Assessing the potential fire risk of laundered fabrics after contamination with emollients using ATR-FTIR spectroscopy and chemometrics

Keywords: emollients; fire risk; residues after washing, secondary transfer during washing, ATR-FTIR analysis, PCA and novel cluster network analysis.

ABSTRACT

Since 2010, more than 50 UK fire deaths, have been reported as linked with emollients. This prompted the Medicines and Healthcare products Regulatory Agency (MHRA) to issue advice on their safer use in 2018. The advice was in response to concerns raised by the National Fire Chiefs Council, coroners' reports, and flammability tests. The test results show a significant reduction in ignition time of fabrics contaminated with paraffin-based and paraffin-free skin care product residues. The MHRA report also included advice on washing clothing and bedding at high temperatures but warned this may not remove all emollient residues. This paper reports on new research on the removal of skin care products from clothing investigated by laundering contaminated 100% cotton fabric at 30, 40 and 60˚C using both biological and non-biological based detergents. As part of the experiment, non-contaminated (blank) napkin samples were included in the wash experiments to assess the possible transfer from fabrics contaminated with emollients to uncontaminated clean fabrics during washing. Washed and dried fabrics were analysed using Attenuated Total Reflectance, Fourier Transform Infrared (ATR-FTIR) spectroscopy and further interpreted via principal component analysis (PCA) and network analysis. Results suggest that the majority of the 6% white soft paraffin-based lotion and paraffin-free cream were removed at all temperatures. Residues of 21% paraffin-based cream (6% light paraffin/15% white soft paraffin) remain, and more residues persist of the 100% paraffin-based ointment (5% light paraffin/95% white soft paraffin) after washing at 30, 40 and 60˚C. The wash experiments show unequivocal transfer of the 100% ointment from the contaminated napkins to clean control napkins placed within washes at 30˚C. Furthermore, residues of the ointment were observed within the machine drum, and washing machine door seal, though this did not cause secondary transfer to subsequent wash experiments. There were no differences observed when using biological versus non-biological detergents, nor when employing a pre-wash treatment in the removal of residues of the 21% cream and 100% ointment. These results suggest that a single application of an emollient when soaked and dried into a fabric is not removed by a single wash at 30, 40 or 60˚C. Instead, the residue remains a persistent potential fire risk and, its high paraffin content presents an additional fire risk via contamination of other fabrics.

1.0 Introduction

The Medicines and Healthcare products Regulatory Agency (MHRA) recently reported that over 50 UK fire deaths have been linked with clothing or bedding impregnated with emollients [1]. However, the number of fatalities is thought to be much higher, owing to the lack of public awareness and underreporting by the health care profession [2], and fire and rescue services [3]. Reports that do highlight the concerns regarding the flammability of skin care products when dried on clothing, bandages, dressing and bedding suggest that their presence was a significant factor in the ignition and the development rate of the fire [4-7]. This is also reflected in various coroners' reports, recommending that more information needs to be available to patients and healthcare professionals [8-13].

Initial advice on this fire risk was released in 2007 by the National Patient Safety Agency (NPSA) [14], then in April 2016, the MHRA released a further warning in relation to products containing 50% or higher paraffin content [6]. However, in 2018, as a response to flammability research [15] and further fatality reports [9-13], the MHRA advice [1] now relates to lower paraffin content and paraffin-free skin care products. Laundering of contaminated clothing and bedsheets at higher temperatures was also recommended in the updated MHRA report [1]. The report suggests laundering may not completely remove emollient residues, which corresponds with problems voiced by emollient users and their carers, regarding soiled and ruined clothing even after washing [16,17].

The many different medicinal [18] and other skin care products comprise a range of diverse ingredients. Some £2.2 billion of these products were purchased over the counter in 2018 [19], when over £70 million worth of emollient and barrier creams were prescribed in the UK [20]. It is therefore pertinent that correct advice is given in any preventive messages on laundering of fabrics to remove dried on residues of such products. Several publications report on the removal of contaminants, such as soil, being more effective with powdered detergents [21]. There are few reports on the removal of oil-based contamination, and these largely focus on protective clothing [22-26]. These reported that higher water temperatures were effective at removing the contamination, with less oil distribution within fabrics [27]. The use of pre-wash products were also shown to be effective in the removal of oil [28,29]; but also increased clothing flammability.

Initial flammability tests assessing the difference in burn potential when textiles are contaminated with skin care products [15] show significant decreases in ignition time of 100% cotton sheeting from 68.0 ± 29.6s (uncontaminated) to 6.0 ± 0.7s when contaminated with 27.1% paraffin-based cream and dried for 24hrs ($p = 0.001$). This paper describes laundering experiments used to present preventive advice. The study investigates the removal of residues of four different skin care products from 100% cotton fabric, and transfer to clean fabrics using a domestic washing machine, at different temperatures. The removal of the dried-on residues was analysed using Attenuated Total Reflectance, Fourier Transform Infrared (ATR-FTIR) spectroscopy, and further interpreted via principal component analysis (PCA) and visualised using a combination of cluster and network analyses.

2.0 Materials and Methods

The (contaminant) emollient skin care products used were a 6% paraffin-based lotion (6% white soft paraffin), a 21% paraffin-based cream (15% white soft paraffin / 6% liquid paraffin), a 100% paraffin-based ointment (5% light paraffin/95% white soft paraffin) and a paraffin-free based cream (castor oil based). The paraffin-based products were manufactured by Bayer and the paraffin-free based cream by Dermato Logical Ltd. The textiles used were 100% cotton, 200 thread count, 115 gm^2, 400 mm by 400 mm hemmed white napkins (n = 198) purchased from 'Absolute Home Textiles'. The 100% cotton king size bed sheet, 300 thread count, used for ballast in each wash was purchased from Wilkinson Hardware Stores Limited. Both non-biological liquid detergent and biological liquid detergent capsules were manufactured by Unilever and the pre-wash stain remover spray by Tesco PLC.

2.1 Textile Sample Preparation

Each of the four emollients tested, was applied to five different napkins. The emollient was applied to each quarter of the napkin using a spatula (equating to 1.25 mL or 0.25 tsp), giving a total of 5 mL (1 tsp) of emollient added to each napkin. The emollient was subsequently dispersed onto each quarter of the napkin using a fingerprint roller (WA products Ltd). Each napkin was weighed prior to and immediately after emollient application to calculate napkin contaminant mass (Table 1). The contaminated napkins were reweighed after 24 hours air-drying.

2.2 Laundering of Samples

A Beko freestanding washer dryer - WDR 7543121 was used for laundering. The washing and drying methods used in this study were adapted from the standard methods BE EN ISO 6330/2012 [30] and BE EN ISO 12138/2018 [31]. Local mains 'hard water' was used, with a mean calcium carbonate content of 1.98 mmol/L [32]. A 26.3 g biological or non-biological liquid detergent capsule was used in each wash.

