https://doi.org/10.1186/s40691-023-00329-9
Fashion and Textiles

RESEARCH **Open Access**

New 3D knitted absorbent pad for a prospective safer and ecological reusable baby diaper

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Abstract

Disposable diaper is one of the most polluting products in the world and presents many potential health risks for children. In this paper, to avoid those diaper problems, propose a safer reusable baby diaper with the same performances as disposable diapers with non-harmful materials. A comparative study has been conducted on the developed 3D knitted reusable diaper and some commercial disposable diapers including the most popular diaper goods. Thus, diaper performances have been measured and limit values have been checked. The obtained results prove that the properties of the developed reusable diaper are comparable to those of the disposable baby's diapers available on the market. Finally, using chromatography analysis, we prove the non-harmful compounds in the developed baby diaper. For further investigation, a a new design of the risk assessment matrix related the menace trigger has been also prepared. The developed reusable diaper can be a promising alternative of the diaper with an efficient quality and functionality.

Keywords: Reusable diaper, 3D knitted fabric, Risk Assessment Matrix, Expert perception, Ecological solution

Introduction

In the low and middle-income countries, the achieving of broad coverage of sanitary products especially baby diapers always constitute a major challenge. Health care and hygiene are intended to cover foremost features of a baby well-being and should be equally accessible to all family.

Disposable diapers are the third most polluting product and account for around 4% of solid waste. Disposable diapers increase 60 times the amount of solid waste. Manufacturing and disposable diapers require 2.3 times more water than fabric manufacturing (Ajmeri & Ajmeri, 2016). We also note that according to the World Health Organization (World Health Organisation, 2019), a baby wears a diaper averagely between 15 and 28 months. The diaper is changed between 5 and 6 times during the day. This constitutes a great number of diapers used, around 1800 diapers per year. Some of poor families cannot afford the weekly average cost of the disposable diapers. The deficiency of attention for baby diapers poses risks for all children hygiene, but particularly those with low family incomes (who could not afford baby diaper charges). So, disposable diapers present not only an environmental big problem but also a harmful risk on the baby health. So, disposable diapers represent not only an environmental big problem but also a harmful risk on the baby health. Thus, all disposable diapers elements could contain risky substances either they are formed during the manufacturing process or added after that to the diaper (such as perfumes, lotion). Since by wearing an average of five diapers per day, the risk of toxicity will increase up to 4 to 5 times, in case of presence of dangerous elements.

Recently, many researches have been focused on the negative impact of baby diapers needs on children's health and lives. For example, in his study M.V Smith et al. confirms that more than 30% of American mothers reported diaper needs (Smith et al., 2013). The major drawback of this research is that an insufficient supply of diapers is a high-risk factor for children's health. Thus, in order to economize, the mothers on need reduce the diaper's change frequency and even dig out the contents of the diaper and reuse it. Those dangerous practices could cause infections and diaper rash on the urination area. In fact, an inquiry study of Huggies and Kimberly Clarck declares that one of three families in the USA struggles to get a clean diaper for their baby (Raver et al., 2010). This huge number was coming from the most powerful economy in the world, the situation is certainly worst for families in the developed countries. For this reason, the French Health Security agency (French Health Security agency, 2019) published a safety report, following an examination of 23 references of bestselling baby diapers on the international market. Many dangerous substances have been reported such as: added perfumes, dioxins formed during the manufacturing process; chlorine for bleaching process; volatile organic compounds (VOCs), formaldehyde, pesticides (Yan et al., 2009). In addition, in his study, C.J. Parka et al., was measured the amounts of volatile organic compounds (VOCs) and phthalates contained in sanitary pads and diapers (Chan et al., 2019). They observed that the concentrations of these elements were significantly higher than the allowed limits and they concluded that for a prolonged period those risky elements in direct skin contact could be immersed into the reproductive organs. Similarly the French agency for Environmental and occupational Health Safety (Wang et al., 2007) and the National Reference Center for staphylococci have found that there was a potential risk that toxic elements could migrate to the surface through baby's urine. These elements could attack the baby's organs and its immune system. They could also be allergenic, cause toxic shock syndromes (TSS) and after extended contact, they could be carcinogenic (Centre national de référence, 2017).

We can conclude after this diagnostic by the fact that to avoid all diaper problems, the diaper must be safe and free from toxic elements. So, the use of the reusable diaper could be a relevant solution to reduce toxic risks of these diapers and the amount of waste from disposable products. The challenging issue is to develop a new reusable diaper with an efficient quality and functionality. New 3D knitted structure has been developed and used for the reusable diaper. Manufacturing technique will be described in detailed in this paper. Then, diapers properties will be analyzed and compared to other disposable diapers available on the market. Finally, for a comparative purpose, a new design of the risk assessment matrix was developed and conducted in this paper.

