

# Effects of alkaline hydrolysis and autoclaving on inorganic components present in healthcare waste

S. C. Pinho · M. F. Almeida · O. C. Nunes

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**Abstract** In this work, samples of components usually present in healthcare waste, such as cotton, diapers, transfusion tubes, surgical gloves, examination gloves, adhesives, surgical masks, urine bag collectors, serum bottles and syringes, were subjected to alkaline hydrolysis or autoclaving and the effects of these treatments were assessed. Both treatments were carried out at 135 °C, and the weight loss and the carbon loss of the components as well as the total organic carbon and the chemical oxygen demand in the effluents were determined. The biodegradability of effluents was assessed by measuring the biochemical oxygen demand after 5 days. Alkaline hydrolysis caused appreciable degradation in most of the components, with the adhesives and the diapers having the highest weight losses and carbon losses. Components made with low-density polyethylene, high-density polyethylene and polypropylene showed good chemical resistance with 2 M NaOH solution. The effluents obtained after alkaline treatment of healthcare waste are hazardous due to their very high alkalinity. The effluent obtained after treatment of a mixture of all components using a 2 M NaOH solution was biodegradable with the following parameters: 6.5 g C/l of total organic carbon, 29.8 g O<sub>2</sub>/l of chemical oxygen demand and 14.9 g O<sub>2</sub>/l of biochemical oxygen demand after 5 days. Although the autoclaving treatment degraded

the components much less than alkaline hydrolysis, the effluents obtained from some components showed an appreciable organic load.

**Keywords** Medical waste · Hospital waste · Wet treatment · Thermal analysis · Principal components analysis

## Introduction

Healthcare waste (HCW) includes all the waste generated by health care establishments, research facilities and laboratories (Pruss et al. 1999). HCW is a heterogeneous mixture of waste with different components produced in variable amounts, differing among countries according to their particular medical management practices (Pruss et al. 1999). Characterisation, composition and quantities of HCW generated per year and per country or region can be found in the literature (Lee and Huffman 1996; Diaz et al. 2008). About 75–90 % of HCW are not infectious and can be treated as municipal waste. The remaining 10–25 % are classified as hazardous waste. Hazardous HCW requires special attention due to the risk that represents for public health and environment. An inadequate HCW-handling operation is a potential contamination source for all people handling this type of waste, and an inappropriate treatment and disposal of HCW can contaminate soil and groundwater through leaching as well as the air through emissions to the atmosphere (Franka et al. 2009; Tamplin et al. 2005; Park et al. 2009). These types of problems arise particularly in rural areas of undeveloped countries, where the population is poor and the infrastructures are scarce (Manyele and Anicetus 2006; Blenkharn 2006; Gupta and Boojh 2006; Shinee et al. 2008).

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Autoclaving and incineration are the main processes used for treating HCW (Sukandar et al. 2006), the last being the oldest and, until now, the most used (Lee and Huffman 1996). In order to meet the Stockholm Convention on Persistent Organic Pollutants, the World Health Organisation promotes the use of non-incineration technologies to treat medical waste, eliminating the risk of dioxins and furans emissions that may be generated by medical incinerators. Under such guidelines, alkaline hydrolysis emerges as an alternative process for treating HCW in some countries, as reported in USA and in United Kingdom (Health Care Without Harm 2007). This treatment has been shown to have significant advantages compared to other HCW treatments, because it sterilises and destroys at once, and also reduces the total waste volume. It may have a range of application larger than autoclaving, since it can also accept organic tissues.

The complete inactivation of various microorganisms using alkaline hydrolysis has been proven in several studies (Taguchi et al. 1991; Taylor et al. 1997; Murphy et al. 2009). This technology is used to destroy animal carcasses, tissues, anatomical parts, blood, body fluids, toxic agents and fixatives (Thacker and Leon 2004; Kalambura et al. 2011). For this purpose, it requires an aqueous solution with sodium hydroxide or potassium hydroxide at temperatures around 150–300 °C to convert all the organic materials present into a sterile solution of small molecules such as proteins, amino acids, carbohydrates and fatty acids salts (Thacker and Leon 2004).

Studies on the degradation of polyethylene terephthalate (PET) using alkaline solutions showed the depolymerising of PET into small molecules as ethylene glycol (Kao et al. 1998; Kumar and Guria 2005; Karayannidis et al. 2002). Shin et al. 1998 studied the effect of NaOH concentration on the degree of polyvinyl chloride (PVC) dehydrochlorination at high temperatures (between 150 and 250 °C) using 0–7 M NaOH solutions, obtained the maximum rate with the 3 M NaOH solution. Gilev and Spaseska 2007 described the alkaline dechlorination of PVC in organic solvents at 30–80 °C for 1–5 h. The final products were polyvinyl alcohol with small chloride content and NaCl.

Gu et al. 2001 evaluated the changes on polyester films using 3 M NaOH solutions at room temperature measuring mass and total organic carbon losses, among other parameters. Their results showed an increase in mass and organic carbon losses with increasing exposure time. This fact was attributed to the hydrolysis of ester groups and the subsequent leaching of low-molecular mass and water-soluble fragments of the polyester material into the solution.

The cellulose degradation under alkaline hydrolysis results in acids with low-molecular weight; and, the composition of the degradation products is influenced by some reaction parameters, such as temperature, type of the

alkaline solution and concentration. Increasing the pH up to 11–12 increases the amount of high-molecular-weight compounds produced (Knill and Kennedy 2003).