For each laundering experiment, the 5 cotton napkins contaminated with one of the emollients were washed together with 3 uncontaminated cotton napkins and a ballast of a new 100% cotton king size bed sheet to give an approximate wash load of 1 kg. For each experiment, the "cotton" setting on the washing machine was selected and a wash temperature of either 30, 40 or 60˚C. The full wash cycle at each of the test temperatures was 128 minutes. The cycle consisted of ca. 60 minutes of light agitation with water and detergent followed by ca. 60 minutes of drain, rinse, and spin, repeated 3 times. The cycle ended with a final super-fast spin and then light intermittent spinning for the remaining 2 minutes. Control samples comprised of six blank napkins washed with either non-biological (n = 3) or biological (n = 3) detergent using the same settings and the same ballast as described above.

When the napkins contaminated with 100% ointment were washed at 30˚C, the drum and seal were cleaned to remove any residues, with an additional blank wash cycle in between to avoid cross-contamination.

2.2.1 Pre-Wash Stain Remover Experiments

Four 'sprays' of the pre-wash stain remover were applied onto each quarter of the uncontaminated cotton napkins (n = 15) and napkins contaminated with either the 21% paraffin cream (n = 15) or the 100% paraffin ointment (n = 15), the napkin was then folded in half and light pressure was applied with gloved hands to 'rub' the material and stain remover for 5 seconds and then left for 5 minutes.

The contaminated napkins (n = 5) were then washed at each of the three temperatures tested, with three uncontaminated napkins and the ballast.

2.3 Attenuated Total Reflectance - Fourier Transform Infrared (ATR-FTIR) Analysis

An Agilent Cary 630 FTIR spectroscope, equipped with an ATR accessory, was used with Microlab software. Each analysis comprised 16 background scans and 16 sample scans with a resolution of 4 cm^{-1} and a wave number range of 4000 – 650 cm^{-1}. All repeat spectra were averaged using Spectragryph (v 1.0) software. The mean spectra were baseline corrected and smoothed using the Savitzky-Golay 2nd derivative method, with an interval of 10 and polynomial order of 3 based on common pre-processing techniques for near-infrared spectra [33,34].

Initially, the blank napkin controls washed with the non-biological powder (n = 3) and biological powder (n = 3) were analysed using ATR-FTIR spectroscopy to ensure the bands in the spectra of the contaminated cotton napkins originated from the applied emollients and not the washed cotton substrate. For the unwashed emollient contaminated napkins, each napkin was analysed using ATR-FTIR spectroscopy (n = 10). For the washed samples, all napkins were initially line-dried [30,31]. For each emollient, the five contaminated napkins were then analysed ten times (n = 50) and, for the emollient transfer experiments, the three uncontaminated cotton napkins included in each wash were analysed three times (n = 9).

Table 1.0 ***Mass of napkins and emollient used, and mass loss after 24hrs drying***

Washing experiment and skin care products applied	**Mass of napkin specimen /g [a]**	**Mass of product added /g [a]**	**% mass loss after 24hrs**
Non-biological & biological detergent - washed at 30°C, 40°C and 60°C			
100% paraffin ointment	22.673 ± 0.609 (2.7%)	5.553 ± 0.128 (2.3%)	0
21% paraffin cream	22.656 ± 0.461 (2.0%)	5.317 ± 0.213 (4.0%)	61.9
6% paraffin lotion	22.497 ± 0.436 (1.9%)	5.889 ± 0.205 (3.5%)	73.9
Paraffin-free cream	22.893 ± 0.713 (3.1%)	5.986 ± 0.173 (2.9%)	55.8
Biological detergent, + pre-wash spray - washed at 30°C, 40°C and 60°C			
100% paraffin ointment	22.375 ± 0.442 (2.0%)	5.394 ± 0.015 (0.3%)	0.6
21% paraffin cream	22.655 ± 0.493 (2.2%)	5.319 ± 0.178 (3.4%)	63.6

[a] *mass ± standard deviation (relative standard deviation)*

2.4 Chemometrics

The PCA and network analysis was carried out using two distinct wavenumber ranges (3000.507 to 2799.231 and 1490.935 to 1360.478 cm^{-1}) which exhibited various decreases in intensity in the IR spectra below (Figures 1, 2, 4 and supplementary Figure 5). Initially relationships between the transmittance values for 180 wavenumbers across the 198 replicate samples were explored using a conventional R-mode principal components analysis [35] and on the MultiVariate Statistical Package [36] software platform.

To display the results more effectively without removing data, the alternative multivariate approach of cluster analysis [37], was also used, which often yields groupings that corroborate those derived from ordination [38]. Cluster analysis was applied to the total data set, employing an unpaired group mean average (UPGMA) linkage method and a simple Euclidean distance (Ed_{ij}) algorithm. While effective, and appropriate, the clusters proved difficult to visualise, so a novel graphical approach was adopted to display the clusters more like ordination biplots than conventional 'stick diagrams' or 'trees'. To achieve this, Euclidean distance cluster groupings were uploaded to MS Excel 365, condensed groups with a $Ed_{ij} < 5$ into clusters of ≤ 10 objects to display larger clusters as closely spaced cluster groups. Each sample was identified as a treatment-coloured square, circle, or triangle; each temperature as different sized shapes, size 4 (30˚C), size 5 (40˚C) and size 6 (60˚C) and computed (secondary linking) nodes as (size 3) grey circles.

The cluster network was formatted for display using the Pajek [39] network analysis software, employing the Kamada & Kawai (1989) algorithm [40] to minimise overlapping lines of neutral length. The [x] 'generate in time' function was used to highlight groupings within the final network, displaying circles as t1, squares as t3, and intermediate (core) nodes as t2. This allowed the partition of the network to show the core and circles (t2 + t1), core and squares (t2 + t3) or all 'actors'/ objects (t1 + t2 + t3).

3.0 RESULTS

In all of the spectra shown in Figure 1a-d, the most intense peaks originate from the unwashed samples, where each emollient was applied to the napkins and dried for 24 hrs and analysed without washing. The C-H stretch (doublet) between 2950 - 2800 cm^{-1} is clearly visible in all of the unwashed spectra. The band at 2916 cm^{-1} results from the asymmetric stretching vibration and the band at 2849 cm^{-1} from symmetric stretching vibration of the $–CH_2–$ group [41]. All of the unwashed spectra, also have a peak that corresponds to a C–H deformation at approximately 1460 cm^{-1} resulting from the $–CH_2–$ scissor vibration [41].

3.1 IR spectra of non-biological detergent washes to assess the removal of emollients

Figure 1a shows the spectra of the unwashed and washed samples that had the paraffin-free cream applied. In the spectra, as well as the C–H stretches and deformations, there is a pronounced band at 1736 cm^{-1}, which corresponds to a C=O stretching vibration of a saturated ester functional group,

originating from ethoxylated hydrogenated castor oil, the main constituent in the paraffin-free cream. The intensity of the bands originating from the paraffin-free cream decrease in intensity after washing the pre-treated napkin at each of the temperatures tested (30˚C, 40˚C and 60˚C), indicating that most of the paraffin-free cream is removed when washing with the non-biological detergent.

