Journal of Hospital Infection 126 (2022) 37–43

Available online at www.sciencedirect.com

Journal of Hospital Infection

journal homepage: www.elsevier.com/locate/jhin

Impact of material properties in determining quaternary ammonium compound adsorption and wipe product efficacy against biofilms

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ARTICLE INFO

Article history:
Received 4 March 2022
Accepted 31 March 2022
Available online 12 April 2022

Keywords:
Biofilm
Surface disinfection
Disinfectant wipe
Quaternary ammonium compound
Adsorption
Non-woven

SUMMARY

Background: Disinfectant wipes containing quaternary ammonium compounds (QACs) are widely used within health care. Viscose remains a popular material for these products, although limited information is available concerning its impact on performance against biofilms when compared with alternatives.

Aim: To identify disinfectant wipe materials and surface properties which optimize product performance against biofilms.

Methods: Biofilm eradication performance of two commercial viscose-QAC wipes was determined against *Staphylococcus aureus* and *Acinetobacter baumannii* dry surface biofilms (DSBs) using an ASTM E2967-based procedure. Additionally, five materials were impregnated with a commercial liquid formulation containing didecyldimethylammonium chloride (DDAC). Following 24 h of storage, eradication performance and DDAC content of extracted liquid were determined and compared with material properties, including zeta potential, hydrophobicity and surface area.

Findings: Under stringent test conditions, eradication of DSBs by commercial products was no greater than equivalent materials impregnated with water. Extract from one viscose-based product contained 89% less DDAC than the impregnation solution, indicating extensive adsorption. Of the other tested materials, viscose performed worst; nearly 70% of DDAC had depleted from material extracts within 24 h. In contrast, DDAC depletion from polypropylene extracts was only 25%, and DSB eradication was >100 times greater than viscose. Biofilm eradication performance against both species correlated with the DDAC content of extracts, which, in turn, correlated with zeta potential and hydrophobicity.

Conclusion: Biofilm eradication performance of QAC-based wipes was significantly greater when selecting thermoplastic substrates over viscose. However, these materials are non-sustainably sourced and non-biodegradable. This study highlights a need to develop new wipe products that are more effective against biofilms.

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https://doi.org/10.1016/j.jhin.2022.03.013

Introduction

Disinfectant wipes have been a leading product for healthcare surface decontamination over the past decade. Comprising non-woven textile impregnated with a liquid formulation, 11 billion single-use wipes are estimated to be used in the UK every year. Many wipe products contain plastic components, and their production and disposal are non-sustainable [1]. Cellulosic materials such as viscose are derived from renewable plant sources, are biodegradable, and are popular options for companies interested in marketing more sustainable products.

Quaternary ammonium compounds (QACs) are cationic surfactant biocides. The hydrophilic head facilitates electrostatic interactions with negatively charged microbial surfaces. Upon interaction, the hydrophobic tail region subsequently partitions into the membrane, disrupting intermolecular bonding between phospholipids. This leads to catastrophic loss of membrane integrity and inactivation of treated cells [2]. Due to their low cost, broad spectrum of activity and good surface compatibility, QACs are one of the most popular biocides for general surface disinfection. Deposition of QACs on to treated surfaces may also provide residual protection against surface recontamination [3].

The interactions between surfactants and the polymers from which wipe materials are comprised are likely to affect cross-compatibility. Physiochemical processes, including van der Waal forces, hydrophobic interactions and electrostatic effects, importantly contribute to these interactions [4]. Material properties, including surface charge, hydrophobicity, surface area and absorptivity, may play important roles in affecting the performance of disinfectant wipes containing QAC-based formulations. For example, the isoelectric point of cellulose is <2.8 and fibres are negatively charged under most environmental conditions [5,6]. QACs are known to adsorb to cellulosic materials [7,8], which may have a negative impact on biocidal performance.

The antimicrobial performance of disinfectant wipes can be determined through simulated-use tests, such as EN 16615 or ASTM E2967. In these tests, antimicrobial performance against dried inocula is a function of both mechanical removal and biocidal activity. Whilst there is no performance threshold indicated in ASTM E2967-15 [9], European tests such as EN 16615 require a $\log_{10}$ reduction factor of ≥ 4 (99.99%) to substantiate claims of bactericidal efficacy [10]. Despite being readily detected on healthcare surfaces [11,12], there are currently no standardized tests for assessing the performance of disinfectant wipe products against biofilms which account for mechanical action. EN 16615 is poorly suited for this purpose, as biofilms cannot be cultured easily on the 5-cm^2 fields of floor tile sections. However, ASTM E2967 can be readily adapted for biofilm testing, as dry surface biofilms (DSBs) can be cultured on the 10-mm stainless steel coupons used for the test [13].

