

Article

Characterisation Study of Various Disposable Diaper Brands

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Abstract: Seven disposable diaper brands that are commonly used in Clermont, Kwa-Zulu Natal (South Africa) and some frequently found along river bodies (due to illegal dumping) were characterised through proximate analysis, thermogravimetric analysis (TGA), ultimate analysis and analytical pyrolysis–gas chromatography/mass spectrometry (Py–GC/MS). A novel approach entailing separation of the diapers into two fractions, interior (constituting mainly biomass fibres) and exterior (mainly constituting non-biomass polyethylene), assisted in assessing thermochemical conversion of the disposable diaper's potential as well as likely threats to the environment. In a comparison of the volatile matter between the two fractions, the exterior fraction is more combustible (due to a higher volatile fraction). Hence, it is more suitable for energy recovery. The present study investigates the use of pyrolysis to manage disposable diapers to potentially recover pyro-oil, pyro-gas and pyro-char. In this primary investigation, it was observed that each disposable diaper brand reacts differently to constant heating. However, the proximate and elemental analysis also highlights the likely negative environmental threats, such as that the high volatile content can potentially release dangerous permanent gases such as chlorine and cobalt into the atmosphere after the diaper is disposed of illegally and in landfill.

Keywords: disposable diapers; waste management; proximate analysis; thermogravimetric analysis; ultimate analysis; pyrolysis

1. Introduction

Evolving consumption patterns and population growth are significant contributors to the accelerated generation of municipal solid waste in high quantities. The rising waste quantities have resulted in a backlog in waste management. In addition to this, limited reliable data on the characteristics of municipal solid waste is hindering the progress of waste management, especially in developing countries [1]. The use of disposable diapers in developing countries such as South Africa has grown over recent years, which has added to the quantities of municipal solid waste disposed of in landfills. In South Africa, approximately 1.1 million tonnes of disposable diaper waste is produced per year [2]. Disposable diapers entered the markets in the late 1950s in the American and European nations; their evolution has progressed to the African markets, as well. Disposable diapers generated by infants are known to be relatively more convenient and accessible in terms of their single-use and absorbency properties for parents compared to conventional cloth diapers.

There are a few case studies and limited in-depth research literature that has been carried out to investigate the impacts of waste disposable diaper disposal. The impacts include material recovery and economic effects, as well as adverse environmental and health impacts of disposable diapers that have

been cited on a global scale. The outcomes of composting the organic fraction of disposable diapers have been investigated by the authors of [3]. Their study concluded that there are no technical issues in the biological process when assessing the stability of compost, however, the high concentrations of zinc in the compost and unknown behaviour of the super-absorbent polymers (SAPs) in soil raises concerns [3].

Another study carried out in reference [4] investigated the impacts of disposable diapers using the method of focus groups with mothers in the urban context of Harare, Zimbabwe. The results of the study suggest that disposable diapers could be collected and recycled as an alternative to managing their final disposal. In other cases, life cycle assessment studies on disposable diapers have been carried out [5–7]. For instance, a study conducted in reference [5] assessed the water resource depletion, energy consumption, solid waste, and land area used by disposable diapers, home-washed diapers, and commercially washed diapers. The results revealed that consumers play a vital role to decrease environmental impacts associated with diapers. The study in reference [5] highlighted that water depletion for disposable diapers, in particular, is about 35 m³ to 71 m³ followed by energy consumption of 3.1G J to 6.3 GJ along with solid waste generation of 0.72 t to 0.90 t and land use area for the production of raw materials was an estimated 407 m² to 829 m². On the other hand, reference [6] reveals that each life cycle assessment phases of diapers should be quantified and treated carefully. From the study, it was concluded and suggested that disposable diapers should be recycled to add environmental benefits to the process itself.

Several suggestions for reducing the environmental impacts of disposable diapers were investigated in reference [7]. From the study, it was concluded that valid measures of reducing environmental impacts are dependent on the product design, such as the constant upgrading of SAPs, which is designed to increase absorbent capacity and improve comfort in disposable diapers.

Recycling disposable diapers has been gaining momentum. For instance, in Italy the Fater Smart diaper recycling facility emerged in 2018 as one of the first industrial scale facility in the world [8]. In addition, a study in reference [9] points out that areas such as the Netherlands (Knowaste), Japan (Total Care), and the United Kingdom (Knowaste) have disposable diaper recycling facilities. Hence, these have measures in place to minimise the environmental impacts associated with the products.

Finally, progressive recent studies have shown a shift towards technologies that foster for material recovery as methods to handle disposable diaper waste. For instance, biodegradation, pyrolysis and composting are coined as more suitable despite being newer technologies and posing several drawbacks [10]. In addition, microwave pyrolysis is another potential method of recovering pyro-liquid and pyro-char from disposable diaper waste [11]. Moreover, the feasibility of pyrolysing disposable diapers through the application of kinetics as a means to understand their devolatilisation patterns in order to recover important materials and to incorporate the type of waste into the circular economy has also been explored [12].

Although disposable diapers are known to be an environmental and health threat, little has been explored about their devolatilisation patterns and their behaviour when they are thermo-chemically treated, particularly at elevated atmospheric conditions (i.e., high temperature and pressure). The motive in carrying out the thermo-chemical treatment study of the disposable diapers is to profile the negative environmental and health threats as a result of illegal dumping or landfilling of disposable diapers. Hence, this study seeks to devolatilise the exterior and interior fractions of various disposable diapers through qualitative and quantitative methods to dispose and manage diapers carefully.

In this research, a unique approach that consisted of studying thermal devolatilisation patterns of disposable diapers using the thermogravimetric analysis (TGA) method was followed. Quantitative analysis of the chemical composition was conducted using the analytical pyrolysis–gas chromatography/mass spectrometry (Py–GC/MS) and ultimate or elemental analysis (EA). These methods were used to assess both the interior and exterior fractions of the disposable

diapers. This study aimed to evaluate the socio-environmental impacts of disposable diapers when they are improperly landfilled as well as to illustrate potential benefits such as valuable chemical or energy recovery. Hence, characterising to determine the thermo-chemical (merely chemical composition) of disposable diapers will aid in the understanding of how the compounds react to atmospheric conditions; elevated conditions and the presence of leaching solvent, such as water, to determine their harmfulness along freshwater bodies. Therefore, this research will contribute significantly to bridging the gap in the literature and analysis on the impacts of disposable diapers when improperly disposed of along freshwater bodies and in landfills.

2. Materials and Methods

2.1. Materials and Sample Preparation

The samples of clean/unused disposable diapers brands were purchased from Pinetown CBD and Clermont, KwaZulu-Natal, South Africa. The diaper brands were as follows: My Kids, Sun Free, Huggies, Pampers, Best Baby, Sweet Baby and SR7. The disposable diaper brands mentioned above are the most commonly used in the Clermont area. Each disposable diaper brand had three full samples that were used for the experiments (preparation and re-testing). Additionally, the diapers were sampled by hand separation (interior and exterior fractions) and were crushed by cutting and cryogenic milled to fine particles (diameter less than 1 mm) and the total mass for all the samples was an estimated 354.57 to 357.90 g. Finally, the fractions were kept separately as the interior and exterior for each disposable diaper brand.

