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Review

End-of-life management of single-use baby diapers: Analysis of technical, health and environment aspects

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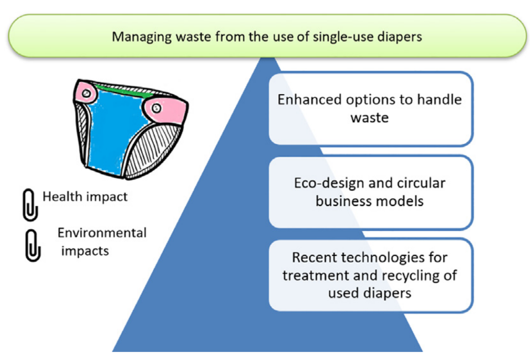
HIGHLIGHTS

- Environmental and health concerns can be associated with baby diapers.
- Single use and disposable diapers are analysed, focusing on materials and waste.
- Enhanced design, use and waste management options are provided.
- Systemic challenges and future perspectives are described.
- Holistically safe(r) and sustainable diapering processes are addressed.

GRAPHICAL ABSTRACT



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ABSTRACT

Single-use baby diapers belongs to an important group of products used in the parenting journey because of their high performance and convenience. Single-use baby diapers are normally thrown away after one-time use, resulting in a waste management problem. The goal of this paper was to better understand main environmental concerns of different types of diapers and address how to reduce them, with a special consideration of waste management strategies and user behaviour practices. Furthermore, health and environmental hazards potentially associated with materials included in diapers, or substances formed from diapers during the waste treatment stage, are also analysed (e.g., phthalates, pesticides, dioxins, pesticides). Three main types of baby diapers have been analysed: single-use baby diapers, reusable baby diapers, and biodegradable single-use diapers. Each type of diaper comes with technical characteristics and environmental concerns and challenges, which are discussed in this paper to support the development of measures for the safe(r) and sustainable design, use and end of life management of baby diapers.

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1. Introduction

Single-use baby diapers belongs to an important group of products used in the parenting journey because of their high performance and convenience. Contrary to reusable cloth diapers, single-use baby diapers are normally thrown away after one-time use, resulting in a waste management problem. However, cloth diapers requires to be washed, dried and folded, and this is why single-use baby diapers are an indispensable item in the everyday life of many working parents (Khoo et al., 2019). Consequently, disposable baby diapers constitute the largest market share (in terms of sales) of absorbent hygiene products (AHPs), which also include other products such as menstrual pads and adult incontinence products.

The European Union (EU) dominates the global market, slightly in front of the Asia Pacific and North America (Newswire, 2018). The global market of all types of diaper reached in total a value of more than US$ 54 Billion in 2016, and what is worth to notice, the market is expected to exceed the value of US$ 71 billion by 2022 (Newswire, 2021). This translated into consumption of raw materials to produce units of single-use diapers, as well as generation of waste. Public awareness on environmental issues associated with baby diapers has grown over time. As a result, nowadays, different solutions have been developed to mitigate the environmental burdens associated with the production, use and disposal diapers, such as the introduction of eco-design practices, eco-friendly waste treatment and recycling processes for used diapers, as well as eco-labels (Cordella et al., 2015).

The goal of this paper is to better understand potential environmental and health concerns associated with different types of diapers (Section 2), and address the prevention and mitigation of such concerns (Section 3). Special attention is given to waste management strategies, design options and user behaviour practices since they are key factors determining the overall impacts of diapers. The paper systematically integrates research available in the literature, often specialised in specific technical, environmental, or health aspects. Such information is crossed with results from a user survey, to understand practices of use in real life and public awareness about the handling of diapers. Challenges and future perspectives are then described (Section 4), before drawing conclusions. The result of this paper is a comprehensive analysis which can support the development of measures for the safe(r) and sustainable design, use and end of life management of baby diapers.

2. Types of diapers and their health and environmental impacts

Diapers are AHPs that can come in a wide variety of shapes, sizes, and materials (Ng et al., 2013). Most of the materials which compose baby diapers contain an absorbent core which properties must allow for the absorption of fluids by diffusion and/or capillary absorption (Tesfaye et al., 2019). Depending on how many times a diaper can be used, diapers are classified into two main categories, i.e., single-use (disposable) and reusable ones (Mendoza et al., 2019b), as described in the following sections. Research has shown that a baby on average uses near to 7000 diapers during the diapering period (i.e., before being able to autonomously use the bathroom), and that 95% of diapers are of single-use (Edana, 2008; Heather Reese and Breanna Alman, 2015).

There is increasing awareness and concern over the environmental burdens associated with diapers (Fig. 1). These include issues such as water, air, and soil pollution, resource consumption, and waste production, which led corporations to start ideating greener design options and technologies to reduce such burdens (Alhogbi, 2017; Ntekpe et al., 2020). However, environmental concerns associated with disposable and non-disposable diapers are different. Key impacts are due to the use of materials and production of waste for single-use diapers, and to the use phase for cloth diapers. Apparently, cloth diapers are – under certain use conditions – better than disposable ones (Notten et al., 2021). These aspects are discussed in the following section.

2.1. Reusable diapers

According to the definition given above, non-disposable material diapers can be used for many times after laundry (Ng et al., 2013).

Reusable diapers, also called cloth diapers, are mainly composed of many layers of fabric such as cotton, bamboo, hemp, polyester, or polyurethane (Leverich, 2010). These products are manufactured to satisfy customers' requirements such as impermeability, user-friendliness, absorption potential, durability, and breathability (Hoffmann et al., 2020). A cloth diaper consists of an absorbent part and an impermeable cover.

Reusable diapers can be made from renewable resources such as cotton, bamboo, or hemp fibres. Until the decade of 1960, when single-use diapers were introduced into the market, cloth diapers were made from 100% cotton materials (Krafchik, 2016). Frequently, non-disposable diapers are still manufactured from cotton fibres, alone or in combination with other fabrics and materials obtained from other natural or synthetic fibres (Meseldzija et al., 2013). For example, a wide combination of fibres, such as cotton, bamboo fleece, hemp, polyamide and polyester microfibres, can be used as absorbent materials of modern cloth diapers (Hoffmann et al., 2020). A polyester net laminated with polyurethane (PUL) is also used as cover material to allow permeability and fast drying characteristics (Mukhopadhyay and Vinay Kumar, 2008).

It is well-known that cotton-made materials require a lengthy and strict fabrication sequence during their manufacturing processes (Tesfaye et al., 2019). In recent years, bamboo has become a very popular material in reusable diapers fabrication. Bamboo fibres offer satisfactory absorbency performance and are made from a rapidly growing plant (Meseldzija et al., 2013).

Cloth diapers are reusable and do not contribute to the generation of waste and following accumulation in landfills. However, it is critical to highlight that reusable diapers can also produce environmental contamination during their manufacturing and cleaning. For example, they demand energy which can often come from non-renewable resources (Ntekpe et al., 2020).