Despite some achievements in degradation of materials with alkaline solutions, little is known about the interaction of materials under alkaline hydrolysis when digested together and the emissions resulting from this treatment. Also, the effects in common inorganic materials present in HCW during the autoclaving process as well as the final effluent composition and its treatability are not well known. This lack of knowledge makes authorities to have some reluctance in licensing autoclaving plants and in permitting their effluents to be discharged into domestic sewage.

In this work, the effect of a treatment similar to autoclaving in some inorganic components present in HCW was studied as well as when they were treated with NaOH alkaline solutions. The effect on components was assessed by measuring weight loss (WL) and carbon loss (CL). In addition, thermogravimetric (TG) and differential scanning calorimetric (DSC) analyses were performed on samples before and after the treatments. The effluent obtained after treating each component alone was characterised with respect to total organic carbon (TOC) and chemical oxygen demand (COD). Also, principal components analysis (PCA) was used to establish differences among the results obtained and to establish differences among the components and consequences of the two types of treatments.

Additionally, biochemical oxygen demand after 5 days (BOD<sub>5</sub>) was determined in the effluents resulting from testing a mixture of all analysed components in order to assess its biodegradability and the possibility of being discharged in a domestic wastewater treatment plant.

This work was carried out on 2010–2011 in the Department of Metallurgical and Materials Engineering, Faculty of Engineering, University of Porto.

## Materials and methods

### Materials

Healthcare waste materials include textiles, glass, metals, anatomical waste and others, but mostly plastics and paper (Pruss et al. 1999). These materials are present in diapers, transfusion tubes, surgical gloves, examination gloves, adhesives, surgical masks, bag collectors for urine, serum bottles and syringes, but also in some minor components, such as sensors for analysing characteristics from biological fluids (Gupta et al. 2003). Due to their clinical application, materials of these components are subjected to additional treatments during the manufacturing process, such as disinfection, application of anti-allergic substances, additives and others. Samples of most of those HCW

**Table 1** Components of the HCW used in the experimental work, their materials and carbon content

| Material                | Composition   | C, % <sup>a</sup> |
|-------------------------|---|-------------------|
| Serum bottle            | Low-density polyethylene (LDPE)   | 84.76 ± 1.11      |
| Syringe                 | Polypropylene (PP) and high-density polyethylene (HDPE)   | 89.01 ± 0.74      |
| Transfusion tube        | Polyvinyl chloride (PVC)  | 47.76 ± 1.38      |
| Bag collector for urine | PVC   | 50.76 ± 1.34      |
| Examination glove       | PVC   | 53.27 ± 0.15      |
| Surgical glove          | >90 % natural rubber  | 75.22 ± 1.63      |
| Cotton                  | 94 % cellulose  | 45.16 ± 0.53      |
| Surgical mask           | PP (outer and middle layer); polyester (PE) and pressed PP (inner layer); polyurethane (tapes)                                | 84.54 ± 0.72      |
| Diaper                  | Cellulose fibre and PP (70–80 %); PE film; thermoplastics adhesives; elastic threads; flocgel (5–10 % of sodium polyacrylate) | 43.27 ± 1.35      |
| Adhesive                | Non-woven polyester; synthetic adhesive from rubber   | 77.67 ± 0.05      |

<sup>a</sup> Mean of three determinations ± standard deviation (SD)

components, including cotton, were considered in this study.

Table 1 shows qualitative data on the HCW components used in the trials, according to the respective suppliers, as well as their total carbon (TC) determined in several samples.

## Methods

### *Alkaline hydrolysis and autoclaving-like treatments*

The treatments were performed in a Parr batch reactor with a titanium vessel of 450 ml capacity under temperature control and with a pressure gauge. The reactor operated at 135 °C, with a heating rate of 10 °C/min up to 135 °C and holding time of 30 min. A liquid/solid ratio of 10:1 (w/w) was used in all the tests. The NaOH concentration in the alkaline solutions tested consisted of 0.1 M, 1 M and 2 M, the last two being also studied by other authors (Taguchi et al. 1991; Taylor et al. 1997). The autoclave-like treatment was performed under the same conditions in the absence of NaOH; therefore, the solids were usually immersed in water and not only in a water vapour-saturated atmosphere. Despite that, it is believed that the consequences of this treatment are not much different than from those obtained from classic autoclaving. For simplicity, the autoclave-like treatment is herein referred to as autoclaving.

All the tests were made using samples with 2 g of each component; 5 g was used when a mixture was studied (0.5 g of each component). Since syringes were composed of two distinct materials, a sample with equal weight of each was taken. Except for cotton, the components were cut into fragments of approximately 1 cm<sup>2</sup> before the tests.

After cooling to ambient temperature, the resulting product was filtered, and in the case of alkaline hydrolysis, the solid fraction was washed with distilled water in order to remove all of the sodium hydroxide. Subsequently, it

was dried, held for 48 h in a desiccator at room temperature and finally weighted. Figure 1 shows a diagram of the process. The pH, TC, TOC and COD, as well as chlorides in case of the clinical materials composed by PVC, were determined in the solutions resultant from the treatments. All the experiments were repeated three times, and the results showed in the tables are the mean values of the three tests under the same conditions.

