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Single-use nappies and their alternatives

Recommendations from Life Cycle Assessments

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Executive Summary

Globally, plastic pollution is on the rise. A new report from The Pew Charitable Trusts warns that, without action, **the annual flow of plastic into the ocean alone will nearly triple by 2040 to 29 million metric tonnes per year**, the equivalent of 50 kg of plastic for every metre of coastline worldwide. This seemingly unstoppable rising tide of plastic threatens human health and ecosystems and undermines important economic sectors such as tourism, fishing and shipping.

Single-use or disposable nappies are one of the biggest contributors to plastic waste globally. Since their invention in the late 1940s and early 1950s, these cheap and convenient products have become the **leading choice for parents worldwide.** A booming industry, **the global nappy market is expected to exceed US$71 billion by 2022.** This growth is being fuelled by high birth rates in developing countries coupled with improving economies and urbanisation, along with increased availability and marketing, amongst other factors. At the same time, in countries where nappy consumption and nappy waste is decreasing because of falling birth rates, aging populations are likely to drive an increasing consumption of adult incontinence products.

Manufactured from wood pulp, cotton and viscose rayon as well as several plastics (polyester, polyethylene, polypropylene, etc.), **single-use nappies have environmental impacts across their entire life cycle** and are also a **leading cost for local authorities** that are most often tasked with their disposal.

There is a clear need to consider alternatives to single-use nappies but, while reusable cloth nappies are promoted as the more environmentally friendly option, their comparison with single-use nappies is not a straightforward one. Reusable nappies require water and energy for washing and drying, with variability in usage rates and washing practices making the environmental impact of cloth nappies difficult to evaluate. In addition, innovations in the design of standard single-use nappies and end-of-life treatments are helping to reduce their impacts.

To assist policy makers in making informed choices about the regulation of single-use nappies and their alternatives, this report **summarises current knowledge about the environmental performance of these products.** It includes a **meta-analysis of seven Life Cycle Assessment (LCA) studies** covering a range of geographies. The LCA studies chosen for analysis include recent studies comparing single-use and reusable nappies, as well as those evaluating improvements in the design and end-of-life treatment of single-use nappies. Insights from previous review studies and wider relevant literature are included in the discussion and conclusions. The key findings of the LCA studies covered in the meta-analysis are summarised in the table at the end of the executive summary.

LCA is a well-established tool for assessing the potential environmental impacts associated with a product or service, providing a structured framework within which to model its consequences on the natural environment and society. **Especially valuable is an LCA's ability to highlight areas of highest potential impact along the value chain** and also to **highlight trade-offs between different impacts**.

The analysis demonstrates that, when comparing single-use nappies with reusable nappies, **reusable options when washed so as to minimise water use (e.g., in a fully loaded, modern washing machine) and in an energy-efficient manner have lower environmental impacts**.

Consumer behaviour emerges as a key factor in many of the studies regarding both single-use and reusable nappies. While there is significant variability in the

Single-use nappies are a substantial contributor to plastic waste globally. They have environmental impacts across their entire life cycle and are also a leading cost for local authorities that are most often tasked with their disposal.

environmental impacts of reusable nappies, and overlap in performance between reusable and single-use nappy systems, a key difference lies in assumptions around the laundering of reusable nappies, with consumers holding the whip hand. **Notably, consumers using reusable nappies can reduce their environmental impacts** by washing full loads in their washing machine, choosing water- and energy-efficient washing machines, washing below 60°C, line-drying nappies and reusing nappies as many times as possible (e.g., by using their nappies on a second child, selling/donating nappies after use or purchasing second-hand nappies).

When comparing the life cycle environmental impacts of single-use nappies, it was found that **the greatest reductions in environmental impacts of single-use nappies can be achieved through the design of lighter products**, since the production of raw materials are the major source of impacts. Another improvement potential relates to the type of material used. For instance, using bio-plastics or increased cellulose-based fluff pulp for the absorbent part of the nappies, in place of fossil-based plastic, also results in environmental benefits in some impact categories.

Additionally, **novel processes for the recycling of nappies show good potential for decreasing the end-of-life impacts of single-use nappies** but will need to overcome significant social and economic barriers to become mainstream.

The report focuses on **nappies for babies** but many of the general **findings are equally relevant to adult incontinence products**.

CRITICAL PARAMETERS INFLUENCING THE ENVIRONMENTAL IMPACTS OF NAPPIES

Based on the studies reviewed in the meta-analysis, the following variables need to be considered when undertaking and interpreting LCAs of single-use nappies and their alternatives. Below is a non-exhaustive list of these.

Material type and weight: Material production is consistently the largest contributor to most of the life cycle environmental impacts. Nappy designs and materials have changed considerably over the years so LCA studies should be based on current designs and data, and be aware of future improvements.

Geographical context: The location of production, use and disposal of nappies is an important consideration, particularly in how this determines energy and waste management options. The former is important as, when reusable nappies perform poorly relative to single-use nappies, this is largely due to energy impacts – typically electricity – used in heating water and powering washing machines and driers. The latter is important as impacts will be underestimated if single-use nappy waste is modelled with sanitary landfill or incineration in a country with high rates of open dumping and littering. This is a significant shortcoming, since at least 33% of global solid waste is conservatively estimated to be openly dumped, with this number rising to up to 93% in low-income countries.

Consumer behaviour: How consumers act and the choices they make affects the environmental impacts of both single-use and reusable nappies. For all types of nappies, both the number of nappy changes per day and the age of the child when toilet trained affect the scale of the environmental impacts. For reusable nappies, the number of nappies purchased and nappy washing and drying behaviour strongly affect the results.

Equivalence of the nappy systems: In any comparative LCA, ensuring that the product systems to be compared deliver an equivalent function is critical. In the nappy studies, the functional unit is mostly taken as "one toilet-trained child", which translates to the number of nappies required over a duration of 2.5 years. However, none of the studies in this analysis look into the issue of equivalence in more depth.

Choice of environmental impact indicators: The LCA studies covered in the meta-analysis were primarily in developed-country contexts (none were African and only one was Latin American). A limitation of the LCA studies is that none take into account nappies not disposed of appropriately, such as nappies dumped or ending up in watercourses, with the result that end-of-life impacts of single-use nappies are likely under-represented in the studies.

RECOMMENDATIONS FOR POLICY MAKERS

Consumer awareness of the environmental impacts of single-use nappies is growing and the risks for producers and governments in not acting to minimise these is increasing too. Policy makers need to act decisively, drawing on best practice guidelines to reduce plastic pollution and minimise environmental impacts while also protecting the health and safety of their citizens.

This meta-analysis serves to highlight important aspects that policy makers should consider when evaluating environmental information (often in the form of LCA studies) on single-use nappies and their alternatives to inform policy development. Policies (on nappies) must be context specific and locally relevant. The table below plots the results of the LCA studies reviewed in this meta-analysis into an easy-to-read matrix that takes a snapshot of the relative preference for the nappy system, based on geographical, technological, and behavioural contexts. It is a snapshot of what the LCA studies currently tell us under the various scenarios.

LIFE CYCLE ASSESSMENTS OF NAPPIES: WHAT THE SCIENCE TELLS US

Single-use or reusable nappies depending on waste management context and behavioural considerations

This matrix helps countries, regions and cities to identify the closest scenario and current most appropriate options for their context. The content of the matrix is simplified, and the suggested preferences are indicative. Please read in conjunction with the text box below and refer to the full narrative of the meta-study for details.

Considerations of geographical and technological context	Eco- or cost-conscious Consumer: EFFICIENT WASHING & LAUNDERING PRACTICES (wash below 60ºC, line dry, fully filled machine)	Eco- or cost-conscious Consumer: REUSABLE NAPPIES RE-USED ALSO ON 2ND CHILD OR CHILDREN	Eco- or cost-conscious Consumer: APPROPRIATE DISPOSAL OF NAPPIES (no littering, flushing or contamination of recyclables)	Indifferent Consumer: INEFFICIENT WASHING & LAUNDERING PRACTICES (wash above 60ºC, tumble dry, partially filled machine)	Indifferent Consumer: REUSABLE NAPPIES USED ONLY A FEW TIMES	Indifferent Consumer: INAPPROPRIATE DISPOSAL OF NAPPIES (littered, flushed or disposed of with recyclables)
NO FORMAL WASTE MANAGEMENT & POOR RECYCLING SUPPORT unsanitary landfill, open dumps, open burning	**Reusable** preferred regardless of nappy type	**Reusable** preferred	**Reusable** preferred	**Single-use** preferred **Reusable** preferred if low-carbon electricity	**No clear preference**	**Reusable** preferred
FORMAL WASTE MANAGEMENT BUT POOR RECYCLING SUPPORT sanitary landfill and/or incineration with energy recovery	**Reusable** preferred	**Reusable** preferred	**Reusable** preferred **Single-use** preferred if poor laundering practices, high carbon electricity and/or low number of uses	**Single-use** preferred, especially nappies with lightweight designs	**Single-use** preferred, especially nappies with lightweight designs	**Reusable** preferred
ADVANCED WASTE MANAGEMENT & GOOD POLICY SUPPORT AND INFRASTRUCTURE FOR ADVANCED WASTE TREATMENT* (e.g., recycling, industrial composting, anaerobic digestion)	**Reusable** preferred	**Reusable** preferred	**No clear** preference but slight preference for single-use if nappies are recycled*	**Single-use** preferred, potential for bio-based nappies	**Single-use** preferred, potential for bio-based nappies	**Reusable** preferred

* Recycling of single-use nappies is yet to be implemented on a large scale, with the main logistical and infrastructural challenges currently being the separate collection and storage of dirty nappies. Recycling and other advanced waste treatment options for single-use nappies have however been shown to be technically feasible with good environmental outcomes in pilot studies.

Reusable nappies preferred | **Single-use nappies preferred** | **No clear preference for reusable or single-use nappies**

EXECUTIVE SUMMARY

The meta-analysis shows that, in general, reusable nappies have lower environmental impacts than single-use nappies. Thus, an overarching policy recommendation is that there should be greater advocacy for and incentives to adopt reusable nappy systems. That said, in the matrix on the previous page where single-use nappies are found to be preferred, it would be sound to find ways to improve consumer behaviour and make reusable alternatives practical. In particular, the following are needed:

- Adequately educate consumers on efficient laundering practices
- Incentivize "nappy service" business models and service companies that can wash reusables efficiently
- Encourage multiple reuses of nappies
- Focus efforts on transitioning to low-carbon electricity

There are also actions needed to lessen the environmental impacts of single-use nappies. These include:

- Ensure adequate waste collection and appropriate disposal of single-use nappies
- Incentivise the design of nappies that are light-weight and require less materials
- Investigate the potential for bio-based/ compostable nappies in tandem with the provision of infrastructure for their disposal (industrial composting or digestion)
- Invest in nappy recycling

Overall, the meta-analysis recommends that **taking a life cycle perspective is essential for nappies,** where the highest impacts of reusable nappies occur not in manufacturing but in the use phase, while for single-use nappies, the design of the nappy (the weight and its materials) along with its management at end-of-life are the important life cycle stages.

Furthermore, it is critical to **recognise that the "nappy system" sits within a wider social, economic and environmental system**, and that there are wider factors that need to be considered in order to develop appropriate policy. For single-use nappies, particularly important is the local waste management context. For reusable nappies, the most critical aspects are consumer behaviour and perceptions, both in recognising the need for convenience and cost effectiveness, and in washing habits that strongly affect the environmental impacts of reusable nappies. Other highly relevant aspects to both single-use and reusable nappies are energy sector developments, and implementation costs and barriers. Many of these considerations are not only country specific, but also vary with time.

This report highlights policy considerations in four broad areas:

- **Policies must consider differences in and suitability of end-of-life processes**. It is important that, before deciding on policies affecting single-use nappies, the end-of-life fate of nappies is correctly and appropriately modelled for the particular country context, taking into account the limitations of existing infrastructure and technologies (as well as the potential of future technologies). Policy makers should also be aware that LCA studies underestimate the impacts of the end-of-life disposal of single-use nappies in contexts where leakage to the environment is high or where landfills are not well managed. Furthermore, LCA studies do not take into account the strain on local municipalities and the economic costs of managing single-use nappy waste, let alone the economic costs of marine litter.

Taking a **life cycle perspective is essential** for nappies. The **highest impacts** of **reusable nappies** occur in the **use phase**, while for **single-use nappies, the production of materials** along with the **management of the nappy at end-of-life** are the important life cycle stages.

