Cellulose (2021) 28:4485–4494
https://doi.org/10.1007/s10570-020-03666-w

ORIGINAL RESEARCH

Soil biodegradation of cotton fabrics treated with common finishes

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Received: 21 June 2020 / Accepted: 24 December 2020 / Published online: 17 March 2021

Abstract Cotton is one of the most widely used natural fibers available. However, to overcome some of its shortcomings, manufacturers have placed various finishes on cotton fabrics to improve wrinkle recovery, flame retardancy, anti-microbial behavior, water repellency, etc. This study measures the impact of common finishes on the biodegradability of 100% cotton fabrics in a soil laboratory environment. Under a controlled laboratory environment, cotton fabrics treated with 9 different finishing chemicals or chemical combinations were tested according to the standard test method, ASTM D5988-12, for up to 154 days. Results indicate crosslinked fibers show better protection from biodegradation when compared to the control fabric and non-crosslinked fabrics. The production of carbon dioxide (CO_2) as a function of time was measured to determine the degree of biodegradation. Untreated cotton samples produced 2500 mg of CO_2 after 154 days, approximately 40% more than that of the crosslinked treated fabric. Weightless studies showed the untreated fabrics and non-crosslinked finished having 40–60% weight loss after 154 days, while the crosslinked fabrics had unless than 20% weight loss over the same time period. Scanning electron microscope (SEM) images were used to observe the visual degradation level for each sample showed certain treated fabrics showed a less evidence of cracking on the fiber surface along with less microorganism growth. Fourier-transform infrared spectroscopy (FTIR) analysis showed that in general, treated fabrics with higher CO_2 production and higher weight loss showed greater evidence of microorganism growth when analyzing peak bands typically associated with microorganism growth irreversibly bonded to the fibers.

Graphic abstract

Keywords Biodegradation · Cotton · Chemical finishes · Soil burial test

Supplementary Information The online version of this article (https://doi.org/10.1007/s10570-020-03666-w) contains supplementary material, which is available to authorized users.

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Introduction

Cotton, consisting mostly of cellulose, is the most widely used natural fiber in textiles and apparel, making up 40% of worldwide textile production (Chapagain et al. 2006; Fletcher 2012; Griffin et al.

2017). Cotton is utilized for its high absorbency, softness, high tensile strength and breathability. However, cotton has few drawbacks including high flammability, poor wrinkle recovery, and susceptibility to microbial attack. Researchers and companies have tried to resolve these drawbacks with the use of functional chemical finishes on the cotton fabric (Lam et al. 2012). This includes the introduction of crosslinking agents to react with the hydroxyl groups in the cellulose backbone to create wrinkle-resistant apparel (Frick et al. 1960), the application of flame-retardants to alter the mechanism of pyrolysis (Horrocks 2001) and antimicrobial finishes to inhibit microorganism growth (Gao and Cranston 2008). Finishes are not only limited to addressing these drawbacks but can be used to satisfy aesthetic and functional performance requirements of consumers such as the application of softeners (Reddy et al. 2008).

Though the use of chemical finishing is extensive, there is limited research on the effect of newer finishes on the biodegradability of the cotton textile. Increases in world fiber consumption and hence its resultant deposition after use has led to a wide issue with textile waste; with the Environmental Protection Agency (EPA) estimating the United States sending 11.2 million tons of waste to the landfill in 2017 alone. Cotton naturally is biodegradable, however chemical modification can affect the rate of degradation (Primc et al. 2016). Cotton biodegradation causes depolymerization of the cellulose macromolecules. This depolymerization is mainly initiated by microorganisms that cause hydrolytic and oxidative degradation of cellulose (Montegut et al. 1991; Szostak-Kotowa 2004). Some researchers have found nanoparticle finishes on the surface of cellulose fibers might decrease biodegradability (Primc et al. 2016; Milošević et al. 2017) though there are discrepancies for different test methods. Others have found that elemental silver nanoparticles and titanium dioxide did not have a significant impact on degradation (Klemenčič et al. 2010; Tomšič et al. 2017). However, researchers did find the used of silver chloride based finishes had a much greater impact on decreasing degradation. Tomšič et al. found the introduction of crosslinking agents greatly reduced the biodegradation by strengthening the amorphous regions and increasing hydrophobicity (Tomšič et al. 2007).