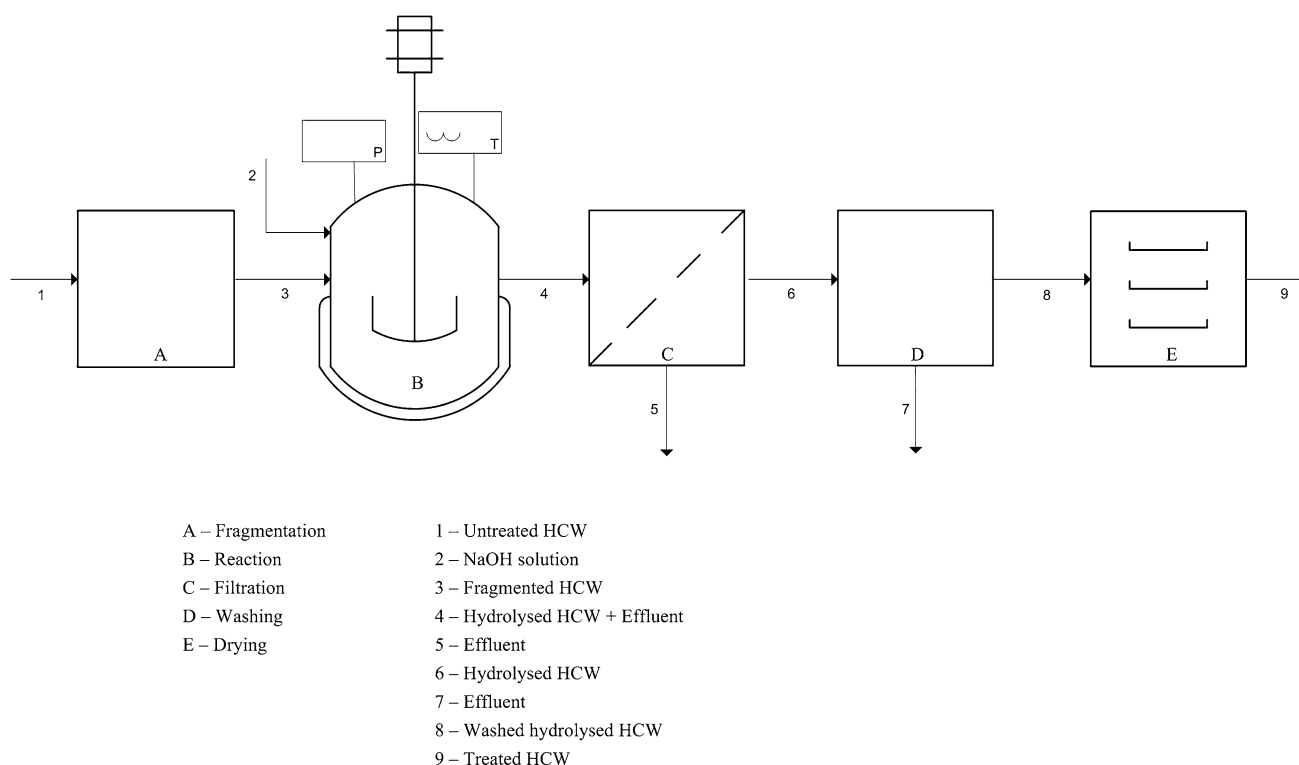
Total carbon and total organic carbon in solutions were determined with a Shimadzu TC analyser model TOC-VCSH, according to EN 1484 1997. TC in the materials was determined with the same equipment using its solids module, according to EN 1313 2001. Measurements of pH were taken with a pH meter model 632 of Metrohm. Chlorides were determined following 4,500 B: Argentometric method. COD was determined following 5,220 D: Closed reflux—colorimetric method; and BOD<sub>5</sub> was determined following 5,210 B: 5-day BOD method as described by the Standard Methods for Examination of Water and Wastewater (APHA 1998).

### *TG and DSC analyses*

Thermogravimetric and differential scanning calorimetric analyses on the selected components were performed using two equipments (Setaram, model 92-16.18 and model Lab-sys, respectively). Samples with almost the same volume, ranging from 9 to 40 mg due to their different densities, were placed in a platinum crucible (TG), or aluminium crucible (DSC), heated at a rate of 10 °C/min up to 135 °C and held 3,600 s at that temperature; for syringes and surgical masks, composed by polyethylene and polypropylene (PP), the DSC analyses were prolonged by heating up to 200 °C at the same rate, in order to reach the end of melting peaks of both materials (data not shown).

Blank tests were carried out for both TG and DSC analyses with unloaded crucibles using the same





**Fig. 1** Diagram of the alkaline hydrolysis process

conditions. Thermal analysis was carried out on original components samples, in those from autoclaving and in those from alkaline hydrolysis with 1 M NaOH solutions. All the TG analyses were carried out in triplicate. The profiles shown are a mean of the 3 values of WL at the same temperature, corrected with the values obtained in the blank test.

#### Statistical analysis

The effect of autoclave-like and alkaline hydrolysis treatments on the tested components, based on WL, CL, TOC and COD parameters, was assessed through PCA using the software package CANOCO, version 4.5.

## Results and discussion

### HCW components transformations and effluents produced

Table 2 reports the WL values of the tested components after alkaline hydrolysis and autoclaving treatments, computed as the percentage of their initial weight. The low-density polyethylene (LDPE) serum bottle and the high-density polyethylene (HDPE) plus PP syringe samples had the smallest WL values not only after autoclaving but also

at all the three NaOH concentrations tested. These results demonstrate the excellent chemical resistance of such materials to alkalis (Ehrenstein 2001).

The surgical mask samples, composed of several materials (not exclusively PP), had non-detectable WL under autoclaving but were degraded through alkaline hydrolysis. These treatments degraded the adhesives and diapers significantly, mainly when the 1 M and 2 M NaOH solutions were used. The WL obtained for diapers and adhesives with these two solutions were above 20 %, being similar to or higher than the range of 20–35 % reported for autoclaving after HCW size reduction (Pruss et al. 1999). The assayed adhesive samples shrank drastically during the alkaline treatments, being kept agglomerated with part of its glue or any other binding agent. Most polyester present in composition was probably lost into the solution (Bendak 1991).