- **Consumer behaviour and preferences must be considered when developing policies regarding reusable nappies.** Policy support will be needed to develop innovative reusable nappy systems that offer the same level of convenience and cost effectiveness as disposable nappies. Consumer education is essential to ensure that the environmental benefits of reusable nappies are realised. Educating consumers on how best to wash nappies for effective hygiene and lowest environmental impacts will be an important aspect of any policy on reusable nappies.

- **Policies should be geographically adapted and account for likely future developments in production processes and related systems.** More recently developed technologies and materials may be at a disadvantage to other more established technologies and materials owing to their scale or lack of data availability. This is true of bio-based polymers and the potential for composting and recycling single-use nappies at end-of-life. Many of the aspects that affect environmental performance are also geographically dependent, such as available feedstocks for bio-based materials, electricity generation mixes (important for heating water for laundering reusable nappies), consumer behaviour with regard to reusable alternatives, and available waste management infrastructure. It is critical that policy makers understand and appreciate the implications and feasibility of proposed policies in the context of geographical constraints. In the same way that policies need to take into account country- or region-specific characteristics, **policies must be culturally and socially adapted** and take into account the characteristics of the consumer population that will be impacted on by the policy.

- **Policies must recognise and manage trade-offs in impacts and risks of burden-shifting,** especially to impacts that have not been quantified in the studies. For nappies, hygiene aspects, as well as potential for littering and adding to marine plastics, are aspects not covered by LCA studies.

Table E1: Overview of studies included in the meta-analysis.

The option with the lowest climate impact

Study	Functional unit	Material				Geographic scope	Main conclusions
		Single-use	Reusable				
LCA studies comparing single-use and reusable cloth nappies							
Life cycle assessment of innovative circular business models for modern cloth diapers *Hoffmann, Morais and Teodoro (2020)* This study compares single-use (disposable) nappies and modern cloth nappies, analysing the potential for circular and innovative business models for the application of cloth nappies in Brazil.	One toilet-trained child (number of nappies to ensure the absorption of a baby's faeces and urine from birth until 2.5 years old).	Standard nappy	Cloth nappy with nappy-as-product business model, nappies washed at home	Cloth nappy with simple nappy-as-service model, nappies washed in on-site laundry	Cloth nappy with simple nappy-as-service model, nappies washed off-site in Industrial laundry	Brazil	Reusable nappies have lower potential ecosystem and human health impacts and lower potential damage to ecosystems than single-use nappies. The optimised "nappy-as-service" has the lowest ecosystem impacts as water and energy use are optimised.
An updated lifecycle assessment study for disposable and reusable nappies *Aumónier, Collins and Garret (2008), update of Life Cycle Assessment of Disposable and Reusable Nappies in the UK (Aumónier and Collins, 2005)* This study compares single-use (disposable) and reusable nappies in the UK. The 2008 study builds on the 2005 study updating the three nappy systems modelled in the first study with more recent electricity, energy consumption, manufacturing and waste management data. Furthermore, developments in the market of reusable nappies in the UK mean that the most meaningful reusable nappy to consider in the updated LCA was shaped reusable cloth nappies, home laundered.	The use of nappies during the first 2.5 years of a child's life.	Standard nappy	Terry towel nappy	Cloth nappy pre-folded	Shaped nappy	UK	The environmental impacts of reusable cloth nappies can be higher or lower than those of single-use nappies depending on how they are laundered. Unlike single-use nappies, the environmental impacts of reusable nappies are primarily driven by consumer behaviour.
Life cycle assessment: Reusable and disposable nappies in Australia *O'Brien, Olive, Hsu, Morris and Bell (2009)* This study compares reusable and single-use (disposable) nappies in Australia. Two reusable scenarios were considered, that of nappies washed at home and that of nappies washed in a commercial laundry. The nappy systems were evaluated against four inventory-level categories, namely water resource depletion, non-renewable energy depletion, solid waste (mass) and land area.	The use of nappies during the first 2.5 years of a child's life.	Standard nappy	Home-washed	Commercially washed		Australia	A key difference between reusable and single-use nappy systems is that the consumer has significantly more control over the environmental impacts of reusable nappies. Home-washed reusable nappies, washed in cold water in a front-loading washing machine and line-dried, use less energy and land resources and comparable water resources, and produce similar or lower quantities of solid waste, than single-use nappies.

Table E1: Overview of studies included in the meta-analysis.

The option with the lowest climate impact

Study	Functional unit	Material			Geographic scope	Main conclusions
		Single-use		Reusable		
LCA studies comparing single-use nappies – improvements in design						
Improving resource efficiency and environmental impacts through novel design and manufacturing of disposable baby diapers *Mendoza, Popa, D'Aponte, Gualtieri and Azapagic (2019)* AND **Disposable baby diapers: Life cycle costs, eco-efficiency and circular economy** *Mendoza, D'Aponte, Gualtieri and Azapagic (2019)* These two studies evaluate the economic and environmental impact of using an optimised absorbent core and innovative bonding technologies to replace gluing systems in nappy manufacturing.	Manufacture and use of 1,000 single-use baby nappies	Standard nappy	Glueless nappy	N/A	Europe	Glueless single-use nappies are more eco-efficient than standard single-use nappies, with lower environmental impacts on a range of indicators including consumption of raw materials, primary energy demand and global warming potential. They also have more than 50% lower eutrophication, ozone depletion, human toxicity and ecotoxicity potentials. Lower raw material inputs also reduce transport and waste management requirements. The key driver for the lower environmental impacts of single-use glueless nappies is their greater material efficiency.
Life cycle assessment of bio-based products: a disposable diaper case study *Mirabella, Castellani and Sala (2013)* The study compares the eco-design and eco-innovation of the "WIP" nappy produced in Italy that substitutes two different bioplastics (PLA and a starch-based biopolymer) for a significant proportion of the petroleum-based plastics in a standard nappy produced in the UK. The study focuses on material production and nappy manufacturing (cradle-to-gate) and investigates three end-of-life scenarios in a sensitivity analysis.	1 nappy	Standard nappy	Bio-based nappy	N/A	Europe	The bio-based single-use nappy has a better environmental profile than a standard single-use nappy with lower potential environmental impacts across a number of impact categories (including climate), but has higher agricultural land occupation, land transformation and water depletion. The study identified several areas to improve the environmental profile of the bio-based nappy, including selecting biopolymer suppliers on the basis of their environmental performance, reducing transport distances along the supply chain, and ensuring the nappy is composted at end-of-life.
LCA studies comparing single-use nappies – focus on end-of-life treatment						
Technological, environmental and social aspects of a recycling process of post-consumer absorbent hygiene products *Arena, Ardolino and Di Gregorio (2016)* This study investigates the technical feasibility, environmental compatibility and social aspects of a novel recycling process for absorbent hygiene products and assesses three end-of-life options for a standard single-use nappy.	The treatment of 500 kg of absorbent hygiene product waste.	Recycled at end-of-life	Landfilled or incinerated at end-of-life	N/A	Italy	Recycling a single-use nappy results in lower environmental impacts than incinerating or landfilling it, leading to significantly lower global warming potential and non-renewable resource consumption.

Abbreviations

TERM	DEFINITION
ATB	Air-through bonded
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low density polyethylene
ODP	Ozone layer depletion potential
OECD	Organisation for Economic Co-operation and Development
PET	Polyethylene terephthalate
PLA	Polylactic acid
PP	Polypropylene
PUL	Polyurethane laminated fabric
SAP	Super absorbent polymer
TAC	Technical Advisory Committee
TCF	Totally chlorine free
UNEP	United Nations Environment Programme

01 Introduction

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1.1 BACKGROUND

Plastic pollution is reaching crisis proportions as the world's production and consumption of single-use plastic products far outstrips its capacity to dispose of these items safely. In the past few decades, plastic production has soared from 2 million metric tonnes in 1950 to 348 million metric tonnes in 2017. It is a powerful global industry valued at US$522.6 billion that is on track to double in size by 2040 (The Pew Charitable Trusts and Systemiq, 2020). An estimated nine billion tonnes of plastic have been produced to date, mostly from fossil fuels – a significant portion of which is in the form of packaging and other single-use items (Geyer, Jambeck and Law, 2017; UNEP, 2018). About 60% of this is estimated to have ended up in landfills, or in oceans and waterways; plastic recycling rates remain very low with only 9% of all plastic ever produced recycled (Geyer, Jambeck and Law, 2017). In urban environments, particularly in low-income countries where as much as 93% of waste is openly dumped, plastic waste causes flooding and waterborne diseases by clogging drains and respiratory diseases by releasing toxins and particulates when burned (Kaza et al., 2018).

Visible plastic pollution has not only an environmental and health impact, but also an economic impact, particularly on industries like tourism, fishing and shipping. And because most plastic does not biodegrade, but rather breaks down over time into smaller and smaller pieces, eventually becoming "microplastics", these particles have been found in almost every natural habitat on earth. Ultimately microplastics are finding their way back into the food chain via organisms and animals and have been found to be ingested by deep sea amphipods in six of the deepest marine ecosystems on earth (Jamieson et al., 2019).

Single-use (disposable) nappies are one of the biggest contributors to plastic waste. Vanuatu is the first country to consider banning single-use nappies, after it came to light that nappies account for 27% of the nation's solid waste (Savvy Vanuatu, Mamma's Laef Vanuatu and Bambino Mio, 2021). Since the emergence of early prototypes in the late 1940s and early 1950s, the single-use nappy market has boomed globally. Some 33 billion single-use nappies per year are estimated to be consumed in the EU alone, resulting in around 6.7 million tonnes of waste annually (Cabrera and Garcia, 2019). These numbers continue to rise, with the global nappy market expected to exceed US$71 billion by 2022. The growth is fuelled by the high birth rate in developing countries coupled with improving economies and urbanisation, along with increased availability and marketing, amongst other factors (Khoo et al., 2019). Furthermore, while some countries, notably those in Western Europe, are seeing a decreasing trend of nappy consumption and nappy waste because of falling birth rates, aging populations in these countries are likely to drive an increasing consumption of adult incontinence products (Cabrera and Garcia, 2019). Manufactured from wood pulp, cotton and viscose rayon as well as several plastics (polyester, polyethylene, polypropylene, etc.), single-use nappies have environmental impacts across their entire life cycle. Most single-use nappies are disposed of in landfill. For example, in Europe and the USA, approximately 87% and 80% respectively of nappies end up in landfills (Arena, Ardolino and Di Gregorio, 2016; Cabrera and Garcia, 2019).

Reusable cloth nappies are promoted as an environmentally friendly alternative to single-use nappies. However, reusable nappies require water and energy for washing and drying, with variability in usage rates and washing practices making their comparison with single-use nappies not a straightforward one. Furthermore, the weight of the average single-use nappy has been reduced by nearly 50% over the last three decades, significantly decreasing their environmental impacts and rendering them more competitive with reusable options.

Nonetheless, there is a clear need to consider alternatives to single-use nappies. *Resolution 9 of the fourth edition of the United Nations Environment Assembly (UNEA-4) in March 2019, on "Addressing Single-use plastic products pollution" (UNEP/EA.4/R.9)*, "encourages member states to take actions, as appropriate, to promote the

Some **33 billion single-use nappies** are estimated to be consumed per year in the EU alone, resulting in around **6.7 million tonnes of waste annually**. These numbers continue to rise, with the global nappy market expected to exceed **US$ 71 billion by 2022**.

identification and development of environmentally friendly alternatives to single-use plastic products, taking into account the full life cycle implications of those alternatives" (UNEP, 2019). The UN Environment Programme was requested by UNEP/EA.4/R.9 to make available existing information on the full life cycle environmental impacts of single-use plastic products compared to their alternatives.

Guided by UNEA-4, Resolution 9, this study aims to inform decision makers on the environmental impacts of single-use nappies and their alternatives from a life cycle perspective. It is part of a *series of meta-studies*, each covering other widespread single-use plastic products and their alternatives, including *bags*, *bottles*, *take-away food packaging*, *beverage cups*, *tableware*, menstrual products and face masks (personal protective equipment).[1]

1.2 PURPOSE, SCOPE AND METHOD

This report provides insights from Life Cycle Assessments (LCA) to inform decisions on single-use (disposable) nappies and their alternatives. It is based on the review and analysis (meta-analysis) of selected existing LCA studies that compare single-use nappies and their alternatives. The different solutions in this report thus include only those options that have been covered in the LCA literature. The following single-use and reusable options are considered:

- Single-use standard nappies
- Single-use glueless nappies
- Single-use bio-based nappies
- Reusable cloth nappies

Searches were initially performed on Web of Science to identify relevant peer-reviewed studies published between 2000 and 2020. Thereafter, further searches were performed using Google Scholar and Google to ensure that the literature search was comprehensive and included both academic literature and company- and industry-sponsored LCA studies. A Technical Advisory Committee (TAC) and relevant professional networks were also consulted to identify studies that the web searches might have missed.

