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Review on the Manufacturing and Properties of Nonwoven Superabsorbent Core Fabrics used in Disposable Diapers

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Abstract

Absorbent hygiene products are made up of different types of raw materials, renewables and non-renewables, to create the absorbent core which acts as a fluid storage structure in the product. With the addition of superabsorbent polymers in the absorbent structure, disposable diapers moved from being just a convenient item to a thinner, safer, and efficient absorbent product which resulted in reduced leakage of the collected fluid. Numerous changes in the design of diapers led to an increase in environmental problems such as excessive resource consumption, water and air pollution, excessive use of energy as well as waste disposal. This is due to the presence of specialized biological inert polymers and superabsorbent polymers which are not easily digested by bacteria present in public and private sewage treatment plants. Hence, sustainable production and consumption strategies are being explored for the production of bio-based products to reduce the use of non-renewable raw materials. This report reviews procedures for the manufacture of disposable diapers, problems emanating from the usage of fossil-based products and use of sustainably resourced materials that could replace the fossil-based ones. It appears that chicken feathers could be used to manufacture disposable diapers as they meet the property and characteristic requirements.

Keywords: ***Baby diapers; Absorbent pads; Raw materials; Sustainable***

Introduction

In high-tech textiles, medical textiles are the most developed and rapidly expanding sector whose primary role is to enhance the health comfort to consumers. These textile products are produced by weaving, knitting, and or braiding. However, most are made by nonwoven techniques. Absorbent hygiene products (AHPs) ranging from disposable to non-disposable ones are designed to receive, absorb and retain body fluids and solid wastage [1,2]. The products include baby diapers, sanitary napkins, tampons, incontinence products, panty shields, and wipes which are mostly single-use items [3]. The global market for these hygiene products has been growing at a significant rate in pace with the single-use products. Although this market sector faces challenges from increasing prices of raw materials, due to global economic concerns and shortage in bio-based resources [4], AHPs continue to be the preferred choice of many households.

The usage of baby diapers globally indicates that, before 30 months of age, one child uses about 4 to 5 diapers per day - thus a typical child will use about 4100 disposable diapers a year [5]. The global single-use diapers market for 2013-2019, reported in FIG. 1A, has been based on four major regions: North America, data mostly collected from U.S., Canada, and few American countries; Asia-Pacific (APAC), looking at China, India, Japan, South Korea and the rest of APAC; Europe, UK, France, Germany, Spain, Italy, Eastern Europe and rest of Europe; and the rest of the world (RES), including South Africa, Saudi Arabia, Oceania, rest of the Middle East and Africa. The highest growth noted in Asia-Pacific is driven by the improving standard of living and the growing middle-class population [4], leading to an increase in birth rate. In South Africa, about 80% of households with babies utilize disposable diapers [6] and the geographical distribution of waste AHPs generated by these households is shown in FIG. 1B.

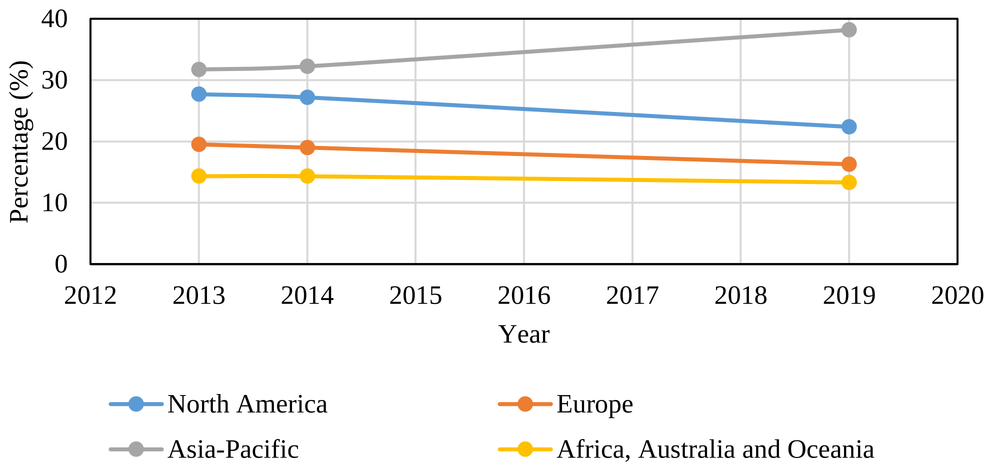

FIG. 1A. **An estimated global market share of disposable diapers by region [4].**

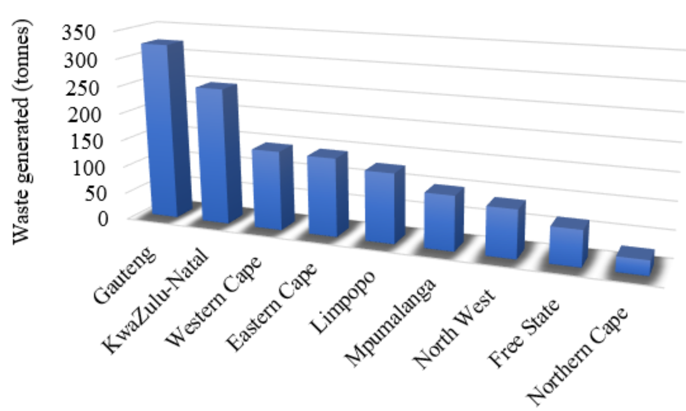

FIG. 1B. **Estimated geographical distribution of waste AHPs generated in South Africa [7,8].**

As a commonly accepted principle "prevention is better than cure"; consequently, maintaining a better hygienic environment obviates the need for curative measures in dealing with the various environmental effects of absorbent hygiene products. In this review the anatomy and mechanism of the main parts of disposable diapers, viz., the absorbent pad is discussed together with an exploration of the use of renewable materials which provide reliable leakage prevention such as cellulose fluff. The environmental impacts and progress to date towards the manufacturing of AHPs has also been reviewed.