Table 3 reports the CL values of the tested components after both treatments, calculated as the percentage of their initial carbon content, shown in Table 1. The values of CL followed the trend seen for the WL values (Table 2), i.e. the highest and lowest CLs were observed on the components that had the highest and the lowest WL, respectively. CL is a relevant part of the WL and contributed significantly to the high organic load of the effluents resultant from alkaline hydrolysis treatment, particularly for adhesives and diapers (Tables 4, 5).



**Table 2** Weight losses (WL) in the samples of HCW components subjected to autoclaving and alkaline hydrolysis tests at 135 °C

| Material                | WL, % <sup>a</sup> |              |              |              |
|-------------------------|--------------------|--------------|--------------|--------------|
|                         | Autoclaving        | 0.1 M NaOH   | 1 M NaOH     | 2 M NaOH     |
| Serum bottle            | N.D.               | 0.05 ± 0.01  | 0.03 ± 0.00  | 0.01 ± 0.00  |
| Syringe                 | N.D.               | 0.07 ± 0.00  | 0.10 ± 0.00  | 0.10 ± 0.00  |
| Transfusion tube        | 0.06 ± 0.01        | 0.60 ± 0.08  | 0.75 ± 0.18  | 1.12 ± 0.07  |
| Bag collector for urine | 0.18 ± 0.04        | 0.48 ± 0.07  | 1.35 ± 0.10  | 4.85 ± 0.45  |
| Examination glove       | 1.41 ± 0.15        | 1.60 ± 0.08  | 5.73 ± 0.80  | 9.16 ± 1.20  |
| Surgical glove          | 2.33 ± 0.17        | 2.42 ± 0.08  | 2.90 ± 0.00  | 3.58 ± 0.41  |
| Cotton                  | 1.59 ± 0.10        | 2.80 ± 0.29  | 5.36 ± 1.70  | 9.37 ± 0.96  |
| Surgical mask           | N.D.               | 1.82 ± 0.17  | 6.24 ± 0.84  | 8.14 ± 0.94  |
| Diaper                  | 9.40 ± 0.82        | 11.90 ± 0.73 | 21.70 ± 1.33 | 32.10 ± 0.00 |
| Adhesive                | 0.28 ± 0.05        | 6.03 ± 0.60  | 45.87 ± 9.91 | 53.79 ± 8.50 |

<sup>a</sup> Mean of three experiments ± SD

N.D. not detected

**Table 3** Carbon losses (CL) in the samples of HCW components subjected to autoclaving and alkaline hydrolysis tests at 135 °C

| Material                | CL, %        |            |          |          |
|-------------------------|--------------|------------|----------|----------|
|                         | Autoclaving  | 0.1 M NaOH | 1 M NaOH | 2 M NaOH |
| Serum bottle            | 0.01         | 0.14       | 0.21     | 0.28     |
| Syringe                 | 0.01         | 0.16       | 0.21     | 0.22     |
| Transfusion tube        | 0.04         | 1.05       | 1.07     | 1.13     |
| Bag collector for urine | 0.11         | 0.93       | 2.52     | 3.31     |
| Examination glove       | 0.71         | 1.73       | 2.14     | 4.17     |
| Surgical glove          | 0.35         | 1.05       | 1.77     | 1.65     |
| Cotton                  | 0.38         | 3.03       | 7.15     | 8.57     |
| Surgical mask           | 0.04         | 1.61       | 6.42     | 6.47     |
| Diaper                  | <sup>a</sup> | 15.25      | 24.98    | 43.86    |
| Adhesive                | 0.09         | 5.15       | 49.27    | 59.79    |

<sup>a</sup> CL was not determined because the diaper sample absorbed all the solution

As expected, all the effluents resultant from the alkaline hydrolysis assays showed high pH values, being approximately 12.7, 13.3 and 13.8 when 0.1 M, 1 M or 2 M NaOH were used, respectively. On the contrary, those from the autoclaving tests were close to neutrality. The alkaline effluents showed higher organic load than the autoclaved ones. In general, a positive correlation between the TOC and COD values and the NaOH concentration used was observed. TOC of the effluents resulting from the treatment of serum bottles and syringes were below 100 mg C/l under all the conditions tested. This result is overall agreement with the small WL obtained for such components. On the contrary, the effluents resulting from the treatment of diapers and adhesives showed the highest TOC and COD,

which is also in agreement with the WL verified in both treatments. Chloride concentrations in the effluents from treatments of components made with PVC (such as the transfusion tubes, the examination gloves and the urine bag collectors) were below 10 mg/l (limit of detection for the method of analysis used). This fact confirms that there was a very slight PVC decomposition under the studied conditions. Therefore, chlorides will not become a problem in the treatment of the respective effluents when these technologies are to be applied to treat HCW.

Table 6 shows TOC, COD and BOD<sub>5</sub> values of the effluents resultant from the treatments of a mixture of samples of all components. The estimates of TOC and COD values were calculated as a linear combination of the average values of these parameters in the effluents from individual tests of samples of each component. They were a reasonable first approximation to the TOC and COD values for the effluents resultant from the alkaline hydrolysis of a mixture of these components. Using the COD and BOD<sub>5</sub> values for calculating BOD<sub>5</sub>/COD ratio, one obtains 0.44, 0.53 and 0.50, respectively, for the alkaline hydrolysis effluents and 0.35 for the autoclaving effluent. Thus, despite the fact that the effluents obtained from alkaline hydrolysis had a much higher organic load, they were more biodegradable than the ones from autoclaving. Since all ratio values are above 0.4, the alkaline effluents, after neutralisation, could be accepted in a common domestic wastewater treatment plant.