Aims

This study sought to investigate the interactions between a selection of wipe materials and a QAC-based formulation containing didecyldimethylammonium chloride (DDAC). The biofilm eradication performance of wipes containing different materials was ascertained against DSBs of *Staphylococcus aureus* or *Acinetobacter baumannii*. The degree of DDAC adsorption to each substrate within 24 h was ascertained and compared with measurements of material properties, including zeta potential, surface area, hydrophobicity and absorptivity.

Methods

Disinfectant products

Two pre-wetted disinfectant wipe products and one liquid disinfectant formulation were included in this study. Wipes A and B consisted of viscose impregnated with QAC-based formulations. The liquid disinfectant used throughout this study consisted of the same formulation used in Wipe A, and was stated to contain 3 mg/L DDAC as the active substance. Wipe B was from a different manufacturer and was stated to contain a combination of DDAC and benzalkonium chloride at a total concentration of <5 mg/L. Materials used in the commercial wipe products were also provided by the manufacturers in their dry, non-impregnated form.

Preparation of materials

Five commercially available materials designed for use in disinfectant wipe products were investigated in this study: 100% viscose; 40% viscose, 60% polyethylene terephthalate (PET) blend; 40% lyocell, 60% polyethylene (PE) blend; 100% polypropylene (PP); and 100% PET.

Materials were cut aseptically into 10 4-cm^2 sections, and soaked in 50 mL of liquid formulation for 5 min. Following soaking, each section was wrung out gently to remove the excess liquid. The mass before and after impregnation was measured to determine absorptivity (termed 'wet pick up'; i.e. relative mass gain post-impregnation) and potential differences in impregnation rate (Table II). Impregnated wipes were placed in sealed, inverted Petri dishes and stored at 20 °C for 24 h. The mechanical removal performance of each material was also ascertained by soaking each in water and testing under the same protocol.

Challenge organisms and culture conditions

S. aureus ATCC 6538 (Gram-positive bacterium) and *A. baumannii* ATCC *19568* (Gram-negative bacterium) were selected as challenge organisms, as recommended by ASTM E2967-15 [9].

DSBs were prepared as described previously [13]. In brief, DSBs were cultured over a 12-day period on 10-mm-diameter 430 stainless steel coupons (2B finish) using alternating 2-day cycles of hydration and desiccation. Coupons were placed aseptically in a 24-well tissue culture plate. One millilitre of bacterial suspension [1—5 x 10^6 colony-forming units (CFU)/mL] in tryptone soya broth supplemented with 3 g/L bovine serum albumin (TSB/BSA) was added to each well. Plates were incubated for 2 days at 20 °C under orbital shear, after which media was removed and plates were desiccated at 20 °C for 2 days. Following the first phase of desiccation, 1 mL of sterile TSB/BSA was added to each well and incubated for a further 2 days at 20 °C on the orbital shaker. The biofilms continued to be

hydrated and desiccated in 2-day intervals for a total period of 12 days, after which a homogenous layer of biofilm had formed on each coupon.

Assessment of wipe product efficacy

Product performance was determined using the ASTM E2967-15 'Wiperator' protocol, a standardized method for determining wipe efficacy [9]. Product performance is the sum of mechanical removal from the surface and biocidal inactivation. The test measures reduction from an inoculated coupon and transfer to sterile secondary carriers.

Prior to use, the Wiperator was disinfected with 70% ethanol and allowed to air dry. Pre-soaked 4-cm^2 sections of wipe materials were secured to the boss using a rubber O-ring. Inoculated coupons were loaded on to the holding stage of the Wiperator, which was flamed between uses. A sterile stainless steel coupon was placed in the secondary slot of the stage for determination of transfer. To engage the wiping action, the stage was lifted to make contact with the boss. Coupons were wiped orbitally for 10 s, with 300 g of downward force. The wiping parameters chosen reflect the use of wipes in practice rather than the diverse manufacturers' recommendations. Following the first wiping action, the secondary sterile coupon was also wiped under identical conditions. As inoculum was present on both sides of the coupons, coupons were transferred aseptically to a second stage and placed underside up. A fresh wipe substrate was then secured to the boss and the process was repeated. As both sides of the coupon needed to be wiped, the contact time could not be controlled precisely, although the wiping procedure took approximately 60 s in total to complete from initiation. Three biological repeats were performed for each sample.