Construction, Composition and Manufacturing Process of Diapers

Diaper construction and properties

Disposable baby diapers, by definition, are well-engineered multi-layer structures consisting of nonwoven layers of different materials and are classified into two major types: fluff and superabsorbent disposable diapers, depending on their compositions. They are considered as AHPs, purposely designed to absorb and retain urine and faeces of a baby for a certain period. Most disposable diapers consist of three sheets (FIG. 2A), each having specific functions designed to impart maximum comfort to babies.

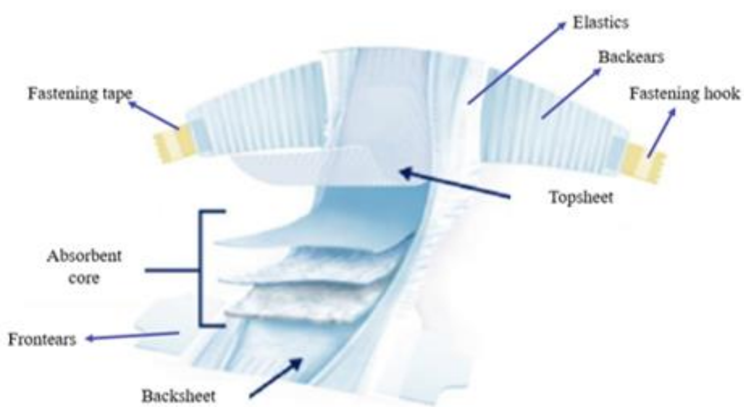

FIG. 2A. **Composition of modern disposable diapers [9].**

The fluid acquisition stratum (top sheet), situated on the inside of a diaper, is a soft porous nonwoven fabric in contact with the baby's skin. It is designed to attract and transport urine away from the baby's skin, moving it on to the next layer below it. Once the fluid is absorbed by the next layer, the top sheet feels dry against the baby's skin. Currently, premium top sheets are treated with small amounts of lotion-containing pharmaceutical grade petrolatum and stearyl alcohol. This ointment acts as both a barrier to moisture and a skin-conditioning agent, which reduces skin hydration and the severity of rash and irritation on the diapered area [9-13]. The fluid storage stratum or the inner/absorbent core of the modern diaper is made of a superabsorbent polymer (SAP), also known as an absorbent gel material. The superabsorbent polymer can absorb more than 30 times its own weight in fluid. In this inner core, fluid is bound into the SAP and locked away. Even though SAPs swell and transform into gel-like substances when wet, they do not dissolve in the fluid and do not completely break even under high pressure [11]. Although SAPs have been proven friendly and safe for contact with baby's skin, diaper manufacturing companies continue to produce SAP-free disposable diapers with low absorbency capacity to meet the demand of consumers for sustainably sourced materials. The fluid distribution stratum (backsheet) of the diaper is typically made of a non-bioactive hydrophobic film that serves as a microporous barrier. This sheet is designed to have small pores, thereby preventing water drops from leaking through. The outside of the backsheet is therefore dry and has lower relative humidity than the inner layers.

Composition and Selection of Materials

Requirements for disposable diaper raw materials

Disposable diapers consist of separated layers bonded together as an absorbent sheet. Each layer is made of a specific raw material working complementarily to each other to guarantee serviceability of the end products. Since a single property can rarely determine the value of raw materials such as fibres and bonding agents, a combination of properties is of special importance. Basically, for disposable diaper applications, these properties are related to (1) acceptable fineness and softness properties, to provide good comfort; (2) acceptable moisture regain of 10% or more to prevent the fibres from plastering onto the baby's skin, thus avoiding a clammy feeling; (3) strong swelling in water and moderately strong acid and base media, allowing the product to absorb fluid and keeping the baby's skin dry all the time; (4) acceptable flexibility and density (usually lower density) providing comfort, easy care and wearability (5) absence of toxic compounds and high resistance to fire [14].

Current raw materials used in the manufacture of disposable diapers

Disposable diapers generally consist of the following raw materials: (i) a nonwoven nylon, polypropylene (PP) or polyethylene (PE) sheet used as a liquid-permeable membrane lining of the inside surface/topsheet; (ii) a PP, PE, starch, woven cloth or rubber membrane on the outer surface/backsheet; (iii) a fibrous material (cellulosic fluff pulp, hemp or synthetic materials) enclosed in water-resistant paper, the absorbent core; (iv) a superabsorbent polymer suspended on the absorbent core (AC) and (v) finally, minor amounts of tapes, elastics, spandex, pigments and adhesive material (FIG. 2A) [15,16]. Man-made cellulose pulp fibres completely dominate in diaper production, accounting for over 40% of the total output. There exist two classes of cellulose fibres used in disposable diapers: fluff cellulose fibres (standard) and chemically modified fluff pulp fibres (compressible) with an improved degree of curl and stiffness. The estimated composition of these raw materials in a single diaper is shown in FIG. 2B:

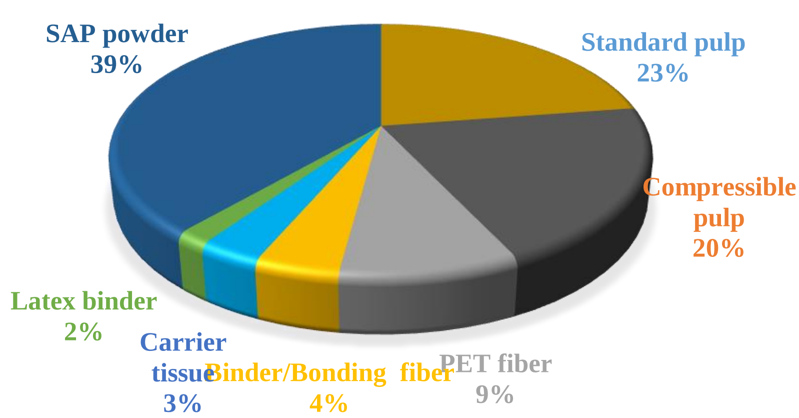

FIG. 2B. **Composition of raw materials in a typical diaper [4].**

Topsheet

A typical topsheet is made from spun or thermo bonding technique and its weight varies between 15 and 20 mg per square meters. It usually contains:

Polypropylene and Polyethylene: Polypropylene (PP) and Polyethylene (PE) fibres are widely used in the nonwovens industry, especially in hygiene textiles because of their unique combination of properties such as chemical stability, softness, and low density (less than that of water) which enable them to be processed into lightweight fabrics. Despite their availability in cut lengths, these standard polyolefin fibres are resistant to biological degradability [17,18]. The technical characteristics of the PP required for the production of spunbonded nonwoven topsheet are summarized in TABLE 1.

TABLE 1. **Technical properties of PE and PP desired for diaper usage [19].**

Properties	**Unit**	**PP resin**
Density	(g/cm^3)	0.90
Melt-index	(g/10 min)	36
Tensile Strength – yield (50 mm/min)	MPa	35
Elongation – Break (50 mm/min)	%	20
Flexural modulus (1.3 mm/min)	MPa	1500
Notch Izod Impact strength – 23°C	J/m	20
Hardness (Rockwell)	R scale	95
Heat deflection temperature (0.46 N/m^2)	℃	100

Viscose rayon: Viscose rayon is man-made regenerated cellulosic fibre produced from the cellulose xanthate process. It is extensively used in the medical and hygiene sectors, mainly because it is very hydrophilic and has similar absorbency characteristics to wood pulp. Viscose is considered as one of the first biodegradable chemical fibres [20] which are currently used in the production of sustainable disposable nonwovens that are easily broken down in waste treatment plants [17]. It is generally utilized as a bi-component or a blended-in with PP fibres.

Absorbent core

Wood pulp: AHPs generally utilise fiberized wood pulp, often termed "fluff pulp". It is made from a fully bleached Kraft process pulp [21] and, because of the cellulose in the fibre, has the capacity to absorb 10 times its weight in fluids in the capillaries [22,23]. It has been used in the core of single-use diapers to prevent gel blocking. TABLE 2 shows the technical properties of fluff pulp used in absorbent core.

TABLE 2. **Technical properties of fluff pulp fibres used in disposable diapers [19].**

Properties	Unit	Commercial fluff pulp	Recycled fluff pulp
Length	mm	2.45	2.41
Width	µm	33.3	32.9
Curl	%	14.8	17
Coarseness	µg/m	296.1	339.4
Kink angle	-	50.6	54.7
Kink index	-	1.67	1.81
Fines content	%	5.8	1.0
Water retention value before beating	g/g	1.0	1.2
Water retention value after beating	g/g	2.1	1.9
Ash content	g/g	0.8	1.5

Superabsorbent polymers (SAPs): Among several improvements brought in the design of diapers, the introduction of superabsorbent polymers as part of the diaper core in the 1980s is one of the most important breakthroughs [5]. These polymers can absorb as many times as their own weight in aqueous liquids, e.g., about 200 times for tap water. The absorption is generally dependent on the ionic strength of the fluid. Absorbent fabrics with about 70-80% swelling capacity were developed using polymers which have high water affinity and are hydrophilic, i.e., polyvinyl alcohol (PVA), acrylamide, or polyethylene oxide (PEO) [24]. TABLE 3 show the required properties of SAPs currently used in disposable diapers. These properties are compared to the properties of biodegradable SAPs which are still under study since they do not meet the absorbency requirement.

TABLE 3. **Properties of SAPs required for use in disposable diapers [19].**

Properties	Unit	Commercial SAPs	Bio SAPs
Colour		White	Off white
Moisture content	w--t%	3.2	13.0 max
Free absorbency	g/g	58	
Free absorbency in 0.9% NaCl	g/g	-	24.0 min
Free absorbency in tap water	g/g	-	49-55
Retention capacity	g/g	34.0	Not specified
Absorbency underload (0.7 psi)	ml/g	22	6.4
Residual monomer	ppm	350	N/A
Bulk density	g/ml	0.64	0.52-0.70
pH	-	6.1	5.5-7.5
Particle size distribution through 20 mesh (850 µm)	%	0.5	1.0 max
Particle size distribution through 100 mesh (150 µm)	%	2.5	10.0 max

Chemistry and properties of SAPs: In designing disposable diapers, layers are assembled in such a way that the absorbent pad is sandwiched between the top and bottom sheets. If the absorbent pad were placed on top, the diaper would not work as expected and would leak rapidly. The mechanism of assembling these 3 sheets enables urine to pass through the surface layer to the absorbent core, where it is absorbed by SAPs and retained within the absorbent core. Sodium polyacrylate, a SAP that is commonly used in diaper manufacturing, is a partially neutralized polyacrylate with incomplete cross-linking between molecules. When they come in contact with water, urine or other aqueous solutions, the liquid diffuses through the polymer into the inside of the molecules via osmosis [25]. Once equilibrium has been reached, the polymer will then stop collecting liquids. As the concentration of water and salt inside and outside the polymer is balanced, the polymer stops absorbing the liquid and unwinds due to the increase in repulsion between the ionized groups in the polymer chains (FIG. 2C-b), forming a gel-like polymer [25,26]. The more concentrated (yellower) the human's urine is, the less absorbing the absorbent pad (FIG. 2C-a) of the diaper containing SAPs will be because of the presence of excess reactants (sodium) counteracting the equilibrium effect [26,27].