Nappies have been a relatively active area of research in LCA. Studies between 1990 and 2009 are well documented in a review by Ng et al. (2013). Cordella et al. (2015) also provide an overview of the literature, particularly with regard to environmental impact categories covered and evolution in nappy design. This meta-analysis therefore focuses on the most recent studies and those studies that consider alternatives to single-use nappies, although insights from the review studies and wider relevant literature are included in the discussion and conclusions. The studies covered in the meta-analysis were shortlisted based on the following criteria, with input from UNEP and the TAC:

- **Type of product:** Studies that focused on single-use and reusable nappies were included.
- **Completeness of the study:** Full LCA studies were selected over preliminary or screening LCA studies.
- **Transparency of the study:** Only studies that included sufficient details in the publication were shortlisted, particularly on methodological assumptions, sources of data and impact assessment methods.
- **Geographic coverage:** Electricity grid mix, available waste management technologies and efficiencies, and recycling rates differ significantly by geographic region. Thus, selecting studies to cover as many regions as possible was important for the meta-analysis. This report is intended to have global applicability, which provides further rationale for selecting studies for broad geographic coverage.
- **Publication date:** Technologies improve over time and so, although the original screening considered publications from 2000 onwards, more recent studies were given preference in the final selection.
- **Language:** The meta-analysis only included studies published in English.
- **Peer review:** Preference was given to studies that have been through peer review. Compliance with international standards is not a selection criterion, as this is often not explicitly stated in publications. Furthermore, it is assumed that the peer review process would focus on compliance with relevant standards.

Seven studies fulfilled the criteria and were selected for the meta-analysis. Table E1 summarises the studies covered in the meta-analysis, which cover single-use and reusable nappies. In terms of geographic scope, the studies comparing single-use and reusable nappies cover the United Kingdom, Australia and Brazil. The studies focused on improvement in nappy design are European in scope.

1 *All these reports are available from https://www.lifecycleinitiative.org/single-use-plastic-products-studies/*

1.3 LCA METHOD IN BRIEF

Life Cycle Assessment (LCA) is a well-established tool for assessing the potential environmental impacts associated with a product or service, providing a structured framework within which to model its consequences on the natural environment and society. All stages of a product's life cycle are considered, from mining, extraction or growing of raw materials to its manufacturing, distribution and use, right up to the final disposal of its components. LCAs have a number of benefits, including the following:

- Creating awareness that decisions are not isolated, but that they influence a larger system
- Promoting decision-making for the longer term, by considering all environmental issues and potential knock-on effects associated with a decision choice
- Improving entire systems, and not just single parts of systems, by avoiding decisions that fix one problem but cause another unexpected issue

An LCA identifies the impacts and significance of each life cycle stage of the product analysed and makes possible comparisons with different products or systems and between different materials. International standards on LCAs (ISO 14040 and ISO 14044) divide LCAs into four main stages:

- **Goal and scope definition:** Objective (goal) and the methodological approach (scope).
- **Inventory analysis:** All raw materials and emissions (inputs and outputs) are considered for each of the unit processes that make up the life cycle of the product. Inputs include the use of natural resources, such as land and water, as well as manufactured materials such as fuels and chemicals. Outputs are released to air, water and land, as well as all products and by-products. Taken together, these unit processes make up the life cycle system to be analysed, as defined by the product system boundary. The life cycle inventory (LCI) is a comprehensive list of resources and emissions (inputs and outputs).
- **Impact assessment:** The LCI is assessed by connecting resources and emissions to their corresponding impacts on the environment and human health. In this way, the inputs and outputs are summed up into common areas of environmental concern such as impacts on human health, impacts on ecosystems, etc. This can be done at varying degrees of complexity, and a number of different life cycle impact assessment (LCIA) methods have been developed to quantify the potential environmental impacts of a product system.
- **Interpretation:** Findings are evaluated in relation to the defined goal and scope in order to reach conclusions and make recommendations.

It is important to note that, although the LCA method is standardised, there is still room for a range of methodological choices that have an impact on the results. Additionally, LCAs predict *potential* environmental impacts or damages, as the necessarily global nature of the predictive LCIA models means they do not take the specific receiving environment into account. Life cycle inventory data (the basis for impact assessment) span multiple geographical locations across countries and continents in today's global supply chains, thus LCIA's predictive models are not like environmental impact assessment (EIA) models that accurately characterise the actual risks associated with emissions at a particular location. Indeed, the value of an LCA study lies not so much with the final numbers, but rather with the exploration and consequent understanding of the system it assesses. **Especially valuable is an LCA's ability to highlight hotspots along the value chain** (i.e., show the areas of highest potential impact), and also to **highlight trade-offs between different impacts**. It is seldom that one system or decision option performs better than another in all aspects of environmental impact. Understanding these trade-offs is a prerequisite towards improving the sustainability of product systems.

LCA is a well-established tool for **assessing the potential environmental impacts associated with a product or service**, providing a structured framework within which to model its consequences on the natural environment and society.

02 Meta-analysis of the LCA studies

This chapter presents the **main findings and results of the analysed LCA studies**, which are grouped as follows:

- LCA studies comparing single-use and reusable cloth nappies
- LCA studies comparing single-use nappies – improvements in design
- LCA studies comparing single-use nappies – focus on end-of-life

For each study a short description is provided together with a summary of the results and main conclusions. This is followed by a tabular summary of the study, which presents further details of the products studied and highlights key assumptions. Results are summarised using colour coding to depict the relative performance of products across the impact indicators considered in the study. Note that the colour coding denotes only relative and not absolute impacts and the reader is referred to the original reference to appreciate the range and scale of the impacts calculated by the studies.

All LCA studies have an inherent degree of variability and uncertainty in their results. To address this, where the difference in impact category scores between two options is only around 10%, or where a statistical analysis in the study shows the options to be overlapping, they are ranked equally in the tables. For example, in Aumónier and Collins (2005), the single-use nappy system was found to have a global warming potential (GWP) of 626 kg CO_2e and the home-laundered reusable "terry" nappy system a GWP of 559 kg CO_2e. The difference between the two options in terms of their climate impact is thus only 11%. Furthermore, a sensitivity analysis showed significant overlap between the two, with the range in GWP for the single-use nappy system falling within the range in GWP found for home-laundered nappies. They are thus ranked equally in the summary table for this study (Table 2).

02 META-ANALYSIS OF THE LCA STUDIES

2.1 LCA STUDIES COMPARING SINGLE-USE AND REUSABLE NAPPIES

2.1.1 Life cycle assessment of innovative circular business models for modern cloth diapers: Hoffmann, Morais and Teodoro (2020)

This study compares single-use (disposable) nappies and modern cloth nappies, analysing the potential for circular and innovative business models for the application of cloth nappies in Brazil. Using the principles of the circular economy, the authors formulate three potential business models for the cloth nappies:

- **"Nappy-as-product":** The cloth nappy is sold without any additional service, that is, it is washed at home using the domestic washing machine typical of the Brazilian market (top loader without hot water supply)
- **Simple "Nappy-as-service":** Nappies are rented, with consumers paying a monthly subscription fee. The nappy service is managed by day-care centres with the nappies washed on site.
- **Optimised "Nappy-as-service":** Nappies are rented through a pay-per-service system (as opposed to a subscription system). The nappy service is a large-scale operation with the nappies washed in an industrial laundry operating continuous batch washers.

The three circular business models are compared with the current Brazilian situation, that of standard single-use nappies with the waste nappies disposed of to landfill (both sanitary and unsanitary).

Summary of results and conclusions

Reusable nappies have lower potential human health impacts and lower potential damage to ecosystems than single-use nappies. The business model where consumers pay for the service of having a clean nappy with nappies washed in a large industrial laundry (optimised "nappy-as-service") also has lower water and resource depletion than single-use nappies. This model also has the lowest ecosystem impacts, as water and energy use are optimised.

Further specific findings include the following:

- **The main contributor to potential damage to ecosystems is climate change for all nappy types other than the home-laundered reusable nappy, to which land transformation makes the highest contribution**. Single-use nappies have the highest potential impact on climate change, arising mainly from waste management (greenhouse gas (GHG) emissions from landfills at end-of-life). Cloth nappies have high agricultural land occupation, natural land transformation and terrestrial ecotoxicity impacts, primarily owing to growing cotton. The home-washed nappy scenario ("nappy-as-product") has the highest potential damage to ecosystems. This is due to the use of palm-oil soap and vinegar in the laundering (use phase) of the nappies, with the production of palm-oil associated with high natural land transformation. The "nappy-as-service" scenarios assume the nappies to be washed with detergent, so do not have as high a land transformation impact.

- **Reusable nappies have lower potential damage to human health than single-use nappies.** The main contributor to potential human health damage is climate change. Single-use nappies disposed of in unsanitary landfills have considerably higher GHG emissions than single-use nappies disposed of in sanitary landfills. **Single-use nappies also have the highest potential human toxicity impacts** (with human toxicity the second-highest contributor to the human health damage category). As with climate change, human toxicity impacts from single-use nappies are primarily driven by waste management (landfill disposal). **Differences in the climate and human toxicity impacts between the reusable nappy scenarios are due to differences in laundering practices and the products used in laundering**. Machine washing with water heated with electricity was found to have higher GHG emissions than machine washing with water heated with natural gas. Home washing in cold water was found to have lower GHG emissions than machine washing with heated water (when both use detergent). Furthermore, home washing with detergent was found to have lower potential human health impacts than home washing with natural products (palm-oil soap and vinegar).[2] Overall, the industrial laundry with optimised energy and detergent was found to have the lowest climate and human toxicity impacts, followed closely by home washing with detergent.

- **The home-washed reusable nappy has the lowest resource depletion,**[3] owing to the fact that in this scenario the nappies are washed in cold water. Home-washing with natural products has lower fossil-resource depletion than washing with synthetic detergents. Reusable nappies machine-washed with water heated by gas (the simple "nappy-as-service" scenario) has the highest fossil-resource depletion. The single-use nappies were found to have resource depletion similar to that of machine-washed nappies in heated water (but considerably higher than the home-washed nappies and the optimised laundry scenario).

- **Reusable nappies have higher water depletion than single-use nappies, except when washed in a large-scale industrial laundry where water use is optimised**. Water pollution is also an important issue to consider, but freshwater and marine ecotoxicity, eutrophication and acidification impacts are low for both single-use and reusable nappies. This is due to the assumption in the LCA that wastewater from nappy production and washing is treated correctly and significant quantities of pollutants are not released to the environment.

A **sensitivity analysis** was performed on the reusable nappies to analyse the impact of doubling the number of absorbents (cotton) and covers (PUL[4]). **Doubling the nappy covers has a negligible impact on the results** owing to low material needs for nappy cover production and the assumption that the polyester in nappy covers is made from recycled material. **Increasing the cotton component of the nappy (absorbents), however, causes a substantial increase in all impacts**. Lastly, it was assumed that all three business models/laundry scenarios had the same rate of material fatigue. In this case, reusable nappies still had lower potential ecosystem and human health impacts than single-use nappies, however, the differences between the systems were less pronounced.