Immediately after wiping, coupons were transferred to McCartney bottles containing 3 g glass beads and 1 mL neutralizing solution (30 g/L polysorbate-80, 30 g/L saponin, 3 g/L sodium thiosulphate, 3 g/L L-α-lethicin, 1 g/L L-histidine, 8.5 g/L NaCl; 1 g/L tryptone). Each sample was vortexed for 1 min to resuspend the remaining cells, and a 10-fold dilution series was prepared in sterile tryptone sodium chloride (TSC; 8.5 g/L NaCl, 1 g/L tryptone). Total viable counts were then ascertained by the Miles and Misra method, following a 18—24-h period of incubation at 37 °C. Log_{10} reduction values were calculated relative to controls consisting of untreated coupons. As 20-μL droplets were used for recovery, the reliable lower limit of detection was 50 CFU/mL; this figure was used in reduction calculations when observed CFUs were below this value. The neutralizing solution was validated for efficacy and toxicity against the liquid disinfectant according to EN 16615 [10].

Quantification of DDAC content of wipe liquid extracts

QAC content was determined using the colorimetric disulphine blue active substance assay [14]. Following a 24-h period of storage, soaked wipes were transferred into barrel syringes, and the plunger was pressurized to extract the liquid. For each sample, the extract was diluted 2000-fold in ultrapure water to yield a QAC concentration within the linear detection range of the assay.

In brief, 25-mL aliquots of diluted sample were transferred to 50-mL centrifuge tubes. Next, 2.5 mL of buffer (115 g/L anhydrous sodium acetate and 35 ml/L glacial acetic acid in deionized water) was added to each tube, followed by 1 mL of dye (0.64 g/L disulphine blue, 8 mL/L ethanol in deionized water) and 7.5 mL of chloroform. Each tube was agitated vigorously for 2 min, then allowed to separate for a minimum of 5 min. Using a glass Pasteur pipette, the organic phase was removed carefully from the bottom of each tube and placed into quartz cuvettes. A_{628} was measured spectrophotometrically and compared with a calibration curve prepared using standard solutions of DDAC (0, 0.1, 0.5, 1 mg/L). Depletion of DDAC from the liquid extract was calculated relative to the determined content of the liquid formulation.

Electrokinetic measurements

Surface zeta potential of the five materials was determined by measuring the streaming potential as a function of electrolyte pressure in a SurPASS3 (Anton Paar) electrokinetic analyser [15]. Two Ag/AgCl electrodes present at the inlet and outlet of the streaming channel were used to measure the potential in the channel. Multiple 14-mm discs were cut out from each material and stacked between two perforated support discs. A permeability index between 104 and 109 was achieved by slight compression of the stacked layers; the number of layers required for each material was dependent on the permeability of the individual material. A 1-mM KCl solution was used as the electrolyte, with 0.1M HCl and 0.02M NaOH being used to alter the pH of the electrolyte between 2.5 and 9.5 using the inbuilt titrator. The electrolyte pressure through the material was varied between 200 and 600 mbar. For each pH value, average zeta potential was calculated from four repeat measurements.

Determination of surface area

Surface area of each of the materials was determined by Brunauer—Emmett—Teller (BET) surface analysis. In brief, 200—250 mg of sample material was loaded into a 9-mm cell and degassed at 100 °C for 3 h in a FloVac degasser (Quantachrome). Samples were then loaded into a Quarasorb BET analyser, and nitrogen adsorption was determined at 77 K. Surface area was calculated automatically from the adsorption isotherm using the BET equation [16].

Water contact angle measurements

Hydrophobicity of the sample materials was determined by contact angle goniometry. Samples of material were flattened on to the platform of an Mitutoyo Surftest SV-2000 goniometer. A 4-μL droplet of deionized water was then loaded manually on to each sample, and images of the droplet were acquired digitally. Contact angles were measured manually using ImageJ v1.53 for macOS.

Statistical analyses

Statistical analyses were performed using Prism 9.2.0. For biocidal tests, differences between treatment groups were resolved by analysis of variance (ANOVA) with Šídák's (comparison of water vs formulation) or Tukey's (comparison of materials) post-hoc tests. The correlation between DDAC content of wipe extracts and biocidal performance was probed by one-tailed Pearson correlation. A multi-variate analysis

matrix (two-tailed Pearson) was used to identify potential relationships between various material properties and DDAC adsorption.

Results

Commercial wipe products offered similar biofilm eradication performance against *S. aureus* and *A. baumannii* (Figure 1) under the reported test conditions (10 s of mechanical wiping followed by 30–60 s of contact post wiping). For both products, the same material impregnated with water offered a similar performance under the test conditions ($P>0.05$; ANOVA, Šídák).