While the existing works provide valuable insight on various finishes, they all focused on only one type of finish in comparison to the untreated cotton. However, because these studies are done under different conditions, comparing the effects of these finishes on biodegradation to each other is very limited. To better address these comparison gaps in the current available research, we used various widely used finishes in the textile industry. This offers us the advantage of making direct comparison of the effect of these finishes on the soil biodegradation of the cotton fabrics. In this work we aim to investigate the biodegradability of cotton fabrics with nine finishes consisting of wrinkle recovery, water repellent, flame-retardant, softening, and antimicrobial finishes. In a controlled lab soil environment, the degradation of these finished fabrics was studied using a variety of measurements including analyzing CO_2 production, weight loss, visual degradation via SEM and photographs and FTIR. The degradation of the fabrics was followed over a 5-month period, with samples analyzed at regular time intervals to gain an understanding of the gradual change in fabric structure and degradation. We aim to show that finishes will have an impact on the degradation of cotton based on each finish's ability to impact microorganism activity.

Experimental

Materials

Finished fabrics were provided by Cotton, Inc. Cary, NC. Nine finished 100% cotton interlock knit fabrics and one relevant control (no finish) fabric were tested. The details of the finishes used in this study were given in Table 1. The full names of some of the finishes presented are as follows: DMDHEU = Low formaldehyde dimethyloldihydroxyethyleneurea, DMUG = Dimethylurea glyoxal and PBI = Polyfunctional blocked isocyanate crosslinker.

The compost soil was Garden Scape Cow Manure and Compost soil purchased from Lowe's. It is a blend of composted manure, wood compost, and sand. The soil was sieved to less than 2 mm particle size and stored at 4 °C for 7 days before use. The pH of the soil was measured as 7.9. The moisture of the soil was determined from the weight loss after drying in the oven at 105 °C for 24 h and found as 22.9%.

Table 1 Cotton Fabrics and their various finishes

	Finish type	Finish type	Application technique	Finish formula	Wet pick-up, %
1	DMDHEU & Catalyst	Wrinkle recovery	Pad-dry-cure	Permafresh 600, 50 g/L	115.6
				Catalyst KR, 27.5 g/L	
2	DMUG & Catalyst	Wrinkle recovery	Pad-dry-cure	Arkofix NZF, 80 g/L	113.0
				Catalyst NKD, 8 g/L	
3	C6&PBI	Water and oil repellent	Pad-dry-cure	Unidyne TG-5543, 80 g/L	104.2
				Phobol XAN 16 g/L	
				Acetic acid 2 g/L	
4	Wax&PBI	Water and oil repellent	Pad-dry-cure	Smartrepel Hydro CMD, 150 g/L	96.9
				Phobol XAN, 20 g/L	
				Acetic acid, 2 g/L	
5	PBI only	Water and oil repellent	Pad-dry-cure	Phobol XAN, 20 g/L	107.4
				Acetic acid, 2 g/L	
6	Silicone Softener	Softener	Pad-dry	Marsil GSS, 50 g/L	92.8
7	Polyethylene Softener	Softener	Pad-dry	Turpex ACN New, 50 g/L	106.4
8	Antimicrobial (Silver-Based)	Antimicrobial	Pad-dry	Polygiene AT300, 6 g/L	108.0
9	Flame Retardant	Flame retardant	Pad-dry-cure	Pekoflam HSD, 400 g/L	120.0

Elemental analyses of the fabrics and soil were performed on a Carlo Erba NC2500 elemental analyzer at the Cornell Nutrient Analysis Laboratory.