2.2. Methods

2.2.1. Thermogravimetric Analysis (TGA)

The proximate analysis was performed using the TGA, which was carried out on each diaper brand to determine the mass loss as temperature increases. The maximum temperature was set to 800 °C. Nitrogen (N₂) and the air, both generated in-house, were used as a carrier gas and as a combustion medium in order to trace the devolatilisation profile and to determine the ash content, respectively. A TA 60 WS model TGA (Shimadzu, Kyoto, Japan) was used for all experiments. The proximate analysis was done using calculation methods from reference [13] which is the universal standard used for this type of experiment.

2.2.2. Analytical Pyrolysis in the Pyrolysis Gas Chromatography/Mass Spectrometry (Py-GC/MS)

The disposable diaper fraction samples were directly pyrolysed using analytical pyrolysis unit EGA-PY-3030 D Multi-Shot Pyrolyser (Frontier Labs, Fukushima, Japan). The sample amount for all pyrolysis experiments was 1 mg for each of the fractions (interior and exterior) and was pyrolysed at 600 °C, and helium gas (99.999 wt.% purity, Air Products, South Africa) was used as a carrier gas. The interior and exterior fractions were analysed separately. The evolved hot volatiles were qualitatively and quantitatively analysed using a Shimadzu, GCMS-QP2010 series model (Shimadzu, Kyoto, Japan) gas chromatography coupled with mass spectrometry (GC/MS). The GC oven temperature program was set to maximise elution of major chemicals from the hot volatiles of the diaper fractions (both interior and exterior). Volatiles from analytical pyrolyser connected to the GC/MS were then introduced in a 60 m × 0.18 mm ID × 0.10 µm film thickness, non-polar Rxi-5Sil-MS capillary column using as a carrier gas at a constant volumetric flow of 1.2 mL/min (linear velocity of 27.9 cm/s) at 348 kPa. The GC injector was maintained at a temperature of 280 °C and was operated in a split mode with a split ratio of 1:20. The GC oven temperature was programmed as follows: 40 °C (held for 5 min) ramped by 0.7 °C/min up to 104 °C and at 10 °C/min to 300 °C, held for 5 min. The transfer line to the MS was kept at 300 °C, and the MS was operated in full scan mode from 35 to 350 *m/z* at a scan rate of

4.5 scans/s with standard electron ionisation energy of 70 eV. The electron multiplier (EM) voltage was 1188 V. The ion source temperature was set at 230 °C for all the experiments.

3. Results and Discussion

3.1. Proximate Analysis

In the present study, a proximate analysis was carried out on the seven most common disposable diaper brands. The proximate analysis focused on the four main fractions, namely, high volatile content, volatile matter, fixed carbon, and ash content. These fractions are essential to determining the devolatilisation patterns of disposable diapers when exposed to constant heating up to 800 °C.

3.1.1. High Volatile Content

As depicted in Table 1, the interior fractions of disposable diapers have the maximum high volatile content. For example, the brand with a maximum high volatile content was found to be the Huggies diaper (14.74 wt.%) followed by Sun Free (14.05 wt.%), Best Baby (12.33 wt.%), Sweet Baby (8.79 wt.%), SR7 (8.46 wt.%), My Kids (8.28 wt.%) and, lastly, Pampers (8.09 wt.%). The high volatile content measures the quantity of water in a sample in relation to the increasing temperature [14]. This indicates that the interior fractions of the diapers absorb a significant amount of water and are heavier in terms of weight, which highlights the devolatilisation activity at lower temperatures up to 200 °C. Consequently, this shows that the interior absorbing and drying agents play a significant role in increasing the high volatile content.

Table 1. Proximate analysis of the interior and exterior fractions of disposable diaper brands [12].

Disposable Diaper Brands	Interior Fraction (wt.%)				Exterior Fraction (wt.%)			
	High Volatile	Volatile Matter	Fixed Carbon	Ash	High Volatile	Volatile Matter	Fixed Carbon	Ash
Sun Free	14.05	67.62	12.83	5.50	0.96	79.92	12.61	6.51
My Kids	8.28	67.94	12.24	11.54	0.36	90.60	2.92	6.12
Best baby	12.33	67.95	7.69	12.03	0.41	81.07	9.64	8.88
Pampers	8.09	67.54	11.63	12.74	0.67	94.57	3.14	1.62
Huggies	14.74	61.54	10.63	13.09	0.22	88.82	8.54	2.42
Sweet Baby	8.79	73.64	11.05	6.52	2.49	75.89	11.46	10.16
SR7	8.46	73.08	11.93	6.53	1.19	90.40	1.54	6.87
Average	10.68	68.47	11.14	9.71	0.90	85.90	7.12	6.08

Bold type indicates the total average values which explain the overall outcome of the proximate analysis and see the main differences between the interior and exterior fractions.

On the other hand, Table 1 also highlights that the exterior fractions of the disposable diapers have less high volatile content when compared to the interior fractions. It is shown in Table 1 that the high volatile content of the exterior fractions ranges from a minimum of 0.22 wt.% to a maximum of 2.49 wt.%. Sweet Baby has the highest high volatile content of (2.49 wt.%) followed by SR7 (1.19 wt.%), Sun Free (0.96 wt.%), Pampers (0.67 wt.%), Best Baby (0.41 wt.%), My Kids (0.36 wt.%) and Huggies (0.22 wt.%). As illustrated in Table 1, there is a trend of the exterior fractions showing to be relatively less absorbent of water and lighter in weight. This can be attributed to the fractional composition of the exterior part (outer layer), which consists of polyethylene, elastics, adhesives and dyes for wetness indication [15]. While the interior part also is known as the absorbent core, consists of wood pulp or fluff pulp with absorbent polymer and gelling material, all to draw and contain the urine and faeces [16], hence, the maximum high volatile content. The arguments by authors of [15,16] correlate with the results from both Table 1 and Figure 1. They present that the interior fraction has a greater high volatile content compared to the exterior fractions with regards to the values of their overall average.

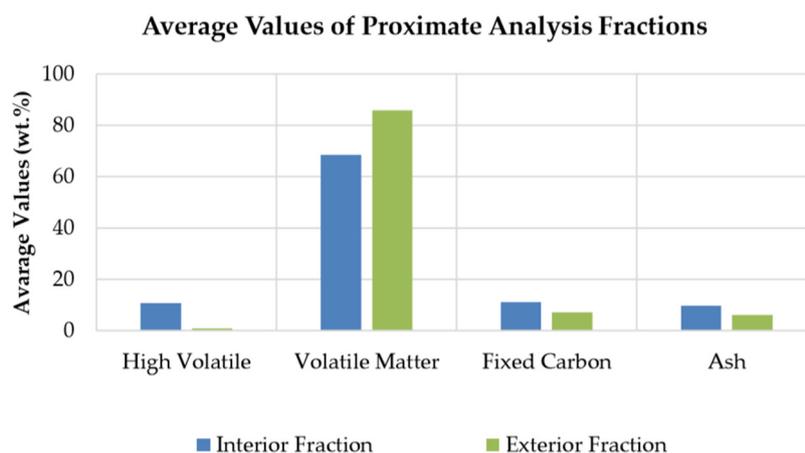


Figure 1. Average values of the proximate analysis fractions.