Methods

Design and development of reusable diaper

Knitting machine and yarns characteristics

The CMS 530 HP STOLL knitting machine was used in this study for the designing of the three- dimensional knitted structures of the disposable diaper. The main advantages of the flat bed technique that is easily enable the patterning the shape and the loop architecture. It is worthy of mention that there is strong relation between three-dimensional forms and volume construction while designing three- dimensional knit structures. In order to obtain the final structural openings and architectural dimensions 3D spacer technique and hollow structures were both combined.

For the knitted structure pad principally hydrophobic polymer fibers were used: Polyamide 6–6 (78 dtex) as pile yarn in the z-direction and Polypropylene (330dtex) as backside cover surface. Referring to the literature, their main advantage is their excellent insulating properties and their exceptional compression force distribution over thousands of cycles. (Gries & al., 2022) In addition of hydrophilic BIO Cotton yarn (34/2) for the frontside cover surface. A water-resistant laminated PE/PP fabric was used as outer layer envelop.

Reusable diaper design specification

The developed reusable diaper is composed by a washable 3D knitted absorbent pad (part I) and a waterproof breathable laminated back sheet (part II). The two parts are enclosed in a packaging (part III), which also serves as mattresses when changing the diaper to the baby (Fig. 1a). The back sheet (part II) contains a clamping system designed to be adjustable for different sizes and an invisible anti-leak tape, which reinforce the edges. To strengthen the system two other anti-leak tapes were added on both sides.

The 3D knitted absorbent pad (part I) (Fig. 1b) is composed by four 3D knitted layers obtained by three knitting techniques. Accordingly, for improved properties of diapers, fibers material order is alternated on both front and backsides of each layer. Besides, the special shape of the 4 layers permits to obtain a structure that absorbs enough urine while giving a feeling dry surface.

Details of the four layers are given in Table 1 and Fig. 2. The layer 1 is based on tubular 3D curved lozenges. Hydrophobic polypropylene was used for front and backsides. A

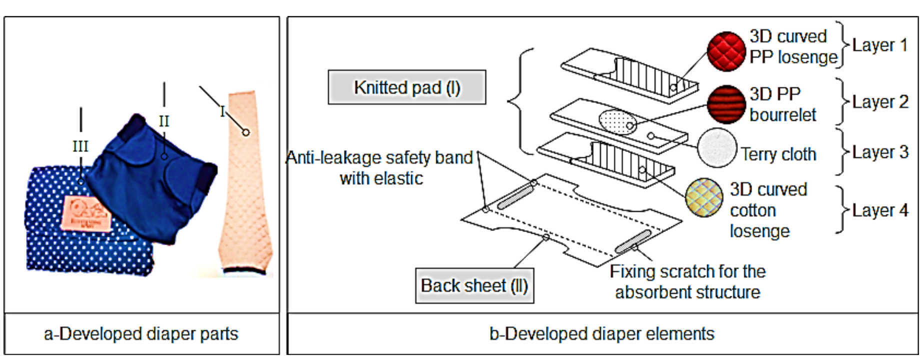
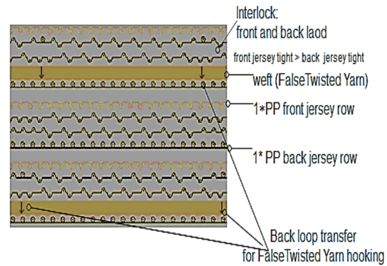
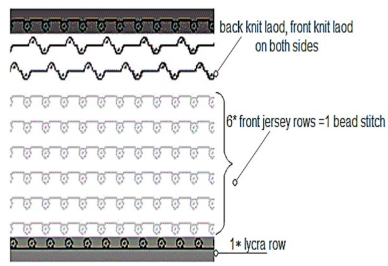
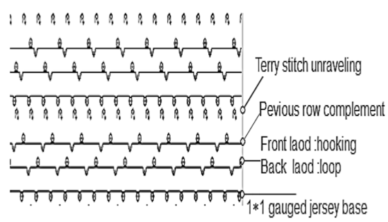
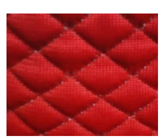
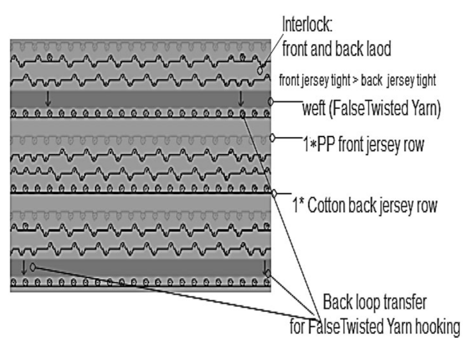


Fig. 1 Schematization of the developed diaper elements

Table 1 Composition of the developed knitted pad

	Material	Technique	Fabric view	Binding details
Layer 1				
Front	Poly-propyl-ene	3D curved lozenge knit		
Back	Poly-propyl-ene	3D concave lozenge knit		
weft	Polyam-ide 66			
Layer 2				
Front	Poly-propyl-ene	3D bead knit		
Back	Cotton	Flat knit		
weft	Lycra			
Layer 3				
Front	Cotton	Terry cloth knit		
Layer 4				
Front	Cotton	3D curved lozenge knit		