2 *This finding may be due to the particular phosphate-free detergent and palm oil-based natural soap assumed in the Brazilian context of the study and should not be generalised to all detergents and natural washing products.*

3 *Resource depletion is divided into fossil-fuel depletion and metal depletion. However, metal depletion is negligible for this system as few/no metals are involved in the production of the cloth and disposable nappies. However, this might change if capital equipment were included, notably washing machines in the reusable nappy systems.*

4 *Polyurethane Laminate Fabric or PUL is a soft, flexible and waterproof fabric comprising two layers: a polyester fabric with a very thin layer of polyurethane film bonded to the reverse.*

Table 1: Summary table: Hoffmann, Morais and Teodoro (2020)

		Products considered in study						
		Single-use nappy		Reusable nappy with nappy-as-product business model using domestic laundry		Reusable nappy with simple nappy-as-service model using on-premises laundry		Reusable nappy with an optimised nappy-as-service model using industrial laundry
Study scope	Material	Fluff pulp, SAP, PP nonwovens, PE sheet, adhesives, elastics		Absorbent: cotton; Cover: PUL		Absorbent: cotton; Cover: PUL		Absorbent: cotton; Cover: PUL
	Functional unit	One toilet-trained child, i.e., the number of nappies to ensure the absorption of a baby's faeces and urine from birth until 2.5 years old. This equates to a reference flow of 4,550 single-use nappies (5 nappy changes a day) and 6,730 clean cloth nappies (7 nappy changes a day)						
	Number used	4,550 nappies		30 nappies; 10 covers		21 nappies; 10 covers		17 nappies; 10 covers
	Geographic region	Brazil						
	Life cycle stages	Cradle-to-grave						
	End-of-life scenario (single-use nappy) and use-phase scenario (reusable nappy)	Sanitary landfill	Un-sanitary landfill	Washed at home with detergent in cold water	Washed at home with soap in cold water	Machine washed and dried; water heated with electricity	Machine washed and dried; water heated using gas	Continuous batch washers (industrial-scale laundry)
Indicators	Ecosystem							
	Human health							
	Resources							
	Water depletion							
Method	ReCiPe 2008 midpoint and endpoint (Hierarchist perspective)							
Other comments	A sensitivity analysis that considered the effect of reducing materials by 15% (based on historical performance in nappy design), reduced GWP and primary energy demand by 12% and 15% respectively.							
Reviewed	Peer-reviewed journal							

Highest relative impact **In-between (neither highest nor lowest)** **Lowest relative impact**

2.1.2 An updated lifecycle assessment study for disposable and reusable nappies: Aumónier, Collins and Garret (2008), update of Life Cycle Assessment of Disposable and Reusable Nappies in the UK: Aumónier and Collins and Garret (2005)

This study commissioned by the UK Environment Agency compares single-use (disposable) and reusable nappies in the UK. The 2008 study builds on the 2005 study, so the 2005 study is also covered in the meta-analysis.

In Aumónier and Collins (2005), three nappy systems were modelled:

- Single-use nappies and their packaging
- Reusable cloth nappies, home laundered
- Pre-folded reusable cloth nappies, commercially laundered and delivered to the home

In Aumónier, Collins and Garrett (2008), the nappy systems were updated with more recent electricity, energy consumption, manufacturing and waste management data. Furthermore, developments in the market of reusable nappies in the UK meant that the most meaningful reusable nappy to consider in the updated LCA was shaped reusable cloth nappies, home laundered.

The functional unit was chosen as the use of nappies during the first 2.5 years of a child's life which, together with a use rate of 4.16 nappies per day, gives a reference flow of 3,796 nappies. Two scenarios with different excreta volumes were applied in the study, with the use of 3,796 nappies resulting in 391.4 kg and 537.6 kg of nappy waste in the two scenarios respectively.

Summary of results and conclusions

The environmental impacts of reusable cloth nappies can be higher or lower than those of single-use nappies depending on how they are laundered. Unlike those of single-use nappies, the environmental impacts of reusable nappies are driven by consumer behaviour.

For single-use nappies:

- The **manufacture of materials and production of single-use nappies are the largest contributors to environmental impacts**. Transport home by consumers is also a significant contributor.
- **Disposal is a significant contributor to ozone depletion and freshwater ecotoxicity,** with the biggest differences seen in these two impact categories when the quantity of putrescible materials sent to landfill and incineration was varied in scenarios.
- The **global warming potential from single-use nappies decreased in the updated study** owing to changes in manufacturing and a 13.3% reduction in the weight of nappies.

For shaped, reusable nappies:

- The **main driver of environmental impacts is electricity consumption in washing and drying nappies in the use phase**. Consequently, high-temperature washing and 100% tumble-drying scenarios have the highest impacts, as a result of high electricity consumption. **The lowest impacts are observed under the extreme sensitivity scenario**, in which nappies are reused on a second child, washed at high load efficiency and line dried 100% of the time.
- For **home-laundered reusable nappies the main source of environmental impacts is home electricity use (washing, drying and ironing nappies)**. The production of detergent and of the terry towel (nappy production) are also significant contributors, depending on the particular impact category.
- For **commercially laundered reusable nappies the main sources of environmental impacts are the electricity and gas used in the laundry**, followed by the transport of nappies to and from the home, and the production of nappies.

A number of sensitivity analyses were performed, which produced the following results:

- The **most important variables** in the reusable nappy system are whether putrescible waste is removed from the nappies before washing, the percentage tumble dried, the age of the washing machine, and the type of nappy fabric.
- The updated study found **light-weighting and anaerobic digestion of single-use nappies at end-of-life offered potential to decrease their environmental impacts**.
- The **results are** relatively **insensitive to the number of nappy changes per day**, omitting minor material inputs and increasing the percentage of liners that are flushed rather than disposed of with solid waste.

Table 2: Summary table: Aumónier and Collins (2005)

		Products considered in study		
		Single-use nappy	Reusable nappy (terry nappy) – home laundered	Reusable nappy (prefold) – commercially laundered
Study scope	Material	Fluff pulp, SAP, PP, PE, adhesives, calcium carbonate, tape, polyester, elastic, lotion, packaging	Cotton, disposable liners (PP and cellulose)	Cotton, wrap/pant (PET), liners (PP and cellulose)
	Functional unit	The use of nappies during the first 2.5 years of a child's life.		
	Number used	3,796 (4.16 nappies per day)	47.5 nappies	52.5 nappies
	Weight per nappy [g]	44.64	115	75.5
	Geographic region	UK		
	Life cycle stages	Cradle-to-grave		
	End-of-life assumptions	Landfill (91%) and incineration (9%)		
Indicators[5]	Global warming			
	Ozone layer depletion			
	Photochemical oxidation			
	Abiotic resource depletion			
	Eutrophication			
	Acidification			
	Human toxicity			
	Terrestrial ecotoxicity			
	Freshwater aquatic ecotoxicity			
Method	CML 2001			
Other comments	Sensitivity analyses found the most important variables to be whether putrescible waste is removed from the nappies before washing, the percentage tumble dried and the age of the washing machine.			
Reviewed	Critically reviewed by an external reviewer in accordance with ISO14040.			

Highest relative impact **In-between (neither highest nor lowest)** **Lowest relative impact**

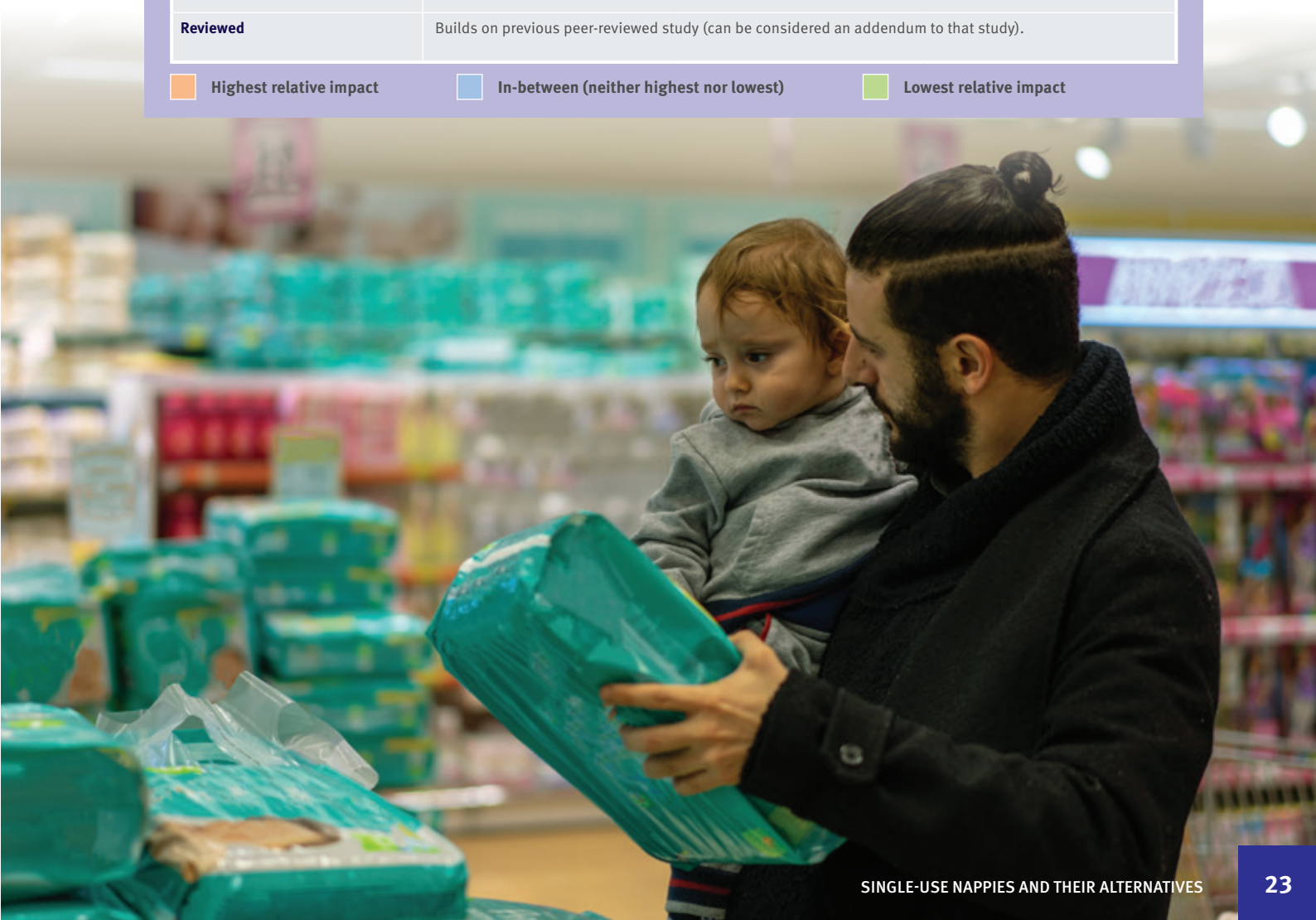
A key difference between reusable and single-use nappy systems is that the **consumer has significantly more control over the environmental impacts of reusable nappies** than they do of single-use nappies.

5 *Nappy systems are compared as ranges across the scenarios and sensitivity analyses, and indicate the high degree of overlap in the results between the three systems.*

Table 3: Summary table: Aumónier, Collins and Garrett (2008)

		Products considered in study	
		Single-use nappy	Shaped nappy
Study scope	Material	Fluff pulp, SAP, PP, LDPE, Adhesives, PET/polyester and other	Nappies: cotton; Wraps: cotton, polyester, polyurethane; Disposable liners
	Functional unit	The use of nappies during the first 2.5 years of a child's life	
	Number used	3,796 (4.16 nappies per day)	30 nappies, 12 wraps
	Weight per nappy [g]	38.6	139.3
	Geographic region	UK	
	Life cycle stages	Cradle-to-grave	
	End-of-life assumptions	Landfill (86%) and incineration (14%)	
Indicators	Global warming		
	Photochemical oxidation		
	Abiotic resource depletion		
	Eutrophication		
	Acidification		
	Human toxicity		
	Freshwater aquatic ecotoxicity		
Method	CML 2001		
Other comments	The sensitivity analysis considers additional excreta, anaerobic digestion, high energy-consumption scenario and light weighting.		
Reviewed	Builds on previous peer-reviewed study (can be considered an addendum to that study).		

Highest relative impact **In-between (neither highest nor lowest)** **Lowest relative impact**



2.1.3 Life cycle assessment: Reusable and disposable nappies in Australia: O'Brien, Olive, Hsu, Morris and Bell (2009)

This study compares reusable and single-use (disposable) nappies in Australia using LCA. Two reusable scenarios were considered, that of nappies washed at home and that of nappies washed in a commercial laundry. For the single-use nappies, two scenarios were evaluated, one where the nappy and its entire contents are placed in the garbage after use, and a second one where faeces are flushed into the sewer system before the nappy is placed in the garbage. However, the impact categories chosen on which to evaluate the nappy systems were not appropriate for discerning differences between the two single-use nappy scenarios, so the results for only one single-use nappy system is shown in Table 4 (since the results were identical for the two scenarios).

The nappy systems were evaluated against four inventory-level categories, namely water resource depletion, non-renewable energy depletion, solid waste (mass) and land area.