Furthermore, the high volatile content average value of the interior fractions is 10.68 wt.% while the average value for the exterior fractions is 0.90 wt.%, as illustrated in Table 1. From Table 1, it is demonstrated that only the Huggies (14.74 wt.%), Sun Free (14.05 wt.%) and Best Baby (12.33 wt.%) diaper brands have a greater high volatile content which is above the average values of the rest of the interior fractions. Whereas, it can be seen in Table 1 that most of the disposable diaper brands are below the average value (0.90 wt.%) even though the Sweet Baby (2.49 wt.%) and SR7 (1.19 wt.%) brands have a high volatile content at the higher range. However, exposure to excessive heat and high volatile laden wastes devolatilises and produce unpleasant odours [17]. Such conditions attract vectors such as green flies, which may accelerate the spread of diseases, especially to communities near open dumpsites [17].

3.1.2. Volatile Matter

The volatile matter is the combustible fraction, which remains after the high volatile is released at constant increasing temperatures. Table 1 and Figure 1 below illustrate volatile matter averages for both interior and exterior fractions of the diaper brands. In Table 1, it can be noticed that the exterior fractions have a significant high volatile matter with an average of 85.90 wt.%, which indicates that they are relatively instantaneously combustible. Table 1 also highlights that only the Pampers (94.57 wt.%), My Kids (90.60 wt.%), SR7 (90.40 wt.%) and Huggies (88.82 wt.%) disposable diaper brands have a volatile matter which is above the average value. These are the same brands that have high volatile content in the low range from 0.22 to 1.19 wt.%. According to reference [18], if samples consist of higher volatile matter, it indicates that they can readily ignite at a low temperature.

On the contrary, Table 1 and Figure 1 also highlight that the interior fractions have a lower volatile matter in terms of their average values. The volatile matter of the interior fraction, as depicted in Table 1, ranges from the lowest of 61.54 wt.% to the highest of 73.64 wt.%. Despite this, diaper brands, such as Sweet Baby (73.64 wt.%) and SR7 (73.08 wt.%), are shown to have a volatile matter percentage higher than the average value among the interior fractions. The relative lower volatile matter in the interior fractions may be related to high volatile content, as discussed in the above section. In addition, a high volatile matter content favours waste-to-energy production or thermochemical processes, such as gasification and pyrolysis. Methods such as gasification and pyrolysis are energy-intensive because they are designed to potentially reduce the volume of waste by converting it into syngas or oils after thermochemical conversion treatment [19]. For instance, syngas is a product of waste gasification which can be used for gas engines, turbines and power generation [20]. Although gasification is not widely used at a larger scale, it has the potential for future use as a mechanism for clean energy recovery from solid waste [20,21].

The use of pyrolysis as a form of thermal devolatilisation of solid waste in the absence of oxygen has the potential for fuel recovery [22]. According to reference [23], the pyrolytic liquid from the condensation of the volatiles can be developed into a fuel, referred to as pyro-oil, after upgrading and/or as an intermediate for the synthesis of fine chemicals. As a result, this suggests that as an additional benefit, volatile matter could be extracted in disposable diapers after they have been used. Finally, Table 1 shows that both the interior and exterior fractions have a high volatile matter. It is important to note that a high volatile matter is potentially readily leached to the river and immediately at the point of disposal in the communities before collection to the landfill since it evaporates rapidly. Subsequently, communities are highly prone to adverse environmental and health problems.

3.1.3. Fixed Carbon

Fixed carbon is the fraction that remains after the volatile matter, high volatile and ash are subtracted. From Table 1, it is observed that the interior fractions of the disposable diapers have higher fixed carbon content compared to the exterior fractions. This shows that interior fractions are more resilient to heat in terms of the fixed carbon fraction. Authors of [24] argue that a higher fixed carbon percentage acts as a significant generator of heat during combustion. On the other hand, authors of [25] argue that a higher fixed carbon percentage in a fuel makes the combustion process last longer. Furthermore, fixed carbon can be upgraded to activated carbon, which has proven to be useful, especially in waste water treatment and minimising pollutants in the environment. Reference [26] shows the uses of activated carbon for the removal of pesticides, other organic chemicals, taste, odour compounds, cyanobacterial toxins, and total organic carbon. Activated carbon is effective because it is characterised by large surface area, adsorption capability of contaminants and controlled high porous structures/materials [26].

3.1.4. Ash Content

The ash content may be relatively low, but it plays a significant role, particularly in the handling and processing costs of waste. Both Table 1 and Figure 1 illustrate that the interior fractions have higher ash content. As illustrated in Table 1, the ash content of the disposable diaper brands ranges from the highest at 13.09 wt.% to the lowest at 5.50 wt.% and a total average of 9.71 wt.% for the interior fractions. Although the results in Table 1 also indicate that diaper brands, such as SR7 (6.53 wt.%) followed by Sweet Baby (6.52 wt.%) and Sun Free (5.50 wt.%) have the lowest ash contents from the interior fractions. On the other hand, Table 1 highlights that disposable diaper brands, such as Huggies (2.42 wt.%) and Pampers (1.62 wt.%), have the ash contents at the low range for the exterior fractions because they are lower than the total average of 6.08 wt.%.

Hence, this indicates that if the ash content is low, it is likely to be used to speed up the rate of combustion. This is important because the ash fraction plays a significant role in combustion efficiency [25]. This is in agreement with reference [24] in the argument that the lower the ash content, the more it is suitable for industrial applications. If disposable diapers are to be incinerated as a final disposal method, then the generated ash would be undesirable because more residuals will be produced. However, authors of [27] argue that mixing municipal solid waste incineration ash and cement is an effective method that can be used in the construction of roads, bank filling and improving soil bearing capacity of the structure to produce energy. However, the incineration method has been criticised for emissions of pollutants to the atmosphere, which leads to the generation of contaminated groundwater and ashes [3].

Furthermore, since disposable diapers contain several polymers and organic compounds, such as wood pulp, their incineration process may generate other polluting substances, such as chlorine and cobalt [3]. In contrast, the interior fractions of the diaper brands, such as Huggies (13.09 wt.%), Pampers (12.74 wt.%), Best Baby (12.03 wt.%) and My Kids (11.54%) are the highest for ash fractions being discussed. According to reference [18], the high ash content causes slag deposits resulting in higher thermal resistance to heat transfer. Hence, it needs more expensive equipment for maintenance.

3.2. Ultimate Analysis

The ultimate analysis was carried out to determine total carbon, hydrogen, nitrogen, sulphur and oxygen present in the interior and exterior fractions of various disposable diaper brands. As observed in Table 2, two main elements were present in the ultimate analysis, namely, carbon and hydrogen. From Table 2, it is observed that in the interior fractions, the percentage of carbon is always the highest amongst disposable diaper brands, such as Pampers (54.12 wt.%), followed by My Kids (40.06 wt.%). Table 2 also depicts that disposable diaper brands, such as SR7 (37.88 wt.%), Sun Free (37.43 wt.%), Huggies (37.35 wt.%), Sweet Baby (36.35 wt.%) and Best Baby (36.22 wt.%), have a lower carbon content. According to reference [28], the highest concentration of carbon is essential for fuel combustion. This supports the proximate analysis results where it was shown that some of the disposable fractions with a higher volatile matter are more suitable for fuel production.