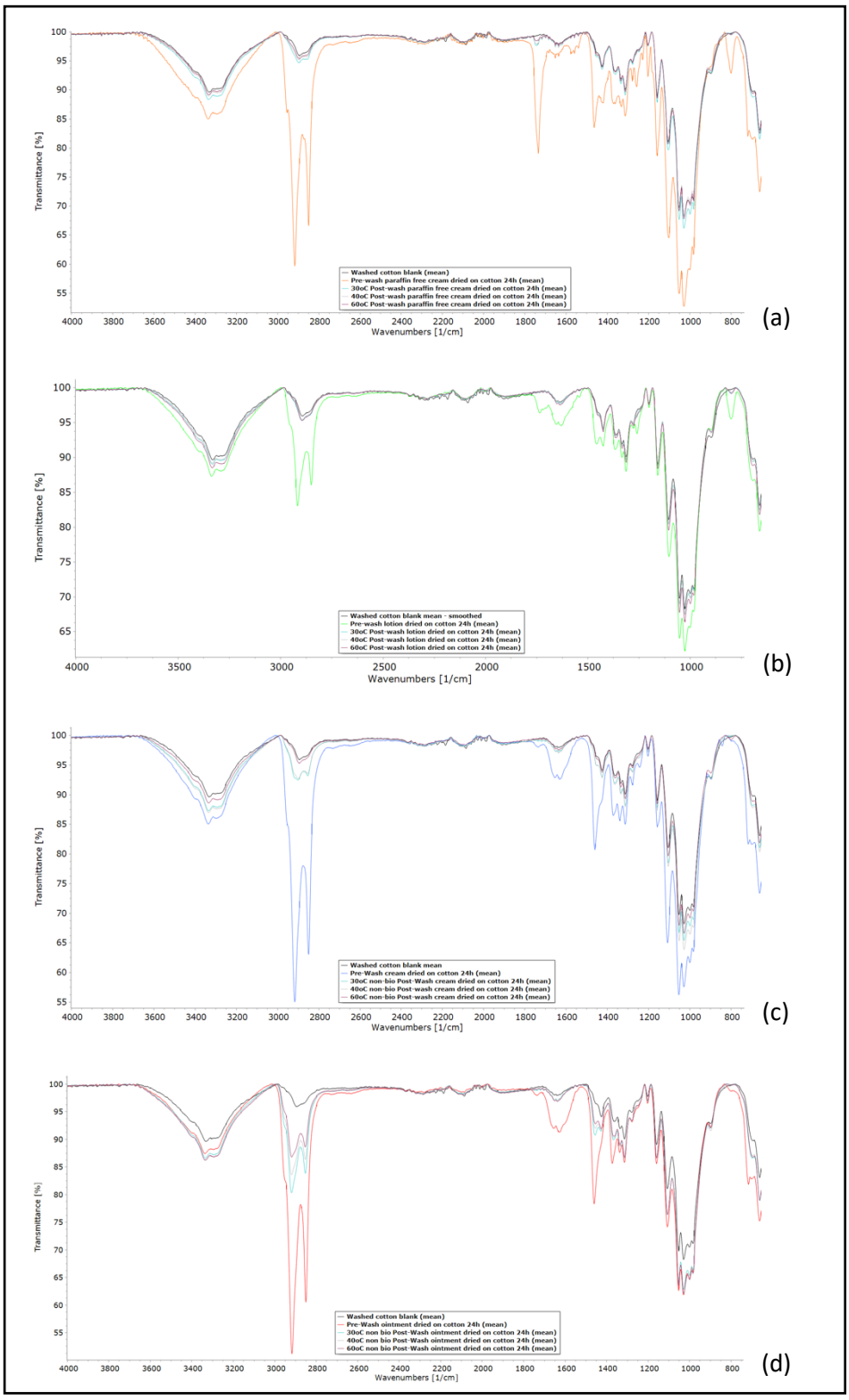

Figure 1 *Spectra (mean) of cotton napkins washed at 30˚C, 40˚C and 60˚C with non-biological detergent, when contaminated and dried for 24h with (a) paraffin-free cream (b) 6% lotion (c) 21% cream (d) 100% ointment with controls of washed napkins and unwashed, dried contaminated napkins.*

A similar pattern is observed from the napkins contaminated with the 6% paraffin base lotion (Figure 1b). The percent transmission of the C–H stretching and C–H deformation bands are of a similar intensity, after washing with the non-biological detergent, to the blank control napkin, suggesting that washing at each temperature successfully removes the majority of the lotion, and in comparison to the paraffin-free cream, even less residues remain. PCA was then used to assess if residues of the paraffin-free cream and 6% paraffin lotion remain. The $–CH_2–$ stretching doublet and deformation bands originating from the 21% paraffin cream are still evident in the spectra of the contaminated fabrics after washing at 30 and 40˚C, suggesting that the cream is not removed by washing at the lower temperatures. The bands from the cream are less pronounced in the samples that were washed at 60˚C and therefore, further assessed with PCA, to confirm that washing at higher temperatures does not necessarily ensure residues are removed (Figure 1c). Similarly, for the fabric samples contaminated with the 100% ointment (Figure 1d), the bands attributed to paraffin are still evident at all the temperatures tested, when washed using a non-biological detergent.

3.2 IR spectra of control napkins during non-biological detergent washes to assess transfer from emollient contaminated napkins.

Three uncontaminated napkins were included in each of the wash cycles to assess emollient transfer at each temperature. The mean spectra of the uncontaminated napkins that were washed with the paraffin-free cream, 6% paraffin lotion and 21% paraffin cream contaminated napkins, all have peaks at a similar intensity to the washed blank napkin control (Figure 2a). This suggests that there is no transfer of these emollients to other fabrics when washed at all three temperatures with a non-biological detergent. However, the uncontaminated napkins washed with napkins contaminated with 100% paraffin ointment do show transfer. The mean spectra (Figure 2a) show the presence of the C–H symmetric and asymmetric stretch between 2950 - 2800 cm^{-1}, indicating transfer to the blank cotton napkins. This is more evident in Figure 2b, with a decrease in % T of the C–H symmetric and asymmetric stretch as the wash temperature increases. These stretching bands indicate that the temperature used to wash fabrics contaminated with some emollients is critical to reduce emollient transfer within the wash. Furthermore, there was evidence of residues left around the seals and within the drum of the washing machine following washing napkins treated with 100% paraffin ointment experiments at 30˚C using both non-biological and biological detergents (Figure 3). Swabs of this residue were analysed, showing similar spectra to the 100% paraffin ointment control.