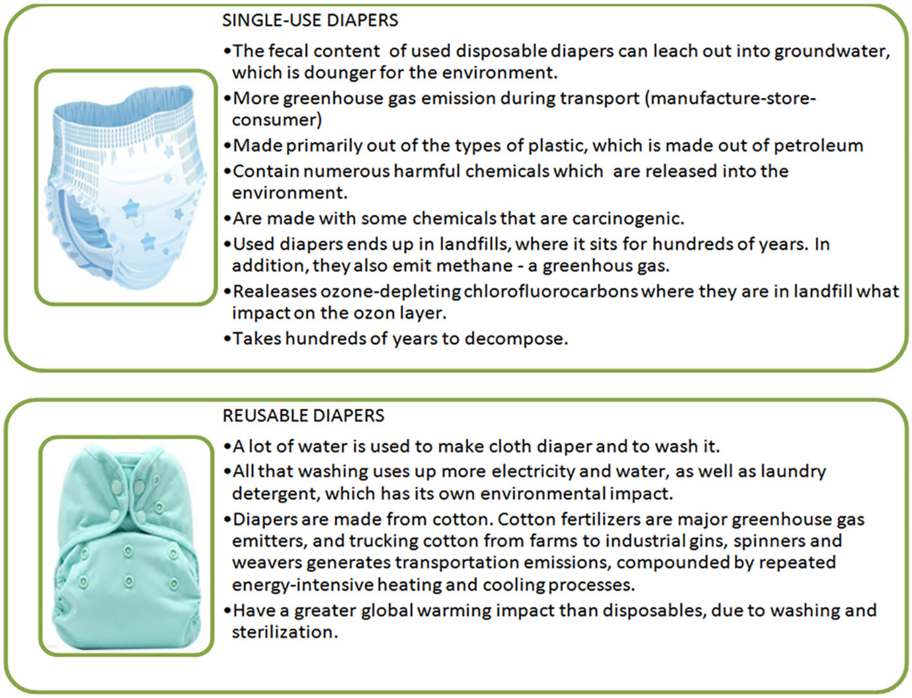

Fig. 1. Environmental impacts of single-use and reusable baby diapers.

Manufacturing of cloth diapers consumes renewable materials (e.g., cotton, bamboo, hemp) and other resources such as water, fossil fuels and chemicals (Alhogbi, 2017). Furthermore, the manufacturing process is also responsible for the production of waste and polluting emissions to air, water and soil. However, environmental impacts associated with the manufacturing of a reusable diaper unit occur once in time and are then diluted over the number of reuses of the product.

Another concern for reusable diapers is the amount of water and energy consumed during the use phase (Aumônier et al., 2008), i.e., washing diapers after use. In Europe, wash cycles in washing machines on average consume 75 L of water per load (3 kg per average load), for an energy consumption of 1.19 kWh at 60 °C and 2.06 kWh at 90 °C. According to research (Aumônier and Collins, 2005), it takes near to 85,000 L of water to launder the cloth diapers one baby uses in her/his life.

Besides, during the wash cycles, detergents and softeners are used, which require resources for their production and contribute (together with the cleaning of residues of urines and faeces) to water and soil pollution and human exposition to hazardous compounds. At least 135 g of detergent per wash are used in washing machines, which involve the use of chemicals such as nonylphenol, tetraacetylethylenediamine, sodium carbonate and anionic surfactants (Goel and Kaur, 2012; UNEP - United Nations Environment Programme, 2021). In addition, according to the UK Environment Agency (EA) (Aumônier et al., 2008), 49% of the reusable diaper users use softeners at an average dose of 100 g per wash cycle. The composition of softener products is usually 10% of cationic surfactants and 90% water (Aumônier and Collins, 2005; Spataru et al., 2017).

2.2. Single-use diapers

Single-use diapers (also known as disposable diapers) are made of various kinds of polymers and composed of four parts fulfilling specific functions: an inner protective layer, an absorbent core layer (including an acquisition and distribution layer), and a plastic outer layer (Cordella et al., 2015; Counts et al., 2017; Elmogahzy, 2020).

The inner layer is made of a polymer-based material isolating the core layer and protecting the baby's skin from wetting again (Mendoza et al., 2019b). This layer consists of a sheet usually made of polypropylene-based materials. Some sheets can also contain pharmaceutical-grade petrolatum and stearyl alcohol to hydrate skin and provide more comfort. The outer layer is conventionally made of polyethylene materials and prevents leakage from diapers (Tesfaye et al., 2019). The most important part of the diaper is the core, which major function is to absorb and retain the liquid excretion. This is typically made of fluff pulp from cellulose materials, or super-absorbent polymers (SAP) such as sodium polyacrylate. Raw materials used to produce single-use diapers are shown in Table 1.

Differently from cloth diapers, single-use diapers are produced, used, and thrown away after use. Compared to reusable ones, their use can cause more pressures in terms of waste generation and consumption of natural resources. However, it must be highlighted that actual impact profiles also depend on specific characteristics of the territories where production, use and disposal are in place (Meseldzija et al., 2013; Notten et al., 2021).

Production of disposable products requires natural resources, including materials and energy. Some studies have estimated that over 22 kg of petroleum and 136 kg of wood are needed to produce single-use diapers for one baby per year (Heather Reese and Breanna Alman, 2015). Furthermore, in a house with children, single-use diapers contribute to at least half of the total household waste (Meseldzija et al., 2013). A massive amount of single-use diapers end up in the garbage every day, and are not easily biodegradable (Lehrburger, 1988). Single-use diapers are in fact made of plastic and absorbent polymers, which can remain in the environment for long periods. According to the EPA, it takes 500 years for a single-use diaper to degrade and they are the 3rd largest consumers item in landfills in the U.S. (NSW EPA, 2014).

Single-use diapers are classified as "municipal solid waste", and are handled after use using traditional disposal practices (Central Polution Control Board, 2018; OECD, 2022; Velasco Perez et al., 2021). Conventionally, diapers can end-up in landfills and incineration plants. However, in some cases, they are flushed directly into the toilet or burned in the ground at open air. These disposal practices contribute, to different extents, to water, soil and air pollution (Remigios, 2014).

2.3. Biodegradable single-use diapers

Biodegradable single-use diapers represent a specific type of single use diapers made of a variety materials that can break down in the environment in relatively short time (Alhogbi, 2017). Biodegradable single-use diapers can be a better option when a collection-composting system is in place (which is not always the case). Usually, biodegradable diapers and other AHPs are made of natural fibres from plants or animals (Asim et al., 2015; Mukhopadhyay and Vinay Kumar, 2008; Patiño-Masó et al., 2019; Ramamoorthy et al., 2015; Shanmugasundaram and Gowda, 2011). Some examples for novel materials used in biodegradable diapers can be silk, wool, leaves (pineapple, sisal), seeds (cotton, kapok, coir) or grass (bamboo, bagasse). As drawback, this type of diapers can be more expensive (Mendoza et al., 2019a).

2.4. Health impacts

Apart from the environmental concerns described so far, diapers and materials used in diapers can also be the source of inherent hazards for the health of users.

Diapers are used to avoid baby's incontinence and keep them clean during the day. However, they increase skin wetness and create friction with the children's skin creating an adequate microenvironment for the development and growth of bacteria and pathogens potentially leading to diaper dermatitis, also known as nappy rash (Prasad et al., 2003). Diaper dermatitis is a condition characterized by the inflammation of the skin covered by the diaper causing an erythematous rash on the convex surfaces of the perineal and perianal areas (diaper area) (Jordan et al., 1986). This is due to the interaction of different factors such as the alkalinization of the urine pH, the presence of fecal enzymes and microorganisms, and increased wetness in the diaper area (Fernandes et al., 2009; Prasad et al., 2003).

Normally, diaper dermatitis is mild and requires minimal intervention such as adequate hygiene and lotions (not containing any irritant substance). However, in some cases is a concerning situation because SAPs used in diapers fabrication could be a contributing factor in the development of Toxic Shock Syndrome (TSS) because it might lead to the accumulation of some pathogenic microorganisms in the diaper surfaces (Berkes et al., 2017). TSS is a lethal condition mediated by toxins during infections caused by microorganisms such as Group A Streptococcus and *Staphylococcus aureus* (Lees et al., 2016). This is the consequence of a systemic inflammatory response caused by antigens that activate T-cells leading to hyperketonemia and hyperinflammation. In consequence, the cytokine storm causes the generation of typical manifestations and symptoms of TSS (DeVries et al., 2011). Thus, it is essential to differentiate types of dermatitis and know how to best treat them and avoid future complications.

Another concern are potential sanitary and health issues relating to the end of life disposal of diapers. Diapers disposal with municipal solid waste might lead to exposure to different kinds of pathogens and other contaminants. Research has shown that infants under 12 years of age are effective carriers of enteric pathogens such as *E. coli, Shigella, Salmonella, Bacillus, and Streptococcus* species (Ntekpe et al., 2020). Also, a wide variety of viruses can be found, such as *rotaviruses, adenoviruses*, and *enteroviruses,* that are responsible for a wide variety of enteric diseases (Carr, 2001). People could get in contact with microorganisms leaking from used diaper. Thus, the way diapers are disposed can represent a severe public health problem (Miller-Petrie et al., 2016).