Table 2. Ultimate analysis of the interior and exterior fraction of disposable diaper brands.

	Interior Fraction		Exterior Fraction	
	Carbon (wt.%)	Hydrogen (wt.%)	Carbon (wt.%)	Hydrogen (wt.%)
Best Baby	36.22	5.18	74.53	10.92
Huggies	37.35	5.45	75.89	11.41
My Kids	40.06	5.81	73.55	11.18
Pampers	54.12	7.93	78.29	11.83
SR7	37.88	5.45	73.85	10.99
Sun Free	37.43	5.45	61.03	8.98
Sweet Baby	36.35	5.10	58.38	8.76

On the other hand, the percentages of carbon for the exterior fraction are almost twice the content of the interior fraction. From Table 2 below it is observed that the carbon percentages vary from 78.29 wt.% to 58.38 wt.%. From the results, it is presented that carbon percentages range as follows, Pampers (78.29 wt.%), Huggies (75.89 wt.%), Best Baby (74.53 wt.%), SR7 (73.85 wt.%), My Kids (73.55 wt.%), Sun Free (61.03 wt.%) and Sweet Baby (58.38 wt.%). Interestingly, the Pampers disposable diaper brand remains with the high carbon percentage for both interior and exterior fractions. This could indicate that the Pampers disposable diaper brand is more suitable to be processed as a source of fuel for industrial and household applications and for the combustible process itself. Additionally, the results of the proximate analysis for the exterior fraction, in particular, concurs with the elemental analysis because it was observed that the Pampers brand has the highest volatile matter of 94.57 wt.%.

Shown in Table 2 are the percentages of the hydrogen element. From the interior fraction, it is observed that most disposable diaper brands have hydrogen percentages of 5 wt.% except for the Pampers brand, which has 7 wt.%. In more detail, the results obtained from Table 2 highlight that the percentages of hydrogen as follows: Pampers (7.93 wt.%), My Kids (5.81 wt.%), Sun Free (5.45 wt.%), SR7 (5.45 wt.%), Huggies (5.45 wt.%), Best Baby (5.18 wt.%) and Sweet Baby (5.10 wt.%). On the other hand, the results from Table 2 depict that the exterior fraction has the highest hydrogen percentages as compared to the interior fraction. From Table 2, the following hydrogen average percentages are observed: Pampers (11.83 wt.%), Huggies (11.41 wt.%), My Kids (11.18 wt.%), SR7 (10.99 wt.%), Best Baby (10.92 wt.%), Sun Free (8.98 wt.%) and Sweet Baby (8.76 wt.%).

The common trend amongst the interior and exterior with regards to the hydrogen element, in particular, both Pampers and Sweet Baby brands remain as the highest and lowest percentages of this element, respectively. Hence, this may prove that disposable diaper brands with a high volatile matter and high carbon, especially for the exterior fractions, are the most suitable for energy recovery, in the use of fuels in particular. This is supported by reference [29] in the case study, where it is shown that low hydrogen percentages may present a problem since both hydrogen and carbon are considered as important elements in determining the energy content of solid waste.

3.3. Thermogravimetric Analysis

3.3.1. Interior Fraction

The thermogravimetric analysis (TGA) of the interior fractions is shown in Figure 2. From the results in Figure 2, it has been revealed that the TGA has four main stages. The first stage is due to the water/high volatile fraction loss at the temperatures between 0 °C and 105 °C. This is observed through the slight negative slope in the TGA curve, which is associated with the loss of water or some components that have evaporated. For instance, disposable diaper brands, such as Sun Free, My Kids, Huggies, Pampers, Sweet Baby and SR7 exhibit the first gradient of the 1st derivative thermogravimetric analysis (DTG) curve before reaching 200 °C whilst the Best Baby brand's DTG curve remains relatedly flattened. Hence, this stage is critical because it can be associated with the first light volatiles being evaporated.

As the temperature increases from 250 to 400 °C, in the TGA curve of the disposable diaper brands, another sharp negative slope was observed. The slope can be associated with the main devolatilisation stage, where volatile materials are being devolatilised. From Figure 2, it is observed that the DTG curve also magnifies TGA curve trends. In more detail, the Huggies disposable diaper brand shows multiple mass loss gradients in the DTG curve at a temperature of 200 °C. The results in Figure 2 also highlight that disposable diaper brands, such as Huggies and Best Baby, have their TGA curves decrease to even below 2 mg as the temperature constantly increases. At the same time, Best Baby, Huggies, Sweet Baby and SR7 brands all show the highest DTG gradient of which was found between 0.025 and 0.035 mg/s. Furthermore, at a temperature between 370 and 400 °C, maximum devolatilisation and pyrolysis rate were observed, as shown in Figure 2 through the steep gradients of the DTG curves of all the disposable diaper brands. The volatile matter in this range is devolatilised, and samples release vapour as temperature increases.

It has been mentioned above by reference [23] that high volatile matter content plays a significant role, particularly in fuel production. However, using volatile matter derived from disposable diapers as an alternative for organic residue instead of waste to energy is seen as harmful. High volatile content harmfully affects crop growth and yield, especially if derived from the process of pyrolysing disposable diapers [30]. Subsequently, from the two arguments, it clearly shows that, so far, disposable diapers may play a better role as an alternative in waste to energy conversion.

At the temperatures above 500 °C, it is observed that devolatilisation is minimal, and mass loss is insignificant. Hence, Figure 2 shows that disposable diaper brands, such as Sun Free, My Kids, Huggies, Sweet Baby and SR7, display TGA and DTG gradients except for the Best Baby brand, which remained constant. This is the stage where fixed carbon is combusted when oxygen is introduced and samples show that the material has relatively less fraction to devolatilise as the heat increases. Finally, the inorganic ashes or residue remaining are observed at the temperature between 580 and 800 °C, where both the TGA and DTG curves remain relatively constant for the disposable diaper brands as shown in Figure 2. The fourth stage can be attributed to the ash fraction. According to Table 1, disposable diaper brands, such as Huggies, have a high fixed carbon and ash content. From the study by authors of [30], it was observed that a high fixed carbon and ash content from used and treated disposable diapers might increase crop yields because the ash contains plant nutrients, such as potassium and calcium. In this study, it is evident that pyrolysis of disposable diapers has the potential to be treated as an alternative to be used in the agricultural sector.