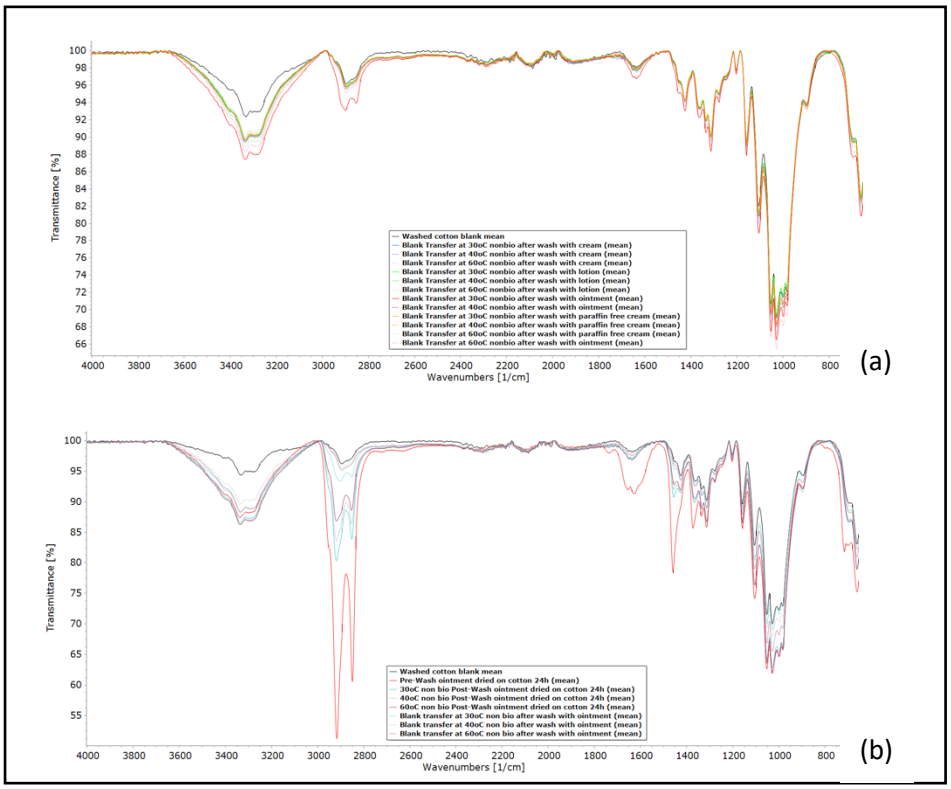

Figure 2 *(a) spectra (mean) of blank cotton napkins washed within a non-biological detergent wash at 30˚C, 40˚C and 60˚C of cotton napkins contaminated with paraffin-free cream; 6% lotion; 21% cream and 100% ointment (b) spectra (mean) of blank cotton napkin within a non-biological detergent wash at 30˚C, 40˚C and 60˚C of cotton napkins contaminated with 100% ointment with a control of unwashed ointment contaminated napkin.*

Figure 3 *Typical image of drum seal residues after 100% paraffin-based ointment wash experiment at 30˚C.*

3.3 IR spectra of biological detergent washes and with a pre-wash stain remover to assess removal of emollients.

The results shown in Figures 1 (c-d) indicate that residues of the 21% paraffin cream and 100% paraffin ointment remain after washing with a non-biological detergent. Further tests were conducted

to investigate whether these emollients were removed by washing with biological detergent at 30˚C, 40˚C and 60˚C (Figures 4a and 4b) and biological detergent after application of a pre-wash spray (Figures 4c and 4d).

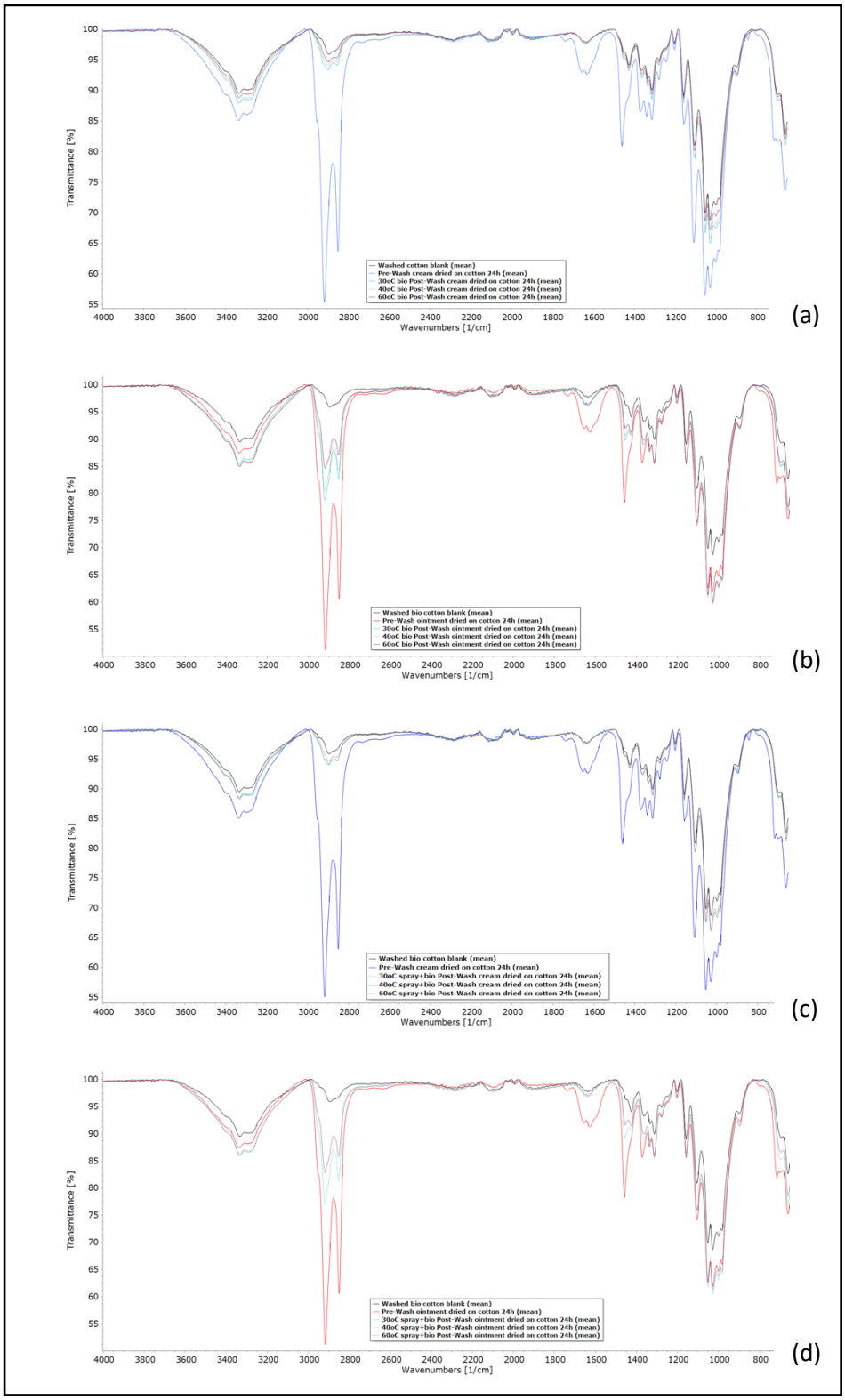

Figure 4 *Spectra (mean) of cotton napkins washed at 30˚C, 40˚C and 60˚C with biological detergent when contaminated and dried for 24h with (a) 21% cream (b) 100% ointment and with a pre-wash spray and biological detergent when contaminated and dried for 24h with (c) 21% cream and (d) 100% ointment.*

The most intense bands in the spectra shown in Figures 4 (a-d) originate from the contaminated unwashed napkins. The C–H stretching doublet resulting from the asymmetric and symmetric stretch of the $–CH_2–$ group at approximately 2916 cm^{-1} and 2849 cm^{-1} are clearly visible, as is the $–CH_2–$ scissor deformation at approximately 1460 cm^{-1}.