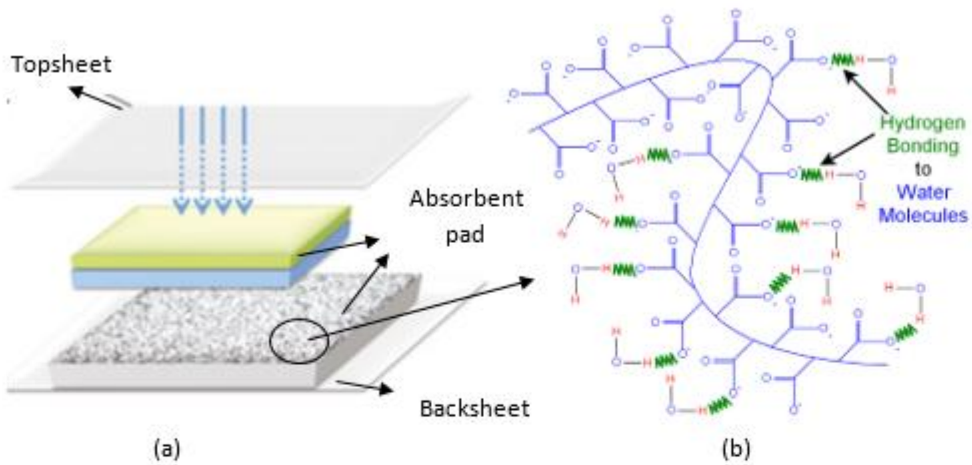

FIG. 2C. **(a) Liquid absorption mechanism in disposable diapers; (b) attraction between water molecules and sodium polyacrylate monomer in the absorbent [27].**

Cotton pulp: Cotton fibres are widespread vegetable fibres consisting of four commercial species (Gossypium hirsutum, Gossypium barbadense, Gossypium arboretum, and Gossypium herbaceum) that are popularly cultivated on a large scale all over the world [28]. Egyptian cotton, Pima and Sea-island cotton, all from the Gossypium barbadense plant are mostly used in textile industries accounting for 3% of the world's cotton production - because they possess extra-long staple cotton fibres-a desirable property in the textile industry [29]. Raw cotton is treated by alkali treatment to develop fluid absorbency characteristics, thus increasing its range of applications. Raw cotton contains impurities that are difficult to remove completely, and this restricts their applications, e.g., to the manufacture of high-quality nonwovens [17] which demand high levels of quality and purity.

Polylactic acid: Traditionally, nonwoven sheets used in baby diapers are formed of spun fibres including polyolefin resins. Whereas the resins exhibit soft tactile feel and desirable mechanical properties, they are derived from petroleum [30]. Nonwoven suppliers continue to be challenged to explore alternative raw materials that are quickly biodegradable and still deliver cost-competitive fabrics meeting performance specifications. One such alternative is using fibres, polymers and/or composites derived from natural resources of plant or animal origin. Some of these alternative biodegradable raw materials are still in the research and development stages, whereas others have been extensively used and recently identified in "eco-friendly" disposable diapers known to be free of chlorine, latex, dyes, and perfumes [31,32]. For example, there are two commercial products of green disposable diapers made from bamboo fibres and marketed as “Bamboo Nature” and “Andy Panty” brands. The products contain petroleum-based absorbent gels but are 80% compostable [33].

Composites: In AHPs, most innovations came through the introduction of nonwoven composites prepared by using a combination of different materials and different technologies. Currently, the major emphasis is in the development of green composite nonwovens using spun-melt composites with polylactic acid (PLA) resins as biodegradable composite films with hydrophobic and/or hydrophilic properties. However, since 100% PLA nonwoven webs do not meet the flexibility, tactile softness and smoothness specifications desired in hygiene products, the PLA is usually combined with polyolefin resins in a core-sheath configuration, where spun PLA fibres form the core section and PP, or PE form the sheath section [34].

Backsheet

In current products, PE or PP is used to produce the back cover of disposable diapers. Several studies have reported on the production of the bottom sheet for disposable diapers using compatibilized thermoplastic polymers comprising 5% to 95% bio-based raw material, i.e., starch [35,36]. However, to our knowledge, these products have not reached commercial production yet. Thus, traditional thermoplastic sheets are still in use.

Manufacturing Process

Production of the absorbent core

There are several processes involved in the production of baby diapers: (i) fibreisation of the fluff pulp plus addition of superabsorbent polymers and then formation of the absorbent pad; (ii) lamination with films and placing of nonwoven materials and elastic elements; finally, (iii) shaping, cutting and packaging of the product. However, this section will focus on the formation of the absorbent pad, which is the main layer in disposable diapers.

The absorbent pad is basically a nonwoven structure composed of 2-3 nonwoven layers, obtained from nonwoven processes. This technology involves the formation of a web using a wet-laid or dry-laid technique; thereafter, the web goes through one of several web bonding techniques to solidify the bond between the fibres, thus stabilising the web structure; finally, a finishing process is done on the fabric to achieve the desired properties – in the case of disposable diapers, a high absorptive capacity is required. Therefore, the term “nonwoven” can simply be defined as a sheet or web structure of directionally or randomly oriented fibres, bonded together by entangling fibres or filaments, by various mechanical, thermal and/or chemical processes [18]. TABLE 4 shows an overview of the different processes in nonwoven manufacturing technologies.