Summary of results and conclusions

There is significant variability and overlapping within and between reusable and single-use nappy systems. A key difference between reusable and single-use nappy systems is that **consumers have significantly more control over the environmental impacts of reusable nappies than they do over those of single-use nappies**. Home-washed reusable nappies, washed in cold water in a front-loading washing machine and line-dried, use less energy and land resources than single-use nappies and produce similar or lower quantities of solid waste and use comparable water resources to them.

Detailed findings include:

- **Reusable nappies washed in a top-loading washing machine have the highest water resource depletion**. Washing, which includes soaking and flushing faeces, accounts for 40% to 80% and 7% to 15% of the total water used by home-washed nappies and commercially-washed nappies respectively. The higher water efficiency of the commercial washing process accounts for its lower contribution to total water use. However, as commercially washed nappies have a shorter lifespan (owing to the assumption that stains and discoloration would not be acceptable in a commercial setting as they would be in a home environment), more cotton (and consequently more water to grow the cotton) is required over the life cycle.

- **Home-washed nappies have the lowest energy resource depletion** (including non-renewable energy). Energy used to heat water for soaking nappies accounts for 30% to 56% of the total energy consumed. Nappies that are tumble dried or washed in hot water have higher energy resource depletion and GHG emissions than those that are line-dried and washed in cold water. Energy resource depletion is relatively insensitive to variations in the number of nappy changes per day and the mass of nappies. The type of washing machine used was found to have a greater impact on water resource depletion than on energy resource depletion for home-washed nappies.

- **Single-use** and **commercially-washed reusable nappies have similar ranges in energy resource depletion**. Pulp production accounts for 75% of non-renewable energy resource depletion in single-use nappies, even with 46% of energy used for pulping being from renewable sources. Most of the energy resource depletion in commercially laundered nappies (56% to 62%) is due to transporting the nappies between the home and the laundry.

- **Single-use nappies produce 20 times more solid waste than reusable nappies** (both home-washed and commercially washed), with urine accounting for more than 50% of the mass of solid waste generated. The mass of the nappy itself accounts for the remainder of the solid waste mass. Flushing the faeces reduces the solid waste mass by 86kg but increases water consumption.

- **Single-use nappies require substantially more land area for resource production than reusable nappies do**, and commercially washed nappies require two to three times more land area than home-washed nappies. This is because commercially washed nappies have a shorter lifespan and more cotton is required.

Table 4: Summary table: O'Brien, Olive, Hsu, Morris and Bell (2009)

		Products considered in study		
		Single-use nappy	Home-washed reusable nappy	Commercially washed reusable nappy
Study scope	Material	40% cellulose pulp	Cotton and plastic pants	Cotton and plastic pants
	Functional unit	The use of nappies during the first 2.5 years of a child's life		
	Number used	4.2–7 per day (5.5 average/typical	5–9 changes per day 24–48 nappies	5–9 changes per day 46–136 nappies
	Weight per nappy [g]	45–55	100–150	100–150
	Geographic region	Australia		
	Life cycle stages	Cradle-to-grave (material production, manufacture, use and disposal)		
	End-of-life assumptions	Landfill	Landfill	Landfill
Indicators	Water resource depletion			
	Energy resource depletion			
	Solid waste			
	Land area			
Method	Inventory-level assessment (water, energy, solid waste and land use)			
Other comments	The user has more control over the environmental impact of home-washed reusable nappies, whereas for single-use and commercially washed reusable nappies the environmental indicators occur largely outside the control of the user. Recycling water and using renewable electricity will reduce the impact of home- washed nappies.			
Reviewed	Not known			

Highest relative impact **In-between (neither highest nor lowest)** **Lowest relative impact**

2.2 LCA STUDIES COMPARING SINGLE-USE NAPPIES – IMPROVEMENT IN DESIGN

2.2.1 Improving resource efficiency and environmental impacts through novel design and manufacturing of disposable baby diapers: Mendoza, Popa, D'Aponte, Gualtieri and Azapagic (2019) and Disposable baby diapers: Life cycle costs, eco-efficiency and circular economy: Mendoza, D'Aponte, Gualtieri and Azapagic (2019)

These two studies evaluate the economic and environmental impact of using an optimised absorbent core and innovative bonding technologies to replace gluing systems in nappy manufacturing.

Summary of results and conclusions

When compared with standard single-use nappies, **glueless single-use nappies reduce consumption of raw materials by 23%, primary energy demand by 25% and global warming potential by 10%.** They also have more than 50% lower eutrophication, ozone layer depletion, human toxicity and ecotoxicity potentials. Lower material inputs also reduce transport and waste management requirements.

In terms of their economic impact, **glueless nappies reduce cradle-to-grave life cycle costs**[6] **by 11%** compared to standard nappies.

The **driver for the lower environmental impacts of single-use glueless nappies is their greater material efficiency**, with glueless nappies weighing 23% less than standard nappies.

Further specific findings include the following:

- The **manufacture of materials is a significant contributor to the impacts of single-use nappies**. The trend is the same for glueless nappies, with the contribution from materials production ranging from 80% in global warming potential to 97% in depletion of abiotic resources.

- **Fluff pulp and super absorbent polymer (SAP) are responsible for 44% to 85% of the impacts from raw materials for standard nappies** because they account for 70% of the weight of the nappy. The impacts of fluff pulp and SAP are 1.2 and 3.7 times lower for glueless nappies as lower quantities of these materials are used. Removing the glue reduces the impact of materials bonding by 66%. However, the use of the air-through bonded (ATB) layer to build the absorbent core results in higher impacts from nonwovens in glueless nappies. Nonwovens account for between 2.7% (ozone layer depletion potential) and 40% (terrestrial ecotoxicity potential) of the impacts, and are 5% to 170% higher in glueless nappies.

- **The lower material use of the glueless nappies results in lower transport impacts, lower waste management impacts and lower packaging impacts.** Transport is a key contributor to five impact categories for both single-use nappy types: acidification potential (contributing 11% and 19% to standard and glueless nappies respectively), eutrophication potential (11% and 13%), freshwater aquatic ecotoxicity potential (11% and 16%), human toxicity potential (9% and 13%) and marine aquatic ecotoxicity potential (7% and 16%). Waste management is also an important contributor to a number of impact categories: eutrophication potential (contributing 22% and 31% for standard and glueless nappies respectively), GWP (15% and 18%), photochemical oxidants creation potential (10% for both) and terrestrial ecotoxicity potential (13% and 16%). Between 87% and 100% of these contributions are attributed to landfilling. The contribution of packaging to impacts is minor for both nappy types.

- **Nappy manufacture contributes less than 2% to the impacts,** with the exception of ozone layer depletion potential (ODP) (where nappy manufacturing contributes 4% and 9% to ODP for glueless and standard nappies respectively). This is due to the use of solvents to clean glue applicators (glueless nappies still require some gluing). New manufacturing processes for glueless nappies reduce the impacts of terrestrial ecotoxicity potential and human toxicity potential by 30% and almost 100% respectively.

A **sensitivity analysis** was performed to analyse the impact of reducing key raw materials by 15%. Reducing the raw materials by 15% would reduce the GWP of the standard and glueless nappies by 12% and 15% respectively. This would in turn reduce the GWP savings from glueless nappies relative to standard nappies by 5.8%.

6 *Following the methodology and guidelines of Hunkeler et al. (2008), Environmental Life Cycle Costing, Society of Environmental Toxicology and Chemistry (SETAC), Pensacola.*

The **life cycle costs** of standard and glueless single-use nappies are estimated at €106.3 and €95.1 respectively. As a result of greater material efficiency, **glueless nappies are 10.6% more cost efficient than standard nappies**, saving 9.2 kg of material per 1,000 nappies.

- For both types of single-use nappies raw materials account for over 85% of the total costs, although the raw material costs for glueless nappies are 8% lower than for standard nappies. This is mainly due to the reduction in fluff pulp content as well as the glue removal, lower use of SAP and reduced packaging.

- Transport and waste management account for 7% and 3% of the total costs respectively. Transportation and waste management costs are reduced by 26% and 22% respectively for glueless nappies.

- The use of alternative bonding technologies in glueless nappies results in a reduction in labour costs, accounting for almost 61% of the cost savings. Lower maintenance requirements and energy consumption contribute 32% and 7% to the savings respectively.

- The maintenance of the glue applicators in standard nappy manufacturing determines up to 98% of the total maintenance costs. The use of alternative bonding technologies in glueless nappies reduces the operating and maintenance costs by 47% and 89% respectively.

- The electricity consumption of a glueless nappy is 9.8% lower than that of standard nappies.

Eco-efficiency combines the life cycle costs and the environmental impacts and is expressed as €/impact. The lower potential environmental impacts and life cycle costs of the glueless single-use nappies translate to their being more eco-efficient than standard single-use nappies in all but two impact categories.

- The better eco-efficiency of the glueless nappy relative to the standard single-use nappy ranges from 7% higher for photochemical oxidants creation potential to 170% higher for ODP. The high eco-efficiency improvement with respect to ozone depletion potential is due to no longer needing solvents to clean the glue applicators in the manufacture of the glueless nappies.

- The eco-efficiency of freshwater ecotoxicity is 136% higher for glueless nappies owing to the reduction of fluff pulp used in the manufacture of the absorbent core. Abiotic depletion potential and terrestrial ecotoxicity potential are the only impacts for which standard nappies are more eco-efficient, by 9.6% and 4.7% respectively.

- Eco-efficiency with respect to global warming potential is comparable for both nappy types.

- Normalising and aggregating the eco-efficiency indicators into a single score (assuming equal importance of the impact categories) finds glueless nappies to be 32% more eco-efficient than standard nappies.

Novel design to reduce the amount of materials in nappies, results in **single-use nappies** that are **more cost efficient and environmentally sound.** The lower the amount of materials used in nappies, the lower also are the impacts from packaging, transporting and disposing of nappies.

Table 5: Summary table: Mendoza, Popa, D'Aponte, Gualtieri and Azapagic (2019)

		Products considered in study	
		Glueless nappy	Standard nappy
Study scope	Material	Similar to standard nappy. An ATB nonwoven is incorporated and the fluff pulp/SAP ratio changes from 40/60 to 20/80 (w/w).	Nonwovens (PP, PE and polyester fibres), elastics, SAP, fluff pulp, plastic film (LDPE).
	Functional unit	1,000 units	
	Number used	1,000	
	Weight per nappy [g]	30.7	39.8
	Geographic region	Europe	
	Life cycle stages	Cradle-to-grave	
	End-of-life assumptions	Incineration (38%) and landfill (62%)	
Indicators	Abiotic depletion potential of elements		
	Abiotic depletion potential of fossil fuels		
	Acidification potential		
	Eutrophication potential		
	Freshwater aquatic ecotoxicity potential		
	Global warming potential		
	Human toxicity potential		
	Marine aquatic ecotoxicity potential		
	Ozone layer depletion potential		
	Photochemical oxidants creation potential		
	Terrestrial ecotoxicity potential		
	Primary energy demand		
Method	CML 2001 method (version 2015) plus primary energy demand based on net calorific value		
Other comments	A sensitivity analysis that considered the effect of reducing raw materials by 15% (based on historical performance in nappy design), reduced GWP and primary energy demand by 12% and 15% respectively.		
Reviewed	Peer-reviewed journal		

Highest relative impact **In-between (neither highest nor lowest)** **Lowest relative impact**

2.2.2 Life cycle assessment of bio-based products: a disposable diaper case study: Mirabella, Castellani and Sala (2013)

This study evaluates the life cycle impacts of a bio-based nappy. The study compares the eco-design and eco-innovation of the "WIP" nappy produced in Italy with a standard nappy produced in the UK (with data for the standard nappy taken from Aumónier, Collins and Garrett (2008)). The WIP nappy substitutes two different bioplastics (PLA and a starch-based biopolymer) for a significant proportion of the petroleum-based plastics, along with minimising energy consumption and the use of renewable energy at the manufacturing plant. The study focuses on material production and nappy manufacturing (cradle-to-gate) but, given the potential of end-of-life disposal to influence the eco-profile of the bio-based nappy, three end-of-life scenarios are investigated in a sensitivity analysis:

- Bioplastic nappy, composting
- Bioplastic nappy, landfill, composting and incineration
- Standard nappy, landfill and incineration

Summary of results and conclusions

The **bio-based single-use nappy has a better environmental profile than a standard single-use nappy, although there is some risk of burden shifting**. Despite lower climate impact and lower potential environmental impacts across a number of impact categories (including human toxicity, freshwater eutrophication and marine ecotoxicity), the bio-based nappy has higher agricultural land occupation, land transformation and water depletion.