For the napkins contaminated with either 21% paraffin cream or 100% paraffin ointment, the bands originating from the asymmetric and symmetric stretch are still present at all three wash temperatures. For napkins contaminated with the 100% paraffin ointment, the spectral bands of the contaminated napkins washed at 30˚C and 40˚C are of a similar intensity. The intensity of the bands in the mean spectrum of the ointment contaminated napkins washed at 60˚C are less pronounced, showing the higher washing temperature is more efficient at removing some of the paraffin ointment from the fabrics (Figure 4b). However, the results still indicate that some of the emollient remains on the napkins, after washing the contaminated samples with biological, as well as non-biological detergents.

The mean spectra of the emollient contaminated napkins that have been washed with the biological detergent after application of a pre-wash spray are shown in Figures 4(c) and 4(d) respectively. The Figures, clearly show that using a biological detergent with the additional application of a pre-wash spray, still does not remove all of the 21% paraffin cream nor the 100% paraffin ointment, similar to the non-biological washing experiments.

3.4 IR spectra of blank cotton napkins during biological detergent washes to assess transfer from emollient contaminated napkins.

The mean spectra of the uncontaminated napkins that were washed with the 21% cream and the 100% ointment contaminated napkins using either biological detergent only or biological detergent with the pre-wash spray are shown in supplementary Figures 5a and 5b respectively. Although the spectral bands are less intense than in Figures 2a and 2b when using a non-biological detergent, supplementary Figures 5b still shows a decrease in %T of the C–H symmetric and asymmetric stretch between 2950 - 2800 cm^{-1}, indicating low-temperature transfer of the ointment to the blank cotton napkins.

3.4 PCA and Cluster Analysis Networks of wash experiments

All washing experiments were included for both PCA and the cluster analysis networks. 1) The control mean of unwashed contaminated napkin (dried for 24hrs) with all of the 4 products (n=4). 2) The washed napkin mean when contaminated (and dried for 24hrs) for all 4 products washed at the 3 temperatures with non-biological detergent (n = 90). 3) The cream and ointment contaminated washed napkin means at the 3 temperatures with biological detergent (n=45). 4) The cream and ointment-contaminated washed napkin means at the 3 temperatures using a pre-wash spray with

biological detergent (n=45). 6) The blank napkin mean included in all the wash experiments to assess transfer (n=72) included in washes using non-biological or biological detergent, with and without biological detergent and the pre-wash spray. Different colour and symbol permutations were used to discriminate between blank napkin post wash control results (triangles), post wash results (squares), transfer to blank napkins (circles) and prewash results of dried on emollient controls (triangles).

3.4.1 Results from PCA of wash experiments

A covariance PCA extracted 99.47% of net variance on axis 1, but only 0.33% on axis 2, yielding an almost linear scatterplot. Axes 2 and 3 (0.33% vs. 0.13%) presented three diagonal 'stripes' of points (controls, red squares and 'the rest') clearly indicating the axes are interdependent. We countered this with a simple correlation PCA which extracted 93.91% of variance on axis 1, and a more 'useable' 3.42% on axis 2. This showed overlapping, rather than discrete, groups of points with axis 1 separating the 'red squares' from the other tests and axis 2 tests from controls. Axes 2 (3.42%) and 3 (1.59%) did not show evidence of interdependence but failed to separate any groups of symbols.

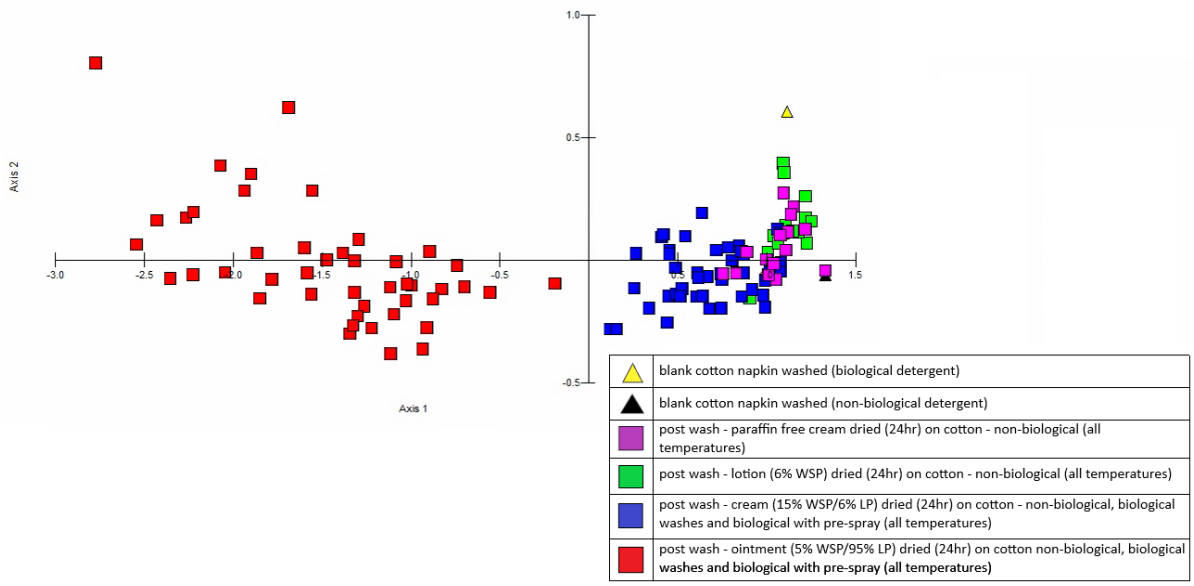

Figure 6 PCA correlation of wavenumber ranges (3000.507 to 2799.231 and 1490.935 to 1360.478 cm^{-1}) of different wash experiments at all temperatures.

In Figure 6, the symbols used to distinguish between results are triangles (representing the blank napkin controls), and squares (representing the post-wash results). As shown in Figure 6, there are two consistent clusters, a diffuse linear cluster comprising of post-wash contaminated napkins with the 100% paraffin ointment washed at all three temperatures (red squares). These orientate at 90˚ to, and converge with, the second cluster of post-wash contaminated napkins with the 21% paraffin cream washed at all three temperatures (blue squares). These follow the same linear trend as a cluster comprising post-wash napkins contaminated with paraffin-free cream (purple squares) and on the outer edge of this cluster 6% paraffin lotion, washed with non-biological detergent at all

temperatures (green squares) and a washed control (yellow triangle). The pattern corroborates the partitions into product type sets derived from the previous IR analysis (Figure 1 and Figure 4), and that the cotton fabric still retains ointment and cream residues in all washing experiments.

