comparative model, the foreground system does not include multifunctional production processes

Table 3 Main assumptions for each of the absorbent mats

Absorbent mat	Main assumptions
Disposable A and B	Economic flows for manufacturing based on LCA literature of disposable diapers (Cordella et al. 2015, Aumonier and Great 2005)
Disposable C	Standard viscose from Ecoinvent was used instead of Lenzing viscose*
Reusable A	One reusable mat was disposed of after 100 use cycles. Washing was done at full capacity, at washing settings provided by the industry, and with non-ionic surfactant as detergent**. For the transport between the laundry and the LUMC the mass of the rolling container is neglected.

Legend: *Lenzing viscose is a type of rayon fibre that is produced by Lenzing AG. They claim that their viscose is more sustainable compared to standard viscose (Vreede and Sevenster 2010). Ecoinvent has no process for Lenzing viscose and no detailed inventory data was available. Thus, standard viscose from Ecoinvent was used

**No information was available about the composition of the detergent, so data from EcoInvent was used instead. For detailed inputs and outputs of the washing cycle, see Appendix 5.3

that generate co-products requiring allocation. But it does include a multifunctional recycling process (see Fig. 2), the laundering process in the system of Reusable A.

Downstream processes were modelled directly per functional unit of 1,000 mat uses. Upstream processes, such as material extraction and production, follow the standard allocation rules of the Ecoinvent database cut-off system model. As mentioned before, within the foreground system, the industrial laundering process of Reusable A represents a multifunctional recycling process, with a waste input (used mat) and a product output (cleaned mat) (see Fig. 2). However, this process forms a closed-loop system in which both functions, treatment of the used mat and delivery of the cleaned mat, are part of the same reusable mat product system. Therefore, the laundering process was modelled as a service delivering the function of washing, avoiding the need for allocation between waste treatment and product output. Figure 3 presents a schematic overview of the laundering process modelled as a service. It illustrates how the main unit processes are connected and how all flows are assigned to the functional unit.

2.1.3 Impact assessment

While the Environmental Footprint (EF) 3.1 method is gaining recognition as a European standard for impact assessment, the ReCiPe2016 method remains the preferred approach in most LCAs of healthcare textiles, such as face masks, scrub suits, protective textiles, and surgical gowns (van Straten et al. 2021, Boix Rodríguez et al. 2021, Rizan et al. 2021, Mikusinka 2012, Lee et al. 2021). These healthcare textiles have a similar material composition to absorbent mats, commonly consisting of polyester, non-woven polypropylene, cotton, and polyethylene. Consequently, this study employed the ReCiPe2016 Hierarchist method with midpoint impact categories (Huijbregts et al. 2017). Although EF is a valid alternative, its application in healthcare LCAs is currently less common, and ReCiPe2016 was therefore selected to align with prevailing practice in literature. Classification and characterisation steps were performed using Activity-Browser, while normalisation was conducted manually in Excel based on supplementary data provided in the methodology of ReCiPe2016 (Huijbregts et al. 2017, Steubing et al. 2020). The normalisation is based on the interventions of an average world citizen for the