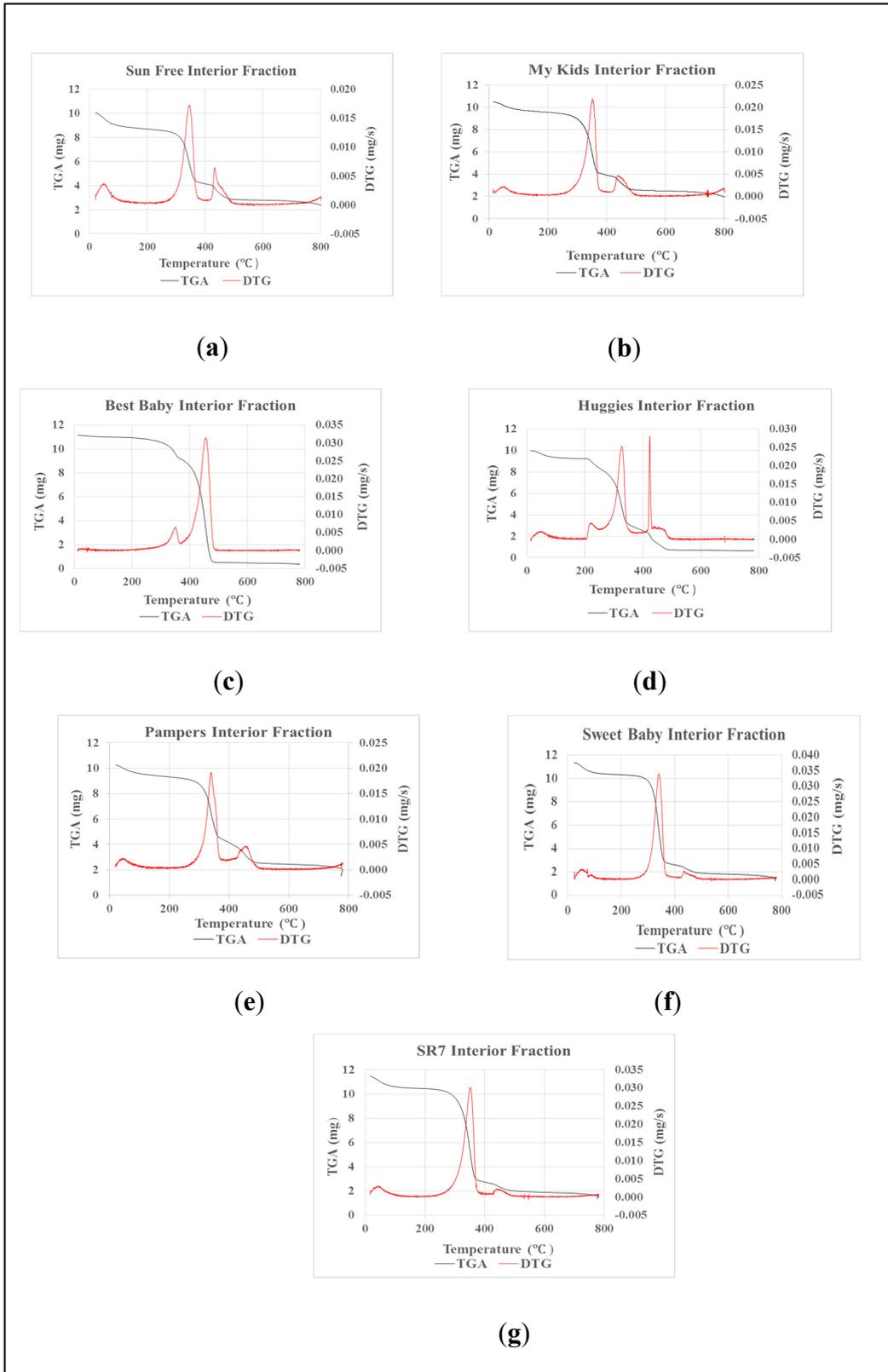


Figure 2. Thermogravimetric analysis (TGA) graphs of the interior fraction of disposable diaper brands. DTG—derivative thermogravimetric analysis.

3.3.2. Exterior Fraction

The TGA results of the exterior fraction are shown in Figure 3. From the TGA results, it is observed that the samples undergo relatively less mass loss as compared to the interior fractions in Figure 2. The TGA curves show a steady devolatilisation between the temperatures of 0 towards 105 °C and 250 °C. This could be associated with the loss of water and it is also supported by the results shown in Table 1 and Figure 1 which highlight the differences in the high volatile average values for interior and exterior fractions. The first mass loss stage of the TGA curve could also be related to the drying up of the samples. Hence, Figure 3 shows that disposable diaper brands Huggies, SR7 and Best Baby, in particular, only exhibit a single DTG gradient before reaching the temperature of 400 °C. On the other hand, the Sun Free, My Kids, Pampers and Sweet Baby disposable diaper brands all have small gradients approximately at 300 °C.

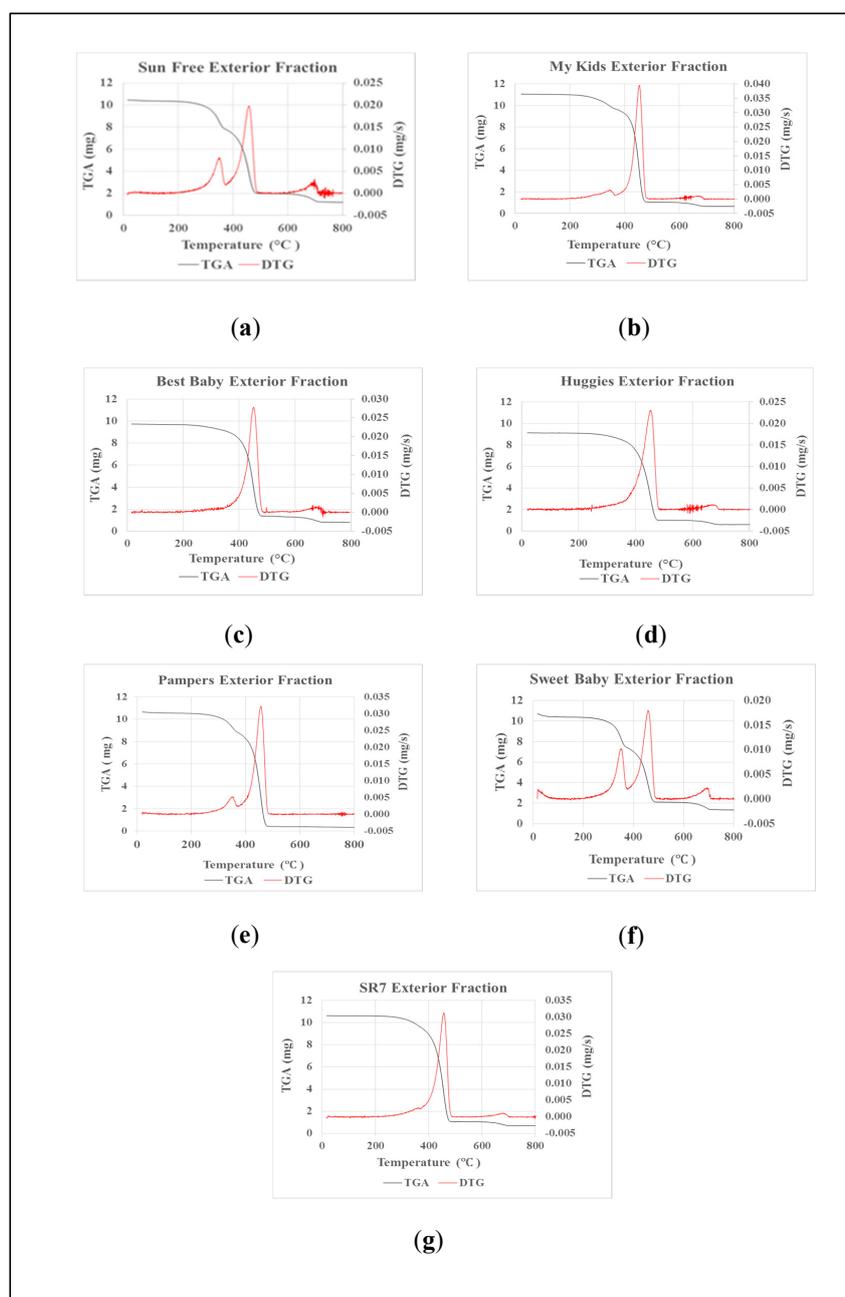


Figure 3. TGA graph of the exterior fraction of disposable diaper brands.