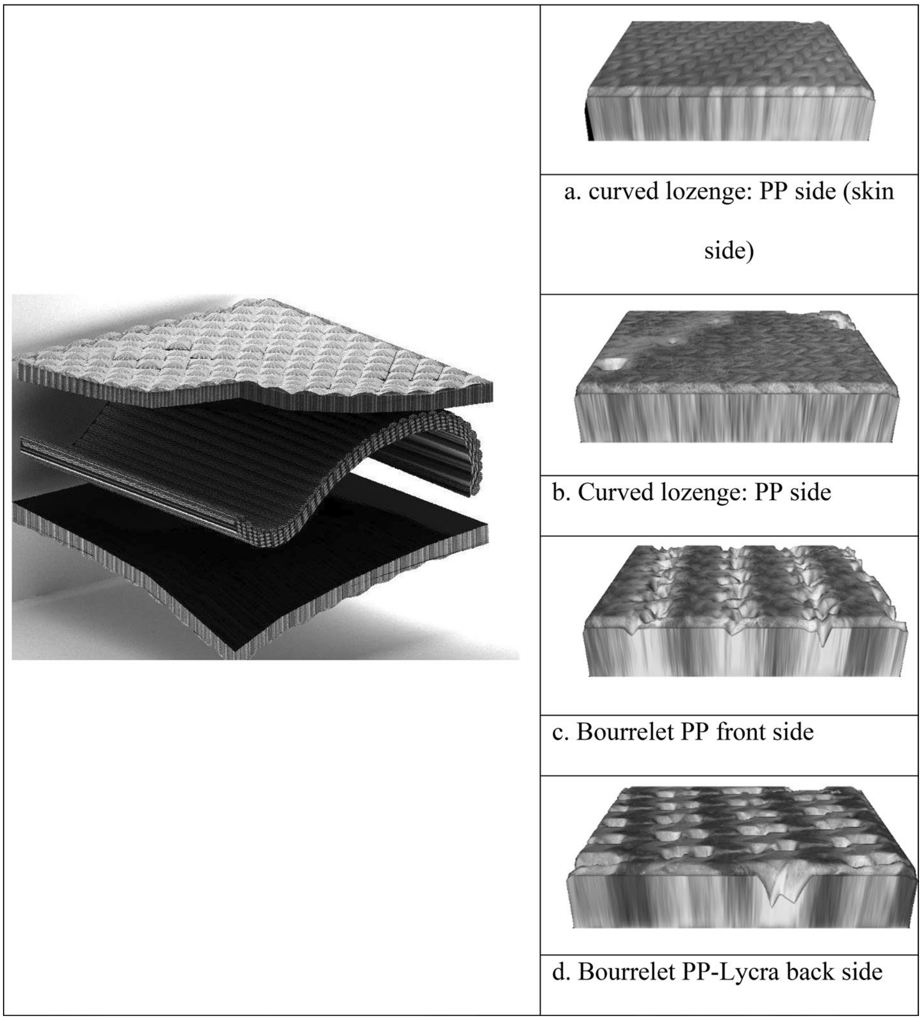


Fig. 2 3D rendering of the developed diaper key parts

polyamide false twisted yarn was used as weft. The layer 2 is made by a 3D bead knitted PP yarn and a flat Jersey knitted cotton yarn. Each bead is composed of six consecutive polypropylene front Jersey rows and a very tight loop. A Lycra yarn was integrated on the backside to create a connection between the layers and to form the final stable bead structure, an absorbent terry cloth organic cotton, allowing the liquid storage in the diaper, made the layer 3. It was obtained through terry knitting technique with front jersey on the backside and a very dense loop on the front side.

A tubular 3D curved lozenge composed the layer 4. A hydrophobic polypropylene yarn was used for front side to prevent leakage. Organic cotton yarn was used on the backside to enhance absorbency. A polyamide 66 false twisted yarn was used as weft yarn to have spacer layers.

For comparative purposes, five of the most popular brands of disposable diaper in the market were examined (noted by Disp-D1; Disp-D2; Disp-D3; Disp-D4; Disp-D5). The tested diapers are made in Turkey, KSA, Algeria and Tunisia.

Risk assessment matrix development and toxicity assessment

Analysis of volatile organic compounds and citral concentration by the Gas chromatography-Mass spectrometry (GC–MS)

To examine the toxicity of diapers, the volatile organic compounds and citral concentration were analysis by GC–MS. According to the Oeko Tex directive (Tex, 2019), the volatile organic compounds (VOC's) were extracted with methanol and dichloromethane from diapers and then analyzed by gas chromatography (GC 6890 N-MS 5975 system with an Agilent DB-5MS GC column). The detected components by gas chromatography were subjected to mass spectral analysis. The obtained results were compared to the reference database available in the NIST2014 MS library (Europeen Parlement Directive, 2004; Wang et al., 2007).