#### TG and DSC analyses

The changes in weight and heat flow detected in the blank tests of TG and DSC analyses were negligible. The WL values of the three TG replicate tests of a given component at a given temperature showed very low scatter with





**Table 4** TOC, in mg C/l, and pH in the effluents resulting from autoclaving and alkaline hydrolysis of individual samples of HCW components

| Material                | Autoclaving  |              | 0.1 M NaOH           |      | 1 M NaOH             |      | 2 M NaOH               |      |
|-------------------------|--------------|--------------|----------------------|------|----------------------|------|------------------------|------|
|                         | TOC          | pH           | TOC                  | pH   | TOC                  | pH   | TOC                    | pH   |
| Serum bottle            | 6            | 5.5          | (21–46) <sup>b</sup> | 12.8 | (37–52) <sup>b</sup> | 13.4 | (33–73) <sup>b</sup>   | 13.4 |
| Syringe                 | 13           | 7.7          | 40                   | 12.7 | 45                   | 13.1 | 78                     | 13.9 |
| Transfusion tube        | 23           | 7.6          | 124                  | 12.7 | 339                  | 13.3 | 473                    | 13.7 |
| Bag collector for urine | 54           | 7.4          | 232                  | 12.6 | 475                  | 13.3 | 1,517                  | 13.8 |
| Examination glove       | 380          | 7.3          | 814                  | 12.8 | 1,061                | 13.4 | 2,129                  | 13.8 |
| Surgical glove          | 265          | 7.2          | 798                  | 12.8 | 1,071                | 13.4 | (513–750) <sup>b</sup> | 13.9 |
| Cotton                  | 171          | 6.1          | 1,051                | 12.7 | 2,782                | 13.3 | 3,649                  | 13.8 |
| Surgical mask           | 37           | 6.0          | 1,487                | 12.7 | 4,940                | 13.4 | 5,311                  | 13.9 |
| Diaper                  | <sup>a</sup> | <sup>a</sup> | 6,381                | 12.6 | 7,943                | 13.3 | 17,325                 | 13.7 |
| Adhesive                | 68           | 5.5          | 3,895                | 12.1 | 38,133               | 13.0 | 45,951                 | 13.8 |

<sup>a</sup> Not determined because the diaper sample absorbed all the solution

<sup>b</sup> Due to the variability of the results, values are presented as its range

**Table 5** COD in the effluents from autoclaving and alkaline hydrolysis tests of samples of individual components

| Material                | COD, mg O <sub>2</sub> /l |                        |                        |                        |
|-------------------------|---------------------------|------------------------|------------------------|------------------------|
|                         | Autoclaving               | 0.1 M NaOH             | 1 M NaOH               | 2 M NaOH               |
| Serum bottle            | 90                        | (101–151) <sup>b</sup> | (156–214) <sup>b</sup> | (154–480) <sup>b</sup> |
| Syringe                 | 109                       | 146                    | 207                    | 247                    |
| Transfusion tube        | 181                       | 269                    | 1,242                  | 1,859                  |
| Bag collector for urine | 423                       | 553                    | 1,210                  | 2,437                  |
| Examination glove       | 563                       | 3,790                  | 4,909                  | 11,440                 |
| Surgical glove          | 1,956                     | 3,827                  | 5,383                  | 7,357                  |
| Cotton                  | 828                       | 2,943                  | 8,875                  | 15,107                 |
| Surgical mask           | 235                       | 2,517                  | 16,778                 | 21,850                 |
| Diaper                  | <sup>a</sup>              | 30,646                 | 34,147                 | 41,971                 |
| Adhesive                | 337                       | 14,192                 | 88,192                 | 143,756                |

<sup>a</sup> Not determined because the diaper sample absorbed all the solution.

<sup>b</sup> Due to the variability of the results, values are presented as its range

variation coefficients of less than 0.7 % in all temperatures ranges up to 135 °C, thus confirming the very good reliability of the analytical method.

All the average TG profiles of health care components after being subjected to autoclaving and alkaline hydrolysis were not differentiable from the original ones, except in the case of diapers and cotton. These cellulose-containing components before the treatments had WL values of approximately 5.7 and 6.2 %, respectively. In case of cotton (Fig. 2), most of the WL is due to water evaporation (Deng et al. 2008). The diaper decomposed more in the alkaline hydrolysis treatment than in the TG analysis; alkaline hydrolysis

increased the decomposition of part of the materials from diapers, mostly sodium polyacrylate from flocgel, keeping a residual material stable at least up to 135 °C.

All the other components had higher WL after alkaline hydrolysis compared to the TG analysis, which means that they were chemically attacked and increasingly degraded by such solutions. Evaluated in the same way, autoclaving significantly affected the examination gloves and the surgical gloves, slightly affected the urine bag collectors and did not affect all the remaining sample components. Syringes, transfusion tubes, surgical masks and adhesives presented slightly less WL after autoclaving than in TG. As a consequence, effluents resultant from the treatment of examination gloves, surgical gloves and urine bag collector was those with the highest COD among all the effluents resulting from autoclaving, as shown in Table 5. The LDPE serum bottle and the HDPE plus PP syringe samples, both before and after the treatments, showed negligible WL under the temperature cycle imposed, as shown in the Fig. 2. This pattern is characteristic of health care components with very good chemical and thermal resistance in the range of conditions tested.

