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LIFE CYCLE AND END-OF-LIFE WASTE MANAGEMENT OF DISPOSABLE DIAPERS: A MINI-REVIEW

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ABSTRACT
Waste management is a crucial priority issue for all countries in this environmentally conscious era. Proper waste management of disposable diapers is one of the issues at the forefront. The unprecedented growth of the world urban population has left many cities grappling with disposable diapers clogging landfills. It is a problematic issue that if not mitigated could overburden existing waste management systems. This mini-review article aims to critically review relevant life cycle assessment studies (LCA) on single-use disposable diapers and the environmental impact incurred at each stage of its life cycle. Different technical and non-technical disposable diaper waste management approaches have been explored in literature, but studies directed towards pyrolysis conversion of disposable diapers post-consumer waste are notably very scarce. The review further examines the potential of pyrolysis as an end-of-life waste management option for disposable diapers. Finally, this study highlights gaps in the literature and recommends the scope for future research.

1. INTRODUCTION

Solid waste management is a significant challenge in a global environment of technological and economic exchange (Achankeng et al., 2003; Hoornweg et al., 2012; Kaza et al., 2018). Social modernisation and economic inclusivity have catalysed an unprecedented increase in urban areas population density, resulting in a billion expansion of the world urban population from 1960 to 2010 (Food and Agriculture Organization, 2013; Scarlat et al., 2015). Therefore, creating an increase in solid waste output from 110 million tons in 1990 to 1.1 billion tons by the year 2000 (Hoorney et al., 2013; Scarlat et al., 2015). The world urban population is expected to reach 4.5 billion by 2025 and 6.4 billion by 2050 (Food and Agriculture Organization, 2013; Scarlat et al., 2017). A previous report from the World Bank (The World Bank, 2012) indicated that the global Municipal Solid Waste (MSW) contributes 1.3 billion tons per year and is projected to reach 2.5 billion tons by 2025 (Scarlat et al., 2017). The rapid increase of MSW has overburdened current waste management systems, particularly cities in developing countries which find it significantly difficult to manage the waste influx due to poor infrastructure (Achankeng et al., 2003; Scarlat et al., 2017, Lavagnolo, Grossule et al., 2018). Indiscriminate dumping and poor waste collection, pose adverse environmental and health-related problems (Achankeng et al., 2003; Scarlat et al., 2017; Godfrey et al., 2017). In recent decades, absorbent hygiene products (AHP's) have been accounted as one of the most rapid growing and problematic waste issues (Kashayap et al., 2016; Arena et al., 2016; Bose et al., 2019; Khoo et al., 2019; Perez et al., 2020).

AHP is a category name for diapers, feminine sanitary and adult incontinence pads. AHP post-consumer waste is estimated to represent a significant proportion of the total Municipal Solid Waste (MSW) and typically considered as the "unrecyclable" MSW (Kashayap et al., 2016; Perez et al., 2020). The most common waste management method of AHP waste is via landfilling and incineration resulting in loss of material resources, as well as high economic and environmental costs (Arena et al., 2016; Khanyile et al., 2020). Production of disposable diaper units in the European Union (EU) and Turkey increased by 81% between the year 1997 to 2009 (Cordella et al., 2015). It is projected that the production volume would likely increase in the EU, creating additional pressure on the environment and existing waste management systems (Cordella et al., 2015). Disposable diapers account for approximately 2-7% of MSW in Europe and landfilling remains the most common waste

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disposal method in European countries, the United States of America (USA) and virtually all developing countries (EDANA Sustainability Report, 2005; Arena et al., 2016). Limited land and environmental pressure make landfilling a less viable waste management technique (Godfrey et al., 2017). Incineration of MSW in waste-to-energy (WTE) plants is one of the main waste management options adopted in developing countries (Quina et al., 2011).

The major drawback of this waste management technique is the emission of greenhouse gases and other air pollutants such as dioxins and furans, which have a detrimental impact on the environment and human life (Quina et al., 2011).

LCA studies provide a framework for which the environmental performance of disposable diapers can be measured. The scarcity on the availability of research studies directed towards diapers was alluded to by Colon et al, (2011). A vast majority of life cycle assessment reports for disposable diapers were prepared by consultancies/ agencies and published in open literature (Fava et al., 1990; Nylander, 1991; Lehrburger et al., 1991; Sandgren, 1993; Sauer et al. 1994; Vizcarra et al., 1994; UK Environment Agency, 2005; 2008; EDANA Sustainability Reports, 2005; 2007 and 2011). An LCA study by Cordella et al., (2015) reported on material and design innovations that could substantially reduce disposable diapers environmental impact. Careful selection and use of materials in the design stage, aimed at designing lighter products and the introduction of super absorbent polymers (SAP), can significantly improve the environmental profile of disposable diaper products and decrease the life cycle impact at the end-of-life stage (Weisbrod and Van Hoof, 2012; Cordella et al., 2015).

The environmental impact of disposable diapers encompasses the entire life cycle, which includes the different phases such as raw material extraction, manufacturing, use and disposal at the end-of-life phase. Therefore, it's of pivotal importance to give a detailed account how each life cycle phase contributes to the entire environmental impact. This study aims to provide a concise literature review of LCA studies directed towards studying disposable diapers environmental impact. This paper focusses on reviewing literature in 4 key areas: (1) The overall life cycle assessment and evaluation of the environmental contribution of disposable diapers (2), End-of-life waste management options (3), The challenges facing the recovery of post-consumer disposable diapers in their End-of-Life phase (4) Identifying gaps in literature and recommending the scope for future work.