The study identified several areas in which to improve the environmental profile of the bio-based nappy. Improvements identified include selecting biopolymer suppliers on the basis of their environmental performance, reducing transport distances along the supply chain, and ensuring that the nappy is composted at end-of-life.

When looking at the most significant impact categories, that is, when looking at normalised impact assessment results, **the bio-based nappy has a better environmental performance than the standard nappy**:

- **Bio-based nappies have lower human toxicity, freshwater eutrophication and marine ecotoxicity** impacts than standard nappies (cradle-to-gate). When composted at end-of-life, bio-based nappies have further improvements in their environmental impacts relative to **standard nappies. However, bio-based nappies have higher water consumption, land use and land occupation than standard nappies owing to the agricultural impacts of bio-based materials.**

- **In the production of the bio-based nappy, the largest contributors to environmental impacts are the sourcing and production of materials.** Energy consumed in the nappy-production process makes a negligible contribution to impacts owing to the manufacturing plant sourcing renewable energy.

- **TCF (totally chlorine free) pulp and SAP are the most impactful materials of the bio-based nappy**. TCF is the highest contributor to impacts in seven out of the 18 ReCiPe impact categories, accounting for 24% to 94% of the total life cycle impacts. This is largely due to the fact that TCF pulp accounts for more than 50% of the total weight of the nappy. SAP has the highest contribution to impacts in five out of 18 impact categories, contributing between 34% and 51%. PLA and transport are the main sources of impact in three categories; PLA mostly affects particulate matter formation, terrestrial ecotoxicity and fossil depletion, while transport affects ozone depletion, photochemical oxidation and marine eutrophication.

Bio-based single-use nappies have a **better environmental profile** than standard single-use nappies, although there is a **risk of burden shifting between environmental impacts**.

Table 6: Summary table: Mirabella, Castellani and Sala (2013)

		Products considered in study		
		Bio-based nappy		Standard nappy
Study scope	Material	SAP reduced from 32% in a standard diaper to 15% (replaced with TCF pulp), PP in top-sheet replaced by PLA, PE in backsheet replaced by starch-based biopolymer, acquisition and distribution layer composed of 50% PLA and 50% PP		As in Aumónier, Collins and Garrett (2008): Fluff pulp, SAP, PP, LDPE, adhesives, PET/ polyester and other
	Functional unit	One nappy at the factory gate		
	Number used	Use phase excluded		Use phase excluded
	Geographic region	Italy		UK
	Life cycle stages	Cradle-to-gate, with cradle-to-grave scenario excluding use		
	End-of-life assumptions	100% composting	37% landfill, 43% composting and 20% incineration	65% landfill and 35% incineration
Indicators	Climate change			
	Ozone depletion			
	Human toxicity			
	Photochemical oxidation			
	Particulate matter formation			
	Ionising radiation			
	Terrestrial acidification			
	Freshwater eutrophication			
	Marine eutrophication			
	Terrestrial ecotoxicity			
	Freshwater ecotoxicity			
	Marine ecotoxicity			
	Agricultural land occupation			
	Urban land occupation			
	Natural land transformation			
	Water depletion			
	Metal depletion			
	Fossil depletion			
Method	ReCiPe 2008			
Other comments	The results were also analysed with IMPACT 2002+. Differences found included PLA gaining the second position in order of magnitude (with pulp confirmed as the major source of impacts) and transports showing a higher relative contribution.			
Reviewed	Peer-reviewed journal			

Highest relative impact In-between (neither highest nor lowest) Lowest relative impact

2.3 LCA STUDIES COMPARING SINGLE-USE NAPPIES – FOCUS ON END-OF-LIFE

2.3.1 Technological, environmental and social aspects of a recycling process of post-consumer absorbent hygiene products: Arena, Ardolino and Di Gregorio (2016)

This study investigates the technical feasibility, environmental compatibility and social aspects of a novel recycling process for absorbent hygiene products. The recycling process consists of an autoclave coupled with a sorting machine that sterilises the waste and separates its cellulosic and plastic fractions. The plastics are recovered, while the cellulose is utilised in a bubbling fluidised bed gasifier to produce the steam used in the autoclave. The study assesses three end-of-life options for a standard single-use nappy with a mixture of urine and faeces:

- recycling
- co-incineration with municipal solid waste, with electricity production and material recovery from bottom ash
- sanitary landfill, with collection of leachate and energy recovery from biogas

Summary of results and conclusions

Recycling a single-use nappy results in lower environmental impacts than incinerating or landfilling it, leading to significantly lower global warming potential and non-renewable resource consumption.

For the disposal of single-use nappies, the most significant impact categories are non-renewable energy use, global warming, carcinogens, non-carcinogens and respiratory inorganics (determined using normalised IMPACT 2002+ results):

- Recycling single-use nappies has negative impacts (potentially avoided burdens) for all five of these impact categories owing to the recovery of plastics and the avoidance of emissions that would otherwise have resulted from their incineration.
- Co-incineration also shows avoided burdens related to the production of electricity and, to a lesser extent, the recovery of materials from the bottom ash, whilst landfilling has limited avoided burdens related to electricity generation from landfill gas. Nonetheless, the avoided burdens of recycling single-use nappies outstrip those of incinerating and landfilling single-use nappies with respect to carcinogens, global warming potential and non-renewable energy use.
- When compared at the damage level (using the IMPACT 2002+ method) **the recycling process has significantly lower resource use and potential impact on climate change than both incinerating and landfilling single-use nappies, but a marginally higher potential for human health damage** than incinerating nappies.

Sensitivity analyses were performed to determine the effect of the main parameters on the environmental performance of the waste management options.

- Decreasing the efficiency of the sorting machine from 95% to 80% did not substantially affect the results.
- Increased moisture content in the waste reduces energy generation and plastics recovery. For instance, increasing the moisture content in the waste from 50% to 70% had a significant effect on both the recycling process and on co-incineration. In the latter, the extent of avoided impacts from electricity generation is reduced, although GHG emissions are also lower.
- For the recycling process, the avoided burdens are also reduced owing to lower plastic recovery but, more importantly, supplementary natural gas is now required to produce the steam for sterilisation. Nonetheless, the recycling process still has the lowest carcinogens, global warming potential and non-renewable energy use, although the extent of the differences between the recycling and co-incineration option is significantly reduced.

Table 7: Summary table: Arena, Ardolino and Di Gregorio(2016)

		Products considered in study		
		Absorbent hygiene products		
Study scope	Material	Average nappy with mixture of urine and faeces		
	Functional unit	The treatment of 500 kg of used single-use nappy waste		
	Geographic region	Italy		
	Life cycle stages	End-of-life		
	End-of-life assumptions	Recycling	Incineration	Sanitary landfill
Indicators	Global warming			
	Non-renewable energy			
	Carcinogens			
	Non-carcinogens			
	Respiratory inorganics			
Method	Impact 2002+			
Other comments	A preliminary social LCA was also conducted, taking into account the economic advantages for the customers and the protection of their privacy, amongst other aspects, related to the temporary storage, collection and transport, and reprocessing of the nappies. The qualitative social LCA results identify areas to be addressed and support the overall sustainability of the recycling process.			
Reviewed	Peer-reviewed journal			

Highest relative impact **In-between (neither highest nor lowest)** **Lowest relative impact**

Recycling a single-use nappy results in lower environmental impacts than incinerating or landfilling it, leading to significantly lower global warming potential and non-renewable resource consumption.

03 Discussion and conclusions

03 DISCUSSION AND CONCLUSIONS

The conclusions are provided in three sections. The first section provides a synthesis of the findings of the meta-analysis in terms of the environmental impacts of single-use nappies and their alternatives. The second section summarises the important aspects to be considered when interpreting LCA studies on single-use nappies and their alternatives. The final section provides guidance for policy makers when using LCA to develop policies that addresses the environmental concerns associated with single-use nappies. This analysis focuses particularly on nappies for babies but many of the general findings are equally relevant to adult incontinence products.

3.1 ENVIRONMENTAL IMPACT OF SINGLE-USE NAPPIES AND THEIR ALTERNATIVES

3.1.1 Comparison of single-use nappies and reusable nappies

Reusable nappies when washed so as to minimise water use (e.g., in a fully loaded, modern washing machine) and in an energy-efficient manner have lower environmental impacts than single-use nappies. However, not all LCA studies find reusable nappies to have lower environmental impacts than single-use nappies, and there is significant variability and overlap between and within nappy systems. The main cause of these differences are assumptions made around the laundering of reusable nappies. For example, a home-washed reusable nappy, washed in cold water in a front-loaded washing machine and 100% line-dried has lower environmental impacts than a single-use nappy. However, a reusable nappy washed at high temperature and 100% tumble-dried, and in a country where electricity is generated from fossil fuels, will have higher impacts than a single-use nappy.

This finding that reusable nappies can have lower or higher environmental impacts than single-use nappies depending on the context in which they are used is consistent with that of an earlier review study on nappies. This review concluded that most LCA studies show that **single-use nappies generate more solid waste over their life cycles than reusable nappies, but reusable nappies create impacts in their use phase** (Ng et al., 2013).

There is no clear preference in the LCA studies for home-laundering over commercial laundering. In a country context where homes tend to have older, inefficient washing machines, commercial laundering is shown to be preferred (Hoffmann, Morais and Teodoro, 2020).

However, where homes have efficient home washing machines and/or where hot water is provided from renewable sources, home laundering might be preferred. In general, **a reusable nappy system which optimises energy and water use has lower environmental impacts than single-use nappies**.

An important insight of the LCA studies is that **the environmental impacts of reusable nappies are driven by consumer behaviour to a much larger degree than those of single-use nappies.** Consumers using reusable nappies have strong leverage to reduce the environmental impacts, for example, by washing full loads in their washing machine, in their choice of washing machine and wash temperature, in their choice of detergent, in how they dry their nappies and by using their nappies on a second child. However, for single-use nappies, the environmental impacts fall largely outside the influence of consumers (in the producing the materials used in nappy manufacture and in the waste-disposal practices of their municipality).

Although not investigated in any of the nappy LCA studies, a study on adult incontinence products found that **a partly reusable product system can decrease the climate impact of single-use adult incontinence products by half** (Willskytt and Tillman, 2019). Reusable outers with a disposable insert might offer a good solution for baby nappies as well, decreasing the waste associated with single-use nappies, while also decreasing the washing requirements of the reusable part. However, it is worth noting that, with modern reusable nappies requiring no pre-soaking or sterilising, the convenience benefits of a partly disposable system are lessened and a fully reusable nappy is still likely to offer the best environmental performance.

A reusable nappy system which **optimises energy and water use** has **lower environmental impacts** than single-use nappies.

3.1.2 Comparison of different single-use nappies

Technological innovations have steadily improved the environmental performance of single-use nappies.

Eco-design of nappies

The materials used in the production of single-use nappies account for most of their environmental impacts. A promising route for decreasing the environmental impacts and life cycle costs of single-use nappies thus lies in the design of nappies (Mendoza, D'Aponte, et al., 2019). **Design has the potential to minimise or avoid environmental impacts, notably through material reductions.** Since the raw materials used in the production of single-use nappies account for the majority of their impacts,[7] it therefore stands to reason that the **greatest reductions in environmental impacts can be achieved through the design of lighter products** (although this obviously has limits with current materials). Further breakthroughs, as happened with the introduction of SAPs, which saw the average weight of nappies produced in the EU fall by over 44% over the last 25 years, accompanied by reductions in most impact categories (Weisbrod and Van Hoof, 2012; Cordella et al., 2015) will require significant innovation. It is also critical that lighter products do not cause additional products to be used, for example, through increased leakage.