Web bonding

Several bonding techniques are used in nonwoven production, viz., chemical/adhesive bonding, thermal bonding and mechanical bonding (needle-punching, stitch-bonding). Currently, thermal bonding is widely used because it offers high production rates, significant energy conservation, and is environmentally friendly since there are no residuals to be disposed of environment [16,18,37]. In this technology, the web is heated at the softening temperature of the binding material (bi-component, thermoplastic fibres) and successively cooled down the web. The chemical bonding technique was previously used in diaper manufacturing processes. However, this technique was recently abandoned because the adhesive binders used caused skin irritations. Additionally, the wet surface of the cover stocks after the drying processes caused discomfort.

TABLE 4. **Overview of different processes involved in nonwoven technology.**

Nonwovens Technology										
Modified paper technology: Fibres of 2-15 mm		Textile carding technologies: Fibres of 10-200 mm					Extrusion technologies: Filaments			
1. Web Formation										
Wet-laid technique	Air laid technique	Dry-laid technique					Filament laid technique			
Wet-lay	Air-lay	Garnett	Woollen cards	Cotton cards	Hybrid Cards	Air-lay cards	Melt blown	Spun Laid	Flash spun	Fibrillated film
Web manipulation										
Cross-laying		Drafting			Spreading		Scrambling		Crimping	
2. Web Bonding										
Adhesive/ Chemical		Heat/ Thermal			Needle-punching		Hydro-entangling		Stitch-bonding	
Calendar/mangle Spray Foam Powder		Melt fibre (monofibre or bi-component) Powder Calendar (plain or embossed) Oven (drum or lattice)			Tacking Plain needling Multi-directional needling Textured needling		Spun lace		With or without yarn	
3. Finishing Process										
Singeing		Coating			Printing		Embossing		Laminating	

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Addition of SAPs to the web

SAPs are added to disposable diapers in two ways: layered or blended. In layered applications, commonly adopted by Japanese manufacturers, superabsorbent polymer powders are dispersed onto a layer of fluff pulp. The fluff is then folded so that the polymer is in a centralized layer in the absorbent structure. American manufacturers adopted the blended application, where the SAP powder is first mixed homogeneously with the fluff pulp after which the mixture is laid down to form the absorbent structure. In both cases, after the absorbent structure is covered with air-laid fluff sheet forming the absorbent pad, it proceeds down the conveyor path to a levelling roller near the outlet of the forming chamber. This roller removes excess fibres at the top of the pad to make it a uniform thickness. The pad then moves by the conveyor through the outlet for subsequent operations [38].

Finishing process

After combining the layers forming the absorbent pad, the product obtained is considered as a raw superabsorbent nonwoven that does not necessarily require a finishing step. In most cases, the finishing process is done after assembling all 3 parts of disposable diapers and it usually involves the addition of fragrance finishing to raise the technical and aesthetical functionalities of the diapers; this finishing step depends on the style of diaper, the manufacturer, and consumer preference [5].

Technical specifications of absorbent core of disposable diapers

Disposable diapers come in variety of shape, sizes and design but most of them contain an absorbent core (AC) whose properties are difficult to describe since they are mark as “good products” but this completely depends on the consumers’ view. Clinical trials, testing the effectiveness of absorbent core, are usually expensive, difficult and time-consuming and because the products’ design is constantly evolving, these tests tend to be out of date soon after or even before the products are in print [39]. Hence, it is important to relate the functional properties of AC to more readily measurable parameters like physical dimensions and liquid absorption. Consequently, the modern absorbent cores are hygiene spunbonded nonwovens grammage between 8 and 10 grams per square meter (GSM), replacing the previous airlaid nonwovens of 10 to 12 GSM; their length varies between 20 and 24 cm, a width between 6 and 7 cm depending and a thickness varying between 40 to 50 mm [40].

Absorbent cores of disposable diapers are designed to absorb fluid either through (1) the pores by capillary absorption or through (2) the fibres by diffusion [41]. Capillary absorption is a phenomenon by which a liquid flows through the fabrics’ pores, which are initially filled with moisture at ambient temperature [42]. AC’ ability to sustain liquid flow is known as “wicking” and it is a significant parameter in designing diapers since it indicates how dry the consumers’ skin will be after using diapers. When ACs swell to contain body’s fluid, there is a significant increase in diapers thickness by more than four times [43]. This swelling may result in diaper sagging making consumers physically uncomfortable. Therefore, the use of multiple nonwoven layers in commercial diapers allows an even distribution of body’ fluid throughout the diapers which then reduces the sagging by improving the wicking performance. To the best of the author’s knowledge, there are no available data showing the required range of wicking value for disposable diapers instead ACs are required to have a quick absorption behaviour along with good wicking properties to keep babies’ skin dry.

Environmental Impacts

Most environmental reports on the consumption of resources in single-use diaper manufacturing industries state that the production and use of disposable diapers require large amounts of renewable and non-renewable resources as well as large water and energy usages. Information on estimated consumption and environmental impacts of resources production process and disposal of diapers is reviewed below.

Impact of raw material selection

Compared to reusable diapers, disposable diapers use 20 times more raw materials such as crude oil and wood pulp. For example, about 137 kg of wood, 23 kg of the petroleum feedstock, and 9 kg of chlorine are used to produce absorbent diapers for each baby every year [44-46]. More specifically, in the production of the waterproof outer layer of a diaper, about 1 534 m^3 of oil are used as raw material to diaper one baby before being toilet trained. The absorbent pad, on the other hand, requires about 200-400 kg of fluff pulp to keep one baby in disposables for one year [44]. About 70% of the total diapers produced are made from wood pulp extracted from trees, whose plantation growth before harvesting requires some plant nutrients, pesticides, mechanical energy, and water. Considering the current utilization of trees in the diaper manufacturing industries – estimated to be 1 billion trees per year for one baby - the diversity of plant species tends to be reduced faster than they are being replanted [44,47].