2. REVIEW METHODOLOGY

A systematic literature search for credible, peer reviewed academic articles was performed and identified articles were analysed in four consecutive phases (shown in Table 1). Articles relevant to each topic were searched for in main search engines and databases namely, Google Scholar, Science Direct, EBSCOhost, Scopus and SciFinder. The search criteria included the use of the following words in the databases: "diapers", "disposable diaper", "waste management", "materials", "life cycle assessment", "LCA", "environmental performance", "end-of-life management" and "pyrolysis". Journals publishing relevant topics were targeted including the Journal of Cleaner Production, Resources, Sustainable Development, Environmental Agency, International Waste Working Group, The International Journal of Life Cycle Assessment, Critical Reviews in Environmental Science and Technology, Waste Management and Research and Detritus Journal amongst others. Each article was categorized and reviewed in relevant sections. Some articles had overlapping information and were included in more than one section. The reference list from articles was screened to identify other journals. A total of 70 sources were reviewed including scientific Journal articles, Books, Peer-reviewed literature, and reports (Refer to Table S2 in the Supplementary material).

TABLE 1: Literature analysis approach.

Phase	How it was used
Phase 1: Database Search Search for academic journals and conference papers in academic search engines and databases.	**Key search words include:** "diapers", "disposable diapers", "waste management", "materials", "lifecycle assessment", "LCA", "Environmental performance", "end-of-life management" and "pyrolysis".
Phase 2: Initial Screening process Screening conditions were optimized to focus results obtained from the searching process.	**Criteria used to narrow search** • Journals publishing relevant topics were targeted. • Articles should have at least one of the keywords reflected on the abstract. • To collate a comprehensive review, articles published from 1980 to date were reviewed. • Reference list from articles was screened to identify other journals
Phase 3: Clustering process Articles were tagged with keywords and clustered based on major topics/thematic areas	**Major topics/Thematic areas** • Disposable diapers lifecycle Assessment (LCA). • Municipal Waste Management • Circular economy. • Pyrolysis conversion of disposable diapers. • Pyrolysis conversion of lignocellulosic material. • Pyrolysis conversion of plastics
Phase 4: Identification of contributions and research Gap	Articles identified were analyzed using constructs mentioned above, to create a body of literature.

3. RESULTS AND DISCUSSION

3.1 Life cycle assessment of disposal diapers

This section provides a general view of the LCA of disposable diapers and gives a synopsis of the reported literature findings. These findings would be used to evaluate the environmental impact induced by disposable diaper materials at each phase of its life cycle, as defined in the ISO 14040-44 standards (International Organization for Standardization; 2006 a, b). In this section, the main materials such as fluff pulp and synthetics (SAP, plastics, adhesives, and others) would be analysed to ascertain its contribution to the general life cycle of disposable diapers as illustrated in Figure 1.

The life cycle of disposable and reusable diapers has gained interest in the scientific community and has been a subject of LCA studies in recent years (Fava et al., 1990;

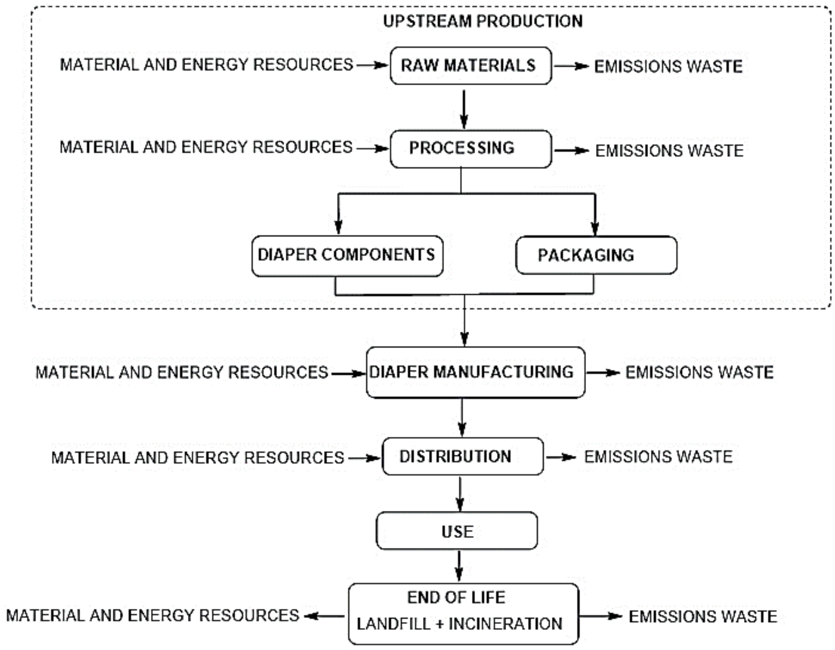

FIGURE 1: Flow diagram representing the life cycle of a generic disposable diaper (Adapted from Cordella et al., 2015).

Vizcarra et al., 1994; Hakala et al., 1997; UK Environmental Agency, 2005; 2008; O'Brien et al., 2009; Cordella et al., 2015; Perez et al., 2020). A study by Ng et al., (2013) gives a detailed account of LCA studies on disposable and reusable diaper systems. This study gives comprehensive conclusions and a comparative analysis of assumptions, results and identifying gaps in literature for future research. The findings indicated that the generation of solid waste emanating from the use of disposable diapers, had a major contribution to the high environmental impacts. The washing of reusable cloth diapers was found to be a significant contributor to the main impacts. Studies reviewed by Ng et al., (2013) came to different conclusions, when evaluating which diaper system was the major contributor to the overall impacts. Studies by Lehrburger et al. (1991) and O'Brien et al. (2009) favours disposable diapers in terms of lower environmental impacts. Other studies such as Little, 1990 and Sauer et al., 1994, recommended reusable cloth diapers. However, based on the information reviewed from some studies, it could be inferred that neither reusable cloth nor disposable diaper systems were superior in terms of environmental impact contributions.