The five test materials provided a similar level of mechanical removal, as indicated by observed $\log_{10}$ reductions in groups treated with wipes impregnated with water (Figure 1, $P>0.05$; ANOVA). After 24 h of storage following biocide impregnation, distinct differences in performance were observed between materials. For *S. aureus* biofilms, both viscose/PET and PP were observed to be more effective than viscose ($P<0.01$; ANOVA, Tukey) and eradication from surfaces increased from approximately 2 $\log_{10}$ to 4 $\log_{10}$. For biofilms of *A. baumannii*, differences were only significant between PP and viscose ($P<0.05$; ANOVA, Tukey), and between PP and viscose/PET ($P<0.01$; ANOVA, Tukey). Overall, PP provided an approximate 100-fold increase in biofilm eradication compared with viscose.

Transfer of micro-organisms to secondary carriers was always below the lower limit of detection, in the case of both commercial products and biocide-impregnated materials (Table S1, see online supplementary material). For materials impregnated with water, transfer ranged from 4 to 5 $\log_{10}$ CFU, although differences between the materials were not significant ($P>0.05$; ANOVA, Tukey).

Substantial differences in DDAC content of wipe extracts were observed following the 24-h storage period (Table I). Extracts from viscose contained the lowest amount of DDAC, whilst PP and PET contained the greatest amounts of DDAC. In the case of Wipe A, which had been stored for a prolonged period between manufacture and use, 89% of the original DDAC content was depleted from the wipe extract.

Whilst significant differences between materials were unable to be resolved in $\log_{10}$ reduction tests, a comparison of $\log_{10}$ reductions with DDAC content of extracts (Figure 2) demonstrated a linear relationship between the two values in the case of both species ($P<0.05$; one-tailed Pearson).

Electrokinetic measurements (Figure 3) indicated clear differences in zeta potential between the tested materials. Examination of the zeta potential around pH 7.2 ($\zeta_{7.2}$; Table II), equivalent to that of the biocide formulation, indicated that viscose (the worst performing material) was approximately -8 mV. In contrast, the zeta potentials of polypropylene and PET, the best performing materials, were equivalent to approximately -63 and -73 mV. Comparison of $\zeta_{7.2}$ and DDAC content of extracts identified a strong negative correlation between the two values ($P=0.0381$; Pearson's r).

Further characterization of materials (Table II) indicated that hydrophobicity, as measured by contact angle, also correlated with DDAC content of wipe extracts ($P=0.016$; Pearson's r). Correlations were not observed in the case of either surface area ($P=0.4710$; Pearson's r) or wet pick up ($P=0.7977$; Pearson's r). Contact angles were unable to be measured for viscose and 40% viscose/60% PET blends as the droplet was unstable on the material surface.

The results presented herein outline the importance of material properties in determining the biocidal performance of QAC-based disinfectant wipes against DSBs of *S. aureus* and *A. baumannii*. Under the reported test conditions (10 s of mechanical wiping followed by 30–60 s contact post wiping), viscose, a leading material for disposable products, was the least effective material of those tested. Differences in biofilm eradication between two commercial viscose-containing wipe

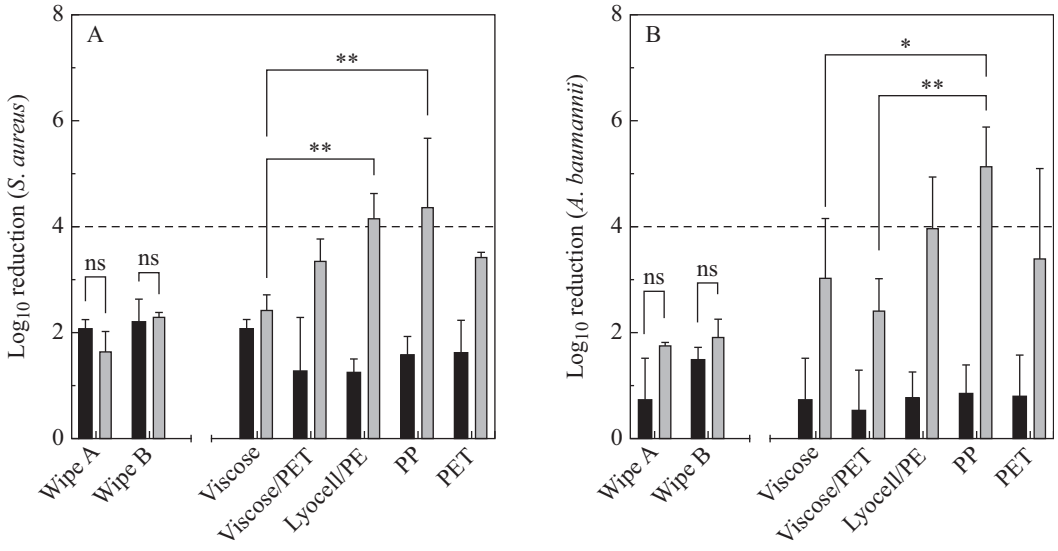

Figure 1. $\log_{10}$ reductions in *Staphylococcus aureus* (A) and *Acinetobacter baumannii* (B) dry surface biofilms following treatment with two commercial viscose/quaternary ammonium compound wipe products and materials stored for 24 h following impregnation. Materials were impregnated with either water (black bars) or disinfectant formulation (grey bars). Water-impregnated versions of Wipe A and Wipe B were prepared from the corresponding dry materials used in their manufacture. PET, polyethylene terephthalate; PE, polyethylene; PP, polypropylene. ns, $P>0.05$.