Methods

Biodegradation testing

Biodegradability of the fabric samples was assessed according to ASTM D 5988–12 (Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil) standard method. Each fabric type was cut into 25 pieces of 2″ × 2″ and 13 pieces of 1″ × 1″ strips. Before starting the experiments, all the fabric pieces were conditioned at constant temperature/humidity at least 24 h hours before being added to the soil. The tests were conducted in desiccators at room temperature. 500 g of soil was placed in the glass container, and mixed with 40 g of DI water and 80 g of ammonium phosphate ($(NH_4)_2HPO_4$) solution (4.72 g/L) was added to give C:N between 10:1 and 20:1 by weight. 25 pieces of 2″ × 2″ and 13 pieces of 1″ × 1″ strips were introduced to the soil and mixed very well. The glass containers which had the soil and fabric samples mixture were placed on the bottom of desiccators. 40 mL of 0.5 N KOH in 150 mL beaker and 50 mL of DI water in 100 mL beaker were placed on the perforated plate in the desiccators. Sealed desiccators were put in the dark cabinet. The amount of CO_2 absorbed by the KOH solution was measured at pre-determined time intervals. The amount of CO_2 produced was determined by titrating KOH solutions placed in the test and the blank (same conditions, but without fabrics) desiccators with 0.25 M HCl to a phenolphthalein end-point. The frequency of titrations ranged from daily to weekly, depending on the degradation rate.

13 pieces of 1″ × 1″ were used to analyze the fabric degradation at different stages of the experiment by SEM and FTIR. After each titration, a fabric sample (1″ × 1″) was taken out of each desiccator, rinsed with DI water to remove all soil residue. Fabric pieces were dried at constant temperature/humidity for 24 h before being weighed. Single weight measurement of each fabric was completed. The extent of biodegradation was estimated by calculation of the fabric weight loss:

$$W_t(\%) = \frac{W_0 - W_t}{W_0} \times 100$$

where $W_t(\%)$ is the percent of weight loss after t days of biodegradation, W_0 is the initial weight of the fabric (g) and W_t is the weight of dry fabric after t days of biodegradation (g).

FTIR spectroscopy

All the fabric samples were analyzed by FTIR spectrometer (PerkinElmer-Frontier, Waltham, MA, USA) in the absorbance mode, at the range 4000–600 cm^{-1}, with a scan resolution of 4 cm^{-1} - and an average of 32 scans. To analyze and compare data, the FTIR spectra were normalized. First, a wavelength and absorbance were determined as a base value then all absorbance values were divided by this determined value. This allowed for better overlay of the graphs in order to calculate peak intensity difference.

SEM analysis

The morphology of the cotton fabrics was examined using a Zeiss 1550 Field Emission Scanning Electron Microscopy (Zeiss FESEM, Oberkochen, Germany). All samples were coated by a layer of Au/Pd and the images were obtained at an accelerating voltage of 3.0–5.0 kV.

Results

One of the ways to assess the degree of biodegradability of a fabric is to quantify the CO_2 generated during the process of fabric mineralization (Park et al. 2004; Li et al. 2010). The larger the amount of CO_2 produced, the higher the degree of biodegradation. For the first two weeks of this study, all the fabrics produced similar amount of CO_2 (Fig. 1). After day 10, however, the flame-retardant finish fabric began to produce, on average, approximately 30% more CO_2 than the control fabric up until day 120. Fabrics with crosslinking agents such as DMDHEU and PBI exhibited the lowest amount of CO_2 production, with the DMDHEU fabric having the lowest carbon dioxide production after 154 days. The DMDHEU finished fabric produced 40% less CO_2 than the control fabric, with wax and C6 containing finish fabrics producing about 30% less. Non-crosslinked finishes, such as softeners, produced only 4–8% less CO_2. At the end of the 154-day experiment, all finished samples produced less carbon dioxide than the control fabric.

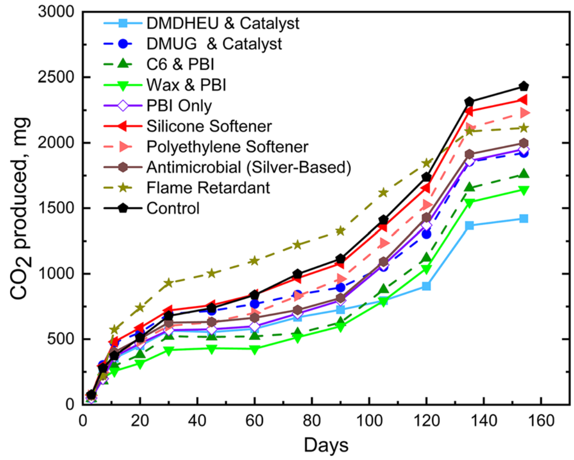

Fig. 1 The accumulated amount of CO_2 produced during biodegradation of cotton fabrics with various finishes in soil according to ASTM D 5988–12. Amounts report have subtracted CO_2 produced by soil blank with $(NH_4)_2HPO_4$