Besides deforestation, disposable diapers may contain traces of dioxin an extremely toxic by-product of the advanced paper-bleaching process used in the production of cellulose fluff pulps used in the absorbent layer. To solve these issues and avoid the supply chain risk of raw material shortage, most manufacturers presently produce fluffless diapers, or new products are produced that use sustainable and completely green materials with the use of fibres extracted from bamboo, hemp etc. Bamboo plant and hemp have been extensively used in the “eco-friendly” single-use diapers because of their rapid growth and regeneration; in addition, the fibres biodegrade quickly and deliver cost-competitive fabrics meeting diaper performance specification [48-51].

Impact of the production process

The production of disposable diapers requires about 2.3 times more water, 3.5 times more energy, and 8.3 times more non-renewable materials than reusable diapers [45]. The high energy consumption in diaper industries comes mostly from the pulping process.

The life cycle for disposable diapers creates waterborne and airborne wastes, which do not just come from the manufacturing process of diapers themselves, but also from the process of procuring the raw materials such as pulp, etc. [45,48]. However, wastewater generated from disposable diaper components and product manufacturing has a relatively low impact on the environment compared to air pollution because the traditional manufacturing process used (wet-laid technique associated with chemical bonding) is gradually being replaced by the dry-laying technique with the use of thermal bonding.

Impact of disposal of products

According to a US Environmental Protection Agency report, disposable diapers are the 3rd largest consumer item in landfills accounting for more than 3.5 million tons of waste per annum in the US [48]. Considering their compositions, they take about 500 years to decompose in sunlight and oxygen-free environment, whereas in the presence of sunlight and oxygen, their decomposition is reduced to approximately 100 years [28]. Today’s disposable diapers are primarily made of specialized biological inert polymers derived from petrochemical synthetic products and arranged in different layers such as top sheet, absorption part, fastening tape, and the waterproof film [2,9,13,50]. These inert polymeric films are not easily digested by bacteria found in public and private sewage treatment plants and act as moisture barriers, thereby causing clogs of piping and sewage equipment [51].

Renewable raw materials that could be used as core absorbents

The primary requirement of disposable diapers is to absorb and retain urine. It is, therefore, important that any selected alternative raw materials for use as core absorbents have good fluid absorbency and retention properties. This section explores some available eco-friendly non-wood fibres that display these properties.

Cellulose fibres

Bamboo: Bamboo fibers are abundant natural cellulosic fibers obtained from woody perennial “evergreen” plants in the Bambusoideae subfamily and mostly cultivated in Asia. They are prospective green fibers with outstanding biodegradable properties and mechanical properties that are comparable to those of conventional fiberglass and wool [52,53]. Bamboo fibers are bacteriostatic, antifungal, antibacterial, hypoallergenic, natural deodoriser, and resistant to ultraviolet light. These versatile properties make the fibers desirable mainly in the textile industry. Furthermore, bamboo grows to its mature size in only 6-8 months, whereas wood takes about 10 years [33,52].

Hemp: Hemp is a cellulosic fibre just like cotton which belongs to a small family of flowering plants called “cannabaceae”. It is a great absorbent fibre and has good properties such as anti-microbial and resistance to mold, mildew, rot, and it is easily degraded by UV-light. These properties make hemp a good raw material for the manufacturing of diapers after treatment. Fabrics made from 100% hemp can cause severe irritations on baby’s skin because hemp fibres are stiff. Therefore, studies are needed to reduce the stiffness properties of hemp fibres. Consequently, hemp fibres are mostly blended with cotton fibres for commercial purposes to overcome the irritation [54].

Pineapple leaf: Pineapple leaf fibres have superior mechanical properties due to their high composition of cellulose (74.33%) compared to hardwood or softwood [55], thus making them suitable in producing good pulp for use as a core material in diapers. They have a white appearance, a silk-like feel, are smooth and soft and display higher tenacity than cotton fibres [17]. However, they have lower moisture and liquid absorption capacity than cotton as well as poor interfacial fibre-matrix adhesion [56]. It is, therefore, advisable to perform surface modification treatment on the fibres to develop better absorption capacity. Also, the extraction pineapple leaf fibres are limited due to low production which make them difficult to be used in industrial applications [57].

Kapok: Kapok fibres are extracted from the fruits of the silk cotton tree. They are considered the finest, lightest fibres and have the highest percentage of hollow structures among fibres. The presence of this wide lumen in their structure gives them the exceptional capability of retaining liquids. Although the fibres are highly hydrophobic due to the small amount of wax (2-3%) coating covering the fibres, they can be chemically modified to make an ideal water-absorption material for hygiene purposes [58].

Jute: Jute is a natural fibre mostly cultivated in the north-east of India. It is abundant and obtained at a lower price than cotton fibres. Jute fibre is an alternative fibre which could replace fluff pulp in diapers because its fibres contain 60-70% cellulose and have high water affinity. Additionally, as opposed to other fibres, jute fibres are much shorter making the preparation of cellulose pulp easier [59].

TABLE 5 summarizes the physical and mechanical properties as well as the chemical composition of the above cellulosic fibres to compare and understand their potential as raw materials in absorbent cores for future development.