Analysis of heavy metal by inductively coupled plasma mass spectrometry (ICP-MS)

The number of heavy metals in the diaper was determined according to the directives of the Germany standard (Deutsches Institut fur Normung, 2010) and the Oeko Tex organization (Tex, 2019). So heavy metal was extracted in a solution of concentrated acidic artificial sweat at 40 °C. Each detected heavy metal was analyzed separately. So, mainly the presence of the Copper (Cu), Nickel (Ni), lead (Pb), Antimony (Sb), Cobalt (Co), Manganese (Mg), Chromium (Cr), Mercury (Hg), Arsenic (As), Cadmium (Cd) metals were checked.

Risk assessment matrix development

The risk assessment matrix for baby diapers was constructed based on the reflux approach presented on the study of Rai et al. (2009). This approach considerate the materials, which are not in direct, contact with the skin and they can rise to the surface through the phenomenon of rewetting. According to the IOMEH (Health, 2014), some toxic elements have disruptive effects even at very low doses and it is essential to think about the exposure duration and to prohibit their existence.

Several practical steps were arising when drawing the risk assessment matrix (Table 2). The first step consists of the identification of the risk since it allows the threat dissection into levels and facilitates its evaluation. Thus, we predict the risky elements that have been found in baby diapers referring to pervious works such as dioxin, citral COV's or heavy metals… (Lalko & Api, 2008; Odio et al., 2000) and have been discerned in this study in tested diapers on laboratory scale. The second step involves the calculation of the risk impact as an indicator of the risk importance on the baby's health. So, the individual severity score of each element was used to calculate the severity score according to Eq. (1). Its probability of occurrence was considered, and the impact level score was calculated according to Eq. (2). Finally, in the third step, the risk score was determined as the sum of the impact level score and the severity score according to Eq. (3).

$$\text{Severity score}(S_s) = \sum \text{individual severity score} \tag{1}$$

$$\text{Impact level score}(I_l) = \sum (\text{individual Impact level score}, \textit{risk probability score}) \tag{2}$$

Table 2 Risk Matrix key for different score calculation

Step	Element identification	Risk type identification	Probable risk description	
Step 1: Risk identification and description	Element identification	Risk type identification	Probable risk description	
			Level	**Score**
Step 2: Risk impact determination	Individual risk severity	Tolerable	Low	0
		Acceptable	Medium	1
		Undesirable	High	2
		Intolerable	Extreme	3
	Individual risk impact level	Acceptable	low	0
		As law as acceptable	Medium	1
		Generally unacceptable	High	2
		Intolerable	Extreme	3
	Risk probability	Improbable	low	0
		Acceptable	Medium	1
		Possible	low	2
			Medium	5
			High	8
			Extreme	11
		Probable	low	3
			Medium	7
			High	9
			Extreme	12
Step 3: Final risk score calculation	Severity score	Equation (1)		
	Impact level score	Equation (2)		
	Final risk score	Equation (3)		

$$\text{Final risk score}(R_s) = \text{Impact level score}(I_l) + \text{Severity score}(S_s) \quad (3)$$

Dimensional stability and appearance for reusable diapers

Pilling test

Pilling resistance was tested according to the ISO 12947–1 standard guidelines (ISO, 2017).

Dimensional stability

Structure stability was tested according to the directives of the (AFNOR, 2012) standard. The overall diaper was washed for 30 min in the drum according to a gentle washing program. A complete test consists of a wash and a drying cycle. The test was repeated five times, the mean values are determined, and the shrinkage value noted S (%) was calculated according to Eq. (4).

$$\text{S}(\%) = \left(\frac{\text{average length after wash} - \text{average length before wash}}{\text{average length before wash}}\right) * 100 \quad (4)$$

Softness analysis by sensory panel tests

An expert sensory panel described in previous study (Rahma et al., 2018) was asked to rank the softness of each baby diaper.

Five panelists are selected from the R&D department of a disposable sanitary products company. The advantage of such panel is its confidentiality and their excellent knowledge for different products and consumer needs. The obtained panel is composed of 10% of women and 90% of men with an age ranging between 29 and 35 years old. Each expert of the sensory panel assessed the baby diapers five times in dry and wet conditions and give scores from 0 (least soft) to 10 (highest). The softness mean value of attributed scores was calculated.