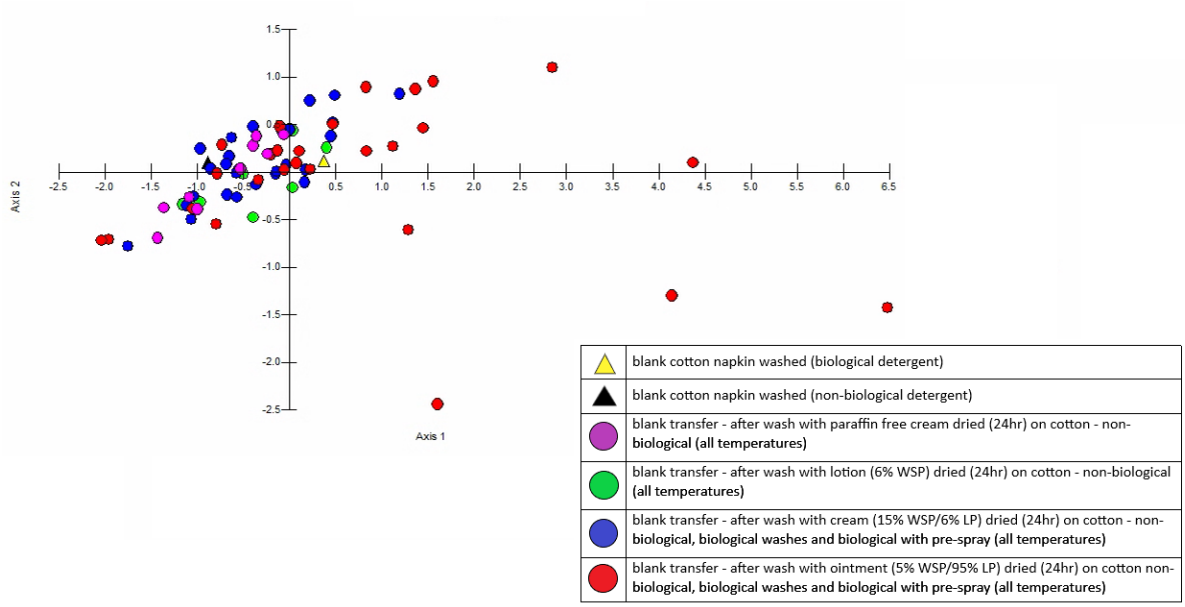

Figure 7 PCA correlation of wavenumber ranges (3000.507 to 2799.231 and 1490.935 to 1360.478 cm^{-1}) to assess transfer to blank cotton napkins within wash experiments at all temperatures.

Figure 7 shows two clusters, firstly a linear group comprising the blank cotton napkins, paraffin-free cream, 6% paraffin lotion, 21% paraffin cream contaminated napkin washes (purple, green and blue circles). This first cluster partly overlaps with a more diffuse second cluster of red circles of blank cotton napkins placed in 100% paraffin ointment washes. This overlap confirms ointment transfer to blank napkins (Figures 2a, 2b and 4).

3.4.2 Results from Cluster Analysis Network of wash experiments

In Figure 8, the symbols identify blank napkin controls washed separately (yellow and black triangle) and emollients controls dried on the cotton napkins before washing (orange, green, blue and red triangles). The squares represent post wash contaminated cotton napkins with the emollients indicated as orange, green, blue and red squares of different sizes to distinguish temperatures of, 30˚C (small), 40˚C (medium) and 60˚C (large). The grey circles are cluster nodes with a Ej_{id} threshold of 5, with all weaker nodes collapsed.

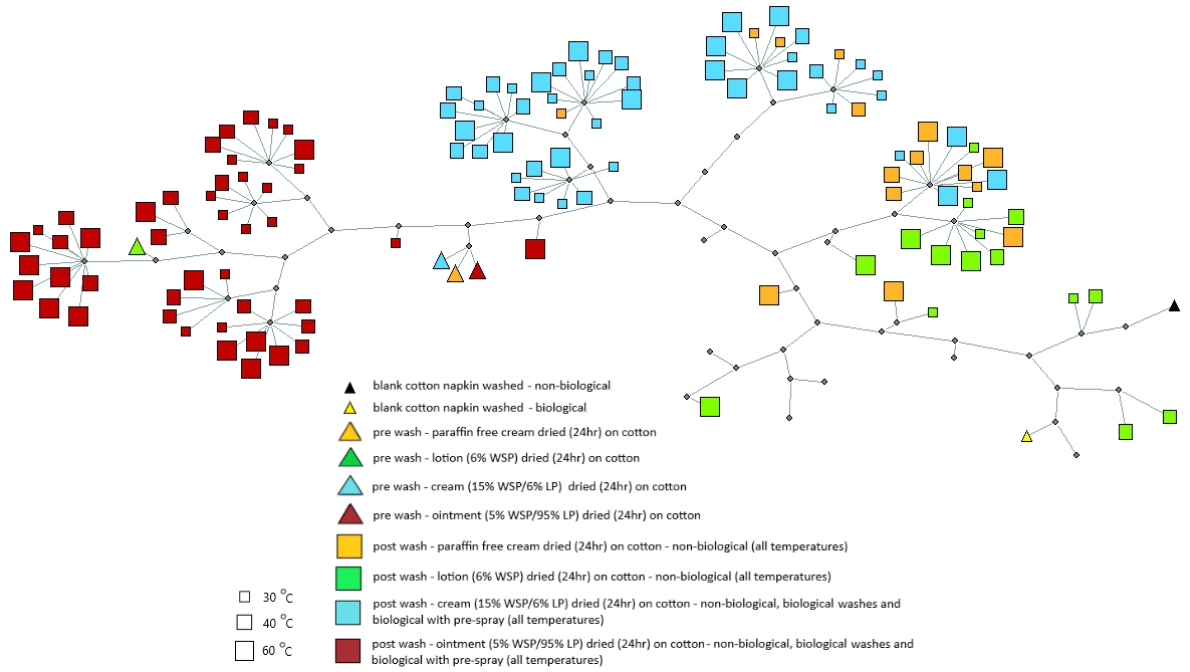

Figure 8 Cluster analysis network of wavenumber ranges (3000.507 to 2799.231 and 1490.935 to 1360.478 cm^{-1}) of different wash experiments at all temperatures.

The clusters show a close proximity of the 100% paraffin ointment (red squares) post wash results and the prewash control (red triangle) which are distinct from the blank cotton controls (black and yellow triangles). Similar trends are also shown with the 21% paraffin cream in all laundering tests (blue squares) relative to the prewash control (blue triangle) and the blank cotton controls. All corroborate the presence of ointment and cream residues in all tested laundering methods.

The cluster of 100% paraffin ointment post wash results (red squares) are near to the pre-wash control of the lotion (green triangle), showing that after washing the ointment residues have similar spectral band intensities to the unwashed lotion. This suggests that substantial residues of the ointment residues remain on the fabric after washing.

The large distances between the paraffin-free cream (orange squares) and the prewash control (orange triangle) versus the blank cotton controls (black and yellow triangles) indicates a significant proportion is removed. The larger distance between the clusters of the 6% paraffin lotion (green squares) and the prewash control (green triangles) relative to the other emollient results confirms the majority of the lotion is removed via a non-biological detergent.