TABLE 5. **Properties of selected cellulose fibres [58].**

Properties	Bamboo	Pineapple leaf[b]	Kapok	Hemp	Jute
Length (mm)	2 – 3	63 – 70	10 – 35	2 – 90	0.5 – 0.6
Width (μm)	6 – 12	20 – 8 0	20 – 43	5 – 32	26 – 30
Density (g/cm^3)	1.32[a]	1.07 – 1.5	1.474	1.14	
Cellulose (%)	73.83	70 – 82	35 – 50	74.4[c]	61 – 71
Hemicellulose (%)	12.49	18.8	22 – 45	17.9[c]	14 – 20
Lignin (%)	10.15	5 – 12.7	15 – 22	3.7[c]	12 – 13
Tensile strength (MPa)	144.3 – 277[a]	413 – 1627	93.3	690[c]	
Young modulus (GPa)	-	34.5 – 82.5	4	30 – 60[c]	3.3 – 5
Elongation at break (%)	14 – 18[a]	1.6	1.2	1.6[c]	1 – 2
Water absorbency (%)	90 – 120	-	-	-	23
[32,60,61]					

The selected cellulose fibres can be considered totally renewable and biodegradable, they have gained economic important due to their unique characteristics. Most of these fibres are currently used in the production of disposable diapers. Although they meet some of the technical requirement to be used as sustainable raw material in diapers, there are no clear answers as to whether the environmental impacts associated with the extraction of these fibres as well as the after life of the product made from them would be minimal them the traditional diapers.

Protein Fibres

Wool: Wool is natural protein fibres extracted from the hair of animals such as sheep, goats, and camels. They are expensive fibres and very desirable in hygiene applications because of their wide-ranging properties. For example, wool fibres are very flexible and can be stretched up to 60-70% when wet and 30% when dry then bounce back to their original shape [62]. They also can absorb a large amount of moisture. Therefore, they can be considered as a potential alternative to cellulose fibres to some extent. Wool fibres are most sustainable material available for cloth diapering materials because they are breathable, naturally bacteriostatic and they do not require special care to maintain its shape and its water-resistant properties [63]. They are currently used in the production of cloth diaper covers that work very well at containing leaks and allowing air to circulate.

Silk: Silk fibres are composed of stemming from sericin-building insects (silk) and are very expensive [57]. They have a moisture regain of 11% and are very fine and light. Although these fibres satisfy most of the raw material requirements in disposable diaper applications, they are usually not used to make superabsorbent disposable diapers because they are costly.

Chicken feather fibres

Chicken feathers are made of approximately equal portions of fibres and quill and are comprised of 91% protein, 1% lipids and 8% water [64]. Thus, feathers are a rich source of protein that could be a desirable biomass component that could be used in a variety of applications. Chicken feathers have potential as renewable materials generated by the poultry industry. Various methods of processing the feather waste into valuable industrial products were investigated. However, of the over 40 billion kg of waste feathers produced per annum by poultry industries worldwide, only a small quantity is beneficiated. The Biorefinery Industry Development Facility at the Council of Scientific Industrial Research (CSIR) and the University of KwaZulu-Natal in South Africa have identified some application areas (TABLE 6) that can be used to beneficiate feather waste produced in South Africa. The research work focuses on demonstrating the feasibility of valorizing chicken feather waste by targeting application areas such as construction industries, pulp and paper industries, hygiene and medical sectors, cosmetic and food industries.

TABLE 6. **Valuable products under investigation at CSIR/BIDF.**

Raw material	Processed raw material	Products	Application area
Chicken feathers	Keratin	Electrospun nanofibres	Biomedical applications
		Binders	Wood composites
		Hydrogels	Medical applications
		Food packaging	Food industry
	Fibres	Composites	Construction industries
		Superabsorbent fabrics	Hygiene applications : Disposable diapers (absorbent core)
		Paper production	Pulp and paper industries

General properties of feathers

Chicken feather fibers are characterized by their low density (0.44-0.91 g/(cm^3)) compared to any natural or commercially available fibers and act as thermal insulators [65-67]. They are comprised of two forms of microcrystalline keratin, the fiber and the quill, and can withstand both thermal and mechanical stresses. They are also highly flexible, hydrophobic and have good compressibility and resiliency, that provides good strength, cohesiveness, and spinnability to textile products made from them [66,68]. Chicken feather fibers are chemically similar to wool but have a much larger surface area because of the much smaller diameter of their fibers. As a result, feather fibers can absorb more water than wool and cellulose fibers [69]. Feather fibers do not have the required length to be processed on textile machines and are thus not suitable for making spun yarns and woven fabrics in 100% form or as blends with other natural and synthetic fibers [70]. However, due to their better sorption properties, higher hygroscopicity and smaller wetting angle compared to fluff pulp, feather fibres can be used to produce a nonwoven absorbent web with higher absorbency capacity than absorbent pads currently used in the manufacture of disposable diapers.

Specific properties of chicken feather fibres ideal for diaper production

The absorbency capacity of a fibre is of prime importance in the manufacture of AHPs. The amount of water absorbed by textile fibres depends on the physical and chemical properties of the fibre, as well as the temperature and humidity of the surrounding environment. Chicken feather fibres have higher moisture content than some cellulose plant fibres, such as pineapple leaf and sugarcane bagasse fibres [32,71]. Examination of their physical characteristics shows large numbers of tiny pores, known as honeycombs, between the barbs and barbules which make them semi-permeable thus allowing moisture to pass through them [72]; the more porous the structure of fibre is, the more is its wettability improved. Furthermore, feathers have both hydrophilic and hydrophobic properties and about 39 of their 95 amino acids present in the keratin monomers are hydrophobic, with serine being the most abundant [73]. Serine molecules contain free hydroxyl groups (OH-) on their surface which can attract water vapour from the air [72,74]. As a result, chicken feather fibres contain 8% to 13% moisture indicating that they are hygroscopic in nature [65].

Data analysis and feedback from parents indicate that characteristics of a good disposable diaper are: (1) high liquid absorption properties; (2) no leakage; (3) comfort and durability; and (4) presentation of no health risks to consumers [47,75-77]. These qualities and characteristics can be achieved with chicken feather fibres as described below TABLE 7.