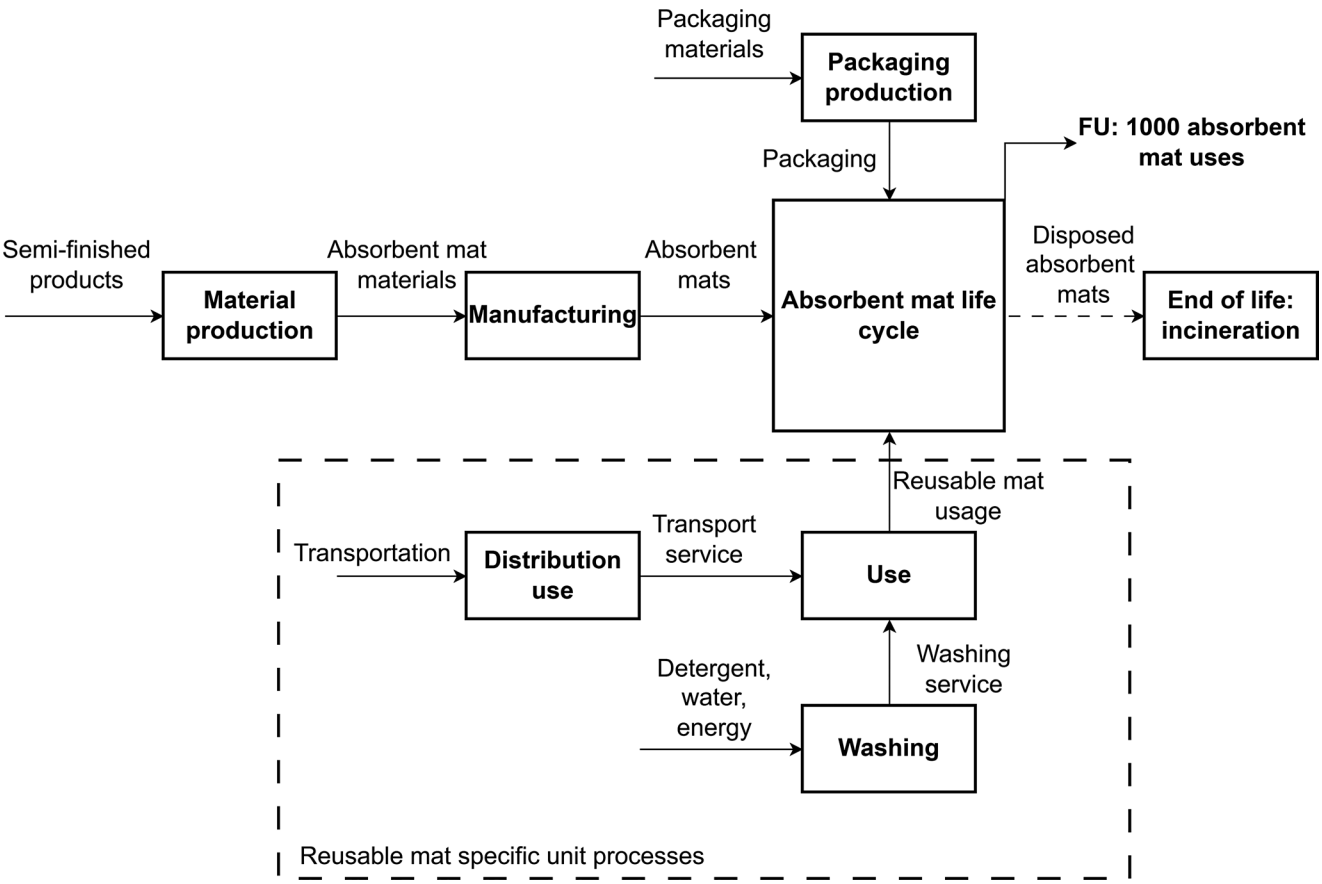


Fig. 3 Laundering process as a service of delivering the function of washing. Legend: It is a assumed that a reusable mat has a lifespan of 100 uses, the manufacturing process contributes 10 mats to the absorbent mat life cycle, while the use phase accounts for 1000 use cycles

year 2010. Since ReCiPe2016 does not provide a standard weighting method for midpoint categories, only weighting factors for endpoint categories, weighting was omitted in this study. For comparative presentation of characterised results, Disposable A, the standard mat used at the LUMC, was selected as the reference.

2.1.4 Interpretation

Life Cycle Impact Assessment (LCIA) results were interpreted through a contribution analysis, sensitivity analysis and a scenario analysis. The sensitivity and scenario analysis were performed at the characterised midpoint category global warming potential (carbon footprint) measured in kg CO_2 equivalents. Additional sensitivity analyses for ozone depletion (ODP) and marine ecotoxicity potential (MEP) were performed.

2.1.4.1 Contribution analysis The contribution analysis identified hotspots and key life cycle stages driving the environmental impact of the absorbent mats using characterised ReCiPe2016 midpoint categories. Foreground unit processes were grouped into four life cycle stages, with transport to the consumer included in the upstream stage (e.g., transport from manufacturer to hospital counted under manufacturing). The analysis further detailed the contributions of background processes within the manufacturing stage for disposable mats and the use stage for reusable mats. Additionally, it assessed the impact contribution of individual materials within the material production stage.

2.1.4.2 Sensitivity analysis For Disposable A and B, manufacturing data were unavailable; therefore, the processes were modelled based on LCA literature for disposable diapers (Cordella et al. 2015, Aumonier and Great 2005). This is justified by the similarity in materials (polymer layers, cellulose pulp, adhesives) and possible production steps between absorbent mats and diapers. Sensitivity analyses applying the manufacturing inputs of Disposable C to Disposable A and B were conducted to assess the robustness of this assumption. The literature for diapers reports three inputs for the assembly stage: gas, water, and electricity. In contrast, the industry-provided data for Disposable C indicate that only electricity is used during manufacturing. To test this assumption, the manufacturing inputs for Disposable C were applied to Disposable A and B. Specifically, gas and water inputs were removed, and the electricity consumption was adjusted to match the value reported for Disposable C. We acknowledge that using diapers as a proxy introduces some uncertainty, as the products are not identical. This source of uncertainty is explicitly considered in the sensitivity analyses.