The environmental benefits of substituting materials used in producing single-use nappies are not clear cut; e.g., bio-plastics reduce some impacts but increase others. While substituting bio-based materials for fossil-based plastics results in environmental benefits in some impact categories, there is potential for burden shifting (Mirabella, Castellani and Sala, 2013). The agricultural processes associated with producing bio-based materials generally leads to their having higher land use and water depletion, amongst other impacts, depending on the particular feedstock. Furthermore, the sourcing of bio-based materials and the context in which the nappy is used, in particular whether it is composted at end-of-life, has important implications for whether the environmental benefits of bio-based nappies are achieved.[8] However, the relative environmental performance of bio-based and fossil-based plastics is not at all well established. A review of published LCA studies of 50 bio-based and 39 fossil-based polymers was not able

7 *This is true under the conditions modelled in the LCA studies, i.e., where nappies are landfilled, incinerated or composted at end of life. Impacts arising from degradation at end of life may be more important in regions with no formal waste management, but this cannot be established from LCA studies currently available in the literature.*

8 *Globally only 5.5% of municipal solid waste is composted (6% in high-income countries) (Kaza et al., 2018), indicating the significant increase of industrial composting infrastructure that would be required to achieve the composting levels assumed in the study.*

to substantiate the prevailing scientific consensus that bio-based polymers have lower climate impacts than fossil-based polymers, finding them to have very similar ranges in energy use and GWP (Walker and Rothman, 2020). Indeed, variations between polymer types and between fossil-based and bio-based polymers were found to be so extensive that it was not possible to conclusively declare any polymer type as having the least environmental impact across any of the seven impact categories analysed in the review. Variations of the order of 200% to 400% between different studies of the same polymer, for both fossil-based and bio-based polymers, suggest that a large part of this variation is due to methodological differences in the LCA studies (Walker and Rothman, 2020).

Innovations in the treatment of single-use nappies at end of life

Improved end-of-life treatment offers another route to decreasing the life cycle environmental impacts of single-use nappies. LCAs show that end-of-life disposal contributes less to life cycle environmental impacts than the production of materials (which account for the majority of the environmental impacts of single-use nappies), although it is still an important aspect to consider. In fact, it is important to recognise that **no LCA studies considered the potential for single-use nappies to be mismanaged at end-of-life**, and that end-of-life emissions are inherently dependent on the assumptions considered for the waste disposal scenario (Cordella et al., 2015). Disposal of single-use nappy waste in poorly managed landfills was found to have higher impacts than disposal in sanitary landfills. Incineration of single-use nappy waste has lower environmental impacts than landfill disposal in most impact categories, especially where nappies are co-incinerated with general waste and electricity is produced. However, incineration has a higher potential contribution to climate change and may also have a higher human toxicity potential, depending on the particulars of the waste management scenario. **No hard and fast rules on the optimal disposal route can therefore be drawn from the LCA studies**, but it is clear that the impacts will vary with the particular waste management context of the study.

A number of advanced waste treatment technologies are under development for the treatment of single-use nappy waste, such as biodegradation and thermal pyrolysis (Khoo et al., 2019). **Novel processes for the recycling of nappies have good potential for decreasing the end-of-life impacts of single-use nappies.** LCAs on two pilot recycling plants, one in an UK context and one in an Italian context, show that recycling single-use nappies decreases their life cycle environmental impacts across all impact categories, relative to current disposal practices (Deloitte, 2011; Arena, Ardolino and Di Gregorio, 2016). While recycling of single-use nappies is technically feasible and environmentally preferable, whether the considerable infrastructural challenges and social acceptability barriers can be overcome still needs to be seen (Arena, Ardolino and Di Gregorio, 2016; Khoo et al., 2019).

None of the LCA studies on nappies for babies particularly engaged with consumer aspects, generally assuming a "typical" or "average" number of changes per day and an "average" or representative single-use nappy product. Of course, single-use nappies come in a range of sizes and absorbencies, and which product a consumer chooses and how frequently the nappy is changed will considerably influence the environmental impacts (since most of the impacts of single-use nappies are associated with their materials). A study on **adult incontinence products** found that **effective use of incontinence products through customisation (ensuring the product of lowest needed absorbency was used) led to decreases in impacts across all environmental impact categories** (Willskytt and Tillman, 2019).

Novel processes for the recycling of nappies have good potential for decreasing the end-of-life impacts of single-use nappies. LCAs on two pilot recycling plants, one in an UK context and one in an Italian context, show that recycling single-use nappies decreases their life cycle environmental impacts across all impact categories, relative to current disposal practices.

3.2 IMPORTANT ASPECTS TO CONSIDER IN LIFE CYCLE ASSESSMENTS OF SINGLE-USE NAPPIES AND THEIR ALTERNATIVES

Based on the studies reviewed in the meta-analysis, the following aspects are identified that should be considered when undertaking and interpreting LCAs of single-use nappies and their alternatives.

Material type and weight: The environmental impacts of nappies are strongly influenced by the weight of the product and weight reduction results in lower impacts. This is because material production is consistently the largest contributor to most of the life cycle environmental impacts. Nappy designs and materials have changed considerably over the years and thus LCA studies should be based on current designs and data, and be aware of future improvements. This is especially important with regard to substituting bio-based materials for fossil-based plastics, where datasets are generally less reliable owing to production processes still evolving and a variety of potential feedstocks. The implications of new materials on other aspects, such as waste management, is also an important consideration.

Geographical context: Where reusable nappies perform poorly relative to single-use nappies is largely due to energy – typically electricity – used in laundering (heating water and powering washing machines and driers). The electricity generation mix, and consequently the geographical context, is thus an important consideration. Waste infrastructure available for the disposal of single-use nappies also varies with the geographical context, with potential solutions better suited to some contexts than others. For example, bio-based nappies are less suitable in contexts where nappies will be incinerated or landfilled because to realise their full benefits they need to be composted. Furthermore, modelling the appropriate end-of-life scenario for the particular country context is important. For example, impacts will be underestimated if single-use nappy waste is modelled with sanitary landfill in a country with high rates of open dumping and littering of nappies. This is a significant shortcoming since at least 33% of global solid waste is conservatively estimated to be openly dumped, with this number rising to up to 93% in low-income countries (Kaza et al., 2018). Furthermore, it is estimated that two billion people lack access to properly regulated solid waste collection, whilst the solid waste from a further one billion people is not appropriately managed (waste may be collected but is not disposed of safely) (Williams et al., 2019).

Behaviour of consumers: The environmental impacts of both single-use and reusable nappies is dependent on assumptions related to their use. For all types of nappies, the number of nappy changes per day, as well as the age of the child when toilet trained, strongly affects the life cycle environmental impacts. For reusable nappy systems, the number of nappies purchased, and nappy washing, drying and ironing behaviour, are particularly influential. For single-use nappies, consumer behaviour around the disposal of nappies is very important and is currently neglected in LCA studies. The limited evidence available suggests considerable lack of knowledge around the correct disposal of single-use nappies; the #binyournappy campaign of the North London Waste Authority reports that one in ten UK parents with children under three has put used nappies in with the household recycling (NLWA, 2019). In rural Vanuatu, burying single-use nappies on the shoreline is considered a safe and acceptable method of disposal (Savvy Vanuatu, Mamma's Laef Vanuatu and Bambino Mio, 2021).

Reusable nappies generally perform better than single-use nappies. Where reusable nappies perform poorly relative to single-use, it is **largely due to the type of energy mix** (electricity used for laundering). The geographical context is thus an important consideration.

Equivalence of the nappy systems: In any comparative LCA, ensuring that the product systems to be compared deliver an equivalent function is critical. In the nappy studies, the functional unit is mostly taken as "one toilet-trained child", which translates to the number of nappies required over a duration of 2.5 years. This enables the fact that, on average, reusables are changed more frequently than single-use nappies and that liners and outer covers are included in the comparison. However, none of the studies look into the issue of equivalence in more depth. SAPs in single-use nappies virtually eliminate accidental leakage which might not be the case with all reusable nappies (especially if not changed frequently enough). This potentially leads to higher washing of bedding, clothing, etc. in the reusable nappy systems than in single-use nappy systems.

The **choice of environmental impact indicators:** The purpose of LCA is to assess environmental impacts across all types of environments so as to understand trade-offs better and avoid burden-shifting. The LCA studies covered in the meta-analysis were primarily in developed-country contexts (none were African and only one was Latin American). Thus, the limitation of LCA to take into account nappies not disposed of appropriately, such as nappies dumped or ending up in watercourses, is not recognised in the studies.

3.3 IMPORTANT ASPECTS IN POLICY MAKING

This meta-analysis is not intended to provide definitive environmental guidance on the "best" nappy and in so doing promote policies that prohibit or limit the use of other alternatives. Rather, this report serves to highlight important aspects that policy makers should consider when evaluating environmental information (often in the form of LCA studies) to inform policy development that is context specific and locally relevant.

A notable aspect, and one that is highlighted through the application of LCA, is that policies should **take a systems perspective.** LCA studies employ a systems perspective in that they consider the life cycle of a product from resource extraction, through production and use, to end-of-life processes. This **life cycle perspective is especially important for nappy systems,** where the highest impacts of reusable nappies occur not in manufacturing but in the use phase, while for single-use nappies, the design of the nappy (the weight and its materials) along with its management at end-of-life are the important life cycle stages.

Furthermore, it is important to recognise that **the "nappy system" sits within a wider social, economic and environmental system.** Thus, there are additional factors that need to be considered in order to develop appropriate policy related to single-use nappies.

For **single-use nappies, particularly important aspects to consider are available and future waste management technologies and infrastructure**. For **reusable nappies, the most critical aspects are consumer behaviour and perceptions**, both in recognising the need for convenience and cost effectiveness that single-use nappies bring, and in the washing habits that strongly affect the environmental impacts of reusable nappies. Other highly relevant aspects to both single-use and reusable nappies are energy and transport sector developments, and implementation costs and barriers. Many of these considerations are not only country specific, but they also vary with time.

With this in mind, this study recommends the following considerations for policy makers:

Policies must consider the suitability of end-of-life processes for single-use nappies

Although found to be less environmentally significant than the weight and type of materials in single-use nappies, end-of-life waste handling and treatment does, nonetheless, contribute to the life cycle environmental impacts of single-use nappies. Furthermore, no LCA studies found in the literature considered the potential for single-use nappies to be mismanaged at end of life, despite data indicating that sanitary products make up a significant proportion of beach litter and marine waste (Cabrera and Garcia, 2019; Roman et al., 2020). There is thus a strong possibility that LCA studies are underestimating the potential environmental impacts of the disposal of single-use nappies. Furthermore, environmental LCA studies do not take into account the strain on local municipalities and the high economic costs of managing single-use nappy waste, let alone the economic costs of marine litter.[9]

It is therefore important that, before deciding on policies affecting single-use nappies, the end-of-life fate of nappies is correctly and appropriately modelled for the particular country context. And this must take into account consumer behaviour and the limitations of existing infrastructure and technologies (as well as the potential of future technologies). Single-use nappies will have higher impacts in contexts where waste management is insufficient, such as where leakage to the environment is high or where landfills are not well managed.

In countries with high single-use nappy use, better ways to manage nappy waste should be a priority. Very few countries (if any) have policies that deal specifically with the disposal of single-use nappy waste, despite the potentially important environmental and public health consequences of disposing of nappies in the general solid waste stream (Reese, 2015). There is also a lack of research to inform the development of guidelines for better management of nappy waste. Consumer campaigns are required to ensure that consumers understand how single-use nappies should be disposed of after use, particularly addressing flushing of nappies and contamination of recycling streams. Governments should work with manufacturers to ensure appropriate and clear messaging on single-use nappy packaging so that the high costs and environmental impacts of inappropriate end-of-life disposal are avoided. This is likely to be increasingly important with nappies marketed as "biodegradable" or "bio-based" as these have the potential to further increase consumer confusion around the correct disposal of nappies.

Technologies for the recycling of single-use nappy waste show potential but still require significant development to overcome their limitations. In particular, they involve complex facilities and technology that require technical skills to operate and maintain. Furthermore, they require ways to collect used nappies that are cost-effective and eco-efficient, while simultaneously overcoming social barriers to recycling (Arena, Ardolino and Di Gregorio, 2016; Khoo et al., 2019). Thus it is clear that recycling of single-use nappies will not be feasible in all contexts and will require significant financial support from governments if it is to succeed. Considerable efforts will also need to be expended to get public "buy in".