Studies on the physical properties of chicken feather fibres (CFFs) based on the recent analysis show the following:

TABLE 7. **Description of chicken feather fibres' properties.**

Physical Properties	**Description**	**Suitability in diapers**
Diameter	varies between 5 μm and 46.6 μm [66,78]	The effect of fibre diameter on fibres fineness is such that the smaller diameter, the finer and softer the fibres are [78]. Using the soft and fine fibres will result in lightweight nonwoven fabrics thus satisfying the comfort requirement of disposable diapers
Length	varies between 1 mm and 45 mm	Although the fibres' length limits their use in the production of nonwoven sheets, this property gives room to utilisation of reinforcement materials to consolidate the fabrics and improve their properties. Moreover, the shorter the length of CFFs, the more accessible the voids present in the fibres are to air or fluids. Thus, improving the liquid absorption of the fibres as well as that of the fabrics.
Aspect ratio	varies between 200 and 4000 depending on the variation in fibre length and well as the variation in fibre diameter	It is generally desired to have fibres with a high aspect ratio since high length to diameter ratio provides great flexibility and high packing density of fibre strands which are an important attribute for

		key performance criteria such as comfort, wearability and fittability.
Medulla diameter	varies between 4.59 μm and 26.88 μm	In most cases, medulla diameter determines the fibre type and is usually associate with the fibre diameter. In addition, it is a good indicator of fabric comfort. The smaller the medulla diameter, the more flexible the fibres are. Thus, indicating good bonding between fibres can be achieved in fabrics made from the CFFs since the degree of fibre bonding is largely dependent on fibre flexibility [66].
Apparent specific density	is in the range of 0.44 g/cm^3 and 0.91 g/cm^3	CFFs are characterised by their lower density; the utilization of fibres in the production of fabrics will results in lightweight materials which are easily handled and provides comforts to consumers.
Fineness	is approximately 36.48 den (40.5 dtex)	Most cellulosic fibres used in disposable diapers have their fineness value between 1 dtex to 13 dtex which appeared to be lower than the fineness value of CFFs. This property shows that CFFs have enhanced fineness and softness properties which are one of the key requirements of fibres used in disposable diapers.
Moisture content	varies in the range of 8% and 13% [72]	This implies that nonwoven fabrics made from chicken feathers fibre will provide good comfort, since fibres with good moisture regain accept dyes and finishes more readily compared to fibres with low regain [62].
Colour	changes from yellow to white during the process of cleaning and decontamination [79]. White is the preferred aesthetic colour of fibres used in hygiene products.	Before converting the feathers into processable fibres, a simple decontamination process involving washing with warm water and soap followed by autoclave pre-treatment is required [65]. At this stage, the feather fibres are pale yellow to yellowish white in colour; do not emit odours; and are free from contamination with micro-organisms [79]. The whiteness colour is simply obtained by treating feathers with ethanol or hydrogen peroxide. In addition, the treatment results in fibres that are flexible and smooth. Whiteness in wood pulp is achieved by bleaching with chlorine

		containing compounds that can cause skin irritation on babies' skin. Hence, chicken feather fibres, when used in disposable diapers, satisfy the health safety and comfort requirements

The physical properties of CFFs studied by different researchers show that the fibres have acceptable fineness, softness and flexibility which will then, result in comfortable AC products with the absence of toxic compounds. Studies on the structural characteristics of chicken feather fibres (CFFs) based on the recent analysis show that feather barbs have many tiny pores, known as honeycombs, between the barbs and barbules which makes them semi-permeable; thus, allowing moisture to pass through them [72]. The presence of tiny honeycombs is the reason of the low density of the barbs, thus resulting in lightweight and comfortable wearable fabrics for diaper usage. In addition, the fabrics made from CFFs are breathable and do not stick on the skin even during hot seasons.

Moreover, the chemical properties of chicken feather fibres (CFFs) reveal that the fibres are semi-crystalline as they are made up from crystalline fibre phase and the amorphous protein matrix phase [33]. Both phases are made up of about 60% hydrophobic amino acid with strong intermolecular interactions, especially hydrogen bonds. Although the hydrophobic nature of the fibres suggests that CFFs are water repellent, their wetting properties can change as a consequence of chemical treatments-bleaching treatment, for example, would oxidize the outer surface of CFF, inducing a decrease of the surface of hydrophobicity; this would result in a decrease in contact angle. Hence, treated CFFs would have high swelling properties and the wettability of the fabrics made from then would be improved [14]. This satisfies the absorbency requirement of raw material used in disposable diapers. Also, because of the strong bonding extensive cross-linking within the keratin structure, feather fabrics would exhibit good durability and resistance to degradation. However, based on the chemical durability results of CFFs [32], the fabrics would degrade rapidly in alkali environments and significantly less in slightly acidic environments. This would be more advantageous, especially when disposing of the pads after usage.

Conclusion

Many single-use absorbent hygiene products have been designed and tailored to meet the needs of different consumers. A historical analysis of the disposable diaper market shows that the introduction of SAPs and their rapid growth in the use of sustainably resourced materials has led to lighter, convenient, effective, and safe disposable diaper products. Despite their higher absorbency, SAPs, coupled with the inert polymers (PE/PP) have significant environmental impacts. This review reveals that there are alternative sustainably-sourced raw materials that could be used to eliminate fluff pulp/SAPs nonwoven sheets in the manufacture of disposable diapers to reduce environmental pollution. Some of these alternative biodegradable raw materials, such as chicken feather fibres, are still in the research and development stages, whereas others, e.g., bamboo and hemp fibres have been extensively researched and recently identified in the market as "eco-friendly" disposable diapers known to be free of chlorine, latex, dyes, and perfumes.

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