The weight loss of each set of finished fabrics can be seen in Fig. 2. Weight loss for most of the samples was very low in the initial stage of the experiment but after 45 days the samples start to lose weight. The only fabric to deviate from this trend is the flame-retardant finish which shows notable weight loss within the first 20 days; showing a 20% greater weight loss compared to the other finishes. Interestingly, after 100 days there

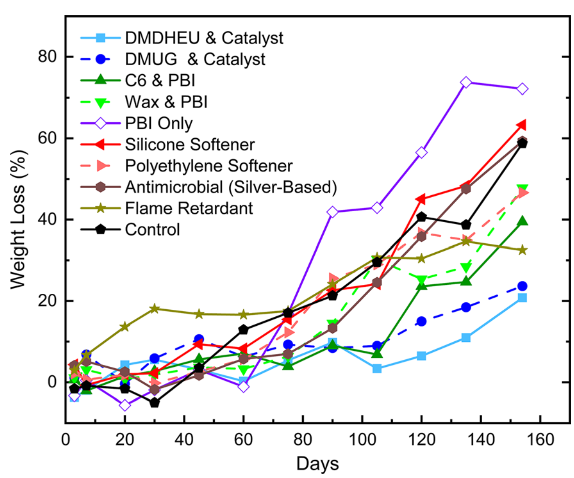

Fig. 2 Weight loss of cotton fabrics with various finishes

was no significant change in the weight loss of the flame-retardant finish fabric. Although this sample showed the highest initial rate of weight loss, the flame-retardant finish fabric had among the lowest overall weight loss at the end of the experiment. Wrinkle recovery finishes containing a five-member ring structure such as DMDHEU and DMUG showed the lowest overall weight loss, losing only 20% of its starting weight after 154 days. The remaining finished fabrics maintained low weight loss during the first half of the experiment followed by rapid increase in weight loss in the last half of the experiment. This was exemplified by the antimicrobial finish which has 90% of its weight loss occurring from day 75 to day 154.

Similar to the CO_2 experiment, most other samples had less than or equal amounts of weight loss than the control. The PBI only finished fabric deviated strongly from this trend. Within the first 60 days, the PBI only fabric showed among the lowest weight loss, however after day 60, the rate of weight loss increased substantially. From day 60 to day 90, there was a 43% increase in weight loss, much higher than the 9% average increase observed for the other finished fabrics. The rapid weight loss continued until the end of the experiment, resulting in the PBI finished fabric having the only significantly higher weight loss than the control fabric. It should also be noted, the finishes that combined PBI with another finish did not show the same drastic increase in weight loss as the PBI only finish. With the C6 and wax finishes totaling 40% and 47% percent weight loss respectively, compared to 72% for the PBI only fabric.

Figure 3 shows a visual representation of the gradual degradation of the fabrics throughout the 154 days of the soil burial tests. During the first week all fibers maintained a uniform color and appearance. As the days progress, the fabrics started to discolor and rot; first showing patches of brown, then black and finally formation of holes and full fabric degradation. The anti-microbial finish was able to maintain the light color of the original fabric the longest before showing visible signs of fiber discoloration at day 90. The majority of finished fabrics showed signs of discoloration after the first week as they start to turn brown. The flame-retardant finish fabric was the first fabric to show the formation of holes in the fabrics though the appearance of holes is not consistent as the days continue. The damage on the flame-retardant finished fabric after 90 days was not homogeneous as evidenced in the large holes appearing. The flame-retardant finished sample taken at 154 days showed no holes, but the fabric was noticeably thinner than the others. After 154 days, the PBI only fabric showed the most degradation, with large portions of the fabric missing. Wax&PBI finishes and silicon softener finishes also showed large portions of the fabric missing. DMDHEU, DMUG and flame-retardant finish fabrics maintained their rectangular shape and showed the least evidence of degradation at the end of the 154 days.