Furthermore, although the use of single-use diapers can be generally considered safe, they could potentially contain hazardous substances (Commission Decision of 24 October 2014 establishing the ecological criteria for the award of the EU Ecolabel for absorbent hygiene products (notified under document C(2014) 7735) Text with EEA relevance, 2014). Some examples of these compounds are phthalates (found in the range of 0.1–1500 μg/g), acrylamide and dyes (found in the range of 0.16–0.4 mg/kg), which are not in direct contact with humans or ecosystems, but that could be released in landfills during the end of life stage (Anderson and Anderson, 1999; Rai et al., 2009), or contribute to the formation of volatile organic compounds (VOCs) and dioxins in case of incineration.

Phthalates play an important role in disposable absorbent hygiene products fabrication, including diapers because all the plastic in these items contains these types of chemical compounds. According to the EPA, these are classified in the list of regulated due to their toxicity and hazard to human health (Kieth, 1980). Some types of phthalates such as di(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), and diethylphtalate (DEP) are considered as endocrine disruptors (López-Carrillo et al., 2010; Ünüvar and Büyükgebiz, 2012) and have been related to cancer and neurocognitive dysfunction development (Engel et al., 2021; Grandjean and Landrigan, 2014; Ventrice et al., 2013). However, not all of them are toxic and not all of them can be found in absorbent hygiene products fabrication.

Another chemical of concern present in diapers is the Tributyltin (TBT; ~100 μg/kg) used for the dye of diapers (Šmajgl and Obhodaš, 2015). TBT is also considered a highly toxic endocrine disruptor that can be absorbed through the skin barrier leads to immune and endocrine system impairment (Sundukov, 2006).

Sodium polyacrylate (SAP) is a chemical compound whose main function is to enable the absorption of fluids. This can constitute a potential health hazard. Although there is no direct exposure to SAP, in cases of accidental contact it can have toxic effects on human health and ecosystems (Prasad et al., 2004). Studies have shown that SAPs in single-use diapers might lead to severe skin irritation, bacteria accumulation (mainly staphylococcal infections) which can lead to toxic shock syndrome (Bucaretchi and Baracat, 2005). In murine models, It was documented that exposure to SAP caused haemorrhages, cardiovascular failures, and deaths (Ntekpe et al., 2020).

Table 1
Raw materials used in single-use diapers.

Part	Materials	Characteristics
Outer layer	○ Propylene (PP) and Polyethylene (PE). ○ Viscose rayon	○ PP and PE fibres are commonly used in hygiene products because of their low density, softness, and chemical stability (Kyrikou and Briassoulis, 2007). ○ Viscose rayon, a synthetic fibre derived from cellulose xanthate, can be also used because of its absorbency properties and hydrophilic characteristics (Hubbe et al., 2013).
Acquisition and distribution layer (ADL)	○ Fluff pulp that can be made of: ○ Cellulose based fibres such as: cotton and wood pulp. ○ Protein based fibres such as silk or wool- ○ SAPs	○ Fluff pulp stores the liquid temporarily before its distribution through capillaries to the absorbent core and can absorb liquids up to 10 times its weight (Cordella et al., 2015).
Absorbent core	○ Cellulose based fibres (wood and cotton pulp) ○ SAPs ○ Polylactic acid (PLA) ○ Protein based fibres (Asim et al., 2015; Mukhopadhyay and Vinay Kumar, 2008; Patiño-Masó et al., 2019; Ramamoorthy et al., 2015; Shanmugasundaram and Gowda, 2011)	○ SAPs are developed with hydrophilic polymers such as polyvinyl alcohol (PVA), polyethylene oxide (PEO) acrylamide, and the most commonly used sodium polyacrylate (Lee and Lee, 2016; Tesfaye et al., 2019). SAP can absorb liquids up to 1000 times its weight. ○ PLA is a novel biopolymer produced from renewable sources and that has desirable properties such as mechanical strength and biodegradability (Singhvi et al., 2019).
Inner layer	○ PE and PP	○ These are used to maintain dryness and comfort by transporting wet through the material (Elmogahzy, 2020).

3. Managing waste from the use of single-use diapers

3.1. Waste production and current waste management practices

Single-use diapers produce an incredible amount of environmental waste. In the United States, 4 million tones are disposed every year, 80% of which buried in landfills (EPA, United States). In Australia an estimate of 3.75 million of disposable diapers are used every day that highly contributes to waste production. In Europe, the daily disposable diapers use is estimated by eight million (Lauren and Lawrence, 2014). Shin and Jin (2018) reported in their study that 240,000 tons of used diapers are generated in Korea every year, leading to increased methane production and leaching of organic compound into the ground water and soil. In South Africa, approximately 1.1 million tons of disposable diaper waste is produced yearly (Khanyile et al., 2020). In developing countries, a challenge is posed due to the increase number of disposable diapers use along with lacking the expertise and financial resources (Muia, 2018). The problem is expected to grow, since globally there is an exponential increase of single-use diaper production and consumption.

Fig. 2(b) shows the main composition of single-use diapers. A key constituent of single-use diapers is cellulose pulp (% by weight might differ in different markets), a renewable materials that is mainly obtained from coniferous woods (Colón et al., 2011). It takes around 200–400 kg of fluff pulp (approximately one billion trees per year) to supply one baby with disposables for 1 year. Most of the materials used in single-use diapers could decompose in relative short time, except for SAP and plastic components, which may require more than 500 years to fully decompose.

SAP, typically sodium polyacrylate, represents 33% of the average weight of a diaper (some products have less SAP percentage than others). The average content of SAP increased dramatically from 1995 to 2005 in the European market, then it slightly decreased in association with enhanced functionality of materials and product's layout (Cordella et al., 2015). These polymers are degraded through the breakout of the cross-linkages between the monomers to degrade with the generation of less harmful chemicals.

Normally, single-use diapers are treated as other municipal solid wastes through landfilling, incineration, composting (Ntekpe et al., 2020).

In most of the developing countries, where there is no waste segregation, single-use diapers are mainly disposed along with other solid wastes, which usually leads to landfills or dumpsites. In these countries, with high unawareness of the negative environmental and health impacts, single-use diapers are haphazardly dumped openly at various points (Jesca and Junior, 2015; Ntekpe et al., 2020). When it comes to parents, some studies in African countries referred that the most used methods by parents are dumping in open spaces, burning them, burying them or flushing them in the toilet, which in many cases shows less awareness of the parents of the hazardous effects on air, soil and health (Remigios, 2014).

Under specific control standards, incineration could help drastically reduce the volume of solid waste in general, although this can come with air pollution concerns and costs. In many other developing countries, the controlled condition for incinerators are not followed, and open burning of diapers takes place. Other users tend to bury the single-use diapers in dug holes in the ground. For example, in Kenya this accounts for 4.6% of the diapers disposal methods (Wambui et al., 2015).

However, in some cities or countries, mainly in western region, incineration is prohibited to avoid air pollution and protocols concerning wastes segregation, storage and transportation including disposable diapers exist to reduce the risks of dissemination of pathogens by preventing human contact. Furthermore, in western countries, having strict policy tools for disposable product waste may include extended producer responsibility (EPR) systems, bans or tolls (UNEP, 2021).

Some countries implemented the EPR since 1980s, which is a principle of environmental policy that aims to make companies responsible for the environmental impacts of their products. Most EPR programmes are compulsory and are applied via take-back requests, disposal fees, or refund accounts. The lack of data sometimes makes the impacts of EPR evaluation difficult. Nevertheless, there is some agreement that EPR has participated in the reduction of the public cost of waste management (OECD, 2022). The Republic of Korea is a famous example of countries that applies an advanced disposal fee to adopt waste management costs of hard to recycle wastes for instance disposable diapers (OECD, 2022).