Similar to Figure 2, it is presented that as the temperature increases to 450 °C, the TGA curve slope became negative steeper. In contrast, the DTG curve highlights this significant difference in all disposable diaper brands. As was mentioned earlier, the gradients are associated with the evolving of volatiles during pyrolysis, especially at the temperatures between 450 and 500 °C. In the case of the DTG curve, the disposable diaper brands, such as My Kids, Pampers, and SR7, show the maximum gradient close to 0.040 mg/s. In the above sections, the value of the volatile matter has been widely discussed, especially concerning waste to energy recovery. This is further explained by reference [22] that there is evidence that would be less spontaneous combustion if the volatile matter is less.

Results shown in Figure 3 highlight the TGA and DTG curves of the exterior fraction, whereby the negative slope and gradient are observed up to 600 °C. The latter is associated with the combustion of fixed carbon. Then, both the TGA and DTG curve profiles are relatively flat. After 600 °C, the TGA and DTG show a relatively flat negative slope and small gradients, respectively. This trend is common in all disposable diaper brands except for the Pampers brand. This pattern is also seen in the interior fractions in Figure 2. However, the interior fractions only show these TGA relatively flat, negative slopes and DTG gradients at lower temperatures at approximately 500 °C. The pattern of the last gradients could be attributed to that, in both Table 1 and Figure 1, the exterior fractions with a higher volatile matter were observed. Furthermore, it is detected that the mass-loss rate in the TGA curve for all disposable diapers brands in Figure 3 decreases to below 2 mg, which is a contradictory pattern of the interior fractions. The last main stage is observed at 700 °C and above where the ash or residue remains, after the samples have been completely combusted.

The reaction progress was used to overlay all the TGA graphs of the disposable diaper brands of the interior and exterior fractions, as shown in Figure 4 below. This was achieved using normalised TGA graphs through the conversion of the devolatilisation extent into fractions. Figure 4 shows that the interior fractions have more distinguishable gradients in the TGA curves of the disposable diaper brands. For instance, from the beginning, it is clearly shown that the samples present a rapid high volatile loss, especially the SR7 disposable diaper brand. The interior fractions also demonstrate that multiple gradients characterise the Huggies brand up to the temperature of 400 °C.

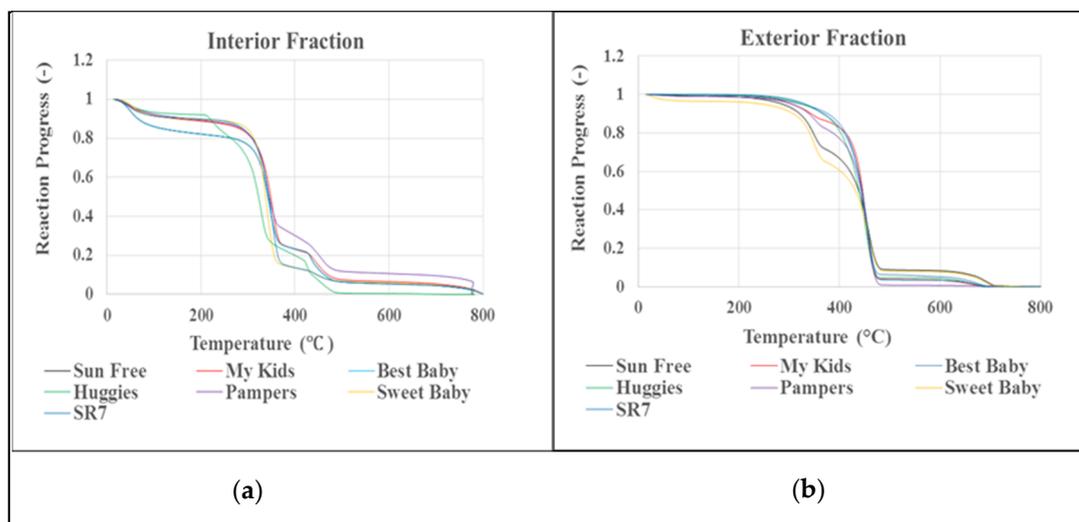


Figure 4. Reaction progress of (a) interior and (b) exterior fractions of disposable diaper brands.

On the other hand, the exterior fraction in Figure 4 shows that the disposable diaper brands do not show a rapid high volatile content loss. The results in Figure 4 also illustrate that between 370 and 500 °C, the TGA curves of the interior fractions profile rapidly decrease, and the SR7 brand remains the lowest, while the Huggies brand is the highest according to the reaction progress. The exterior fractions display a different pattern because, from 370 to 450 °C, the mass loss of the TGA curves decreases.

Finally, the TGA curves for both the interior and exterior fractions remain constant at temperatures above 500 °C.

3.4. Pyrolysis–Gas Chromatography/Mass Spectrometry (Py–GC/MS)

The retention time and peak area percentages were used to measure various compounds that resulted from the Py–GC/MS experiments of several disposable diaper brands. In each disposable diaper brand, the ten most significant compounds from both (interior and exterior fractions) were arranged from highest to lowest. From the top ten compounds, several of the most common compounds for both the interior and exterior fractions were analysed.

The results of the Py–GC/MS show that in the interior fractions of the disposable diaper brands, most of the compounds are classified as hydrocarbons, which have carbon and hydrogen bonds. For instance, Table 3 depicts that in the interior fraction disposable diaper brands, such as My Kids, has the highest area percentage of 2 propanamine (78.03 wt.%), followed by Sun Free with (+)-2-aminoheptane (68.13 wt.%), then Sweet Baby with pentanal at 66.64 wt.%. Whilst Pampers has cyclopropyl carbinol (58.09 wt.%), which is followed by Best Baby with cyclopropyl carbinol (49.71 wt.%), SR7 with cyclopropyl carbinol at 44.42 wt.%, and Huggies with 2,4 dimethylhept-1-ene (14.56 wt.%). The chemical compound cyclopropyl carbinol is the most common for the disposable diaper brands with the highest peaks, especially for brands such as Best Baby, Pampers and SR7 from Table 3. It is also observed that the most prevailing compounds are benzene, toluene, and phenol, 2-methyl-. These compounds are mainly found in disposable diaper brands, such as Best Baby, My Kids, Sun Free, Sweet Baby, SR7 and Pampers. Despite this, Table 3 also highlights that the Huggies disposable diaper brand also consists mostly of the following compounds, 1-undecene, 7-methyl, cyclooctane and 1-methyl-3-propyl.