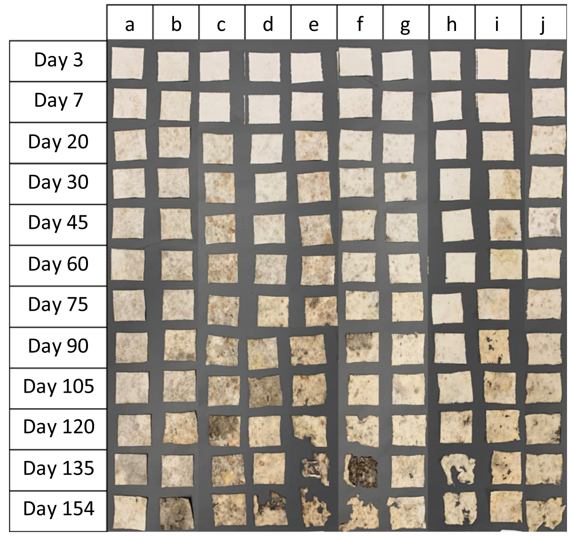

Fig. 3 The photographs of fabric samples at different stage of degradation: **a** DMDHEU and Catalyst, **b** DMUG and Catalyst, **c** C6 and PBI, **d** Wax and PBI, **e** PBI only, **f** Silicone softener **g** Polyethylene softener, **h** Antimicrobial (silver-based), **i** Flame retardant, **j** Control (no finish)

SEM images show the changes in morphological structure for various fibers at different stages of degradation Fig. 4). Figure 4 shows images of samples finished with DMDHEU, C6&PBI, and PBI only, along with the control fabric. Images of remaining fibers can be found in supplemental information (Figure S1-S6). In Fig. 4, a representative finish was chosen for each level of overall biodegradation: low (DMDHEU), medium (C6&PBI) and high (PBI only) compared to the control (medium–high). The twisted smooth ribbon shape of the cotton fibers was obvious in the day 0 samples before degradation. After 154 days, DMDHEU and DMUG fabrics still maintained smooth morphology with little sign of cracking on the fiber surface. There was evidence of microorganism growth on the fibers, but growth was not seen

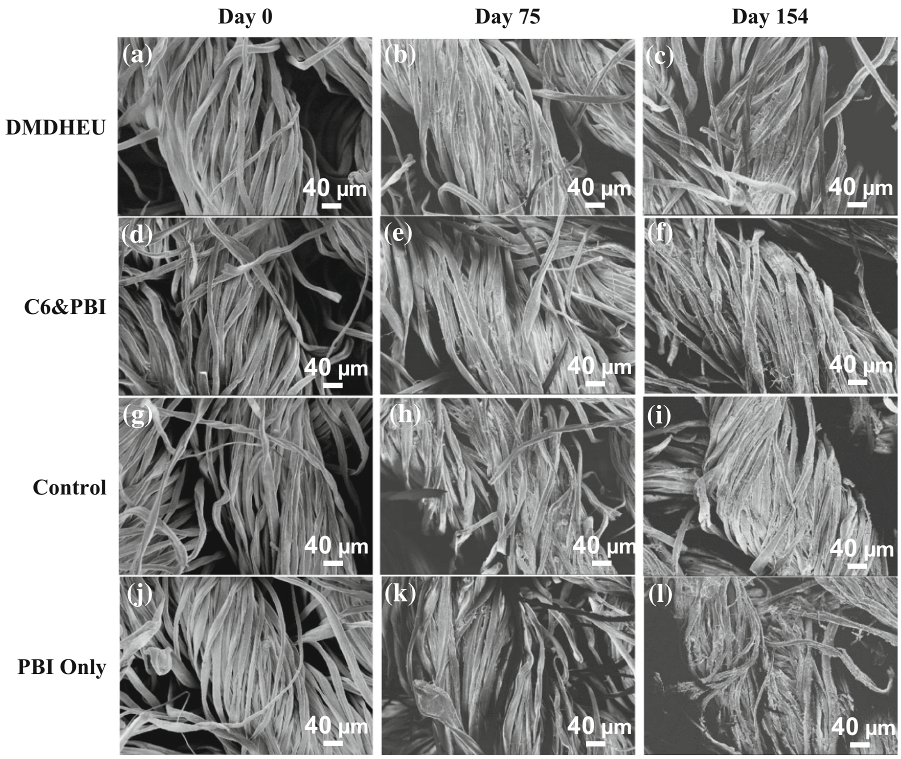

Fig. 4 Scanning electron microscopy images of cotton fabrics with various finishes: DMDHEU **a**–**c** C6 and PBI **d**–**f** control (no finish) **g**–**i** PBI Only **j**–**l** after 0, 75, 154 days