Table I
Didecyldimethylammonium chloride (DDAC) content of liquid wipe extracts

	A_{628}	DDAC (mg/L)[a]	DDAC depletion (%)[b]
Liquid formulation	2.523	3880.3	-
Wipe A	0.306	420.3	89.2
Viscose	0.883	1320.8	66.0
Viscose/PET	1.442	2193.2	43.4
Lyocell/PE	1.761	2691.1	30.7
PP	1.880	2876.8	25.9
PET	2.039	3124.9	19.5

PET, polyethylene terephthalate; PE, polyethylene; PP, polypropylene.
[a] Value adjusted for 1/2000 dilution.
[b] Content relative to liquid formulation.

products and their equivalent materials impregnated with water were unable to be resolved (Figure 1), and, whilst commercial products successfully prevented transfer of viable organisms to secondary surfaces (Table A1 see online supplementary material), these observations suggest that existing QAC/viscose-based wipe products may deliver suboptimal performance against established biofilms.

Distinct differences in biofilm eradication performance were observed between the five tested materials. A 24-h storage period following biocide impregnation was an important step in resolving these differences. Overall, thermoplastics such as PP and PET offered significant improvements in performance compared with viscose (Figure 1). Under the reported test conditions, eradication of *S. aureus* and *A. baumannii* DSBs was approximately 100-fold greater when utilizing PP over viscose. Differences in biofilm removal by water-impregnated materials were relatively small (i.e. not significant), particularly in the case of *A. baumannii* DSBs, and unable to fully explain differences in performance between the disinfectant-impregnated materials. On this basis, the differences in performance are most readily explained by differences in the interactions between the various materials and DDAC, the active substance present in the liquid formulation.

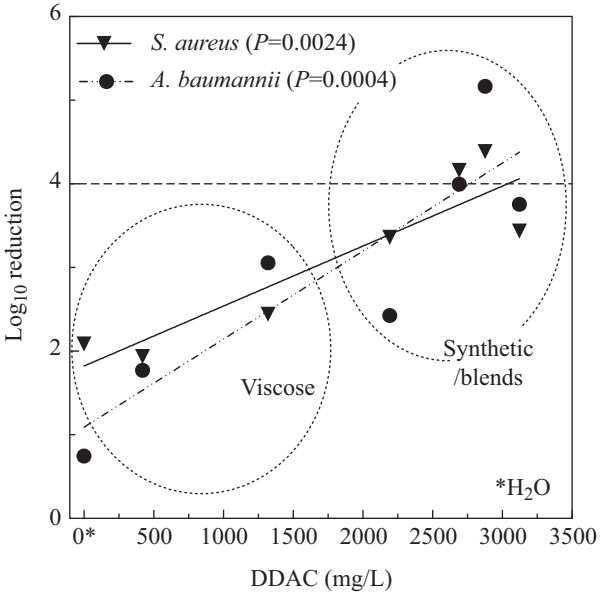

Figure 2. Relationship between didecyldimethylammonium chloride (DDAC) content of wipe extracts and eradication of *Staphylococcus aureus* and *Acinetobacter baumannii* dry surface biofilms. The performance of viscose soaked in water (*) has also been included for reference. Dashed line indicates a reduction threshold of a 4 $\log_{10}$ (99.99%) of effectiveness.

Correlation analysis demonstrated a clear relationship between DDAC content of wipe extracts and eradication performance in the case of both *S. aureus* and *A. baumannii* DSBs (Figure 3). Of the five materials tested, viscose was again the worst performing, and up to 66% of the original DDAC content of wipe extracts was depleted within the 24-h storage period. In comparison, extracts from PP and PET contained more than twice the DDAC content upon analysis.

Due to their cationic charge, QACs are able to adsorb to cellulose-based fibres. Bloss *et al.* reported that, when immersed in a 0.1% solution of benzalkonium chloride, as much as 62% adsorbs to viscose within 3 h of application; the adsorbed QAC remained firmly attached to the material even after squeezing to release the disinfectant solution [7]. In another study, a QAC-based floor disinfectant was found to have no effect on the levels of bacterial contamination on ward floors [18]. As both cotton and polyester/viscose yarns are commonly utilized mop materials, it may be the case that the observed inefficacy of the floor disinfection process may be related to QAC adsorption to the mop head.