Some of the compounds such as phenol, 2-methyl- are often present in high concentrations, which can be used for the production of heat, electricity, synthetic gas or chemicals [31]. This is vital, especially for waste-to-energy production, engine fuel, and household and industrial uses. In addition, phenolic compounds are valuable to the production of fuel, such as pyro-oil [31]. Hence, phenolic compounds are vital, especially in the pyrolysis process since it opens opportunities to use this method as an alternative to both incineration and landfilling. However, it is worth noting that phenolic compounds are also classified as “toxic hazardous” [32]. As a result, phenolic compounds must be safely managed.

Another compound that is mostly seen in disposable diapers is benzene. According to reference [33], benzene is a vital constituent of petroleum. This compound is mainly used in the production of petroleum (gasoline) and heating oils [33]. Despite the value of benzene in the petrochemical industry, it is still considered as one of the most dangerous compounds to use, especially to humans. Benzene is classified as a carcinogenic compound to humans as most of its exposure occurs through inhalation. Hence, it is not safe for workers and the general public [34].

The exterior fraction in Table 4 depicts that, the most prevailing compounds in the exterior fraction are 1-undecene, 7-methyl, propene, pentene, cyclohexane, 1, 2, 3, 5-tetraisopropyl- along with octatriacontyl trifluoroacetate. Additionally, the analysis results of the exterior fraction (illustrated in Table 4) show the significant compounds of disposable diaper brands as follows, SR7 with dimethylketene (75.18 wt.%); Sweet Baby, dimethylketene at 66.97 wt.%; Pampers with propene 2-methyl- (48.40 wt.%); Best Baby, 1-propene, 2-methyl-, at 48.00 wt.%; My Kids, 2, 4-dimethylhept-1-ene at 25.41 wt.%; Huggies with hydroperoxide, heptyl at 21.69 wt.% and Sun Free, 2, 4-dimethylhept-1-ene, 12.96 wt.%.

The retention times were as follows, 5.261 (SR7), 5.926 (Sweet Baby), 4.642 (Pampers), 3.798 (Best Baby), 17.765 (My Kids), 3.996 (Huggies) and 15.630 min (Sun Free), respectively. Table 4 depicts that the most common compounds are cyclohexane, 1, 2, 3, 5-tetraisopropyl- and octatriacontyl trifluoroacetate. The latter is seen in disposable diapers brands Sweet Baby, Sun Free, My Kids and Pampers. According to reference [32], some compounds, such as cyclohexane, 1, 2, 3, 5-tetraisopropyl,

toluene, benzene, and 1, 3–dimethyl- are classified as “toxic hazardous.” Therefore, the latter proves that the disposal of diapers needs to be handled and managed safely to mitigate environmental and health threats.

Table 3. Gas chromatography coupled with mass spectrometry (GC/MS) chromatogram compound list of the interior fraction of disposable diapers brands.

Disposable Diaper Brands	Compound Name	Retention Time (min)	Area (%)
Best Baby	Cyclopropyl carbinol	4.965	49.71
	Benzene	7.561	2.69
	Toluene	12.505	3.66
	2,4 Dimethylhept-1-ene	18.954	6.83
	1-Nonene	24.521	3.00
	1-Decene	31.337	2.01
	1-Pentadecene	53.596	1.39
	Octacosanol	117.827	1.90
	Octadecyl trifluoroacetate	121.492	1.89
	Docosyl heptafluorobutyrane	134.771	1.25
Huggies	2,4 Dimethylhept-1-ene	10.286	14.56
	(S)-(+)-1-Cyclohexylethylamine	5.185	7.54
	Nonane -4,ethyl-methyl	17.420	3.78
	2-Undecanethiol, 2-methyl	34.988	4.30
	1-Undecene,7-methyl	47.955	7.05
	1-Undecene,7-methyl	48.995	4.92
	Cyclooctane,1-methyl-3-propyl	88.614	5.96
	Cyclopentyleicosane	98.591	5.79
	Cyclooctane,1-methyl-3-propyl	107.620	6.16
	Cyclohexane,1,2,3,5-tetraisopropyl	130.714	6.09
My Kids	2-Propanamine	5.206	78.93
	Benzene	8.072	0.72
	Propanic acid, 2-oxo	10.284	3.01
	Toluene	12.715	2.94
	Benzene, 1,3-dimethyl-	21.593	0.78
	Benzene, (azidomethyl)-	24.047	0.93
	Phenol	32.150	0.69
	Phenol, 2-methyl-	35.302	0.96
	Phenol, 2-methyl-	35.302	0.96
	Phenol, 3-methyl-	36.511	0.91
Pampers	Cyclopropyl carbinol	2.073	58.09
	(S)-(+)-1-Cyclohexylethylamine	4.450	1.59
	Toluene	9.634	6.38
	Propanoic acid, 2-oxo-	12.284	5.12
	2,4-Dimethyl-1-heptene	16.336	7.28
	n-Heptyl hexanoate	31.023	4.36
	1-Undecene, 7-methyl-	47.699	1.79
	Octatriacontyl trifluoroacetate	124.794	2.40
	Cyclohexane, 1,2,3,5-tetraisopropyl-	132.848	1.39
	Cyclohexane, 1,2,3,5-tetraisopropyl-	137.328	1.41
SR7	Cyclopropyl carbinol	5.136	44.42
	Benzene	7.861	11.07
	Toluene	12.82	6.83
	Ethylbenzene	20.717	2.15
	Benzene, 1,3-dimethyl-	21.786	1.70
	1,3-Decadiyne	24.418	3.46
	Benzene, 1-ethyl-3-methyl-	31.314	1.72
	2-Nonene, (E)-	41.451	2.02
	1-Tridecene	47.371	1.40
	2(3H)-Furanone, 3-(dihydro-2(3H)-furanilydene)	52.932	1.59
Sun free	(+)-2-Aminoheptane	5.285	68.13
	2-Butanone	6.696	2.73
	Benzene	8.118	1.42
	Toluene	12.758	5.39
	Ethylbenzene	20.624	1.09
	Benzene, 1,3-dimethyl-	21.689	1.79
	1,6-Heptadien-3-yne, 5-methyl-	24.145	1.70
	Phenol, 2-methyl-	35.208	1.92
	Phenol, 2-methyl-	36.431	1.37
	Naphthalene, 1-methyl-	47.775	0.92

Table 3. Cont.

Disposable Diaper Brands	Compound Name	Retention Time (min)	Area (%)
Sweet Baby	Pentanal	5.136	66.64
	Benzene	7.861	6.30
	Toluene	12.820	3.19
	2,4-Dimethylhept-1-ene	18.536	0.98
	Ethylbenzene	20.717	1.05
	Benzene, 1,3-dimethyl-	21.786	1.00
	1,3-Decadiyne	24.418	1.95
	2-Nonene, (E)-	41.451	1.15
	2(3H)-Furanone,	52.932	0.84
	3-(dihydro-2(3H)-furanilyden	124.701	1.06
	Tetracosyl trifluoroacetate		

Table 4. GC/MS chromatogram compound list of the exterior fraction of disposable diapers brands.