Several initiatives have been proposed to ban or to establish standards for disposable products including diapers, for example in the USA,

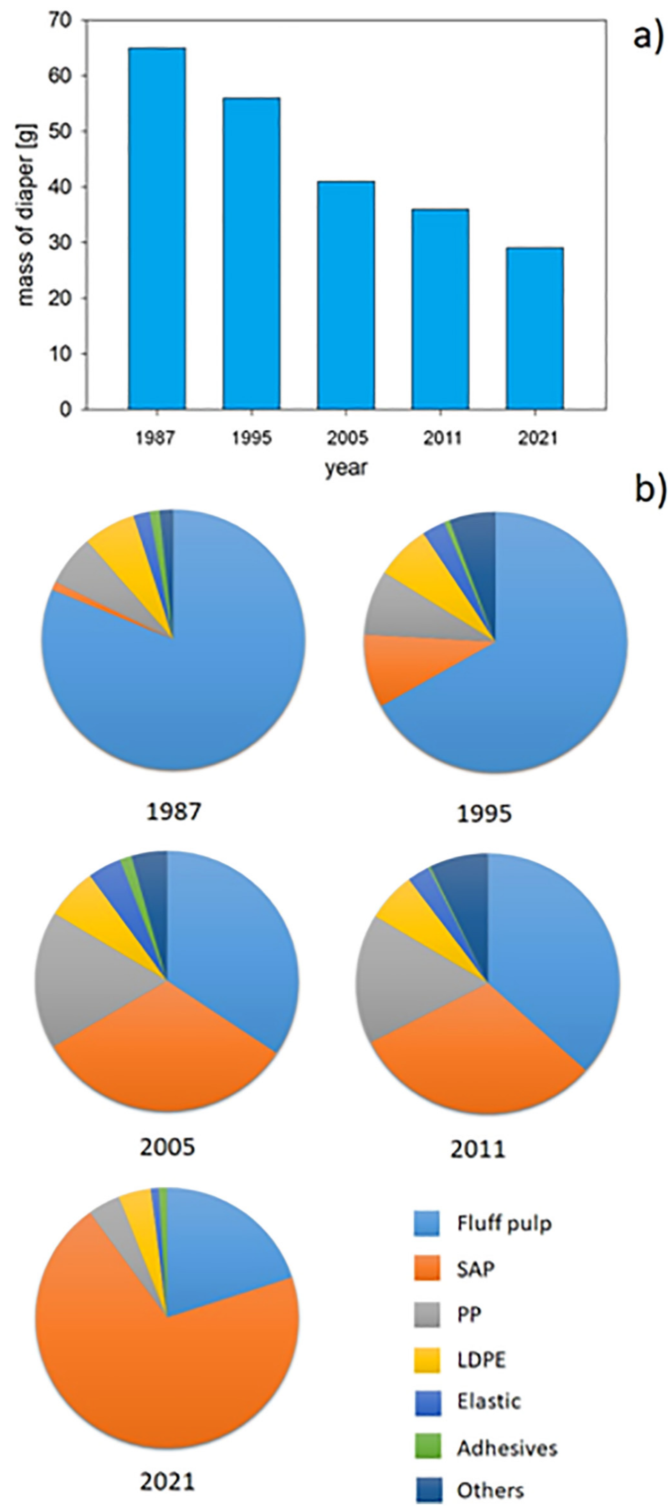

Fig. 2. A: Average single-use baby diapers weights in Europe in 1987–2021. B: Average chemical composition of single-use diaper in 1987–2021. (Based on Cordella et al., 2015; Serpette, 2021).

governments proposed several practices including absolute bans, taxes, and warning labels about the environmental impact of these products (Crews et al., 1994).

In the UK, a bill to establish environmental standards for disposable diapers was presented in the House of Commons (Parliament UK, 2019). It defined the requirements for trading, advertisement, and promotion of disposable diapers. However, the bill proposal was not successfully approved in the Parliament (Parliament UK, 2019). More recently, the Republic of Vanuatu became the first country to officially announce banning of absorbent hygiene products that includes disposable diapers starting January 2021 (Department of Environmental Protection and Conservation, Government of the Republic of Vanuatu, 2019). According to time use surveys, it was found that although banning disposable diapers is an environment protective practice, yet it has some socioeconomic impacts affecting employment opportunities and self-fulfilment (UNEP, 2018).

3.2. Enhanced options to handle waste

3.2.1. Eco-design and circular business models

In the first instance, a reduction in the amount of waste associated with the use of diapers should be pursued through eco-design practices and associated circular business models. In general terms, eco-design is the process of designing and creating products, services, and processes in a way that protects the environment. The main goals of eco-design include the application of fewer ingredients and resources, production of reduced amounts of waste and pollutants, minimizing the ecological impacts of distribution, and smart design to facilitate reuse and recycling products (Kamalakkannan and Kulatunga, 2021; Polverini, 2021; Popa et al., 2015; Wille, 2018). During the design and manufacturing of single-use baby diapers, five main aspects should be pointed out (Wille, 2018), which are presented in Fig. 3 and described in the followings.

3.2.1.1. Material efficiency (mass reduction). In recent years, the amount of materials used in the production of single-use diapers has significantly decreased. In 1987, a standard diaper weighed 65 g and over 80% of its weight was fluff pulp. The average amount of fluff pulp used in diapers gradually decreased over time (about 15 g in 2021), and so the weight of an average diaper did (about 30 g in 2021) (Cordella et al., 2015; Espinosa-Valdemar et al., 2015; Nealis, 2021; Serpette, 2021). Average single-use baby diapers weights in Europe in 1987–2021 are presented in Fig. 2(a). The decrease in diaper weight is mainly due to the replacement of fluff pulp with SAP, which has much higher absorbency properties. Research is still being carried out to improve SAP and its absorbency, which may result in a further reduction in the weight of diapers in the future. The smaller weight of single-use diapers significantly improves the comfort of children and reduces the amount of waste that needs to be processed or disposed of (Wille, 2018). In addition, diaper manufacturing processes are constantly being improved to reduce raw material and energy consumption and produce less manufacturing waste.

3.2.1.2. Use of recycled and renewable materials. Reducing the overall amount of raw materials used in diapers, while ensuring the correct functionality of the product would necessarily result in less generation of waste (Cordella et al., 2015).

A further improvement would be using renewable and/or recycled materials and, where appropriate, biodegradable ones (Lin et al., 2017; Mendoza et al., 2019b). Currently, used raw materials for the production of single-use diapers, i.e., nonwoven or SAP, are usually made of fossil fuels (also due to their relatively low cost). However, some manufacturers are replacing fossil-based materials with biomass-based ones and using also recycled materials. Recycling materials can come from three main sources:

- production waste from the diaper manufacturing process.
- waste from consumables (e.g., bottles, packaging).
- used diapers and other baby care materials (Lacoste et al., 2019; Ünlü, 2013).

The first type of recycled material is the pre-consumer waste from the production of absorbent hygiene products. It is considered as high-grade recyclable due to the fact that the material is slightly contaminated as it has no contact with faeces or urine. The minimum purity of such materials is in excess of 95% (Wille, 2018). That is why more and more component manufacturers are setting up recycling programs for their production waste.

Recyclables from industrial waste are usually mixed with raw materials and reused in the production of individual elements of single-use diapers. Currently, there are a lot of technologies that allow for the recycling of used PET bottles or plastic packaging intended for food storage into fibres for AHP materials production. These technologies are used, among others, for the production of nonwovens from recycled fibres of plastic bottles in the automotive industry. However, currently, recycled nonwovens are not used in the production of single-use diaper items. Similarly, post-consumer AHP waste is neither recycled into new diapers (Somers et al., 2021). In both cases, the reason is the need for the manufacturers of diapers to meet stringent safety and health requirements. Recycled products are generally of lower quality compared to products made from raw materials. Moreover, it is very difficult to rule out the contamination of post-consumer recycled materials.