Additionally, the quality (fossil or renewable) of electricity was altered to assess result robustness under different conditions, and to resemble electricity mixes of different countries for generalisability of the results. Fossil based electricity and renewable electricity were chosen to be 100% coal and wind electricity, respectively. To account for measurement inaccuracies, material mass was increased by 5%, and the soaker material was changed to viscose due to minimal differences in FTIR measurements between viscose and softwood pulp.

The main assumption for Disposable C of using standard viscose instead of Lenzing viscose was analysed for sensitivity by reducing the soaker quantity by two-thirds to reflect the threefold higher environmental impact of standard viscose (Vreede and Sevenster 2010). This analysis should be approached cautiously, as it assumes that reducing standard viscose to one-third equates to manufacturing Lenzing viscose. Additionally, the soaker material was changed to softwood pulp due to minimal differences in FTIR measurements. The quantity and quality (fossil or renewable) of electricity were also selected as sensitivity parameters.

To test the sensitivity of the main assumptions for Reusable A, the following parameters were analysed: the use cycle of the mat was decreased by 50%, the washing was conducted at half capacity, and the mass of the rolling container for transport was included, assuming it could hold 1000 mats in a rolling container of 60 kg (Raja 2023). Additionally, the highest impact inputs for the use cycle were increased by 100%. Specific data was used for energy demand and transport between LUMC and the laundry facility. To generalise results for other hospitals, the distance was increased by 100% and set to zero kilometres, respectively. Energy inputs were tested under a scenario in which the washing machine was operated at half capacity, effectively doubling the energy use per mat.

2.1.4.3 Scenario analysis Two scenarios were assessed: (i) worst-case and best-case scenarios, defined by the parameter values identified in the sensitivity analysis for each absorbent mat (Table 4).

2.2 Practical implementation of reusable absorbent mats

To support environmentally sustainable decision-making in obstetric care, we assessed the practical implementation of reusable absorbent mats at the LUMC obstetric ward. Given the hypothesis that disposable mats serve multiple

Table 4 Worst- and best-case scenarios for each of the absorbent mats

Absorbent mat	Worst-case scenario	Best-case scenario
Disposable A and B	• Electricity manufacturing 100% fossil • Mass of materials increased by 5%	• Electricity manufacturing 100% renewable • Mass of materials decreased by 5%
Disposable C	• Electricity manufacturing 100% fossil	• Electricity manufacturing 100% renewable
Reusable A	• Use cycles decreased by 50% • Washing at half capacity • Electricity washing 100% fossil • Transport distance increased by 100% (240 km)	• Electricity washing 100% renewable • Transport distance reduced by 100% (0 km)

purposes beyond fluid absorption, a reduction in overall mat usage was anticipated. The LCA was conducted first on a per-functional-unit basis (1,000 mat uses) to compare the environmental impact of reusable and disposable mats consistently. Then the mat with the lowest environmental impact was implemented in practice. Monthly usage data were collected from the laundry facility (for Reusable A) and procurement records (for Disposable A and B); Disposable C was not used at the ward due to insufficient absorption capacity. The observed reduction in mat usage was analysed separately to quantify the real-world CO_2 savings. CO_2 emissions were calculated by combining the LCA-derived emission per mat with the actual reduction in mat use. Integrating variable usage directly into the LCA would have compromised comparability, as the LCA is designed to evaluate products on a consistent functional-unit basis.

3 Results

3.1 Impact assessment

Figure 4 illustrates the relative impact across midpoint categories, with absolute and normalised impact scores provided in Appendix 6. Details on energy and material flows for manufacturing are included in Appendix 4, while the material composition of the absorbent mats per 1,000 uses is provided in Appendix 6 (Table S24). Reusable A exhibited the lowest environmental impact in 14 of the 18 impact categories, including climate change, land use, and material resource use. Notably, its climate impact was 87 kg CO_2-equivalents (eq.), compared to 266, 202 and 150 kg CO_2-eq. for Disposable A, Disposable B, and Disposable C, respectively.

The lower environmental impact of Reusable A is primarily due to its reduced material use per functional unit, despite the energy and water required for laundering. While Reusable A outperforms the other mats in most impact categories, it performs less favourably in certain categories, namely water use, ODP, and MEP, where its footprint exceeds that of the alternatives. This is mainly attributed to the use of non-ionic surfactants during the use phase, particularly surfactants derived from soy and coconut oil.

For example, in the case of MEP, 94.3% of the total impact is attributed to the use phase, of which 93.4% stems from the laundering process and the remaining share from distribution. Of the washing-related impact, 76.1% can be directly linked to the use of non-ionic surfactants. A similar pattern is seen for ODP and water use, where the majority of the impact also results from the use of non-ionic surfactants during laundering.