As biofilms are strongly adhered to surfaces, they are poorly removed through wiping procedures alone. With the exception of that used in Wipe B, water-impregnated materials were able to remove only <2 $\log_{10}$ (99%) *S. aureus* and <1 $\log_{10}$ (90%) *A. baumannii* DSBs from coupons upon wiping (Figure 1). In addition to mechanical removal, deposition of biocide from wipe products appears to play an important role when sanitizing biofilm-contaminated surfaces. Differences in the biocidal performance of wipe extracts, in the absence of mechanical action, is an area of ongoing investigation by this group.

Surface zeta potential, surface area, hydrophobicity and absorptivity properties of the test materials were characterized to identify parameters affecting DDAC adsorption. Whilst surface area and absorptivity were not observed to affect DDAC adsorption, both zeta potential and hydrophobicity of the tested materials were identified as correlates (Table II). Measurements (Figure 3) indicated that DDAC adsorption strongly correlated with zeta potential at pH 7.2 (Table II); this pH was equivalent to the pH of the disinfectant formulation. Zeta potential describes the charge behaviour at solid–liquid interfaces. When in contact with a liquid, solids acquire a charge. To compensate for this charge, counterions are attracted to the surface and form an immobile layer. Zeta potential is defined as the potential due to surface charges at the boundary between the immobile layer and the liquid. It is a direct manifestation of the surface charge, and affects the degree of attraction/repulsion between charged surfaces and solutes. As DDAC is a cationic compound, it was anticipated that adsorption would correlate with decreasing charge (i.e. more negative zeta potential would lead to greater adsorption). Unexpectedly, the opposite effect was observed, where a more negative charge was correlated with reduced DDAC adsorption. This apparently paradoxical observation may be explained through the differences by which hydrophilic and hydrophobic materials acquire surface charge.

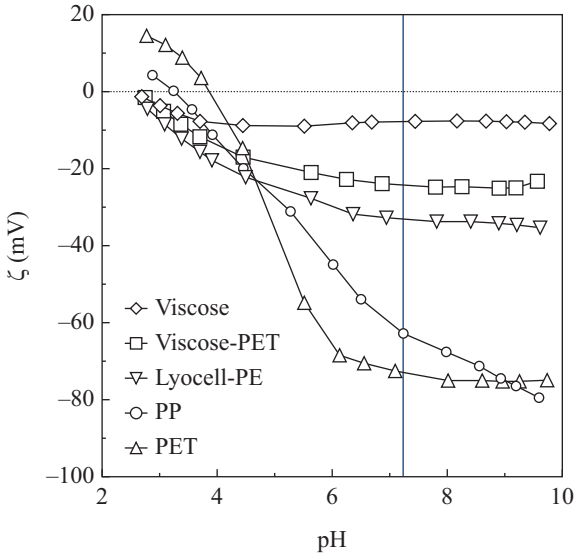

Figure 3. Zeta potential (ζ) measurements of wipe materials across pH range. Formulation pH (7.2) indicated by vertical line. PET, polyethylene terephthalate; PE, polyethylene; PP, polypropylene.

The surface charge of hydrophilic polymers such as viscose arises through dissociation of covalently anchored functional groups (e.g. $-COO^-$, $-O^-$). Both PP and PET non-wovens were observed to be hydrophobic with water contact angles of >120° (Table II). Hydrophobic surfaces accumulate a negative charge in aqueous solutions due to physisorption of water-derived hydroxyl ions at the solid–liquid interface; this process is driven by van der Waal forces induced by water molecule orientation in the bulk phase [19]. Under acidic conditions, where dissociation of water into hydroxyl ions is thermodynamically unfavourable, the surface charge of PP and PET was less negative, and isoelectric points were observed between pH 3 and 4. In contrast, viscose maintained its negative charge under acidic conditions, presumably due to functional groups remaining ionized over the tested pH range.

Based on these observations, potential mechanisms of interaction between QACs and hydrophobic surfaces are proposed. Firstly, the cationic/hydrophilic head group may interact with physiosorbed hydroxyl ions at the material surface; as van der Waal forces underpinning this interaction are relatively weak, they may be readily desorbed during wiping or wringing. Alternatively, QACs may adsorb directly to hydrophobic surfaces through interactions with the tail region, without participation of hydroxyl ions. In the case of hydrophilic substrates such as viscose, it is anticipated that QACs interact electrostatically with the anionic residues bound covalently to the polymer structure. The increased bond energy of electrostatic attractions vs van der Waal forces may explain the differences in adsorption between hydrophilic and hydrophobic materials.