The TG profiles of the PVC components before the treatments were close to those observed in a previous study where similar conditions were used (Deng et al. 2008). Although being based on the same material (PVC), the urine bag collectors and the examination gloves had different TG profiles and WL values after the alkaline hydrolysis when compared to the transfusion tubes. This behaviour is surely due to differences in its composition, namely the additives.

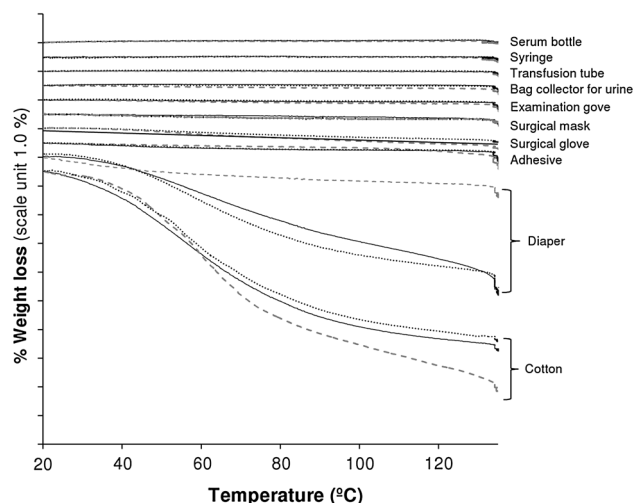
The surgical mask TG profiles showed the same trend of the other reasonably stable components with similar WL before and after the alkaline hydrolysis. TG analyses of adhesives and surgical gloves showed WL of the same



**Table 6** TOC, as mg C/l, and COD and BOD<sub>5</sub>, as mg O<sub>2</sub>/l, in the effluents from autoclaving and alkaline hydrolysis tests of mixtures with samples of the components

|                         | Autoclaving  | 0.1 M NaOH  | 1 M NaOH       | 2 M NaOH       |
|-------------------------|--------------|-------------|----------------|----------------|
| TOC                     | 464 ± 42     | 1,692 ± 245 | 5,286 ± 900    | 6,504 ± 83     |
| TOC <sub>estimate</sub> | <sup>a</sup> | 1,487 ± 7   | 5,687 ± 30     | 7,019 ± 21     |
| COD                     | 958 ± 53     | 5,050 ± 900 | 12,967 ± 1,991 | 29,779 ± 1,212 |
| COD <sub>estimate</sub> | <sup>a</sup> | 5,725 ± 30  | 16,074 ± 72    | 24,682 ± 64    |
| BOD <sub>5</sub>        | 333 ± 32     | 2,237 ± 366 | 6,906 ± 1,407  | 14,875 ± 883   |

Mean of four tests ± SD

<sup>a</sup> Diaper effluent was all absorbed; thus, there was no values for using in computation**Fig. 2** TG profile of HCW components: (solid lines) original, (dashed lines) hydrolysed and (dotted lines) autoclaved

magnitude, both for treated and untreated samples. Nevertheless, adhesives visibly decomposed more than surgical gloves when held at 135 °C for 3,600 s. This behaviour also found in the untreated diaper samples as shown in Fig. 2. This instability was increased by the alkaline hydrolysis. Consequently, the effluents resulting from the adhesive and diaper treatment were the most contaminated of all.

The DSC profiles, Fig. 3, indicate that both autoclaving and 1 M NaOH alkaline hydrolysis caused sensible modifications in all the components. Except for serum bottles, the comparison of the profiles shows that after the autoclaved and alkaline hydrolysis treatments, the components required more specific energy for softening and melting than the untreated ones. This was most probably due to the release of the less stable constituents during the treatments and to the resultant hydration that increases the amount water to be removed during the thermal cycle.

The profiles of the PVC components, i.e. transfusion tubes, urine bag collectors and examination gloves, were similar. This is particularly true for the last two untreated components, which showed exothermic reactions above 105 °C, whereas for transfusion tubes, it was above 120 °C. In case of the