Disposable Diaper Brands	Compound Name	Retention Time (min)	Area (%)	
Best Baby	Propene, 2-methyl	3.798	48.00	
	1-Pentene, 2-methyl	4.754	6.10	
	Cyclopropane (1-methylethylidene	5.679	3.74	
	2,4-Dimethylhept-1-ene	15.921	14.40	
	1-Decene	28.832	3.00	
	1-Undecene, 7-methyl	44.317	2.72	
	1-Undecene, 7-methyl	45.230	1.77	
	1-Tetradecene	49.720	1.54	
	1.19 Eicosadiene	61.329	1.78	
	Heptacosyl heptafluorobutyrate	130.602	2.98	
	Huggies	Hydroperoxide, heptyl	3.996	21.69
		Cyclooctapentane, methyl	4.720	2.94
		3-Heptyne	5.828	5.64
		2,4-Dimethylhept-1-ene	17.785	21.93
		1-Pentanol, 2-ethyl	22.550	7.46
3-Undecene, (E)-		29.274	3.93	
2-Undecene, 4,5-dimethyl, [R*, S*-(Z)]-		33.010	4.63	
1-Undecene, 7-methyl		45.219	8.74	
Cyclooctane, 1-methyl-3-propyl		95.057	3.00	
1-Cyclopentyleicosane		104.106	2.86	
My Kids	2,4-Dimethylhept-1-ene	17.765	25.41	
	1-Propene, 2-methyl-	3.724	10.59	
	1-Pentene, 2-methyl-	4.724	5.39	
	1-Pentanol, 5-cyclopropylidene-	5.758	5.32	
	-Undecene, 7-methyl-	45.792	3.82	
	Cyclooctane, 1-methyl-3-propyl-	95.764	3.12	
	Cyclooctane, 1-methyl-3-propyl-	104.856	2.76	
	Cyclohexane,	113.255	3.25	
	1,2,3,5-tetraisopropyl-			
	Cyclohexane,	120.958	2.90	
	1,2,3,5-tetraisopropyl-			
Cyclohexane,	127.995	2.88		
1,2,3,5-tetraisopropyl-				

Table 4. Cont.

Disposable Diaper Brands	Compound Name	Retention Time (min)	Area (%)
Pampers	1-Propene, 2-methyl-	4.642	48.40
	2,4-Dimethylhept-1-ene	19.618	11.87
	Bicyclo[4.2.0]octa-1,3,5-triene	25.088	7.49
	Toluene	12.700	4.03
	Cyclohexane,	123.430	2.44
	1,2,3,5-tetraisopropyl-		
	Cyclohexane,	130.523	3.08
	1,2,3,5-tetraisopropyl-		
	Cyclohexane,	47.471	2.38
	1,2,3,5-tetraisopropyl-		
1-Undecene, 7-methyl-	48.423	1.55	
1-Cyclopentyleicosane	107.255	2.12	
1,2-Cyclononadiene	7.139	7.21	
SR7	Dimethylketene	5.261	75.18
	1-Hexen-3-yne	7.568	8.45
	Toluene	12.899	5.07
	2,4-Dimethylhept-1-ene	18.940	3.24
	Benzene, 1,3-dimethyl-	21.951	2.30
	1,3,5,7-Cyclooctatetraene	24.472	2.72
	1-Decene	31.315	1.80
	Decane, 1,1'-oxybis-	47.919	1.24
	3-Tetradecene, (Z)-	35.389	0.46
	1,19-Eicosadiene	65.330	0.45
	Sun Free	2,4-Dimethylhept-1-ene	15.630
Propene		3.477	12.38
Pentane		3.874	4.98
1-Pentene, 2-methyl-		4.582	3.66
Octatriacontyl trifluoroacetate		115.911	1.52
Octatriacontyl trifluoroacetate		126.662	4.85
Octatriacontyl trifluoroacetate		127.128	1.72
Hexacontane		131.500	2.12
Octatriacontyl trifluoroacetate		134.547	21.77
Octatriacontyl trifluoroacetate		136.350	4.13
Sweet Baby	Dimethylketene	5.926	66.97
	1-Hexen-3-yne	8.300	4.19
	Toluene	13.692	2.37
	2,4-Dimethylhept-1-ene	19.640	3.78
	Bicyclo[2.1.1]hexan-2-ol,	25.046	1.95
	2-ethenyl-		
	1-Decene	31.042	1.57
	Octatriacontyl trifluoroacetate	127.401	6.00
	Triacetyl heptafluorobutyrate	133.170	2.30
	Octatriacontyl trifluoroacetate	134.761	4.10
Octatriacontyl trifluoroacetate	136.801	5.76	

4. Conclusions

Currently, the management of disposable diapers has become a problem in waste management, especially in developing countries. Disposable diapers pose negative environmental and health challenges. Thus, having a full understanding of their composition will aid in unlocking the potential alternatives to conventional methods of disposal, such as incineration and landfilling. Hence, in this study, seven disposable diaper brands were qualitatively and quantitatively analysed through proximate, thermogravimetric, and ultimate analysis and Py-GC/MS.

The findings of the study revealed that the exterior fraction is easily ignitable as compared to the interior fraction due to the presence of SAPs and fluff pulp in the interior fraction. From the proximate results, it was observed the interior fraction of diaper brands such as Huggies, Sun Free and Best Baby dominated in the high volatile, fixed carbon and ash contents. Contrary to this, in the exterior

fraction the Pampers, My Kids, SR7 and Huggies brands were above average values of the volatile matter content. These proximate analysis findings supported TGA and reaction progress observations where SR7 disposable diaper brand demonstrated a rapid high volatile loss. As a result of the latter, disposable diaper brands in the interior fraction TGA graphs exhibited multiple peaks as compared to the exterior fraction. Despite these differences, this indicates that disposable diapers have the potential to be thermo-chemically treated.

Moreover, the findings of the ultimate analysis provided some interesting observations whereby the Pampers diaper brand had the highest carbon and hydrogen contents both in the interior and exterior fractions. On the other hand, the Sweet Baby diaper brand had the lowest carbon and hydrogen contents from the two fractions. In both cases, the use of the ultimate analysis allowed a space to determine the potential to process waste disposable diapers as a fuel.

Furthermore, the compounds mentioned in the Py–GC/MS analysis are highly likely to be ones to be leached out during the improper disposal of disposable diapers. From the Py–GC/MS findings, it was observed that disposable diaper brands such as Best Baby, Pampers and SR7 had the cyclopropyl carbinol as the most prevailing compound in the interior fraction. However, from exterior fraction showed the Sweet Baby, Sun Free, My Kids and Pampers diaper brands with cyclohexane, 1, 2, 3, 5-tetraisopropyl- and octatriacontyl trifluoroacetate as the dominating compounds. From the Py–GC/MS results, it was concluded that some diaper brands are more suitable for material recovery. The current study confirmed that disposable diapers have the potential to be pyrolysed to produce pyro-oil, pyro-gas, and pyro-char. Hence, pyrolysis will minimise the environmental and health challenges associated with disposable diapers, while improving on energy production for households and industries. Therefore, the sustainability and feasibility study of a material recovery facility (MRF) for disposable diapers is recommended. In addition, the study should evaluate the thermochemical valorisation of diapers under pyrolysis as an alternative method.

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