Disposable C exhibited the highest impact in ionising radiation (IRP), ODP, and water use, primarily due to its viscose-based soaker material and the high share of nuclear energy in its production process. Its ODP impact was largely driven by the polyurethane adhesive, which was used in significantly higher quantities than in other mats. The high water use impact of Disposable C resulted from maize cultivation for its bottom sheet.

In contrast, Disposable B had a 5–37% lower impact than Disposable A across multiple categories, which was attributed to a reduction in soaker and packaging material by approximately 30% and 53%, respectively.

3.2 Contribution analysis

The life cycle contribution analysis results of the life cycle stages are shown in Fig. 5. The largest environmental impact stage differs per absorbent mat type: for Disposable A and B, the manufacturing stage dominates, while for Disposable C, material production has the highest contribution. For Reusable A, the use stage contributes most significantly, primarily due to the laundering process. The disposal stage has the lowest impact for all disposable mats.

Material choices strongly influence impact variation. The soaker material is the dominant contributor across all mat types, with Disposable C showing particularly high impacts due to its viscose-based soaker. Despite its larger quantity, the softwood pulp soaker of Disposable A has a lower absolute impact than Disposable C's viscose. The bio-based materials used in disposable mats (softwood pulp and polylactic acid) result in higher land and material resource use.

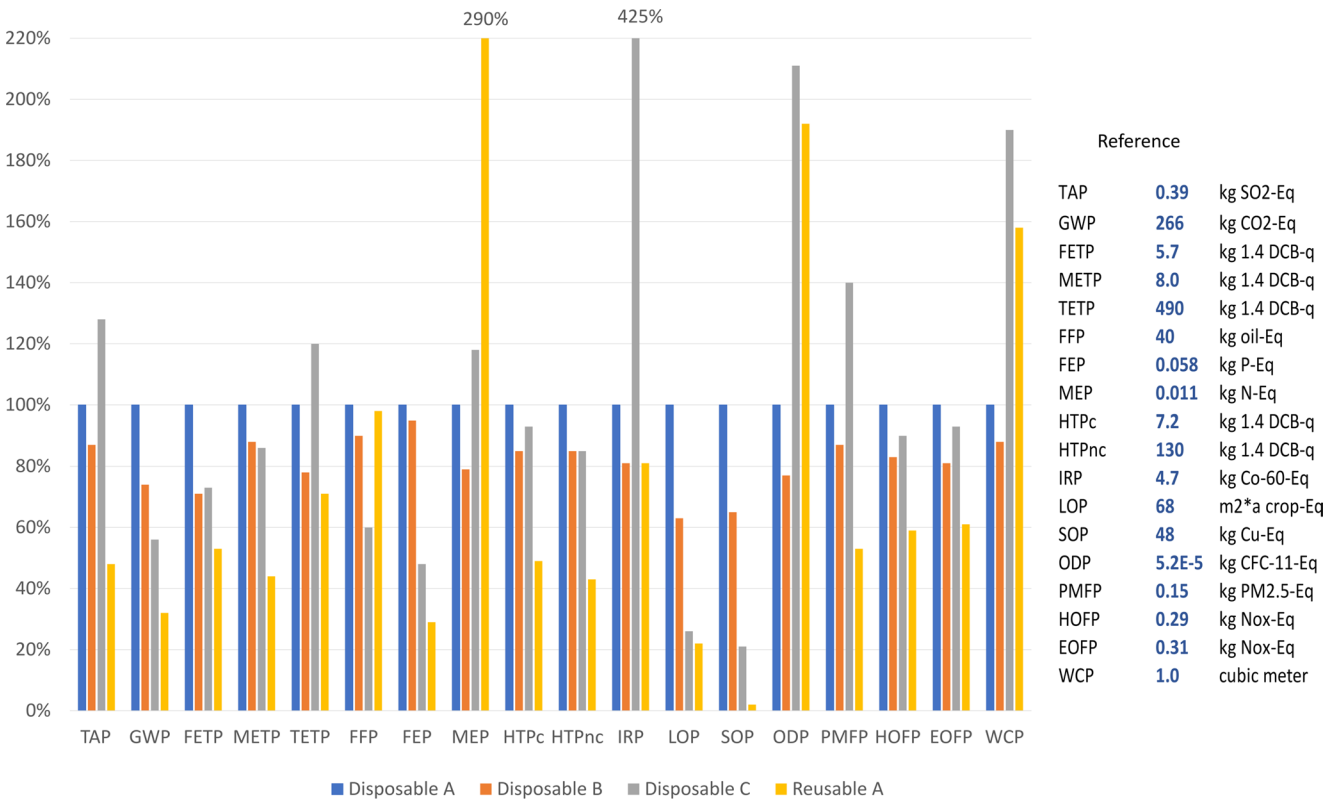


Fig. 4 Relative characterisation results of absorbent mats for 1000 uses (Reference: Disposable A) and absolute impact scores for Disposable A. Legend: Acidification: terrestrial (TAP); Climate change (GWP); Ecotoxicity: freshwater (FETP); Ecotoxicity: marine (METP); Ecotoxicity: terrestrial (TETP); Energy resources: non-renewable, fossil (FFP); Eutrophication: freshwater (FEP); Eutrophication: marine (MEP); Human toxicity: carcinogenic (HTPc); Human toxicity: non-carcinogenic (HTPnc); Ionising radiation (IRP); Land use (LOP); Material resources: metals/minerals (SOP); Ozone depletion (ODP); Particulate matter formation (PMFP); Photochemical oxidant formation: human health (HOFP); Photochemical oxidant formation: terrestrial ecosystems (EOFP); Water use (WCP)