Wetting assessment

Rewet under load tests It was conducted according to *ISO 9073* standard (International Standard Organisation, 2006). It presents the amount of the absorbed liquid by the diaper but rewet again on the diaper surface under pressure. The saline solution, simulating urination, was incorporated three times every twelve minutes on diapers subjected to load pressure. This load simulates the baby's weight on the diaper (Yokura, 2000). Following each urination, the weight of filter papers in contact with the diaper was measured. The rewet was calculated according to the Eq. (5).

$$\mathrm{Rewet}(g) = \mathrm{W\_filter}(\mathrm{w1, w2, w3}) - \mathrm{W\_dry} \tag{5}$$

with, W_filter: wet weight of filter papers in g at different applied weigth (w1, w2, w3); W_dry: dry weight of filter papers in g.

Absorption test The absorption was measured according to (International Standard Organisation, 2006) standard. The diaper was emerged in a bath of NaCl 0.9% solution for 20 min. Then the liquid was removed by manual load spinning. The total absorbency capacity was calculated according to Eq. (6).

$$\text{Total absorbency (g)} = \mathrm{D\_abs} - \mathrm{D\_dry} \tag{6}$$

With, D_abs: diaper weight after absorption in g; D_dry: diaper dry weight in g.

Strike through time test The strikethrough time was determined according to ISO 9073 (International Standard Organisation, 2006). It refers to the time that it takes a diaper to absorb a well-specified volume of a NaCl 0.9% solution. The sample was held under a specified load to simulate the baby's weight (weight 330 g, 3 cm diameter tube) (Yokura, 2000). The liquid test diffuses in the diaper and the time elapsed until the absorption of all the liquid is noted as strikethrough time on second.

Results and Discussion

The presence of toxic elements in reusable diaper was checked to determine potential risk on baby's health. The developed diaper Dev-D7 was compared to disposable diapers to validate its safety. As shown in Table 3 the different tested brands of disposable diapers present elemental concentrations of heavy metals, dioxins, and volatile organic components.

The average concentration in Disp-D1 was 1.63 mg/kg; 1.69 mg/kg Pb, 1.77 mg/kg Mg; 2.26 mg/kg Ni. Similar averages were found in the Disp-D2: 5.8 mg/kg Cu, 2.12 mg/kg Pb, 2.12 mg/kg Pb; 4.4 mg/kg Sb; 2.07 mg/kg Ni. Dioxins were found in both Disp-D3

Table 3 Toxic element present in tested diapers

Metal	Cb (mg/Kg)	Cu (mg/Kg)	Pb (mg/Kg)	Ch (mg/Kg)	Sb (mg/Kg)	Mg (mg/Kg)	Ni (mg/Kg)	COV (mg/m³)	Dioxin	Citral (µg/cm²)
Threshold	4[a]	50[a]	0.2[a]	2[a]	30[a]	90[a]	4[a]	0.5[b]		1400 [C]
Disp-D1	1.63	0	1.69	0	0	1.77	2.26	0	0	0
Disp-D2	0	5.8	2.12	1.69	4.4	0	2.07	0	0	500
Disp-D3	0	5.84	0	0	0.55	0	5,55	0	0.015	0
Disp-D4	0	8.51	0.39	0.15	5.13	0	10.78	0.098	0.025	0
Disp-D5	0	5.9	0	0.18	2.267	0	3.96	0.075	0	0
Dev-D7	0	0	0	0	0	0	0	0	0	0

[a] Data from Oeko Tex. Standard 100 (Standard 100: Limit values and fastness, 2019) for volatile emissions,

[b] Data from Oeko Tex. Standard 100 (Standard 100: Limit values and fastness, 2019) standard for extractable heavy metals,

[c] Data from Research Institute for Fragrance Materials (Technical Dossie, 2006) of No Observed Effect Level of dermal sensitization stimulation to citral (Api et al., 2008)

and Disp-D5. Nonetheless, the developed reuse diaper Dev -D7 was free from toxic elements.

Still, there is a requisite for constant and routine checking of potentially toxic elements in diaper that are widely used in the hygienic industries. The obtained results after the toxicity analysis have highlighted the existence of different hazardous substances in disposable diapers, which in particular is exposed to the skin for a long time or migrate through urine. Prolonged exposure to low levels of potentially toxic elements could result in very severe health problems. For further investigation, we have drawn the risk assessment matrix to study the likelihood of these elements appearing as well as their impact on the baby's health.

Evaluation of disposable baby diapers using risk assessment matrix

Referring to literature (Bettina et al., 2020) there is always different judgments and recommendations on health and environmental impacts of reusable and disposable diapers. Yet, most of these researches comes to diverse assumptions when it comes to evaluate the overall impacts. Baby diaper risk assessment seems to be very interesting to study in this case.

Although, the thresholds have not been exceeded for some substances in the tested samples of disposable diapers (Table 4), it was essential to draw the diapers risk analysis matrix. In fact, it has been found that there are multiple warns elements to be considered when wearing disposable diapers. Considering the diaper in real wear situation, the potential of some materials to be in contact with skin and the diaper wear time exposure, risky materials must be determined.