The use of renewable materials in the production of diapers can also contribute reducing the dependency on fossil fuels and greenhouse gases emissions. Furthermore, biodegradable materials can be recirculated in composting plants, where logistic and infrastructure systems are in place. However, the production of such materials can come with other environmental issues associated for examples with the use of land, water, energy, fertilizers and pesticides (Mirabella et al., 2013).

In many single-use diapers, the fluff pulp is made from wood, thus fulfilling the condition of renewable and biodegradable material. However, fluff pulp is often replaced with SAP, which has better absorbency properties (Abd Manan et al., 2021; Bachra et al., 2020) and allow reducing the overall weight of the product. Conventional SAP is not made from

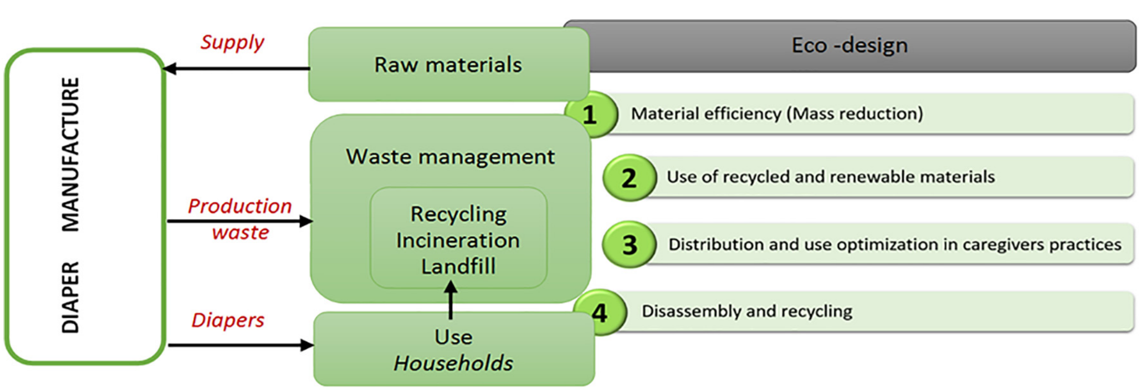

Fig. 3. Eco-design strategies for single-use baby diapers (Wille, 2018).

renewable materials, which limits its recycling or composting. A renewable SAP is available that is made from carboxyalkyl cellulose polymer and starch polymer blended in water. However, this is usually mixed with conventional. Research is being carried-out to develop commercially viable renewable alternatives to SAP, e.g., from corn-starch, itaconic acid from sugars through fermentation, or 3-hydroxypropionic acid.

Renewable materials are used also to produce nonwoven used in internal and external layers. Most of the "eco-brands" use bio-plastics from maize starch or sugar cane (Greenwashing-Disposable Diapers, 2017). Among the bio-plastics used in the production of nonwowens, two types can be distinguished:

- bioplastics with the same structure as PP or PE (they have the same properties as conventional polymers, but they are produced from renewable sources),
- bioplastics with different chemical structure (made from polylactic acid (PLA)).

The first type of bioplastics has the advantage that nonwovens production technology does not need to be changed, but they are not biodegradable or compostable. The advantage of the second type of bioplastics made of PLA is their high biodegradability but requires changes in the production process. The use of nonwovens with PLA can be a good solution where separate collection and composting systems are in place. However, in commercially available single-use diapers nonwovens with PLA are mixed with those made of PP or PE.

3.2.1.3. Distribution and use optimization in caregivers' practices: need for education. Presently, around 95% of families in Europe use disposable diapers for their babies (Makoś-Chełstowska et al., 2021). Despite this fact, parents' knowledge of using diapers is limited. Hygiene procedures around the sub-nappy areas are very often intuitive. Sometimes it is based on knowledge gained in childbirth school, especially before the birth of the first child. In other cases, it is knowledge based on one's own experience or on the advice of other parents or relatives, often outdated, referring more to tradition, social and economic factors rather than the latest scientific discoveries.

To learn more about the practices and caregivers' knowledge in this area a pilot study was carried out (in April–July 2021). The group of respondents were caregivers of babies who use diapers, parents, nursery teachers, legal guardians. They answered closed, open-ended, and multiple-choice questions(Intrygujące życie pieluch, 2021). The purpose of the study was to learn more about the attitudes, practices, and knowledge of caregivers of children who use diapers. Its results allow for gaining a broader understanding of the topic related to the use of diapers in households - from purchase to disposal. 34 caregivers from Poland answered questions concerning their experience related to the usage of baby diapers. The vast majority of respondents were women. 85,3% of respondents have higher education.

Only 14,7% of respondents read the information on the diaper packaging about how to use them. 70,6% is not interested in what is the composition of the diaper. The price (26,5%) and someone's recommendation (26,5%) are the key factors when choosing and purchasing a specific type of diaper. Most of the respondents use single-use diapers, commonly known as "pampers" or "tore-brands". The frequency of changing diapers depends on several factors. 44.1% of respondents change their baby's nappy when it is seen that the nappy is full. 41.2% change the diaper after the baby poops. 35.3% change the diaper every 2–3 h on average, regardless of the diaper content. 14.7% change the baby's diaper when it smells bad.

Diaper hygiene is an important part of education for infants' caregivers. Diaper dermatitis, an acute inflammatory eruption of the skin in the diaper area of baby, is a preventable condition and parents should reduce likelihood of this condition by adhering to proper diaper hygiene and baby's skin care practices. Once a diaper is soiled with either urine or stool, it should be changed as soon as possible to minimize contact with irritants. Thus, a diaper should be changed at least every 1 to 3 h during the day and at least once per night. Even if the diaper is only soiled with urine cleansing with warm water or a gentle diaper wipe to remove irritants from the skin is imperative (Merrill, 2015).

The continuous improvement of SAP's absorbent properties makes it possible to change diapers less frequently. The new generation of single-use diapers does not cause discomfort for children, even if they are lightly soiled. As a consequence, this can help reduce the consumption of diapers and the amount of waste generated after use. An additional benefit of improving the absorbency of SAP and replacing fluff pulp with SAP is the reduction of diaper weight. Transporting lighter products requires less fuel consumption (Wille, 2018). However, it should be remembered that SAP is difficult to biodegrade.

3.2.1.4. Disassembly and recycling. Design of diapers should facilitate its disassembly, recycling and composting after use. However, this is challenging since only a few countries allow for the selective collection and further processing of diapers. In addition, diapers from different companies are characterized by different compositions. Hence, theoretically, each company should provide separate collection points for their used products to provide a constant input to the recycling process. However, this approach would be too difficult and expensive (Wille, 2018).

Cloth diapers are excellent examples of extending the lifetime of products through the possibility of multiple uses. However, the need to constantly wash them makes single-use diapers still much more popular. In recent years, several companies have decided to introduce the so-called modular diapers. Modular diapers are a combination of both versions of single-use and cloth diapers. They mainly consist of three parts that can be easily disassembled (Fig. 4). The outer diaper is made of cotton, micro fleece, or flannel and is the part that gets the least dirty and is suitable for washing. The inner diaper is a waterproof layer that is attached to the outer diaper. The third part of diapers is cloth diaper inserts, which act as absorbent pads. It is a mainly single-use part (fluff pulp or SAP) that can be easily removed after use and directly recycle or biodegradable (Wille, 2018; Windelmanufaktur, 2015). Compared to single-use diapers, less waste is produced, because only one part is single-use. In addition, the need to wash only the lightly soiled part of the diapers reduces the consumption of detergents and water during washing.

Product service strategies are another way to make an efficient use of diapers. For example, there are companies in Belgium and the United States that offer the rental of reusable diapers. These companies deliver cloth diapers to consumers once a week, take back used dirty diapers and wash them. Destroyed diapers that cannot be reused are either recycled or composted (TinyTots, 2021; Wille, 2018). However, this approach has some drawbacks, including higher costs and logistic burdens compared to single-use diapers.