Environmental impacts are largely dependent on the regional conditions such as power generation and waste management infrastructure. Reviewed LCA studies were only limited to developed and industrialized nations, such as the United States of America (USA), Canada, the United Kingdom (UK) and Australia. Therefore, there is a substantial gap, particularly in emergent nations where the regional infrastructure may significantly influence the outcome.

An overview of the reviewed LCA studies gives a detailed account of various studies that have conducted investigations on the life cycle impacts of different types of baby diapers (refer to Table S2 in the Supplementary material). These studies were conducted within specific boundaries and scope, various functional units were assumed and based on such, major conclusions were reported. There is a notable research gap in reviewed LCA studies, only Cordella et al., (2015) accounted for the lifecycle impacts at each LCA phase of disposable diapers (manufacturing, distribution, and product disposal). This information would be critical in developing a circumventive approach to reducing potential impacts at each LCA phase, such as diaper design innovations and optimized supply chain management.

This study will follow the LCA process (ISO, 2006a), sub-divided into four sub-systems (Cordella et al., 2015):

- Production and supply of raw materials and packaging
- Manufacturing of product
- Distribution
- Product disposal (End-of-life)

3.2 The material composition of disposable diapers

Disposable diapers available on the market are offered in a variety of designs and consumer features but the basic design consists of four main components as shown in Figure 2 (Kosemund et al., 2009; Cordella et al., 2015):

- Inner Polypropylene Top sheet
- Acquisition system
- Absorbent core
- Outer Polyethylene Film (waterproof outer layer)
- Fastening System

The top sheet layer is a direct skin contact material, typically composed of polypropylene (PP) nonwovens with a soft smooth and highly permeable surface. Its primary function is to transfer liquid excreta for further absorption while remaining relatively dry and soft (Kosemund et al., 2009; Kakonke et al., 2019). The acquisition and distribution layer (ADL) is an indirect skin contact material composed

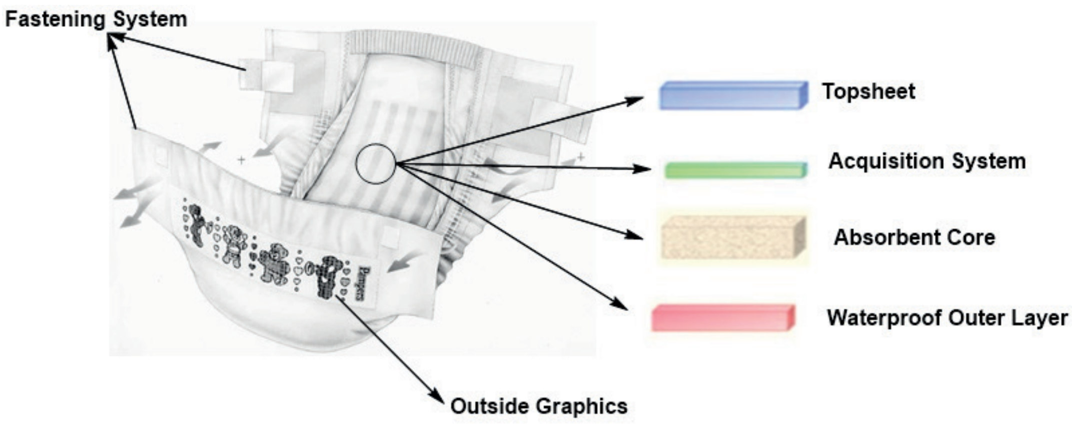

FIGURE 2: Typical disposable diaper anatomy (source: Kosemund et al., 2009).

of a modified cellulose patch and a polymer-based layer (SAP) sandwiched between the polypropylene top sheet and the absorbent core, limiting liquid skin contact (Kosemund et al., 2009). SAPs are synthetic materials capable of absorbing and retaining liquids up to 1000 times relative to its mass (McCormack et al., 2011). Sodium Polyacrylate is the most common type of SAP used in disposable hygiene products (McCormack et al., 2011). The absorbent core is the innermost layer of the diaper and its typically composed of a blend of polyacrylate granules (SAP) and fluff cellulose or polypropylene non-woven layer (Kosemund et al., 2009; Dey et al., 2016; Counts et al., 2017). The primary purpose of the cellulose layer is to facilitate the absorption and transfer of the liquids to the polyacrylate superabsorber. The absorbed liquid is then locked in its polymetric structure and kept away from the skin (Kosemund et al., 2009; Counts et al., 2014). The bottom sheet of the disposable diaper is a water-resistant outer layer typically composed of low-density polyethylene (LDPE) film, laminated with a soft textured cloth-like polypropylene layer (Kosemund et al., 2009). Its primary function is to prevent the leakage of liquids from the disposable diaper to the outer clothing. Micropores are commonly present on the surface of the bottom sheet layer to allow for skin contact materials to dry therefore preventing the occurrence of irritations and infections (Counts et al., 2014). Additional features primarily designed for a good diaper fit and branding include fastening systems (tapes and elastics, inks, and dyes).

The typical composition of diapers has been described in Table 2 (EDANA Sustainability Reports, 2011). Disposable diaper components would be discussed in the following sub-sections.