Consumer behaviour must be considered when developing policies regarding reusable nappies

The primary driver for single-use nappies is convenience and low upfront cost. Countering the perceived inconvenience of reusable nappies is thus perhaps the biggest issue when it comes to promoting the wider uptake of reusable nappies. Circular business models with commercial laundering, such as nappy subscription models or "nappy-as-a-service" models, are a potential solution to make reusable nappies more convenient for consumers. However, transport impacts and higher attrition rates of nappies are trade-offs to be made between the convenience of commercial models and the effort of home-washing nappies. Newer designs of reusable nappies make home-washing far more convenient; for example, shaped nappies and "all-in-ones" and the fact that modern reusable nappies no longer require soaking before washing. Equally important, however, is the need to address the negative perceptions and perceived inconvenience of reusable nappies, along with a general lack of knowledge, especially the kind gained from peers. In a pilot study of modern reusable nappies in rural and peri-urban Vanuatu, price, access to nappies (i.e., nappies being sold in the village) and ease of use were identified as stronger drivers of nappy purchases than reducing washing (Savvy Vanuatu, Mamma's Laef Vanuatu and Bambino Mio, 2021). **Innovative ways to drive the social norming of reusable nappies are required**, through social media influencers, for example.

Consumer education is a critical component of any policy aiming to increase the uptake of reusable nappies. Consumers will need to be shown through campaigns that reusable nappies offer considerable savings in the long run. For poorer consumers, innovative financing solutions will

9 *Zero Waste Europe's report* The Environmental & Economic Costs of Single-use Menstrual Products, Baby Nappies & Wet Wipes: Investigating the impact of these single-use items across Europe *provides an assessment of these costs for Europe (Cabrera and Garcia, 2019)*

need to be found to help carry the higher upfront costs of reusable nappies. Alternatively, governments could support innovative circular business models, such as "nappy-as-service", that allow consumers to pay a monthly or on-demand fee to access reusable nappies.

Consumer education is also essential to ensure that the environmental benefits of reusable nappies are realised. The environmental impacts of reusable nappies are strongly dependent on how they are laundered. Educating consumers on how best to wash nappies for effective hygiene and lowest environmental impacts will therefore be an important aspect of any policy on reusable nappies. Consumer behaviour to minimise environmental impacts of reusable nappies includes the following (Aumónier and Collins, 2005):

- line drying outside whenever possible.
- tumble drying as little as possible.
- choosing energy-efficient appliances when replacing appliances
- not washing above 60°C (many brands recommend washing at 40°C)
- washing full loads
- reusing nappies on other children

Policies should consider potential barriers to the uptake of reusable nappies. In addition to the factors of cost and convenience, governments should be aware of other potential barriers to reusable nappies; for example, where facilities for washing are absent, limited or inconvenient, or where water scarcity is high. A pilot study in Vanuatu found that water access was not a significant barrier (despite a lack of infrastructure in the villages) but that drying time posed a challenge (Savvy Vanuatu, Mamma's Laef Vanuatu and Bambino Mio, 2021). Transport infrastructure is required for "nappy-as-service" business models, along with stable electricity or natural gas supply for machine washing and heating water for laundering nappies.

Policies should be geographically adapted and account for likely future developments in production processes and related systems

More recently developed technologies and materials may be at a disadvantage to other more established technologies and materials owing to their scale or lack of data availability. This is true of bio-based polymers and the potential for composting and recycling single-use nappies at end-of-life. Further LCA studies at a higher level of standardisation are required to fully unpack the benefits and trade-offs between bio-based and fossil-based polymers. The relative environmental performance of single-use and reusable nappies may also change if future developments in energy, transport and waste management systems are incorporated. This is especially true for reusable nappies, where water recycling and an increasing share of renewable electricity in the grid will strengthen their relative environmental preference over single-use nappies. The design of nappies has changed considerably over the years, particularly in terms of dematerialisation. This means that **LCA studies should be current and regularly updated if they are to provide relevant policy advice**.

Polices should stimulate innovation in the manufacture, use and disposal of both single-use and reusable nappies. Hybrid systems such as reusable outers with disposable inserts hold potential by increasing material efficiency and decreasing the volume of waste requiring disposal (although a fully reusable system still offers the greatest material efficiency and best environmental performance when efficiently washed). Using a product of appropriate absorbency, that is, one that is suited to the particular age/weight of the child and time of day, could also offer significant benefits. Effective customisation was found to significantly decrease environmental impacts across all impact categories in adult incontinence products. This is due to the majority of impacts of single-use nappies being associated with the materials, thus being able to use lighter-weight nappies at certain times of the day has the potential to decrease the overall life cycle impacts.

The environmental impacts of reusable nappies are driven by consumer behaviour to a much larger degree than single-use nappies. Consumers using reusable nappies have strong leverage to reduce the environmental impacts. For **single-use nappies**, on the other hand, the **environmental impacts fall largely in the hands of the producers** (design and manufacturing) **and municipalities** (waste management systems and end-of-life treatment).

Many of the aspects that affect environmental performance are geographically dependent, such as available feedstocks for bio-based materials, electricity generation mixes (important for heating water for laundering reusable nappies), consumer behaviour with regard to reusable alternatives, and available waste management infrastructure. It is critical that policy makers understand and appreciate the implications and feasibility of proposed policies in the context of geographical constraints.

In the same way that policies need to consider country- or region-specific characteristics, **policies must be culturally and socially adapted** and take into account the characteristics of the consumer population that will be impacted on by the policy. Cost is important to consider, especially in developing countries, and can have a considerable influence on consumer decisions. The upfront investment cost of reusable nappies might prohibit their uptake in some contexts, despite being a more cost-effective option over time. In such contexts, financial incentives, vouchers or microfinancing from local waste authorities (or other bodies), and nappy libraries are options that policy makers should consider to overcome the upfront cost barrier to reusable nappies.

Policies must recognise and manage the trade-offs and risks of burden-shifting between environmental impacts

Care must be taken to recognise and manage the trade-offs between other quantified and unquantified environmental impacts, such as potential health and disamenity impacts of nappies which have been inappropriately disposed of, and storing and transporting nappies for recycling (in the case of single-use nappies) and laundering (in the case of reusable nappies). Related to the above, **policies must be based on several sources of information for environmental impact.** LCA results need to be considered together with other sources of relevant information on environmental aspects, particularly where gaps exist in LCA methodology. For nappies, hygiene aspects, as well as potential for littering and adding to marine plastics, are aspects not covered by LCA studies [10].

10 *Projects are under way to develop models and methods to account for the impact of plastic pollution in the marine environment, such as the MariLCA project, which aims to integrate potential environmental impacts of marine litter into LCAs.*

References

Arena, U., Ardolino, F. and Di Gregorio, F. (2016) 'Technological, environmental and social aspects of a recycling process of post-consumer absorbent hygiene products', *Journal of Cleaner Production*, 127, pp. 289–301.

Aumónier, S. and Collins, M. (2005) *Life Cycle Assessment of Disposable and Reusable Nappies in the UK*. Available at: *https://www.ch.ic.ac.uk/marshall/4I10/Nappies.pdf*.

Aumónier, S., Collins, M. and Garrett, P. (2008) *An updated lifecycle assessment study for disposable and reusable nappies*. Available at: *https://www.gov.uk/government/publications/an-updated-lifecycle-assessment-for-disposable-and-reusable-nappies*.

Cabrera, A. and Garcia, R. (2019) *The Environmental & Economic Costs of Single-use Menstrual Products, Baby Nappies & Wet Wipes: Investigating the impact of these single-use items across Europe*. Available at: *https://zerowasteeurope.eu/wp-content/uploads/2019/12/bffp_single_use_menstrual_products_baby_nappies_and_wet_wipes.pdf*.

Cordella, M., Bauer, I., Lehmann, A., Schulz, M. and Wolf, O. (2015) 'Evolution of disposable baby diapers in Europe: Life cycle assessment of environmental impacts and identification of key areas of improvement', *Journal of Cleaner Production*. 95, pp. 322–331.

Deloitte (2011) 'Absorbent Hygiene Products Comparative Life Cycle Assessment of Knowaste Ltd', (April 2011). Available at: *http://docplayer.net/53914803-Absorbent-hygiene-products-comparative-life-cycle-assessment-knowaste-ltd-summary-of-findings.html*.

Geyer, R., Jambeck, J. R. and Law, K. L. (2017) 'Production, use, and fate of all plastics ever made', *Science Advances*. Available at: *http://advances.sciencemag.org/*.

Hoffmann, B. S., Morais, J. de S. and Teodoro, P. F. (2020) 'Life cycle assessment of innovative circular business models for modern cloth diapers', *Journal of Cleaner Production*, 249.

Jamieson, A. J. et al. (2019) 'Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on Earth', *Royal Society Open Science*. Royal Society Publishing, 6(2).

Kaza, S., Yao, L., Bhada-Tata, P. and Van Woerden, F. (2018) *What a Waste 2.0 - A Global Snapshot of Solid Waste Management to 2050*. Available at: *https://openknowledge.worldbank.org/handle/10986/30317*.

Khoo, S. C. et al. (2019) 'Recent technologies for treatment and recycling of used disposable baby diapers', *Process Safety and Environmental Protection*. Institution of Chemical Engineers, 123, pp. 116–129.

Mendoza, J. M. F., D'Aponte, F., Gualtieri, D. and Azapagic, A. (2019) 'Disposable baby diapers: Life cycle costs, eco-efficiency and circular economy', *Journal of Cleaner Production*, 211, pp. 455–467.

Mendoza, J. M. F., Popa, S. A., D'Aponte, F., Gualtieri, D. and Azapagic, A. (2019) 'Improving resource efficiency and environmental impacts through novel design and manufacturing of disposable baby diapers', *Journal of Cleaner Production*, 210, pp. 916–928.

Mirabella, N., Castellani, V. and Sala, S. (2013) 'Life cycle assessment of bio-based products: a disposable diaper case study', *International Journal of Life Cycle Assessment*, 18(5), pp. 1036–1047.

Ng, F. S., Muthu, S. S., Li, Y. and Hui, P. C.-L. (2013) 'A Critical Review on Life Cycle Assessment Studies of Diapers', *Critical Reviews in Environmental Science and Technology*, 43(16), pp. 1795–1822.

NLWA (2019) *Bin Your Nappy*. Available at: *https://www.nlwa.gov.uk/campaigns-and-projects/bin-your-nappy*.

O'Brien, K., Olive, R., Hsu, Y., Morris, L. and Bell, R. (2009) *Life cycle assessment: Reusable and disposable nappies in Australia*, *ALCAS--Australian Life Cycle Assessment Society*. Available at: *https://www.nzpsc.nz/wp-content/uploads/2017/12/OBrienetal2009ALCASnappiesv2revisedafterreview.pdf*.

Reese, H. (2015) 'Disposing of children's diapers with solid waste: a global concern?', *Waterlines*, 34(3). Available at: *https://practicalactionpublishing.com/article/2757/disposing-of-childrens-diapers-with-solid-waste-a-global-concern*.

Roman, L. et al. (2020) 'A global assessment of the relationship between anthropogenic debris on land and the seafloor', *Environmental Pollution*, 264, p. 114663.

Savvy Vanuatu, Mamma's Laef Vanuatu and Bambino Mio (2021) *Introducing modern reusable nappies into Vanuatu – a trial study*. Available at: *https://www.mammaslaef.com/wp-content/uploads/sites/105/2021/02/FINAL-Pilot-Study-FullReport.pdf*

The Pew Charitable Trusts and Systemiq (2020) *Breaking the Plastic Wave: A comprehensive assessment of pathways towards stopping ocean plastic pollution*. Available at: *https://www.pewtrusts.org/-/media/assets/2020/07/breakingtheplasticwave_summary.pdf*.

UNEP (2018) *Single-Use Plastics: A Roadmap for Sustainability*. Available at: *https://wedocs.unep.org/bitstream/handle/20.500.11822/25496/singleUsePlastic_sustainability.pdf*.

Walker, S. and Rothman, R. (2020) 'Life cycle assessment of bio-based and fossil-based plastic: A review', *Journal of Cleaner Production*. Elsevier Ltd, 261, p. 121158.

Weisbrod, A. V and Van Hoof, G. (2012) 'LCA-measured environmental improvements in Pampers diapers', *International Journal of Life Cycle Assessment*, 17(2), pp. 145–153.

Williams, M. et al. (2019) *No time to waste: Tackling the Plastic Pollution Crisis Before it's Too Late*. A report by Tearfund, Fauna & Flora International (FFI), WasteAid and The Institute of Development Studies (IDS). Available at: *https://learn.tearfund.org/en/resources/policy-reports/no-time-to-waste*

Willskytt, S. and Tillman, A. M. (2019) 'Resource efficiency of consumables – Life cycle assessment of incontinence products', *Resources, Conservation and Recycling*. Elsevier, 144(June 2018), pp. 13–23.

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