3.2.2. Recent technologies for treatment and recycling of used diapers

Used single-use baby diapers can be classified into the group of municipal solid waste. They contain both organic and inorganic fractions, which greatly complicates the possibility of their separations, and recycling. Typically, urine and faeces occupied about 76% *w*/w of single-use baby diapers

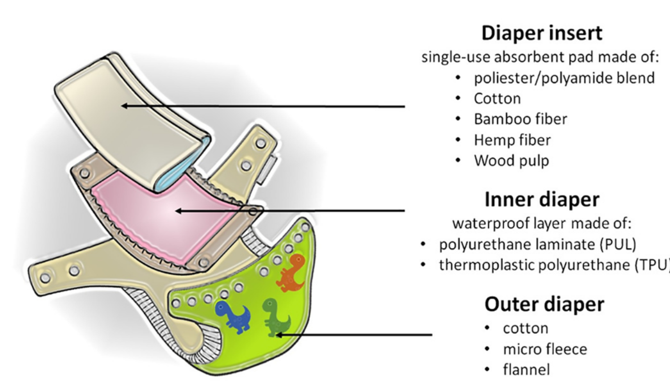

Fig. 4. Example of modular diaper structure (Thinking About Cloth Diapers, 2022).

(Khoo et al., 2019). Such a high urine and faeces content indicates that diaper waste can be successfully biodegradable or recycled. However, in most countries, conventional methods (e.g., incineration and landfilling) are still used (Cordella et al., 2015; UNEP - United Nations Environment Programme, 2021). These methods are not efficient from a sustainability perspective, e.g., they can lead to air pollution, leachate to groundwater, generation of hazardous ashes, high costs related to the maintenance of the installation. Furthermore, in the case of landfilling, the decomposition of waste takes a very long time, which requires its continuous monitoring (Khoo et al., 2019; Mendoza et al., 2019a). Therefore, new green technological solutions are needed to minimize the environmental and health impacts of single-use diapers, including recycling, biodegradation, anaerobic digestion, pyrolysis, and steam sterilization.

3.2.2.1. Recycling. Used diapers contain many valuable ingredients, such as plastics, fibres, and cellulose pulp, which can be extracted and used as raw materials for the production of other products (Khoo et al., 2019). However, the complex composition of single-use baby diapers and the presence of biogenic waste limits the possibility of recycling, because isolating a valuable material requires a complicated and costly procedure consisting of collection, shredding, sterilization, and separation (Arena et al., 2016; Kim and Cho, 2017). In addition, the huge problem with diapers recycling is potentially low quality in the recovered materials (Takaya et al., 2019). Currently, only 0.3% of used diapers in the world are recycled (Diaper Recycling Europe, 2020).

In Europe, only a few countries have technologies to recycle used diapers, including England, Italy, and Netherlands. The technology developed by Knowaste Ltd. and currently used in the UK is composed of several steps i.e., shredded diapers, shaken with a chemical salt (dehydrating agent), autoclave sterilization, and selective separation into fibre and plastic elements (Knowaste, 2021). The technology enables the recycling of approximately 360,000 tons of used diapers per year. In the same country, another company PHS Group recycles used diapers and then converts them into fuels. The process consists of several stages, i.e., mechanical separation, chemical treatment, and transformation of the separated plastic into fuel, and then combustion of RDF to produce heat and electricity (Nonwovens industry, 2017). There is also a diaper recycling company in Italy, which has a processing capacity of almost 100,000 tons per year. In a process consisting of very similar stages as in the technologies located in the UK, about 150 kg of cellulose, 75 kg of plastic and 75 kg of SAP from 1 m^3 of waste are recovered (Leblanc, 2019; Recycling Industry, 2017). Currently, the Netherlands is implementing a technology to recycle used single-use diapers. It consists of collecting, grinding, washing, mechanically separating plastic materials, and then granulating them. The remaining diaper waste, i.e., SAP, fibres, and compost, is sterilized, and the SAP is further subjected to a patented deactivation procedure. The technology assumes that after the end of the process, only 2% of the entire diaper will be a non-recyclable waste (Diaper Recycling Europe, 2020). Recycled materials can be used for the production of construction purposes, cat litter (Diaper Recycling Europe, 2020), stable supercapacitor electrodes (Lobato-Peralta et al., 2021), energy (Nonwovens industry, 2017), etc.

3.2.2.2. Biodegradation and composting. Biodegradation is a method that allows the degradation of complex organic structures into simple molecules. During the biodegradation process, the strong carbon bonds in the natural, and synthetic polymers in diapers are broken through biochemical reactions of bacteria, fungi, protozoa, or other microorganisms resulting in the degradation of polymers to environmentally acceptable products. In the aerobic biodegradation process products are degraded to CO_2, H_2O, and sludge while under anaerobic conditions CO_2, H_2O, and CH_4 are formed (Eskander and Saleh, 2017; Massardier-Nageotte et al., 2006).

Cellulose can be easily degraded by microorganisms (Coughlan, 1991). However, the main problem is the composition of the diapers and the form in which they are discarded. Typically, used diapers are rolled up with a plastic cover on the outside and secured with adhesive tape. In this form, the cellulose remains inside, covered with a waterproof and non-biodegradable layer. Therefore, prior to the treatment of diapers with microorganisms capable of converting cellulose, a complex process with the same steps as in recycling for cellulose extraction should be used (Kim and Cho, 2017). After cellulose extraction from diapers, it can be treated with *Pleurotus ostreatus.* In the biodegradation process, fungi produce enzyme cellulase that hydrolyze β-1,4 linkages in cellulose chains. *Pleurotus ostreatus* can efficiently reduce the total weight of diapers, through enzymatic activities during which cellulose components of waste materials are converted to food source glucose (Lewis, 2014; Pathak and Navneet, 2017) The effectiveness in reducing the total weight of used single-use diapers is up to 80% during 60 days (Espinosa-Valdemar et al., 2011).

Synthetic polymers can be degraded by fungi and bacteria. Nevertheless, fungi are more effective in the biodegradation of polyethylene or polypropylene, which are commonly used in the construction of diapers. Almost complete degradation of the polymers can be achieved after 90 days (Mismisuraya et al., 2021). The group of fungi with the greatest potential for decomposition of polymers include *Penicillium, Pleurotus,* and *Aspergillus*, while among bacteria, *Staphylococcus, Pseudomonas, Rhodococcus*, and *Bacillus* can be distinguished.

Used single-use baby diapers can also be recycled into a garden compost or soil fertilizer through enzyme activities. Typically, in a composting method, diapers are mixed with other food, or plant organic materials. The limitation of composting is the possibility of degrading only cellulose material, but it does not degrade outer plastic, as well as the possibility of pathogens, plastics, or other unfavourable substances in the composted materials, even after many days of the process. In addition, diapers can also contain other problematic compounds such as SAP, creams, lotions, or fragrances. The presence of these substances significantly reduces the quality of the compost.

The presence of enteric pathogens (i.e., Salmonella, Giardia cysts, and Cryptosporidium oocysts) in the raw solid waste and in the waste with used diapers has been also detected in the literature. However, after 175 days, only Salmonella can be detected. This indicates that some pathogens are destroyed during the composting process, due to the temperature rise during the enzyme reaction (Gerba et al., 1995). However, the temperature increase of composted materials is not high enough to destroy all pathogens. Therefore, the diaper compost can only be used for flowers, trees, and bushes. However, such compost is not suitable for a food garden (Baley, 2021). Similar results were also obtained in other studies in which waste diapers were mixing with sludge, and yard waste in a 3:7 *w*/w ratio. In these studies, despite the significant reduction in diaper weight (approximately 87%) with the recovery of plastic films, a high concentration of zinc was detected in the compost, which was most likely from the skincare products found in the diapers (Colón et al., 2011; Espinosa-Valdemar et al., 2014).