3.2.1 Fluff pulp

Disposable diapers are composed of about 37 % fluff pulp, which is commonly made from bleached chemical softwood or loblolly pine (EDANA Sustainability Reports, 2011). In the 1980's disposable diaper producers commercialized the use of fluff pulp in their products due to its low cost and high absorbency (EDANA Sustainability Reports, 2011). Product development such as the introduction of SAPs, has significantly improved diaper performance and environmental profile of the product (Weisbrod and Van Hoof, 2012). The amount of SAP in baby disposable diapers increased from 1 g to 13 g between 1987 and 2005, considerably reducing the demand for pulp as an absorbent (EDANA Sustainability Reports, 2007). Environmental problems cited in the production of the pulp include greenhouse gas (GHG) emissions and deforestation (O'Brien et al., 2009). Pulp production also releases toxic pollutants at various process stages, such as solid sludge generated from the treatment of wastewater plants and toxic air emissions (Ince et al., 2011).

3.2.2 Superabsorbent polymer (SAP)

The growth in the use of disposables is primarily driven by the introduction of several improvements in the design of modern diapers. The introduction of SAP (polyacrylates) in the absorbent core is the most significant design improvement. Compared to conventional cellulose materials, polyacrylates retain liquids in the absorbent core, keeping the skin dry even under pressure, thus improving the comfort and skin health (Kosemund et al., 2009; Adam et al., 2008).

SAP is produced via the polymerization of acrylic acid, Table 3 represents the production inputs required to make

TABLE 2: Percentage composition of disposable diapers (2005-2019).

	EDNA, 2005	EDNA, 2007	Cordella et al., 2015	Mendoza et al., 2019
Fluff Pulp	43%	35%	36.67%	31.91%
SAP	27%	33%	30.83%	38.19%
PP	15%	17%	16.11%	18.84%
LDPE	7%	6%	2.78%	4.77%
Tapes, Elastics, and Adhesives	8%	9%	13.61%	6.29%

TABLE 3: Material energy resources required to produce 1 kg of SAP (Adapted from Gontia and Janssen, 2016).

Input	Amount
Chemical Constituents	1.28 kg
Water	1.70 kg
Wastewater	1.90 L
Electricity	2187 kWh

1 kg of Sodium acrylate. The average diaper weight decreased by 14% between 1987-1995 and by 27% between the 2005 and 2011 (Cordella et al., 2015). The percentage composition (Table 2) of SAP increased drastically from 1% in 1987 to 38% by 2019 (Cordella et al., 2015; Mendoza et al.,2019). This is mainly due to the incremental substitution of fluff pulp, for the purposes of reducing the overall diaper weight, material and energy resource input, improved functionality, and environmental performance.

Studies have shown that SAPs are non-toxic to humans for their intended use (Martin, 1996; Danhof 1982). However, there is limited information on its effect(s) on the environment at its end-of-life phase. Sodium Polyacrylate is biodegradable, and it is decomposed into urea, carbon dioxide, water and sodium (Wilske et al., 2014).

3.2.3 Plastic polymers

Plastics are common materials used in the manufacture of disposable diapers, particularly synthetic polymers such as polypropylene (PP) and low-density polyethylene (LDPE). Plastics have become the most indispensable materials in our contemporary world and are presently non-biodegradable (Sharyddin et al., 2016). Over the past two decades, plastic world markets have grown exponentially due to the cost-effective plastic materials compared to other competitive materials (Young et al., 1994; Mckinon et al., 2018). The global plastic demand increased from 295 million tons in 2008 to 311 million tons in 2014 (Association of Plastics Manufacturers, 2015) and only 9% of the global plastic waste is recycled (Geyer et al., 2017; Van Rensburg et al., 2020). The heterogeneity and complexity of disposable diapers make it difficult to separate and recover additional features such as tapes, elastics and adhesives at the end-of-life phase. There are several environmental concerns associated with the disposal of disposable diapers by conventional methods, such as limited land for landfilling, contamination of aquatic ecosystems and GHG emissions amongst others (Espinosa et al., 2014; Colón et al., 2013).

3.3 Environmental impact

There are several environmental impacts associated with disposable diaper production and disposal. The life cycle stages of disposable diapers span from the extraction of raw materials, processing, manufacturing, assembly, packaging, transport, and disposal (UK Environment Agency, 2005). Weisbord and Van Hoof (2012) reported that sourcing and production of diaper materials are the major contributor to environmental indicators, accounting for 84% of non-renewable energy uses and 64% of global warming potential (GWP).

Table 4 shows the manufacturing waste output per ton of disposable diapers produced in the United Kingdom (UK). It can be deduced that only 55.22% of the waste generated per ton is recycled and the rest (44.78%) is landfilled. Components with high composition percentages contributed the most waste output. This is indicative that changing the material composition or decreasing diaper weight would have a significant impact on reducing the manufacturing waste generated. Technological advancement and the adoption of environmentally friendly materials in the manufacturing of disposable diapers, may present a different outlook on present day disposable diaper production waste outputs (Weisbrod and Van Hoof, 2012; Cordella et al., 2015). Work by Ichiura et al. (2020) alludes to this assertation, which reported a method of recycling pulp and SAP via Ozone oxidation, at the end-of-life phase of disposable diapers. The end-of-life phase is a substantial source of methane emissions and dominates all impact indicators (Cordella et al. 2017). Manufacturing of disposable diapers produces trace amounts of Dioxin, an extremely toxic by-product emanating from the paper-bleaching process. Dioxin is carcinogenic and is considered as one of the most cancer-linked chemicals (Shin and Ahu, 2007).