Table 4 Risk matrix for disposable diapers

Rısk ıdentıfıcatıon			Rısk ımpact			Rısk score			
Element	**Risk type**	**Probable risk description**	**Risk severity**	**Probability**	**Impact level**	**Impact level Score *II***	**Severity score *Sv***	**Final score**	**Probability**
Dioxin	Health	Hepatic function alteration Cancer causing	Undesirable	Possible	High	8	2	10	Risk will likely occur
Volatile Organic Compounds	Health	Asthmatic attack	Intolerable	Probable	Extreme	12	3	15	risk will occur
Heavy metal	Health	Hormonal perturbation Carcinogenic Skin rash	Intolerable	Probable	Extreme	12	3	15	risk will occur
Hydrogels	Health	Syndrome of toxic choc Skin irritation Potential allergies	Tolerable	Possible	Medium	5	0	5	Risk will likely occur
Lotion	Health	Potential allergies	Tolerable	Probable	Medium	5	1	6	Risk will likely occur

A process with a drop-down list of choices was prepared in order to fill the risk assessment matrix shown in Table 4. So, the safety profile of the disposable baby diaper system is implemented. Accordingly, heavy metals and volatile organic compounds have the most important risk scores: ($R_s = 15$). In fact, their risk has a significant potential of probability to occur. Dioxins have also a high level of impact and present a risk score equal to 10 and Lotions and hydrogels has the lowest impact risk to occur.

After the risk matrix definition, we identified the trigger for each element. This is an examination of the diaper part, which may be responsible for the risk. Those potentially toxic elements are commonly used and found on industrial scale. Table 5 summarizes the potential risky elements that were widely reported in literature and doubted to be the cause of skin rushes and dermatitis and identified in baby diapers (Chan et al., 2019; Counts et al., 2017; Dey et al., 2016).

Dioxin could be present in diapers as the derivation from the thermal chlorine bleaching process of fluff pulp that could cause cancer. In addition, heavy-metal components are probably traces from plastic production chain on waste phase and/or dying and printing. Thus, Nickel, cobalt, chrome could be hormone disruptive or cause skin rash. Volatile organic components (VOC's) are also a residue from reagent or solvent used in plastic industry such toluene (Odio et al., 2000; Paris, 2004).

During polymerization of hydrogels the carboxyl group of the super absorbent polymer is partially neutralized (75%) by the residual amount of free acrylic acid monomer (Ahmed, 2015). The super absorbent polymer turns into a gel in contact with urine. Its inhalation can cause inflammation of the respiratory tract in case of skin contact. Based on the weight of evidence approach, the Citral, which is the lemon aroma extensively used in fragrance formulations for top sheet surface treatment, can be a potential allergy trigger (Lalko & Api, 2008). To conclude, it is confirmed that the use of reusable diapers is considered as an effective ecologic solution avoiding any toxicity risk.

Results of physical assessment tests

Pilling test and shrinkage analysis The pilling degree of the developed diaper was evaluated by comparing the tested specimens with visual standards. An average pilling score assigned for the Dev-D7 was equal to 5 on both sides which refers to "no pilling" grade (Fig. 3). It has been found a consistent appearance despite six multiple washing cycle and

Table 5 Risk triggers for disposable diapers

Element type	Risk trigger	
	Responsible part on the diaper	**Trigger**
Dioxin	derived from the thermal chlorine bleaching process of fluff pulp	Chlorine
Volatile organic component	residue from reagent or solvent used in plastic industry (PE)	Toluene(ethylbenzene)
Heavy metal	traces from plastic production chain on waste phase and/or coloring and printing	Nickel, cobalt, chrome
Hydrogel	during polymerization of the super absorbent polymer (SAP), the carboxyl group is partially neutralized (75%) by the residual amount of free acrylic acid monomer that should be present in the SAP	Acrylic acid
Lotion	ingredients of surface treatment chemicals: fragrances and lotions	Citral

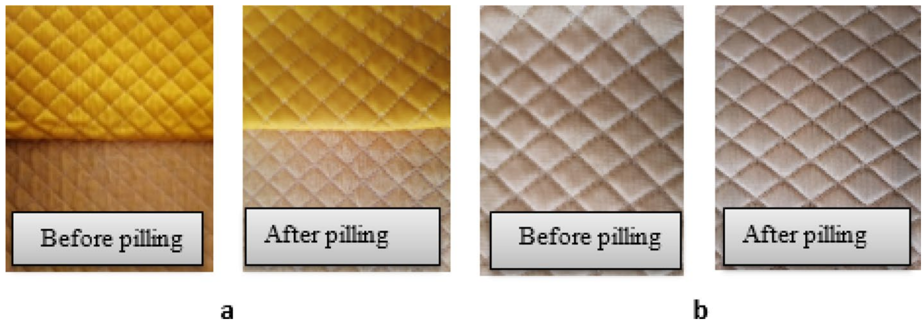


Fig. 3 Appearance before and after pilling test of the knitted pad. **a** Back side, **b** front side

after 5000 rounds of the pilling test (knit versus knit). Accordingly, the Dev-D7 revealed a significantly pill resistant in controlled laboratory tests. So, the pilling of the developed reusable diaper pad will resist to the friction caused by the baby's movement and the multiple washing (Schwartz, 2013).