Electricity consumption during manufacturing is another key driver of impact, with Disposable C exhibiting a higher IRP impact due to reliance on nuclear power. Further details on the in depth contributions to the life cycle stages and material production are provided in Appendix 7.

3.3 Sensitivity analysis

The results of the sensitivity analysis for Reusable A are presented in Fig. 6. Even with substantial variations in key parameters, such as halving the number of use cycles (+24%) or increasing surfactant use (+38%), Reusable A consistently maintains the lowest carbon footprint.

Switching to renewable electricity for washing (-26%) or reducing transport distances (-13%) further lowers the carbon footprint. The comparatively modest reduction from using 100% renewable electricity is due to the fact that, within the use phase of Reusable A, the dominant contribution to the carbon footprint comes from non-ionic surfactant use rather than from electricity consumption. As a result, changes in the electricity mix have a proportionally smaller influence on the overall impact.

The sensitivity analyses for the disposable mats are provided in Appendix 7. Their trends are similar and do not change their ranking. For Disposable A, the carbon footprint remains relatively stable under most variations (<15%), except for a switch to viscose soaker material (+59%). For Disposable C, the carbon footprint is most sensitive to changes in soaker material (-39% for Lenzing viscose, -38% for softwood pulp) and energy sources (+40% for fossil based electricity).

Additionally, we included sensitivity analyses for ODP and MEP for Reusable A, as these were among the few impact categories in which Reusable A performed less favourably than the disposable alternatives (see Table 5). The higher impacts in these categories were primarily associated with the use of non-ionic surfactants during the laundering phase, particularly surfactants derived from soy and coconut oil.

The results showed that ODP and MEP were sensitive to assumptions regarding washing at less capacity, decreased use cycles and surfactant use during laundering. A 100% increase in surfactant use increased ODP from 0.00010 to 0.00014 kg CFC-11 eq. and MEP from 3.5 to 5.0 kg 1,4-DCB