Cordella et al. (2015) conducted a historical analysis to approximate the change in potential environmental impacts due to the production and consumption of an average diaper unit from 1987 to 2011. From 1987 to 1995 the overall impacts decreased by a magnitude of 16-36%, this improvement may be attributed to the increased use of SAP in place of fluff pulp, reducing the average diaper weight by 14%. From 1995 to 2005 the magnitude of impacts decreased by a further 7-16% (Cordella et al., 2015). This improvement was a result of a greater use of SAP, reducing the average diaper unit weight by 27% (Cordella et al., 2015). In more recent years (2005-2011), the over-

TABLE 4: Manufacturing Waste per ton of disposable diapers produced.

Materials	Quantity (kg)	Landfill (kg)	Recycling (kg)
Fluff pulp waste	18.0	13.5	4.5
SAP waste	22.3	16.7	5.6
PP waste	15.1	3.8	11.3
LDPE waste	21.1	5.3	15.8
Tapes, Elastics and Adhesive waste	4.6	4.6	0.0
Associated waste packaging	16.92	0	16.92
Other waste	1.9	0.8	1.1

Source: UK Environment Agency, 2005; 2008

TABLE 5: Comparison of Global warming potential and primary energy demand indicators reported in literature.

	GWP (kg CO_2 eq./1000 diapers)		PED (GJ/1000 diapers)	
	Cordella et al., 2015	Mendoza et al., 2019	Cordella et al., 2015	Mendoza et al., 2019
Raw Materials	81.9	68.9	4.13	3.01
Manufacture	7.8	1.5	0.13	0.03
Transport	2.6	6.2	0.04	0.09
Waste Management	37.7	12.1	0	0.12
Total	130.0	88.8	4.30	3.02

Source: Mendoza et al. (2019) and Cordella et al. (2015)

all impacts decreased by 7-51% and the average diaper unit weight decreased by 12 % (Cordella et al., 2015). This is mainly due to disposal diaper design innovations, in which a reduction of all materials used in the product was achieved.

Studies by Cordella et al. (2015) and Mendoza et al., (2019) investigated the effect of diaper design innovation on the overall impacts from "cradle to grave". Only the global warming potential (GWP) and primary energy demand (PED) indicators were considered as comparative examples (Table 5). Cordella et al. (2015) and Mendoza et al. (2019) used the same impact assessment method (CML) and software (Gabi).

The values reported by Mendoza et al. (2019) were observed to be 30-40% lower compared to those reported by Cordella et al. (2015). The discrepancy is due to the differing diaper weight considered in each study (36.0 and 33.0g/diaper for the Cordella et al. 2015 and Mendoza et al. 2019 respectively). Mendoza et al. (2019) concluded that diaper design innovations lead to a 23% reduction in material input, 10% lower energy consumption, 50% decrease in eutrophication potential (EP), GWP decreased by 10% and PED was reduced by 25%. These findings suggest that a slight improvement in resource efficiency results in significant environmental performance gains.

3.4 Waste management

Effective and sustainable waste management for modern society hinges on four key considerations: health and safety for human life, environmental effectiveness, economic viability and social acceptance (EDANA Sustainability Reports, 2007-2008). Development of sustainable waste management systems involves the adoption of an integrated approach of efficient waste collection, sorting and processing for energy recovery before disposing of residuals in landfill sites (EDANA Sustainability Reports, 2007 – 2008).

Absorbent hygiene products (AHP's) waste is the 4th largest recyclable contributor by volume to landfill space, therefore alternative methods of waste management have been explored to mitigate this issue (Gerina et al., 2016). The next subsections will speak to different technical and non-technical approaches that are currently used in management of AHP's post-consumer waste.

3.4.1 Biological treatment

Biological treatment is a technique used to treat the organic fraction of solid waste. Composting and anaerobic digestion are treatment methods used for the pre-treatment of solid waste to reduce the volume and stabilize it for landfilling. The biogas produced can be harvested as a renewable energy source (EDANA Sustainability Reports, 2007-2008). Modern disposable diaper manufacturing companies are introducing biodegradable and compostable materials to improve the environmental performance of the product (Gerina et al., 2016). Several studies have explored the potential of using bio-based materials (Clancy et al., 2013; Mirabella et al 2013; Gonlia and Jansseen, 2016) and the end-of-life composting of disposable diapers has been reported in the literature (Colon et al., 2010; Espinosa-Valdemar et al., 2014).

3.4.2 Incineration

Incineration is a thermal treatment of the combustible fraction of MSW to either reduce its volume for landfilling or for energy recovery purposes (EDANA Sustainability Reports, 2007-2008). Energy is a very critical issue in developing countries, where a significant proportion of the population does not have access to energy and often rely on traditional biomass (Scarlat et al., 2015). Europe currently has a total incineration capacity of 93 million tons per year of MSW, of which 161 are electricity only and 94 are heat only plants (Scarlet et al., 2019). Developing countries have a significant amount of waste-to-energy potential but often lack the necessary infrastructure and fiscal support, compared to their first world counterparts.

Relative to the incineration of average MSW, disposable diaper waste form less than 10% ash content compared to the 25% produced by MSW (EDANA Sustainability Reports, 2007-2008). Disposable diapers are made from high-quality materials and therefore produces higher quality ash with low or undetectable amounts of heavy metals (EDANA Sustainability Reports, 2007-2008). Modern incinerators designed for energy recovery, particularly in health care facilities can use the energy derived from disposable diapers for heating systems, therefore reducing energy and waste disposal costs (EDANA Sustainability Reports, 2007-2008).