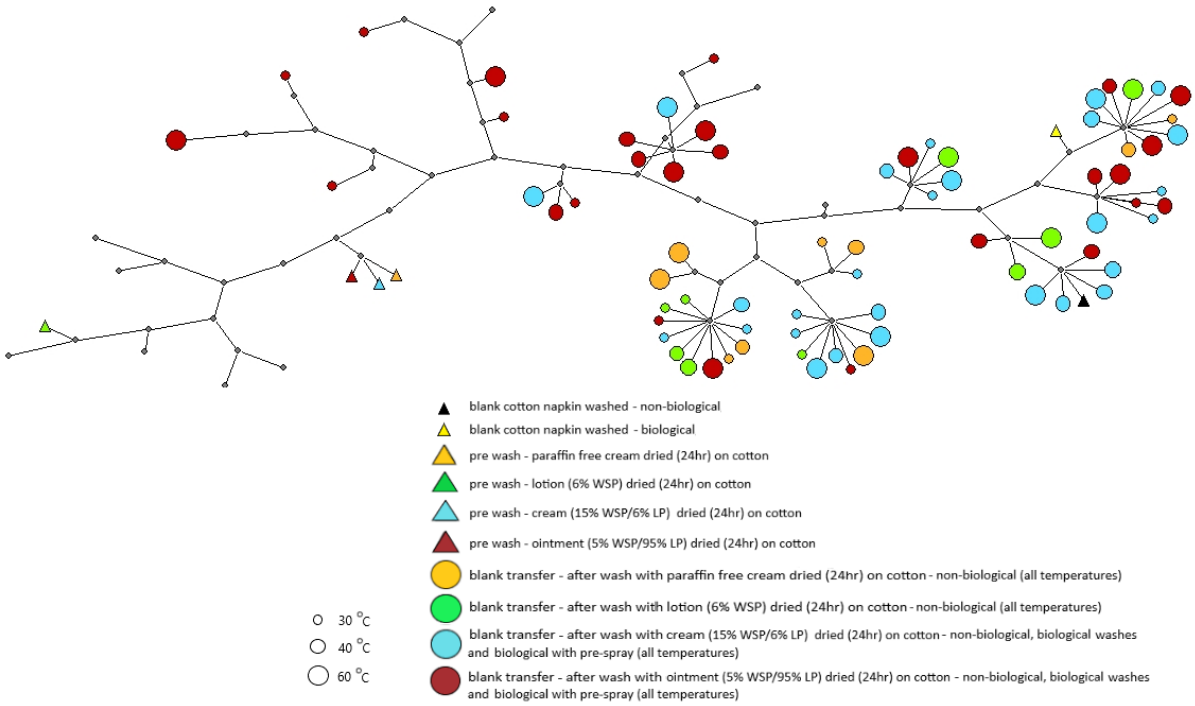

Figure 9 Cluster analysis network of wavenumber ranges (3000.507 to 2799.231 and 1490.935 to 1360.478 cm^{-1}) to assess transfer to blank cotton napkins within the wash experiments at all temperatures.

Figure 9 shows that when the blank napkins are placed in some of the ointment washes (red circles) they group with the prewash control (red triangle). Supporting our suggestions of transfer from napkins contamination with ointment to blank control napkins placed within the wash (Figure 4).

4.0 Conclusion

Both ATR-FTIR spectroscopy and chemometric analysis confirm that the 100% paraffin-based ointment is not removed from soiled fabrics when washed with non-biological detergent or biological detergent or biological detergent with the additional application of a pre-wash spray at each of the three temperatures (30, 40 and 60˚C). The analysis also shows when washing at lower temperatures the ointment could transfer onto and contaminate clean fabrics within the wash. Although beyond the scope of this paper, but worthy of further research, evidence of drum contamination at 30˚C, could present a source of further contamination in subsequent washes. To avoid contamination when laundering at 30˚C the drum and seal were cleaned via an additional ‘empty’ wash cycle between each experiment. Washing, left residues of the 21% paraffin-based cream (15% white soft paraffin / 6% liquid paraffin) on fabrics at all washing temperatures, but (with a non-biological detergent) removed the majority of a 6% white soft paraffin-based lotion and paraffin free cream.

The experimental methods reported here, only incorporated a single application of emollient and one wash cycle. Further work is needed for multiple applications to mirror re-worn clothing over a number of days or weekly changing of bedding. It is also important to consider that some emollients are applied liberally and often as needed. These results confirm that laundering clothing, even at high

temperatures, does not remove the large majority of emollients and therefore does not mitigate the fire risk when exposing fabrics to a flame. Furthermore, the contamination of ‘clean’ fabrics washed with contaminated fabrics and evidence of residues contaminating the washer drum supports a change in advice on, specifically the separate washing of emollient soiled fabrics. We propose the advice on the safer use of emollients requires revision beyond avoiding flames and high temperature source, as recommended by MHRA and health and fire and rescue professionals, until more research is carried out on additional laundering processes. Although awareness of the fire risk of emollients when dried onto fabrics is improving, the dissemination of these results aims to also improve this amongst the forensic science community.

The persistence of emollient residues after washing could still pose a change in the flammability behaviour of contaminated fabrics with a significant reduction in ignition times. While this reduction in time to ignition for emollient-contaminated fabrics is compelling, further work on flammability testing is recommended for washed contaminated fabrics. Comparing the mass of emollients used in these laundering experiments (5.317g of 21% paraffin-based cream) with flammability tests (1.389g of the same cream) after washing could imply persistent residues could contribute to early ignition of the washed 100% cotton fabric. These findings have been passed onto the MHRA and other organisations. It is hoped that disseminating such results will improve future safety advice and information on the fire risk posed by emollients and reduce fatalities linked with such products. Future developments of these methods will explore the use of FTIR spectroscopy and chemometrics to detect remaining residues of emollients on fabrics in fire debris with other forensic analytical techniques. To improve forensic evidence when investigating fire fatalities associated with emollients. This will be of significant interest to fire investigators, presenting a stronger link between the presence of emollients on fabrics and their contribution to fire development.

References

[1] Medicines and Healthcare products Regulatory Agency, Emollients: new information about risk of severe and fatal burns with paraffin-containing and paraffin-free emollients, 2018. https://www.gov.uk/drug-safety-update/emollients-new-information-about-risk-of-severe-and-fatal-burns-with-paraffin-containing-and-paraffin-free-emollients.

[2] F. Al-Niaimi, M. Chadha, and N. Cox, Flammability of paraffin-based products: a primary care survey and a need for product labelling, Clin. Exp. Dermatol. 36 (1) (2011) 97–98.

[3] The Telegraph, Paraffin-based skin creams may be linked to hundreds of deaths, senior firefighter warns, 2018. https://www.telegraph.co.uk/news/2018/02/11/paraffin-based-skin-creams-may-linked-hundreds-deaths-senior/.

[4] S. J. R. Allan and M. J. Tidman, Dermatology dressings: an incendiary potential, Br. J. Dermatol.144 (3) (2001) 649–650.

[5] E. A. Brewer, Patient safety: Paraffin-based products, Br. Dent. J. 223 (2017) 620.

[6] Medicines and Healthcare products Regulatory Agency, Paraffin-based skin emollients on dressings or clothing: fire risk, 2016. https://www.gov.uk/drug-safety-update/paraffin-based-skin-emollients-on-dressings-or-clothing-fire-risk.

[7] F. Al-Niaimi, S. Manickam, and N. H. Cox, Flammability of paraffin-based products: an under-recognized hazard and methods to reduce it, Br. J. Dermatol. 162 (4) (2009) 893–895.