The technology of composting used diapers is currently available in European countries, i.e., Belgium and Germany. A first technology is based on the use of a soil conditioner “Teracottem”, and is successfully used for the conversion of barren plots of land to fertile plots (Bai et al., 2010). A second technology developed by Ayumi Matzusaka is used to convert used diapers into a high nutrient black fertile soil (Matsuzaka, 2021).

3.2.2.3. Anaerobic digestion and dark fermentation. The conversion of used diapers into renewable biogas can also be another enhanced form of handling this type of waste (Tsigkou et al., 2020, 2021). The results obtained by Torrijos et al. (2014) indicate that during the co-digestion process with waste-activated sludge, 280 NmL of methane can be obtained per gram of volatile solid (Torrijos et al., 2014). On average, one ton of diapers can result in 150 kg of dry, biodegradable fraction, from which 130 kWh of electricity can be produced (if an electricity yield of around 33% for a combined heat and power unit is taken into account) (Torrijos et al., 2014).

Another process that can allow for the formation of biogas from disposable baby diapers is dark fermentation. It is a process that is carried out in the dark, and under anaerobic conditions, which involves conversion of an organic substrate to biohydrogen. During the dark fermentation process, 196.45 NmL of hydrogen per gVS was produced from a model cellulose fraction of diapers (Sotelo-Navarro et al., 2020). In an experiment with the use of real whole used diapers without pre-treatment, a significantly lower hydrogen production efficiency of 13.64 NmL/gVS was demonstrated (Sotelo-Navarro et al., 2017). This indicates that at the beginning of the anaerobic and dark fermentation process, a cellulose layer should be separated from the diapers, which is then subjected to biogas production processes.

It has been shown that even a small amount (840 mg/L) of Poly (acrylicacidsodium salt) super absorbent can inhibit methane, and hydrogen production by up to 50%, and 25%, respectively (Lin Chou et al., 1979; Sotelo-Navarro et al., 2020). However, in other studies in which diapers with and without plastic fraction were tested, the obtained results indicate that hydrogen production by means of diapers with plastics elements was unexpectedly higher than using diapers without them (Sotelo-Navarro et al., 2017). Various results indicate that more research is needed on this effect. Omitting the separation step would significantly reduce the costs associated with the production of bioenergy, which would make this method of disposal of used diapers even more attractive.

3.2.2.4. Thermal degradation. Incineration and pyrolysis can be distinguished among the methods of thermal degradation of used single-use diapers. Incineration is the full oxidative combustion of wastes at high temperatures (900–950 °C). Thermal energy is generated during combustion, which can be used to heat water and nearby buildings and/or converted into electricity. In the incineration process, 7.7 MJ/kg energy can be obtained from used single-use diapers (Velasco Perez et al., 2021). Therefore, incineration is widely used in European countries. For example, in Sweden or Switzerland, 50% of all waste is converted into energy (Kumar and Samadder, 2017; Moya et al., 2017). During incineration, potentially hazardous ashes containing dioxins and heavy metals are formed. This significantly limits the possibility of further use of the ash. However, ash can be converted into building materials, cement, or ceramics (Karimi et al., 2020). In addition, the large moisture content of diapers significantly can reduce the efficiency of the incinerator (Liang et al., 2008; Sun et al., 2016).

An innovative method of thermal degradation of used diapers is pyrolysis. Pyrolysis is the thermal decomposition (300–900 °C) of organic wastes in an inert environment (i.e., with no oxygen). The process produces solid, liquid, and gaseous streams. The gaseous and liquid streams could be treated and used as fuel or feedstock source, while the solid residue (called biochar) could be treated and used as soil additive, catalysts or adsorbents (Budyk and Fullana, 2019; Kwon et al., 2021; Lam et al., 2016a, 2016b, 2015). The pyrolysis process is relatively fast, efficient, and significantly reduces the amount of diapers waste (Lam et al., 2016b). In addition, the use of microwave radiation can further improve this process by accelerating the heating and shortening the pyrolysis reaction (Lam et al., 2019). However, a microwave pyrolysis process is currently in a laboratory research stage. There are many technical problems that significantly hinder the commercialization of the microwave pyrolysis process, including, in particular, the variability of the composition of used diapers (i.e., the content of fecal excrement, urine, plastic elements, and absorbent materials). Therefore, detailed optimization of the process parameters (i.e., temperature, heating power) with various feedstock is still needed (Khoo et al., 2019).

4. Challenges and future perspectives

There are currently two main strategies for managing single-use diaper waste. Eco-design and circular business models can offer efficient ways to introduce improved products on the market. These must be coupled with more “classical” end-of-pipe strategies dedicated to the waste management of used diaper products.

Eco-design can provide many valuable suggestions on how diapers can be designed to be more environmentally friendly. Within a circular economy perspective, one of the aim of eco-design is to minimize the use of natural resources and the production of waste (Cordella et al., 2020).

Theoretically, single-use diapers could be produced using recycled materials from different sources. However, due to the relatively low quality of the recycled materials, and the possibility of introducing toxic substances, such as heavy metals, or pathogens into new diapers, it is currently possible to use only sanitized production waste. According to (Wille, 2018), manufacturers of single-use diapers do not intend to use recycled materials from used diapers and food packaging in the near future.

Currently, renewable and biodegradable materials are not frequently used, also because of high cost of materials and technical requirements that they must meet. However, research is being carried out for the development of new materials that could increase the amount of renewable and biodegradable materials used in single-use diapers in the future. However, potential benefits of these materials can be achieved only in presence of appropriate management systems and associated infrastructure.

In recent years, as a result of the gradual replacement of fluff pulp with modern SAP, the weight of diapers is gradually decreasing, and a further weight loss is expected in the following years. Research is constantly being carried out on the improvement of SAP in order to ensure their even greater absorbency, which will further contribute to reducing the weight of diapers. This can also have the benefit of reducing burdens associated with the distribution of diapers. On the other hand, SAP presents some challenges in terms or recycling/composting.

Improving the quality of absorbency of diapers means not only that less materials are used, and less waste is generated, but also that they can be changed less often. However, this requires disseminating this information to parents who change their babies' diapers too often, even if the diapers are only lightly soiled and do not cause any discomfort to the baby (Wille, 2018).

In terms of treatment and recycle of used single-use baby diapers, there are several modern environmentally friendly options such as recycling, biodegradation, composting, anaerobic digestion, dark fermentation, and pyrolysis. However, currently, used diapers are mostly landfilled or incinerated. They are environmentally inefficient practice, but they are traditionally implemented because of their more relative “practicality”. Although they may still be widely used in the near future, landfilling and incineration will be gradually replaced by more modern technologies.

The eco-design concept also includes designing single-use baby diapers that can facilitate the disassembly and recycling of the product. However, it is of primary importance to introduce a separate collection system for diapers, to clearly define the methods of recycling, based on the cooperation of manufacturers with suppliers, retailers, recyclers, and municipalities. Furthermore, some individual companies offer the possibility of renting reusable diapers or the purchase of modular diapers, which contributes to increasing the efficiency of using diapers. Such solutions are becoming more and more popular.

Currently, used single-use baby diapers are recycled in some developed countries. Due to the fact that only a small part of the diaper can be recycled, and the recycled procedure involves a series of complicated steps (i.e., diaper collection, transportation, separation, conversion of selected elements into valuable products), which requires high technology, complex facilities, and high investments cost. This makes only some countries afford the introduction of such recycling technologies. For most countries, implementing recycling technologies is too expensive.

Moreover, to facilitate recycling, a separate collection of used diapers should be carried out in each household. However, many less developed countries (mainly in Asia, Africa and South America) have not introduced any waste segregation so far, while in developed countries, segregation is very extensive, that additional changes could cause people's dissatisfaction. In addition, new government regulations are needed to introduce a separate collection of used diapers.