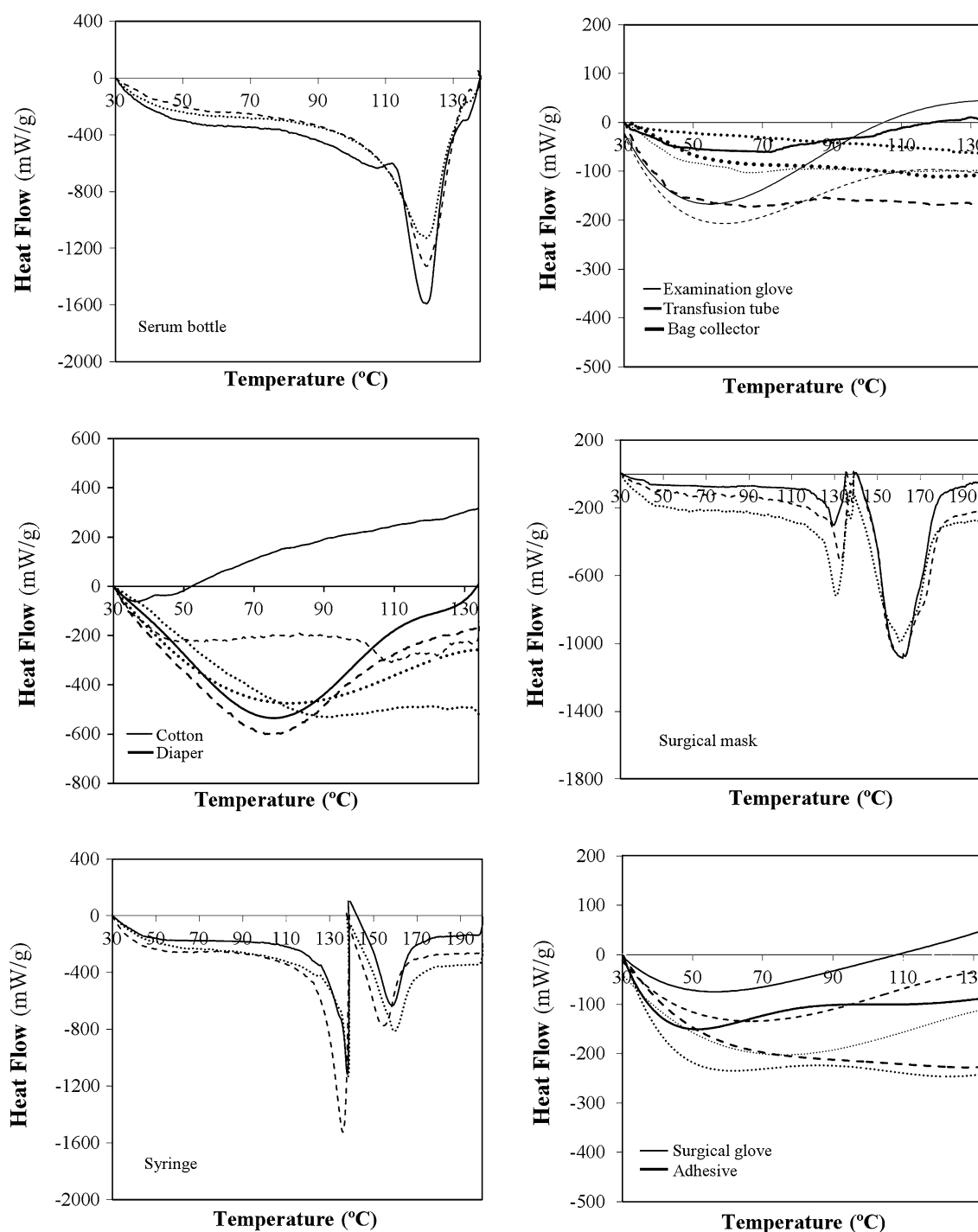
untreated diapers, the exothermic reactions started near 50 °C and held up to the end of the thermal cycle, indicating the continuous degradation of this component. After alkaline hydrolysis treatment, the diaper substances responsible for the exothermic reactions were apparently eliminated. The same happened with the PVC components and the surgical glove. Syringe and surgical mask profiles show well-defined patterns of endothermic transformations with two peaks and the serum bottle showed only one endothermic peak. No significant differences between the peak temperatures in the untreated and treated components occurred. Differences in the DSC profiles of these three components are probably related to their composition. While syringe and surgical masks are multi-material components, serum bottles are composed by LDPE alone.

### Principal components analysis

Through multivariate analysis, it was possible to conclude that the treatments promoted the degradation of all components, as measured by their WL and CL with consequent increase in the TOC and COD of their liquid effluents. The first two axes of the PCA, which could explain 99.4 % of the variation, were found among the components after the treatments. All the parameters used to characterise the components showed high eigenvalues and significant correlation values with axis 1, contributing to separate the samples with the highest WL, CL, TOC and COD values, i.e. those of diapers and adhesives treated with 1 M and 2 M NaOH solutions, from the others, which clustered in group A in Fig. 4a. These results indicate that among all the components and treatments tested, diapers and adhesives were the most prone to alkaline hydrolysis, and that the degree of their degradation correlated with the NaOH concentration used.

In an analysis excluding the diaper and adhesive samples, the 2 first orthogonal axes from PCA explained 97.9 % of total variance (Fig. 4b) and the samples clustered in 3 groups. Among this subset of components, samples of surgical masks after treatment with 1 M or 2 M NaOH, which had the highest WL and CL values and





**Fig. 3** DSC profile of HCW components: (solid lines) original, (dashed lines) hydrolysed and (dotted lines) autoclaved. The DSC profiles of untreated and hydrolysed bag collector for urine coincide with DSC profiles of examination glove