[8] R. E. Ferner, C. Easton, and A. R. Cox, Deaths from Medicines: A systematic analysis of coroners' reports to prevent future deaths, Drug Saf. 41 (1) (2018) 103–110.

[9] C. Wilkinson, Regulation 28 Report to Prevent Future Deaths, West Sussex, 2015. https://www.judiciary.uk/wp-content/uploads/2015/10/Hills-2015-0317.pdf

[10] S. Ormond-Walshe, Regulation 28 Report to Prevent Future Deaths, West London; 2018. https://www.judiciary.uk/wp-content/uploads/2018/07/Kevin-Freely-2018-0180_Redacted.pdf

[11] M. Fleming, Regulation 28 Report to Prevent Future Deaths, West Yorkshire, 2018. https://www.judiciary.uk/wp-content/uploads/2018/10/Brian-Bicat-2018-0277_Redacted.pdf

[12] M. Burke, Regulation 28: Report to Prevent Future Deaths, West Yorkshire, 2017. https://www.judiciary.uk/wp-content/uploads/2018/01/Pauline-Taylor-2017-0330.pdf

[13] C. J. Swann, Regulation 28 Report to Prevent Future Deaths, 2016. https://www https://www.judiciary.uk/wp-content/uploads/2016/08/Holyoake-2016-0163.pdf

[14] National Patient Safety Agency, Fire Hazard with Paraffin-based Skin Products, Rapid

Response Report 4, 2007. https://webarchive.nationalarchives.gov.uk/ukgwa/20170906174326/http://www.nrls.npsa.nhs.uk/resources/healthcare-setting/community-pharmacy/?entryid45=59876&p=3

[15] S. Hall, L. Franklin, J. Bull, A. Beard, G. Phillips, and J. Morrissey, The flammability of textiles when contaminated with paraffin base products, Fire Saf. J. 104 (2019) 109–116.

[16] M. Santer, I. Muller, L. Yardley, S. Lewis-Jones, S. Ersser, and P. Little, Parents' and carers' views about emollients for childhood eczema: qualitative interview study, BMJ Open, 2016. https://bmjopen.bmj.com/content/6/8/e011887

[17] R. Oakley and S. Lawton, Views on unwanted effects of leave-on emollients and experiences surrounding their incidence, Dermatological Nurs. 15 (4) (2016) 38–43.

[18] J.P. Chan, G. Boyd, P.A. Quinn and M.J. Ridd, Emollient prescribing formularies in England and Wales: a cross-sectional study. 2018. BMJ Open. https://bmjopen.bmj.com/content/8/6/e022009.

[19] T. Sabanoglu, Market value of skincare cosmetics in Great Britain in 2018, by product type (in 1,000 GBP), Statista. 2019. https://www.statista.com/statistics/289711/market-value-of-skincare-cosmetics-in-the-united-kingdom-uk/.

[20] National Health Service, Prescription Cost Analysis, England, 2018 [PAS]. 2019. https://digital.nhs.uk/data-and-information/publications/statistical/prescription-cost-analysis/2018

[21] S. L. Paek, The effect of detergent type and laundering temperature on the soil removal and soil redeposition performance of cotton and p/c blends with and without durable press finish, J. Consum. Stud. Home Econ. 7 (4) (1983) 339–348.

[22] E. M. Crown, A. Feng, and X. Xu, How clean is clean enough? Maintaining thermal protective clothing under field conditions in the oil and gas sector, Int. J. Occup. Saf. Ergon. 10 (3) (2004) 247–254.

[23] J. Stull, C. Dodgen, M. Connor, and R. McCarthy, Evaluating the effectiveness of different laundering approaches for eecontaminating structural fire fighting protective clothing, performance of protective clothing, ASTM International. 5 (1996) 447-468.

[24] C. B. Easley, J. M. Laughlin, R. E. Gold, and K. Schmidt, Detergents and water temperature as factors in methyl parathion removal from denim fabrics, Bull. Environ. Contam. Toxicol. 28 (2) (1982) 239–244.

[25] E. L. Finley, G. I. Metcalfe, F. G. McDermott, J. B. Graves, P. E. Schilling, and F. L. Bonner,

Efficacy of home laundering in removal of DDT, methyl parathion and toxaphene residues from contaminated fabrics, Bull. Environ. Contam. Toxicol. 12 (3) (1974) 268–274.

[26] C. V. R. Mettananda and E. M. Crown, Quantity and distribution of oily contaminants present in flame-resistant thermal-protective textiles, Text. Res. J. 80 (9) (2010) 803–813.

[27] M. A. Morris and H. H. Prato, The effect of wash temperature on removal of particulate and oily soil from fabrics of carying fiber content, Text. Res. J. 52 (4) (1982) 280–286.

[28] C. V. R. Mettananda, D. A. Torvi, and E. M. Crown, Characterization of the combustion process of flame resistant thermal protective textiles in the presence of oily contaminants: effects of contamination and decontamination, Text. Res. J. 80 (10) (2010) 917–934.

[29] C. V. R. Mettananda and E. M. Crown, Effects of oily contamination and decontamination on the flame resistance of thermal protective textiles, Fire Mater. 35 (5) (2011) 329–342.

[30] British Standards Institute, BS EN ISO 6330:2012 Textiles - Domestic washing and drying procedures for textile testing, 2012.

[31] British Standards Institute, BS EN ISO 12138 : 2018 BSI Standards Publication Textiles – Domestic laundering procedures for textile fabrics prior to flammability, 2018.

[32] Cambridge Water Company, Water Hardness, 2018. https://www.cambridge-water.co.uk/household/my-water-supply/water-quality/water-hardness.

[33] A. Girod, L. Xiao, B. Reedy, C. Roux and C. Weyermann, Fingermark initial composition and aging using Fourier transform infrared microscopy (m-FTIR), Forensic Sci. Int. 254 (2015) 185-196.

[34] A. Rinnan, F. van den Berg and S. Balling Engelsen, Review of the most common pre-processing techniques for near-infrared spectra, Trends Analyt. Chem. 28 (10) (2009) 1201-1222.

[35] I.T. Jolliffe, Principal component analysis, second ed., Springer-Verlag, New York, 2001.

[36] I. Legendre and P. Legendre, Numerical ecology, Elsevier Scientific Publishing Company, New York, 1983.

[37] W. Kovach, MVSP - A multiVariate statistical package for Windows. Kovach Computing Services, Pentraeth, Wales, U.K., 2007.

[38] P.J.A. Pugh and P. Convey, Surviving out in the cold: Antarctic endemic invertebrates and their refugia, J. Biogeogr. 35 (2008) 2176–2186.

[39] W. de Nooy, A. Mrva and V. Batagelj, V, Exploratory social network analysis with Pajek:

revised and expanded edition for updated software. Third Edition. Structural Analysis in the Social Sciences, 46, (2018) Cambridge University Press, pp. 455.

[40] T. Kamada and S. Kawai, An algorithm for drawing general undirected graphs, Inf. Process. Lett. 31 (1) (1989) 7–15.

[41] G. Socrates, Infrared and Raman Characteristic Group Frequencies: Tables and Charts, third ed., John Wiley and Sons, England, 2001.