3.4.3 Landfilling

Landfilling is currently the most widely used waste management method, due to its lower cost of operation and maintenance compared to other energy-intensive methods such as incineration and MBT (Peng, et al., 2017). Approximately 4% of all waste generated in the European Union is landfilled and up to 90% in developing countries (EDANA Sustainability Reports, 2007-2008; Godfrey et al., 2017). Landfills can cause serious environmental problems such as uncontrolled production and emission of GHG, a major contributor to global warming. Combustible gases produced from landfilled waste may cause fires and explosions, posing a danger to human and animal life (Komilis et al., 1999). The prevailing issue with landfilling is leachate which contains hazardous inorganic and organic pollutants, which contaminates soils and aquifers (Komilis et al., 1999). Biological treatment of leachate is expensive due to the excessive presence of refractory compounds (Youcal, 2019).

3.4.4 Recycling

Material recycling is a process of converting waste material into new materials and products (Villalba et al., 2002). Recycling of disposable diapers ensures environmental sustainability by substituting raw material inputs and reducing the cost of waste output on the economic system.

Itsubo et al. (2020) reported the recycling of pulp and SAP from used disposable diapers into their virgin state. The recycling method developed by Itsubo et al. (2020), demonstrated a reduction in GHG emissions from landfills and incineration processes by 47% and 39% respectively. However, Itsubo et al. (2020), could not ascertain the economic rationality of this method as no comparative study on costs had been conducted.

The Canadian company Knowaste Ltd developed an AHP waste treatment technology, capable of separating disposable diapers into plastics and fibres (Gerina et al., 2016). The plastics are granulated and pelletized to be used in new plastic products or as an ingredient in composite materials (Gerina et al., 2016). The fibres can be recycled and used as a component in various processes such as a tarmac additive, brick manufacturing and insulation materials. The main disadvantage with Knowaste Ltd treatment technology is the high cost associated with their very complicated sterilization process (Gerina et al., 2016). Disposable baby diaper post-consumer waste is likely to increase in the foreseeable future, waste management options such as pyrolysis would allow for chemical and energy recovery with minimum GHG emissions at the end-of-life stage (Lam et al., 2019; Perez et al., 2020).

3.4.5 Pyrolysis

Pyrolysis is an endothermic decomposition of feed materials in the absence of reactive gases such as air or oxygen. Pyrolysis of feed stock results in the formation of gaseous fraction composed of condensable and non-condensable gases (Nkosi et al., 2014). The solid fraction (char) is composed of mainly carbon, metals, and other inert materials (Nkosi et al., 2014). The condensable variables are cooled in the condenser to form pyrolysis oil fraction, composed of organics and non-condensable volatiles are collected as pyrolysis gases (Hirvonen et al., 2017).

The pyrolysis conversion of plastics has been extensively studied under various conditions (Sharuddin et al., 2016; Kalargaris et al., 2017; Al-Salem et al., 2017; Mangesh et al., 2020). In the 1980s, plastic pyrolysis experienced a surge in research efforts, mainly because of expanding global markets, resulting in the accumulation of plastic waste (Scott et al., 1990). The integration of industrial pyrolysis systems into laboratory applications directed research attention towards the development of efficient waste management technology. The key research areas of plastic pyrolysis are the recovery of valuable chemicals such as benzene, toluene, xylene (BTX aromatics), synthetic natural gas and conversion of plastic pyrolysis oil into fuels (Jung et al., 2010; Sharuddin et al., 2016). Analytical pyrolysis is utilized in the pulp and paper industry to study the chemistry of wood and pulps (Sitholé, 2006). Buzanowski et al. (1994) investigated the presence of sodium polyacrylate in environmental samples and proposed a pyrolysis mechanism for the polymer as well as the identification of primary pyrolytic products (Buzanowski et al., 1994).

Unlike plastics the literature on the pyrolysis of disposable diapers is notably very scarce. Gerina et al, (2016) reported on the pyrolysis conversion of disposable diaper waste into coal and gas with a calorific value of 15950-18080 $kJ.kg^{-1}$ and 34400 $kJ.kg^{-1}$ respectively. Lam et al., (2019) were the first to report on the pyrolysis conversion of waste disposable diapers into value-added products via microwave pyrolysis. The primary pyrolysis products in this study were fatty acids (e.g. Isopropyl palmitate) which has potential application as a chemical additive in personal care and cosmetic formulation (Lam et al., 2019). The liquid oil contained aliphatic hydrocarbons which could be used as fuel additives and the carbon-rich ash has potential use as agricultural soil amendments (Lam et al., 2019). Khanyile et al., (2020) characterized the interior and exterior disposable baby diaper fractions by pyrolysis-gas chromatography-mass spectrometry, proximate analysis, thermogravimetric and ultimate analysis. This study revealed that the exterior disposable baby diaper fraction had less volatile content compared to the interior fraction (Khanyile et al., 2020). The high volatile matter content of disposable baby diapers makes it a favourable pyrolysis feedstock, to recover value added products (Khanyile et al., 2020).

4. DIRECTION FOR FUTURE RESEARCH STUDIES

- There is a significant disparity between end-of-life options for developed and developing nations such as the lack of infrastructure required for energy/chemical value recovery waste management systems. A vast majority of LCA studies were conducted in Europe, the United States of America and a few from Australia, Canada and Japan (see Table S2 in the supplementary material). None of the LCA studies reviewed reported on African, Asian, or South American countries, where the disposal issues are uniquely different from first world countries. It would be erroneous to surmise that conclusions from the reviewed studies are relevant to developing countries. There is a substantial research gap in life cycle assessment studies in developing countries. Therefore, more LCA studies need to be conducted in these regions, to get a global perspective.
- There is a limited availability of literature on the utiliza-

tion of thermochemical methods, as a viable end-of-life option for disposable diapers. Pyrolysis conversion of disposable diapers into energy and value-added chemicals has great potential in reducing manufacturing and end-of-life environmental impact. Therefore, more studies should be directed towards investigating the pyrolysis conversion of manufacturing waste and disposable diapers at the end-of-life phase.