Shrinkage test analysis No relative dimensional change is expressed for the Dev-D7 exposed to six multiple washing cycles. A very low shrinkage value of 0.1% was recorded for width dimensions and no change for length of specimens.

Absorption test analysis

As we can see from Fig. 4, the Dev-D7 has not shown the best absorption rate. However, it has a decent overall absorption which is comparable to other commercialized disposable diapers (Fig. 3). This can be explained by the 3D storage developed structure in which liquid is collected. In addition of, the organic cotton used between each bead among the front and backsides to improve the liquid immersion towards the next layer. Disp-D1 and Disp-D2 disposable diapers show the best absorption values. It has been also shown that absorption variations are related to other important parameters, which is the absorption speed rate (the strike through time). In fact, the use of two or three-dimensional structures allow the reusable diaper to assign a good absorption capacity.

Strikethrough time analysis Strikethrough time of the developed diaper Dev-D7 versus other tested diapers are presented in Fig. 5. As it is clear, the developed pad strikethrough time is the shortest (first emersion = 70 s and second emersion = 69 s). In fact, when the strikethrough time is short the liquid is quickly, kept away from the baby skin. The obtained results prove the efficiency of the new developed diaper. A compromise was found to optimize the diaper comfort in this wet environment and in dynamic condition to avoid baby's skin irritation. Since when the relative humidity and moisture content are high, the friction between the skin and the diaper increases. (Adams et al., 2007; Richard et al., 2002).

Rewetting test analysis According to Fig. 6, the developed Dev-D7 presents the best overall rewetting (wt1 (g) = 0.07, wt2 (g) = 0.35, w3 (g) = 1.9). Disp-D1 and Disp-D2 disposable diapers show similar good values of rewetting after different filter paper weight. The Disp-D4 and Disp-D5 diapers presenting the highest rewetting values. This is an

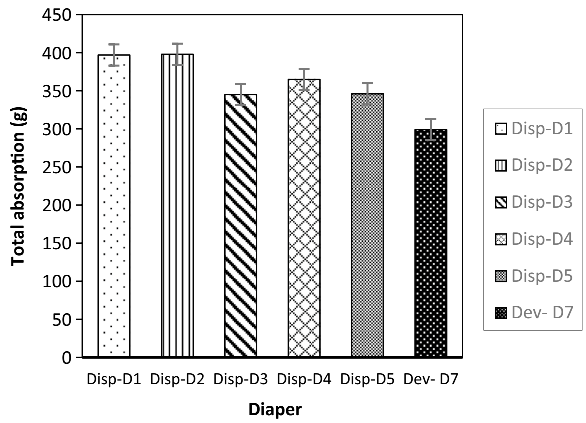


Fig. 4 Absorption values of the developed reusable diaper and commercial disposable diapers

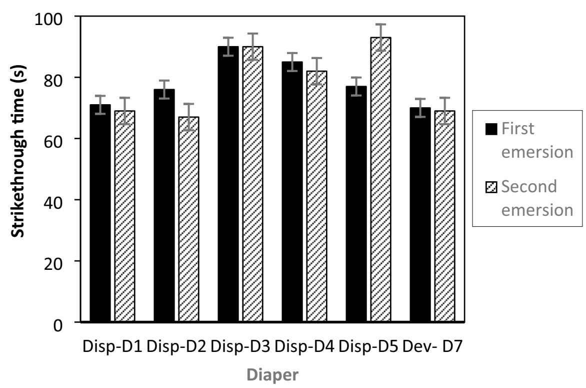


Fig. 5 Strikethrough time values of the developed and commercial diapers

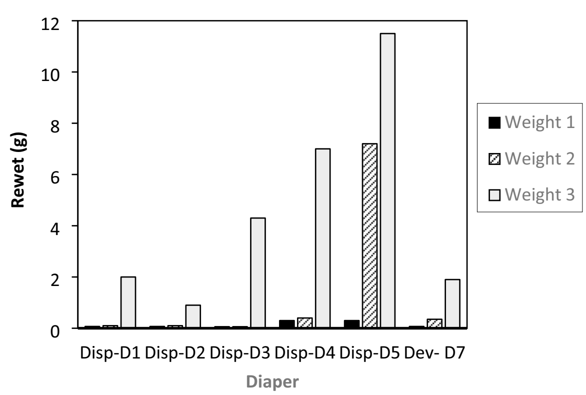


Fig. 6 Rewetting values of the developed and commercial diaper

important value, that can contaminate the baby's skin by transferring toxic elements to the surface as reported by (Yan et al., 2009). By analyzing the diapers composite structures the top sheet layer and the acquisition layer are considered as the key elements that influence the rewet parameter (Tilouche et al., 2020). All studied disposable diaper struc-