Fig. 5 Life cycle stage contributions for 1000 absorbent mat uses

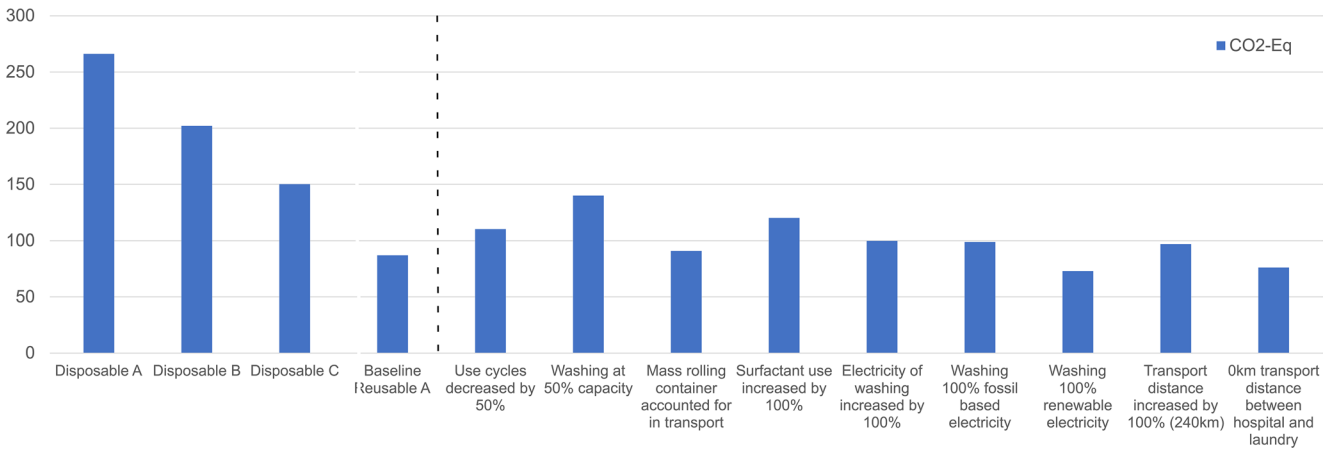


Fig. 6 Sensitivity analysis of Reusable A's carbon footprint. Legend: X-axis: Baseline (left from dotted line) and the effect of varying use cycles, washing capacity, and transport/washing inputs (right from dotted line) for the functional unit of 1000 absorbent mat uses. Y-axis: kg CO_2-equivalents

eq. In contrast, scenarios involving renewable electricity slightly reduced impacts in both categories. These findings confirm that washing capacity, the use cycles, and surfactant use during laundering are the dominant contributors to the observed non-climate impacts associated with Reusable A.

3.4 Scenario analysis

The scenario analysis compares the carbon footprint of the baseline, worst-, and best-case scenarios, also assessing the impact of the impact assessment method on the relative environmental impact of the absorbent mats.

Table 5 Sensitivity analyses of ODP and MEP of the reusable absorbent mat

	Baseline	Use cycles decreased by 50%	Washing at 50% capacity	Mass rolling container accounted for	Surfactant use increased by 100%	Electricity for washing increased by 100%	Washing 100% fossil based electricity	Washing 100% renewable based electricity	Transport distance increased by 100%	0 km transport distance
GWP(kg CO_2-eq)	87.0	110.0	140.0	88	120.0	100.0	99	73.0	97.0	76.0
ODP (kg CFC-11 eq)	0.0001	0.00014	0.00015	0.0001	0.00014	0.00011	0.0001	0.000095	0.00011	0.000096
MEP (kg 1,4-DCB eq)	3.5	4.7	5.3	3.6	5	3.8	3.8	3.4	3.9	3.1

Figure 7 shows that in the best-case scenario, the carbon footprint decreases by 18% for Disposable A, 22% for Disposable B, 2% for Disposable C, and 29% for Reusable A. The worst-case scenario results in increases of 5% for Disposable A, 8% for Disposable B, 40% for Disposable C, and 128% for Reusable A. Despite variations, Disposable A consistently has the highest carbon footprint.

For Reusable A, the 128% increase in carbon footprint in the worst-case scenario compared to the baseline exceeds the baseline impact of Disposable C's baseline and is similar to Disposable B's baseline scenario. However, it remains below Disposable A's baseline, worst-case, and best-case scenarios. The largest increases are primarily associated with fewer use cycles and reduced washing capacity. Appendix 6 provides a detailed overview of all impact category scores, consistently showing that worst-case scenarios are higher than best-case scenarios across all products. Additionally, Disposable C generally scores lower than Disposable A and B, while Reusable A remains below Disposable A in most cases.

3.5 Outcomes of reduction campaign and practical implementation of reusable absorbent mats

Prior to conducting the LCA in 2023, the number of mats used was reduced through educational efforts focusing on *refuse* and *reduce* strategies (Cramer 2014). Between January 2021 and March 2023, Disposable B was used in the obstetric ward of the LUMC, with an average monthly consumption of 4,891 mats. This corresponds to approximately 30 mats per birth. In May 2023, Disposable A was introduced, reducing monthly usage to 2472 mats, a 50% reduction. During this period, the average number of mats used per birth dropped to 16.

From May to July 2024, Reusable A was implemented. Monthly usage averaged 1506 mats, 40% fewer than Disposable A mats. The number of mats used per birth was 9, a decrease compared to both Disposable A and B.

In terms of climate impact, the use of Disposable A resulted in 7891 kg CO_2-eq. annually, whereas the reusable mats reduced emissions to 1572 kg CO_2-eq., representing an 80% reduction in CO_2 emissions.

4 Discussion

This study assessed the environmental impact of three disposable absorbent mats (A, B, and C) and one reusable absorbent mat (Reusable A) using an LCA across 18 impact categories. Reusable A consistently showed the lowest environmental impact in 14 out of 18 categories, including impacts such as climate change, land use, and material