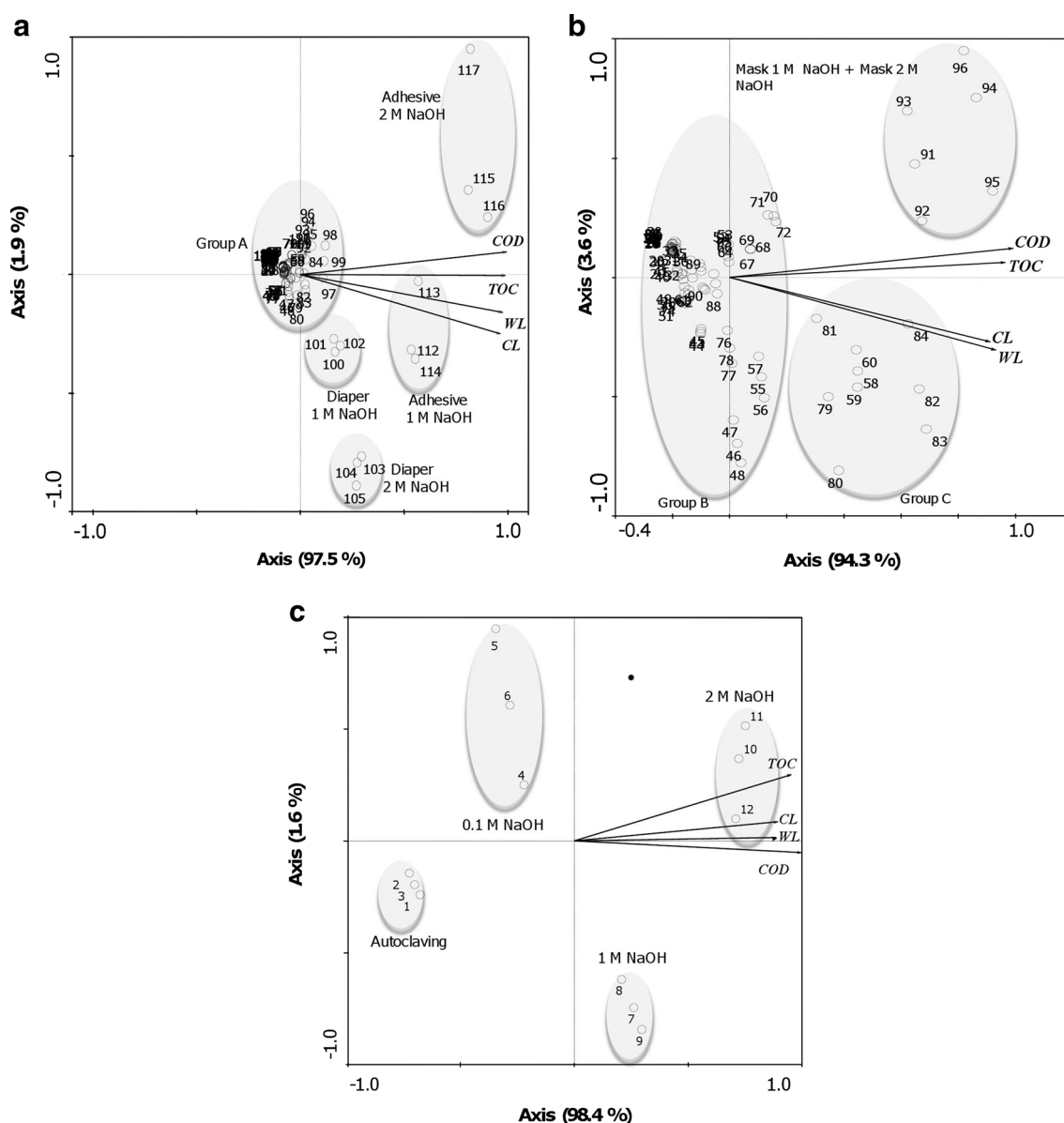
produced effluents with highest load of TOC and COD, clustered together. Among the remaining subset of components, also cotton treated with 1 M or 2 M NaOH and examination glove treated with 2 M NaOH (group C) could be distinguished from the others (group B). These results indicate that after diapers and adhesives, surgical masks followed by cotton and examination gloves are the

components more susceptible to alkaline hydrolysis, if NaOH concentrations higher than 1 M are used.

In order to assess the effect of the tested treatments on the less degradable components, multivariate analyses including the data of individual components were performed. Despite the small variation on the values of the analysed parameters after the different treatments, the PCA







**Fig. 4** Principal components analysis of the HCW treatments results and spatial distribution of the samples; arrows refer the parameters considered in the analysis (i.e. WL and CL of the sample and TOC

and COD in the effluent produced): **a** all the samples; **b** all the samples except diaper and adhesive; **c** syringe samples

biplots obtained, herein exemplified with syringe data (Fig. 4c), indicated that the degree of degradation depended on the NaOH concentration. Therefore, autoclaving was the less aggressive treatment while 2 M NaOH promoted the highest deterioration of each individual component.

## Conclusion

Common inorganic components from healthcare waste subjected to autoclaving or alkaline hydrolysis degraded in a higher or lower degree according to the thermal

resistance of the materials in their composition. Thus, components with LDPE, HDPE or PP that are very stable up to 135 °C showed good resistance to both treatments.

The components tested lost up to 10 % of their weight, which means that the treatments were not efficient in reducing the mass of waste, except in the case of diapers and adhesives where the reduction is appreciable as shown by a 30–50 % mass loss with 2 M the NaOH.

The composition of effluents resulting from the treatment depends on the degradation degree of the components and also on the solutions used. Those from alkaline treatment were hazardous due to their very high pH (> 12.5). On the contrary, the pH of effluents from autoclaving was



close to neutrality or slightly acid. Alkaline effluents showed higher organic loads than those effluents obtained from autoclaving. Also, TOC and COD values increased as NaOH concentration increased in the solution used, reaching a COD of 42 and 144 g O<sub>2</sub>/l for the 2 M NaOH solutions in the case of diapers and adhesives, respectively.

Although with very high organic loads, the effluents produced in alkaline hydrolysis of a mixture of all the components were biodegradable after neutralisation. Therefore, these effluents might be acceptable in a domestic wastewater treatment plant.

Autoclaving degraded components much less than alkaline hydrolysis. Therefore, the resulting effluents presented non-negligible organic loads, mainly from materials such as natural rubber, cellulose and polyvinyl chloride. Nevertheless, when treated under the same conditions, the effluents resulting from autoclaving were less biodegradable than those resulting from alkaline hydrolysis treatment, but showed values close to the limit of biodegradability.

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