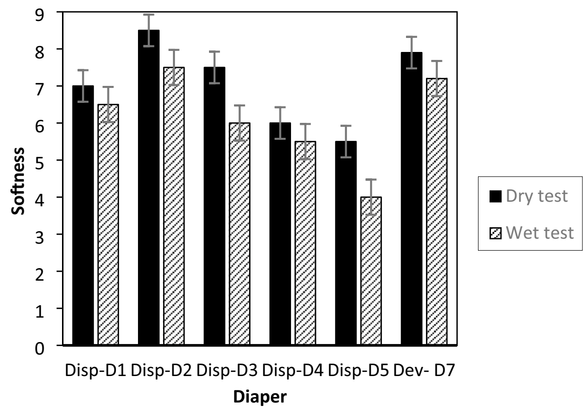


Fig. 7 Softness values of the developed and commercial diapers

tures are reinforced by an acquisition layer (100% PES high loft) that forbids the liquid to rewet (reflux approach). The same methodology has been used on the construction of the Dev-D7 diaper structure. The 100% cotton terry cloth has been used to increase the absorbance property, however, it has a very mediocre rewetting property this can lead to the baby discomfort in humid environment (Wright & Akin, 2005; Guo et al., 2013).

For this reason, we have used sandwiches structure for diaper construction and a spacer knitted fabric made by knitted lozenge PP fabric has been added in contact with baby skin. Thus, the use of hydrophobic fibers on the top avoids the liquid resurfaces phenomena. The PP fiber in the top, while not absorbing liquid it allows rapid moisture transfers (Claude, 2004). So, this structure absorbs properly the liquid and avoids the surface rewet (feeling dry system). Besides, the knitted lozenge structure is always remains sufficiently porous to provide the liquid passage. The added PA 66 textured multi filament yarn confers to the structure the properties of bulk and elasticity and act like an acquisition layer and also to prevent the rewetting phenomena. In fact, good rewetting properties minimize the indirect risk exposure by liquid reflux under body's load (Bae et al., 2018).

Softness test

The sensory panel has been used to evaluate the diaper surface softness. Although the Dev-D7 has not shown the best softness, it has a good hand touch in dry and wet conditions very similar to the best-commercialized disposable diapers. Disp-D3, Disp-D4 diapers had the lowest hand touch after humidification (Fig. 7). In fact, those diapers have illustrated a very mediocre rewet property. In our previous study, in order to simulate the real wearing environment, a total of 30 different expert panel assessment conditions combinations were repeated (wet and dry conditions). As an outcome of our research, results showed that diaper hand touch comfort decreases with the humidity intensification. It is possible to conclude that repeated urine insult (rewetting) appears as a dipping factor of softness parameter. Another research on the mechanical characterization of nonwoven surface quality with tribometer surface tester behaviour (Bueono, 2000)., showed that the dynamic friction coefficient, depends on the tested surface conditions (dry or wet). That can be translate the importance of the stick–slip phenomena (Fontaine

& al., 2009). The observed effects were in a good agreement with existing knowledge on the effect of moisture on the mechanical properties the studied structure. (Yokura, 2000).

Conclusions

This paper is a contribution to the ongoing discussions about the development of a new reusable diaper. The author´s attention was focused not only on baby health and on social effect on low-income families, but also on the positive environmental impact of using reuse diapers. Diaper rash and dermatitis were reported as the most common medical problem during the first three years of child life. Using the Risk Assessment Matrix and toxicology tests, the developed diaper Dev-D7 was compared to other diapers to validate its safety. It has been found that the developed diaper is free of dangerous elements. Also, its absorption and rewetting properties provided are consistent (good feeling dry is ensured).

Based on the results, it can be concluded that the safety assessment research on disposable and reusable diapers has been confirmed. In fact, the reusable diaper can offer a potential safe alternative for children and a practical product to be used by low-income families. Furthermore, many people are aware of the environmentally friendly product. The findings of our research are quite convincing and can be considered as alternative environmental solution. Thus, the developed reusable diaper is considered an environmentally friendly product, because there is no risk of allergic reactions to the baby's skin and it is not as harmful to the environment as disposable diapers. Despite the work that was carried out successfully and is still being conducted at present, there are many areas of interest to be explored.

Acknowledgements
Not applicable.

Author contributions
RT identified the topic of the study, conducted a literature review, and wrote the manuscript introduction, discussion, and conclusion sections of the manuscript. AG conducted the sapmles preparation and the all-machine parameters settings. AG and RT both designed prototypes. FD contributed to the project conceptualization and original draft preparation, developing the content for future studies, review, and editing of the manuscript. XJ and LJ supervised the project manuscript revision. MB supervised the overall project. All authors read and approved the final manuscript.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 8 July 2022 Accepted: 9 January 2023
Published online: 25 March 2023

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