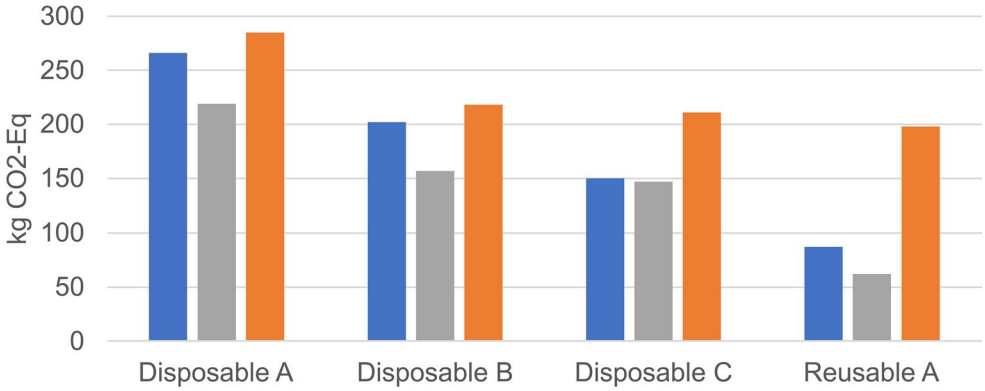


Fig. 7 Comparison of the baseline carbon footprint impact to a worst-case and best-case scenario. Legend: X-axis: blue = baseline; grey = best-case; orange = worst-case. Y-axis: kg CO_2-equivalents

resource consumption. The carbon footprint of Reusable A was 87 kg CO_2-equivalents per functional unit, compared to 266, 202, and 150 kg CO_2-equivalents for Disposable A, B, and C respectively. Sensitivity analyses demonstrated that Reusable A maintained the lowest carbon footprint under varying assumptions. Scenario analyses indicated that, although the worst-case scenario for Reusable A could increase the carbon footprint by up to 128%, it remained below the baseline footprints of disposable mats used currently in use (Disposable A and B). These results highlight the robustness of the environmental benefits of reusable mats, even when accounting for uncertainty in use cycles and laundering conditions.

Furthermore, practical implementation at the LUMC obstetric ward demonstrated a substantial reduction in mat usage following *refuse* and *reduce* strategies. Transitioning from Disposable B to Disposable A halved monthly consumption, and the introduction of Reusable A further reduced usage by 40%. This led to an estimated 80% reduction in annual CO_2 emissions compared to Disposable A.

Material composition plays a key role in determining the environmental impact of absorbent mats. For instance, Disposable C, which uses viscose-based soaker materials, exhibited high environmental impacts due to IRP, ODP, and water use, largely because of the viscose material and reliance on nuclear energy. Environmental performance for Disposable C is strongly influenced by the assumed quantity and type of polyurethane adhesive. These values were based on assumptions and information from a single supplier, as no additional product-specific data were available. Consequently, conclusions regarding biodegradable mats as a class should be interpreted cautiously, and the results should not be generalised beyond the studied product. Further research with multiple suppliers and verified adhesive compositions is needed to reduce this source of uncertainty. Furthermore regarding material composition, Disposable B showed reduced impacts compared to Disposable A, attributed to fewer soaker and packaging materials, demonstrating the potential for material optimisation in reducing environmental harm, although switching to the reusable alternative remains the better choice.

One limitation of this study is that the functional unit was defined as one mat use, rather than the amount of fluid absorbed. While this reflects real-world usage in clinical practice, it may underestimate the environmental benefits of the reusable mat, which demonstrated a higher absorption capacity than the disposable alternatives (Table 1). If absorption capacity were used as the basis for the functional unit, the relative impact of the reusable mat would likely be even lower. Future studies could explore an alternative functional unit based on absorbed volume to assess this potential difference.

Another limitation is, that the end-of-life scenario applied in this study assumes near-complete incineration, reflecting current Dutch healthcare practice. This limits the generalisability of the results to regions where alternative waste management strategies, such as landfill disposal, dominate. Readers should interpret the findings as context-specific rather than universally applicable.

Nevertheless, even though the reusable option is preferable, there is still room for improvement. As an example, the laundering process remains the primary environmental burden for Reusable A, underscoring the need for optimised washing practices to further reduce its environmental impact. The use of surfactants is a major contributor to the environmental impact during the use phase of Reusable A. The majority of the environmental impact related to ODP and water use can be attributed to the use of non-ionic surfactants during laundering. However, the composition of the surfactant used for Reusable A was modelled using generic database data, as product-specific information from the manufacturer was unavailable despite repeated requests. This limits the ability to assess whether alternative, more environmentally friendly surfactants could mitigate these impacts, and should be considered when interpreting the results. Alternative surfactants with improved biodegradability and lower toxicity possibly exist. These alternatives, such as surfactants derived from renewable resources or enzymatic detergents, may provide opportunities to reduce

the environmental burden of laundering. However, due to the lack of detailed data on the surfactants currently used, no definitive conclusions can be drawn about their comparative sustainability. Further research and collaboration with manufacturers are necessary to evaluate and potentially implement these alternatives within the product life cycle.