5. CONCLUSIONS

Life cycle assessments of single-use disposable diapers provides critical information needed for mitigating environmental impacts because the life span of these product is relatively short, and the environmental impacts can be escalated quickly. Most reviewed studies conclude that the production phase of disposable diapers has the greatest contribution on the environmental impact. This study provided a critical review of various life cycle studies conducted on disposable diapers and there is a significant research gap on the pyrolysis conversion of disposable diaper post-consumer waste into valuable products. This review further recommended that more research efforts into pyrolysis conversion of disposable diapers at the end-of-life phase, is required. This would shift the life cycle narrative of disposable diaper products from “cradle-to-grave” to “cradle-to-cradle”.

DECLARATION OF CONFLICTING INTERESTS

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APPENDIX

TABLE S1: List of reviewed studies in this article.

Author/s	Year	Journal
Achankeng et al.	2003	Report
Aumonier et al.	2005	Environment agency
Adam et al.	2008	Pediatric dermatology
Association of Plastics Manufacturers	2015	Report
Arena et al.	2016	Journal of Cleaner Production
Al-Salem et al.	2017	Journal of Environmental Management
Buzanowski et al.	1994	Journal of Chromatography
Bose et al.	2019	2019 IEEE International Conference on Sustainable Energy Technologies and Systems (ICSETS)
Colón et al.	2013	Waste management
Clancy et al.	2013	Journal of cleaner production
Cordella et al.	2015	Journal of cleaner production
Counts et al.	2017	Clinical Paediatrics
Danhof et al.	1982	Human Pharmacology and Drug Therapy
Dey et al.	2016	Int J Dermatology
EDANA Sustainability Report, 2005	2005	Report
EDANA Sustainability Reports, 2007- 2008	2008	Report
EDANA Sustainability Reports, 2011	2011	Report
Espinosa et al., 2014; Colón et al.	2013	Resources, Conservation and recycling
Fava et al.	1990	Report
Food and Agriculture ONU	2013	Report
Gerina et al.	2016	Engineering for Rural Development
Godfrey et al.	2017	Resources
Geyer et al.	2017	Science Advances
Hakala et al.	1997	Report
Hoornway et al.	2013	Nature News
Hirvonen,	2017	Thesis
Hoornweg et al.	2012	World Bank Publication
Islam et al.	2010	International Journal of Environmental Science and Development
Ince et al.	2011	Environmental Management in Practice
Itsubo et al.	2020	Resources
Ichiura et al.	2020	Journal of Cleaner Production
Jung et al.	2010	Fuel Processing Technology
Komilis et al.	1999	Waste management & research
Kosemund et al.	2009	Regulatory
Kashyap et al.	2016	Asia-Pacific Conference on Biotechnology for Waste Conversion
Kalargaris et al.	2017	Fuel Processing Technology
Kaza et al.	2018	World Bank Publications
Kakonke et al.	2019	International Journal of Chemical Sciences
Khoo et al.	2019	Process Safety and Environmental Protection
Lehrburger et al.	1991	Environmental impacts and lifecycle analysis
Lam et al.	2019	Chemosphere
Little	1990	Report to Procter & Gamble
Martin	1996	Science of the Total Environment
McCormack et al.	2011	Journal of occupational and environmental hygiene

Mangesh et al.	2020	Journal of Cleaner Production
Morakanyane et al.	2017	Bled eConference
Mckinon et al.	2018	Book
Mendoza et al.	2019	Journal of Cleaner production
Nylander	1991	Report
Nkosi et al	2014	World Congress on Engineering
Ng et al.	2013	Environmental Science & Technology
Perez et al.	2020	Waste Management & Research
Quina et al.	2011	Book
Sandgren.	1993	Det Norske Veritas Industri Norge
Sauer et al.	1994	Environmental Toxicology and Chemistry
Sitholé,	2006	Encyclopedia of Analytical Chemistry
Shin and Ahu,	2007	Textile Research Journal
Scott et al.	2015	Renewable and sustainable Energy Review
Sharuddin et al.	2016	Energy conversion and management
Scarlat et al.	2019	Waste and Biomass Valorization
UK Environment Agency, 2005	2005	Report
UK Environment Agency, 2008	2008	Report
Vizcarra et al.	1994	Environmental Toxicology and Chemistry: An International Journal
Villalba et al.	2002	Resources, Conservation and Recycling
Van Rensburg et al.	2020	Waste Management & Research
Weisbrod et al.	2012	The International Journal of Life Cycle Assessment
Wilske et al.	2014	Environmental Science and Pollution Research
Young et al.	1994	Sunnier economic climate brightens the worldwide outlook for plastics
Youcal,	2018	Butterworth-Heinemann

TABLE S2: Overview of Reviewed LCA Studies on Disposable Diapers.