Some important experimental limitations should be acknowledged within this study. To standardize comparisons, manufacturer-recommended diverse contact times for commercial products were not strictly respected in this study. However, mechanical wiping time reflected end users' practice. Differences in performance may become less apparent over longer contact times. Whilst considered more stringent and reproducible [20], performance under ASTM E2967 conditions may not predict efficacy under EN 16615 or other tests. Additionally, the lateral surface of the coupons used in this study comprised approximately 12% of the total surface area, and may not be reached efficiently during the wiping action. This may reduce the observed effectiveness of mechanical removal whilst increasing the importance of liquid deposition for decontaminating these areas. The effect of different materials on long-term formulation stability was also not addressed by this study and, as only one DDAC-based liquid formulation was tested, the results may not be generalizable to other QAC-based products. Whilst Wipe B contained both DDAC and benzalkonium chloride and was from a different manufacturer, the overall QAC content between products was comparable. Differences in active substance concentration and the presence of undisclosed excipients may affect QAC adsorption to materials and product performance considerably, whilst the liquid extraction procedure may not entirely model release from products during actual use. Formulations designed to mitigate against adsorption have been described previously [8], although it is unclear whether such approaches have been utilized in existing products due to non-disclosure of excipients in product information sheets.

In conclusion, the observations suggest that, under stringent test conditions, biofilm eradication performance of QAC-based wipes was greater when opting for thermoplastic materials such as PP or PET, as adsorption of the active substance to such materials is minimized. However, thermoplastics are ultimately derived from fossil fuel sources, and so are neither sustainably sourced nor biodegradable. As legislatures around

Table II
Summary of material properties and correlation with didecyldimethylammonium chloride (DDAC) concentration of wipe extracts

Material	DDAC (mg/L)	$\zeta_{7.2}$ (mV)[a]	Contact angle (°)	Surface area (m^2/g)	Wet pick up (%)
Viscose	1320.8	-8	68.3[b,c]	2.40	318
40% viscose, 60% PET	2193.2	-24	Unknown[c]	2.74	315
40% lyocell, 60% PE	2691.1	-33	124.8	2.33	269
100% PP	2876.8	-63	122.3	12.08	359
100% PET	3124.9	-81	128.8	3.87	287
P[d]		0.0381	0.016	0.4710	0.7977
Correlation with [DDAC]?		Yes	Yes	No	No

$\zeta_{7.2}$, zeta potential at pH 7.2; PET, polyethylene terephthalate; PE, polyethylene; PP, polypropylene.
[a] Interpolated from Figure 3.
[b] Value obtained from Peršin *et al.* [17].
[c] Unable to determine due to rapid droplet imbibition.
[d] Multi-variate analysis.

the world move toward policies minimizing the use of single-use plastics, this study provides useful insights as to the potential unintended consequences that these policies may have on infection control. An outright ban on thermoplastic wipe products may be deleterious to patient health and well-being. It is suggested that a gradual phasing out of these materials in healthcare settings (i.e. domestic and commercial products first, where efficacy against biofilms may be less critical) would permit sufficient time to develop alternative approaches to address these concerns. Given that clinical waste is generally incinerated, the potential for plastic pollution related to wipes used in health care is lower than that for wipes used domestically or commercially.

In the short term, an alternative approach which may improve control of biofilms may include opting for spray disinfectants in combination with wiping. This would maximize the amount of QAC deposited on to surfaces, whilst also retaining the key role of mechanical removal in eliminating biofilms. Careful consideration should be taken when selecting cross-compatible materials for this purpose [21], particularly as soaking incompatible materials in disinfectant solutions may still lead to depletion of the active substance over time [7].

Acknowledgements

The authors wish to thank Dr Jean-Noël Bertho for providing test materials, Dr Greg Shaw for running BET analyses, and Dr Wayne Nishio Ayre for assisting with contact angle measurements.

Conflict of interest statement
None declared.

Funding sources
Funding for this study was provided to Cardiff University by Laboratoires Anios. The funding body was involved in the study design and provision of materials, but did not participate in the collection, analysis or interpretation of the data. The SurPass3 used for electrokinetic measurements was funded by EPRSC GaN-DAME (EP/P00945X/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2022.03.013.

Open data access statement

Data to this article can be found online at https://doi.org/10.17035/d.2022.0164873309.