Similar problems are associated with the introduction of other alternative technologies, such as biodegradation, composting, pyrolysis, anaerobic digestion, and dark fermentation. Additionally, some of these technologies are at the stage of laboratory or pilot tests. In these cases, many technological problems have not been yet identified and resolved. Therefore, it is difficult to determine the profitability of the processes.

Detailed advantages and disadvantages of the various treatment and recycling methods for used single-use baby diapers are presented in Table 2. In order to encourage countries to invest in new technologies, the products obtained from used diapers must be of good quality, and the costs of converting diapers into valuable products must be significantly lower than the market price of these products.

5. Conclusions

Diapers are used by every human being at some point in life. The goal of this paper was to understand and address a reduction of main environmental and health concerns of different types of diapers, with a special consideration of waste management strategies and user behaviour practices.

Three main types of baby diapers have been described in this paper: reusable cloth diapers; single-use diapers; biodegradable single-use diapers. Each category comes with technical characteristics and environmental concerns and challenges:

1. Cloth diapers allow reusing the product after use, thus reducing the amount of materials consumed and the production of waste, although this comes with logistic burdens and impacts associated with the need of cleaning used products.
2. Disposable diapers are very popular because of their practicality. However, they fully respond to the traditional “take-make-use-drop” linear economic system, generating pressures in the production and end-of-life stages.
3. Biodegradable single-use diapers have been conceived to tackle the environmental challenges of single-use diapers. However, exploiting this “biodegradability” advantage is possible only under specific conditions of waste collection and treatment, which are not in place in most territories (at least for the moment). Furthermore, the use of biomass feedstock for their production can come with other environmental concerns.

This points out that a fit-for-all solution may not exist to improve the sustainability of diapering, and that each type of diapers come with pros and cons, in terms of functional and environmental performance, that need to be handled considering specificities of a particular context of production and use. In this respect, two key aspects to consider are the knowledge of parents, as well as the technical strategies implemented by manufacturers and organisations responsible for the end of life waste management.

Used single-use baby diapers can be classified into the group of municipal solid waste. They contain both organic and inorganic fractions, which greatly complicates the possibility of their separations, and recycling. There are currently two main strategies for managing single-use diaper waste.

First of all, eco-design and circular business models can offer efficient ways to introduce improved products on the market. In general terms, eco-design is the process of designing and creating products, services, and processes, taking into account the good for the environment by promoting material efficiency, use of recycled and renewable materials, distribution and use optimisation, and enhanced disassemblability and recyclability.

These must be coupled with more “classical” end-of-pipe strategies dedicated to the waste management of used diaper products. In most countries, conventional methods (e.g., incineration and landfilling) are still used but these are not efficient from a sustainability perspective. Furthermore, in the case of landfilling, the decomposition of waste takes a very long time, which requires its continuous monitoring. Therefore, new green technological solutions are needed to minimize the environmental and health impacts of single-use diapers, including recycling, biodegradation, anaerobic digestion, pyrolysis, and steam sterilization.

However, it must be remarked that design strategies cannot be analysed separately from the waste management practices available in a territory, since their presence/absence can influence dramatically the environmental performance of a certain design (e.g., the advantage of having biodegradable materials is lost if the product is landfilled or incinerated).

Furthermore, user behaviour also plays a fundamental influence on the use and disposal of diapers and associated environmental impacts. There is a significant need to revise current clinical guidance and become more

Table 2
Advantages and disadvantages of diaper waste management option.

Method	Advantages	Disadvantages
Landfilling	• Diaper waste, upon reaching the landfill, is immediately covered with a landfill cover. • Typically, landfill can be operated for many years (from 50 to 100 years).	• It takes many years (up to 500 years) to completely degrade underground single-use diapers. • Toxic compounds found in used diapers (mainly pathogens) can cause diseases to landfill workers and residents of nearby housing estates. • It can cause many environmental problems i.e., soil erosion, air and water pollution, land degradation, and greenhouse effect. • High cost of collecting and transporting diaper waste. • Requires a large area of land. • After complete filling landfills needs to be closed and further monitoring the decomposition of waste is necessary.
Recycling	• Reduces CO_2 emissions to the atmosphere by 71%. • Used diaper can be separated and recycled for other purposes.	• A complicated and costly procedure consisting of collection, shredding, sterilization, and separation for isolating a valuable material is required. • Low quality of the recycled materials. • Only a small fraction of used diaper can be recycled. • Potential health problems for workers who are constantly exposed to pathogens.
Biodegradation	• Simple compounds i.e., CO_2, and H_2O are formed during biodegradation process. • Both cellulose and plastic parts of diapers can be biodegraded. • Environmentally friendly process. Secondary pollution is not generated.	• A complicated and costly procedure consisting of collection, shredding, sterilization before the biodegradation process is required. • Biodegradation processes are very long. They can even last more than 90 days.
Composting	• The obtained compost improves soil quality and structure. • Eco-friendly process.	• High cost of collecting, separation, and transporting diaper waste. • Only cellulose can be degraded. • Composting processes are very long. They can even last more than 90 days. • Pathogens and plastic parts of the diaper are not degraded. • Low quality of the compost. • Unpleasant smell and physical appearance. • Efficiency of composting process depends on the amount of organic waste. • Requires a large area of land.
Anaerobic digestion and dark fermentation	• High biogas production (hydrogen or methane) and high diapers degradation efficiency. • Low space requirement. • Pathogen reduction. • Valuable by-products are formed, i.e., compost and fertilizer	• High capital and investment cost. • Long start-up time. • Unpleasant smell. • Limited to large farms only. • Biogas treatment plant is required.
Incineration	• Diaper waste can be completely burnt out in a short time.	• High cost of collecting and transporting diaper waste.

Table 2 (*continued*)

Method	Advantages	Disadvantages
	• Pathogens in diapers are completely destroyed. • The heat generated by the combustion process can be recovered and used to heat water, and nearby buildings, or can be converted into electricity. • The ash generated in the combustion process can be converted into valuable products, i.e., building materials, cement, or ceramics.	• Ash produced during combustion can contain toxic substances. • The efficiency of the incinerator decreases quickly, which requires constant maintenance. • During waste combustion, may lead to the emission of toxic substances into the atmosphere, i.e., furans, dioxins, and other greenhouse gases. • High moisture content increases the time and requires more energy to evaporate and consequently causes a delay time of ignition and increases the operating cost.
Pyrolysis	• Fewer greenhouse gases are produced compared to the incineration process. • Process is fast, efficient, and significantly reduces the amount of diapers waste. • During diapers pyrolysis liquid stream that can be used as a fuel source for domestic or industrial boilers, or used as synthetic diesel, and solid residue that can be used as a soil additive, catalysts, or adsorbents are produced. • Pathogens are degraded in high temperature.	• The processes are now at the stage of laboratory research. There are still unresolved technological problems that prevent commercialization of the process. • A small amount of toxic gases may be emitted into the atmosphere - air purification installation is necessary. • Requires high operational and investment costs. • The obtained ashes are in low quality and can contain high concentration of heavy metal.

sensitive to the needs of caregivers taking economic, health and environmental issues into account. Professional trainings and education could provide clear updated guidelines for midwives, parents and other maternity service providers. In particular, the following information are important: 1. Type and composition of diapers and effects on the baby (which is the healthiest for the skin); 2. Functional and environmental performance of diapers; 3. Optimal frequency of change and environmental pressures associated with over-consumption of diapers; 4. Best handling and disposal/recycling of used diapers.

Now that more and more countries are recognizing the problem of the depletion of non-renewable resources as well as the negative impact of waste on the environment, this paper can assist entities in those countries to define appropriate research, innovation and policy activities, also coupled with financial investments in modern diaper recycling and treatment technologies.

In the near future, an increase in research intensity on new technologies and improvement of existing technologies can be expected for obtaining valuable raw materials from used diapers. In addition, more and more countries are recognizing the problem of the depletion of non-renewable resources as well as the negative impact of waste on the environment, which is likely to result in increased financial investment in modern diaper recycling and treatment technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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