Study	Country	Scope and purpose	Types of diaper studied	Functional Unit	Assumptions and boundaries	Major Conclusions
Procter and Gamble Study (Little, 1990)	USA	Comparing the entire lifecycle of disposable diapers versus reusable diapers from a health, environmental and economic perspective	Disposable and reusable diapers.	Weekly average diaper requirement for a single child	1.The daily number of diaper changes is the same for disposable and reusable diapers 2. 90% of all reusables are laundered at home and 10% by diaper service.	1.In terms of environmental impacts, neither diaper system was found to be more superior then the other. 2.The resource and environmental impact contributions occur through the entire lifecycle of disposable diapers, whereas for reusables, its mainly during the useful/consumption phase.
NADS Study (Lehrburger et al., 1991)	USA	Comparative study of resource consumption and waste output to the atmosphere for disposable and reusable diaper systems	Single-use disposable and cotton reusable diapers.	1000 diaper equivalent use	1.Capital equipment during the transformation process, energy required for space heating and cooling, impact of direct use of fossil fuels and impacts of detergent and pesticides during manufacturing. 2. 1 diaper per change and 1.2 diapers changes were assumed for single use and reusable diaper respectively.	1. Single use diapers were determined to have a greater over-all environmental impact compared to reusables, considering the entire diaper production and the usage phase. 2. Greater energy and water consumption was observed for single use diapers 3. Single diapers produce more post-consumer solid waste compared to reusable diapers. 4. Diaper laundry services create lower impacts than home laundering.

Franklin Associates Study (Franklin Associates, 1992; Sauer et al., 1994)	USA	Comparative analysis of energy consumption, water usage and environmental emissions (such as atmospheric, wastewater particulates and solid waste), for single use and cloth diaper systems (cradle-to-grave analysis).	Single-use diapers with a gel absorbent core, commercially and home laundered cloth diapers	Six months diaper use for a single child. Daily usage of 9.7 cloth diapers and 5.4 single use cloth diapers. Equating to a 1000 single use cloth diapers and 1775 cloth diapers usage over 6 months period.	1.Ecological and human health effects associated with either diaper system was not considered. 2.Packaging (plastic films, paper boxes), plastic pants, pins associated with diaper were investigated. 3. Diaper wipes and ointments were not considered.	1.Home laundered cloth diapers had the greatest energy consumption followed by commercially laundered and single use diapers respectively. 2. Commercial laundered diapers were found to have the highest water consumption, followed by home laundered diapers. 3.Single use diaper system had the highest solid waste output
Canadian Study (Vizcarra et al., 1994)	Canada	Life cycle inventory analysis which includes the evaluation of inputs and output associated with baby diapers. Comparative analysis life cycle inventory analysis of Canadian baby diapers with respect to energy, water requirements, raw material consumption, emissions (air and water) and solid wastes	Disposable diapers, home, and commercially laundered cloth diapers	Weekly usage of 38 disposable diapers and 60 cloth diapers.	Environmental impacts associated with land occupation and use were not considered. Impacts associated with the life cycle of baby diapers and improvement analysis were not considered. Assumptions were made with relevance to the average number of diapers used, cloth-to-disposable diapers usage ratio, life span of cloth diapers, market share of cloth diapers, laundry loads, water temperature and drying conditions	A major difference was found between cloth and disposable diapers, with relevance to water and material consumption Cloth diapers were found to have a higher water consumption and have a greater contribution to the release of waterborne waste compared to disposable diapers.
Environment Agency-1 (Aumônier & Collins, 2005)	UK	To evaluate the life cycle of assessment associated with the use of disposable and reusable nappies in the UK for the year 2001- 2002. Material, Chemicals, energy consumption and environmental emissions during nappy manufacturing were investigate. The scope of the study includes all elements dictated in ISO 14040.	Disposable diapers, home laundered flat cloth diapers, and commercially laundered pre-folded cloth diapers.	Investigation of environmental impacts associated with diaper use for an average child (first two and half years of its life)	Environmental impacts associated with land occupation and use were not considered in this study. Systems evaluated in this study were assumed to be at steady state Environmental impacts associated production of capital equipment and work force burden, were not considered.	None of the three diaper systems studied were found to be more superior then the other, in terms of water and raw materials consumption, waterborne emissions and solid wastes. Disposable diaper system contributed significantly in environmental associated with raw material production and the manufacturing phase of disposable diaper components.
Environment Agency-2 (Aumônier et al., 2008)	UK	To update and align the previous study with changes in the marketplace between 2002/03 and 2005/06. To give a detailed account of the life cycle inventory of environmental impacts associated with entire life cycle phases of nappies. Scope of this study is consistent with the previous study (Aumônier & Collins, 2005)	Similar to the previous study.	Similar to the previous study.	Similar to the previous study.	It was concluded in this study that disposable nappies, create more waste during its manufacturing stage compared to its end-of-life stage (landfill sites). Impacts associated with the use of reusable nappies are entirely dependent on consumer behaviour. Impacts of reusable nappies can be significantly reduced by opting to line drying as compared to tumble drying.

Cordella et al., 2015	Germany	Disposable baby diapers	This LCA was to quantify the environmental impacts associated with disposable baby diapers available in the European markets in 2011 and previous years (i.e. 1987, 1995 and 2005).	The production and consumption of one unit of disposable diaper product as a representative average, for the conditions of purchase and use in Europe in a specific year.	Quantitative assessment of direct user behaviour was considered outside the scope of the study. Results were scaled up by considering the average diaper units used during the diapering period. The assessment covered the product's life cycle from 'cradle to grave'	Fluff pulp was both the most used material in 2011 and that generating the highest contribution to the environmental impacts. SAP was the second most significant contributor in most of the impact categories while impacts of packaging have appeared negligible. The historical analysis of average products between 1987 and 2011, show that the introduction of SAP has resulted in lighter disposable diaper products and significantly reduced environmental impacts.

***LCA methods were not mentioned on the reviewed studies, except for Cordella et al., 2015 (international organization of standardization, 2006a, 2006b).**