References

[1] Wharton G. Call to ditch the 11,000,000,000 polluting wet wipes we use each year. Metro; 2019. Available at: https://metro.co.uk/2019/06/14/call-to-ditch-the-11000000000-polluting-wet-wipes-we-use-each-year-9927757/ [last accessed March 2022].
[2] Ioannou CJ, Hanlon GW, Denyer SP. Action of disinfectant quaternary ammonium compounds against *Staphylococcus aureus*. Antimicrob Agent Chemother 2007;51:296–306.
[3] Burel C, Direur G, Rivas C, Purevdorj-Gage L. Colorimetric detection of residual quaternary ammonium compounds on dry surfaces and prediction of antimicrobial activity using bromophenol blue. Lett Appl Microbiol 2021;72:358–65.
[4] Gawade RP, Chinke SL, Alegaonkar PS. Chapter 17 — Polymers in cosmetics. In: Al-Maadeed M, Ponnamma D, Carignano M, editors. Polymer science and innovative applications. Amsterdam: Elsevier; 2020. p. 545–65.
[5] Ribitsch V, Stana-Kleinschek K, Kreze T, Strnad S. The significance of surface charge and structure on the accessibility of cellulose fibres. Macromol Mater Eng 2001;286:648–54.
[6] Grancarić AM, Ristić N, Tarbuk N, Ristić I. Electrokinetic phenomena of cationized cotton and its dyeability with reactive dyes. Fibres Text East Eur 2013;6:106–10.
[7] Bloss R, Meyer S, Kampf G. Adsorption of active ingredients of surface disinfectants depends on the type of fabric used for surface treatment. J Hosp Infect 2010;75:56–61.
[8] Hinchliffe DJ, Condon BD, Madison CA, Reynolds M, Hron RJ. An optimized co-formulation minimized quaternary ammonium compounds adsorption onto raw cotton disposable disinfecting wipes and maintained efficacy against methicillin-resistant *Staphylococcus aureus*, vancomycin-resistant *Enterococcus faecalis*, and *Pseudomonas aeruginosa*. Tex Res J 2018;88:2329–38.
[9] ASTM International. Standard test method forassessing the ability of pre-wetted towelettes to remove and transfer bacterial contamination on hard, non-porous environmental surfaces using the Wiperator. ASTM E2967-15. West Conshohocken, PA: ASTM International; 2015.
[10] British Standards Institute. Chemical disinfectants and antiseptics. Quantitative test method for the evaluation of bactericidal and yeasticidal activity on non-porous surfaces with mechanical action employing wipes in the medical area (4-field test). Test method and requirements (phase 2, step 2). BS EN 16615:2015. London: BSI Standards Limited; 2015.
[11] Ledwoch K, Dancer SJ, Otter JA, Kerr K, Roposte D, Maillard JY. How dirty is your QWERTY? The risk of healthcare pathogen transmission from computer keyboards. J Hosp Infect 2021;112:31–6.
[12] Ledwoch K, Dancer SJ, Otter JA, Kerr K, Roposte D, Rushton L, et al. Beware biofilm! Dry biofilms containing bacterial pathogens on multiple healthcare surfaces; a multi-centre study. J Hosp Infect 2018;100:e47–56.
[13] Ledwoch K, Said J, Norville P, Maillard JY. Artificial dry surface biofilm models for testing the efficacy of cleaning and disinfection. Lett Appl Microbiol 2019;68:329–36.
[14] Nozière B, Gérard V, Baduel C, Ferronato C. Extraction and characterization of surfactants from atmospheric aerosols. J Vis Exp 2017;122:55622.
[15] Bland HA, Centeleghe IA, Mandal S, Thomas ELH, Maillard J-Y, Williams OA. Electropositive nanodiamond-coated quartz microfiber membranes for virus and dye filtration. ACS Appl Nano Mater 2021;4:3252–61.
[16] Brunauer S, Emmett PH, Teller E. Adsorption of gases in multimolecular layers. J Am Chem Soc 1938;60:309–19.
[17] Peršin Z, Stana-Kleinschek K, Kreže T. Hydrophilic/hydrophobic characteristics of different cellulose fibres monitored by tensiometry. Croat Chem Acta 2002;75:271–80.
[18] Dharan S, Mourouga P, Copin P, Bessmer G, Tschanz B, Pittet D. Routine disinfection of patients' environmental surfaces. Myth or reality? J Hosp Infect 1999;42:113–7.
[19] Zangi R, Engberts JBFN. Physisorption of hydroxide ions from aqueous solution to a hydrophobic surface. J Am Chem Soc 2005;127:2272–6.
[20] Wesgate R, Robertson A, Barrell M, Teska P, Maillard J-Y. Impact of test protocols and material binding on the efficacy of antimicrobial wipes. J Hosp Infect 2019;103:e25–32.
[21] Sattar SA, Maillard J-Y. The crucial role of wiping in decontamination of high-touch environmental surfaces: review of current status and directions for the future. Am J Infect Control 2013;41(Suppl. 5):s97–104.