Another limitation is that the sensitivity analysis focused primarily on climate change and only included selected non-climate impact categories. Additional sensitivity analyses were performed for ODP and MEP, as these categories showed less favourable outcomes for Reusable A compared to the disposable alternatives. These analyses showed that the impacts were particularly sensitive to assumptions regarding the laundering process, especially washing at reduced capacity, decreased use cycles, and increased surfactant use, both of which increased ODP and MEP outcomes. This indicates that the observed non-climate trade-offs are strongly dependent on laundering practices and detergent-related assumptions.

Notably, the sensitivity analysis of Reusable A revealed that changes in factors like reduced use cycles or washing capacity did not alter its ranking as the most sustainable option regarding carbon footprint, but did influence the results. Further improvements could be achieved by transitioning to renewable energy sources and lowering transport emissions, which would further enhance its sustainability profile. Additionally, the reduction in the number of mats used at the obstetric ward indicates a shift towards more sustainable practices, particularly focusing on the *refuse* and *reduce* stages of the circularity ladder (Cramer 2014). The introduction of Disposable A, with its higher absorption capacity, led to fewer mats being used per birth. However, another factor that may have contributed is the awareness campaigns aimed at reducing mat use. The transition to Reusable A resulted in even further reductions in mat consumption, demonstrating the practical sustainability benefits of reusable products in healthcare settings. This decrease in material use aligns with growing sustainability awareness and highlights the important role of education and awareness campaigns in promoting sustainable behaviour within healthcare (van Nieuwenhuizen et al. 2024).

The findings of this study offer important implications for sustainable practices in healthcare. As the healthcare sector continues to face increasing pressure to reduce its environmental footprint, the adoption of reusable absorbent mats presents a promising option for reducing waste and emissions. Hospitals and healthcare providers might be encouraged to rethink their procurement strategies, considering not only upfront costs but also long-term sustainability benefits. The transition from disposable to reusable materials could help shift the focus of procurement policies toward more sustainable, circular models, emphasising the "reuse" aspect in the circularity ladder. Hospital leadership is essential for these decisions, with procurement needing to be supported by the board of directors to make informed choices and invest in sustainable solutions.

Despite the clear environmental benefits, a major barrier to the widespread adoption of reusable mats remains: the higher per-use cost of leasing reusable mats compared to disposables. However, this cost comparison assumes a one-to-one replacement, which does not align with sustainable principles. Referring back to the circularity ladder, we are reminded that the focus should also be on *refusing* and *reducing* use. It is therefore important to consider whether a mat is necessary at all. In cases of minimal fluid, a simple towel may suffice. Reusable mats should primarily be used when there is a need to absorb large amounts of fluid. At the LUMC, we observed a reduction in overall mat use, which helped to offset the higher leasing costs. Furthermore, when developing business cases for hospitals, it is essential not only to consider the direct financial costs but also to account for the long-term environmental benefits of sustainable alternatives. Products with a higher environmental impact should carry an associated environmental cost, reflecting their true cost to society. Healthcare institutions are encouraged to evaluate these factors on a case-by-case basis to support more informed and responsible decision-making.

Additionally, the production of reusable mats in Europe, as opposed to their current production in China, could help mitigate supply chain dependencies and further reduce environmental impacts, especially in terms of transportation emissions. This shift would also support local economies and align with sustainability goals.

5 Conclusions

This study demonstrated that the reusable absorbent mat consistently outperformed the disposable alternatives across the majority of environmental impact categories. Reusable A showed the lowest impact in 14 of the 18 categories assessed, including climate change, where its carbon footprint was substantially lower than all disposable mats. These results were robust across sensitivity and scenario analyses, indicating that the reusable mat remained environmentally preferable even under less favourable washing and reuse conditions. Based on the findings of this study, reusable absorbent mats should be recommended over disposable absorbent mats.

This study aligns with broader global sustainability efforts in healthcare, particularly those emphasised by the Dutch Green Deal (Ministry of Health 2015), which focuses on circularity and the search for alternatives to disposable products. By demonstrating the potential of reusable

absorbent mats, this study contributes to the broader initiative of reducing the environmental footprint of healthcare. The findings also reflect global trends, such as those in Sweden and the UK, where strategies have been implemented to reduce the carbon footprint of healthcare systems through a strong focus on reusable materials and waste reduction. By comparing the Dutch context with these international efforts, opportunities for further improvement in adopting sustainable practices can be identified. Sharing knowledge and best practices between countries could accelerate the transition to more sustainable healthcare systems worldwide. This study highlights the practical potential of reusable mats as a key element in the global transition to sustainable healthcare.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Competing interests All authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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