on all observed fibers. For samples with a medium level of biodegradation represented by C6&PBI (includes C6&PBI Fig. 4d-f), wax&PBI (Figure S4), flame retardant (Figure S6)) biodegradation can be seen on day 75. Most of the fibers are still smooth but with early signs of fraying observed. After 154 days, the fiber remained smooth, however, there was significant bacterial growth observed on the surface of the fibers compared to the low degradation of the crosslinked finish samples. For the PBI coupled finishes, there were signs of fraying along the perimeter of the fiber but little sign of broken fibers. As we move to the mid-high levels of degradation, cracks could be seen along the fiber surface after 154 days and the control fabric showed signs of broken fibers. The softener finishes show much more microorganism growth and damage compared to the control fabric (Figure S2-S3). The polyethylene finish fabric especially shows a great amount of growth, cracks and damage to the individual fibers. Proceeding to the PBI only fiber, the most extreme degradation was seen. There were significant cracks on the surface of the fibers, and some appear torn. The once twisted morphology of the fabric has completely disintegrated and the fibers have separated from each other. Not only are the fibers separating from each other, but the fibrils also appear frayed and broken. The fibers appeared to be completely covered in microorganism growth.

Changes in fiber chemical structure during degradation were explored using FTIR. FTIR spectra taken at day 0, day 75 and day 154 are presented in the supplementary section (Figure S7-S16). The absorption at 3100–3600 cm^{-1} was due to the stretching of OH group, and 2800–3000 for CH stretching. The peak at 1641 cm^{-1} was from the H–O–H bending of the absorbed water and 1416 cm^{-1} was from the symmetric bending of C-H. The bands at 1061 and 1032 cm^{-1} indicated C–O stretching and C–C stretching. These C–O stretching bands gave slight shoulders at 1160 cm^{-1} which represented the antisymmetric bridge stretching of C–O–C groups in cellulose and hemicellulose. The band at 1111 cm^{-1} corresponded to asymmetric glucose ring stretching. The appearance of peak bands at 1640 cm^{-1} and 1548 cm^{-1} was characteristic of Amide I and II. The intensity of these two Amide absorption bands were used as a measure of the degree of microorganism growth and presented in Fig. 5. For most finishes, we saw the Amide I peak showed the greatest increase as biodegradation progressed most notably for PBI only and silicone softener finishes. Though the silicone softener had one of the highest increases in the Amide I band, it showed a lower increase for the Amide II band. The finish that showed the smallest increase in both Amide I and II peaks was the flame-retardant finish with only a 0.01a.u. increase in peak ratio observed in both causes. Following the flame-retardant finish were the wrinkle recovery fabrics with an average increase of 0.04 a.u.

Discussion

Taking into account all the factors discussed, there was an initial trend seen in fabric degradation based on fabric finish. Finishes on the cotton fabric could be divided into crosslinking finishes (DMDHEU, DMUG, and finishes containing PBI) vs non-crosslinking (softeners, antimicrobial and flame retardant). Crosslinking agents such as DMDHEU and PBI formed covalent bonds between the hydroxyl groups of the cellulose molecules in the cotton fiber during the curing stage of the finishing process (Schindler and Hauser 2004; Gilbert 2017). The crosslinking of the polymer backbone appeared to inhibit the conversion of carbon in the anhydroglucose backbone of the polymer to CO_2. This result expands on Tomšič et al. (Tomšič et al. 2007) findings which showed DMDHEU slowed degradation of cellulosic material. Non-crosslinked finishes did not alter the backbone of cellulose within the cotton fiber and therefore had less impact on reducing CO_2 produced. The silver based anti-microbial finish produced similar CO_2 to some of the crosslinked fibers which was expected based on previously published results which found that silver chloride compounds can lessen the degradation of cellulosic fibers (Klemenčič et al. 2010). Though it had been previously noted that silver nanoparticles do not provide adequate protection against microorganisms, silver chloride based finishes, like the one used in this study, were much more effective. Silver

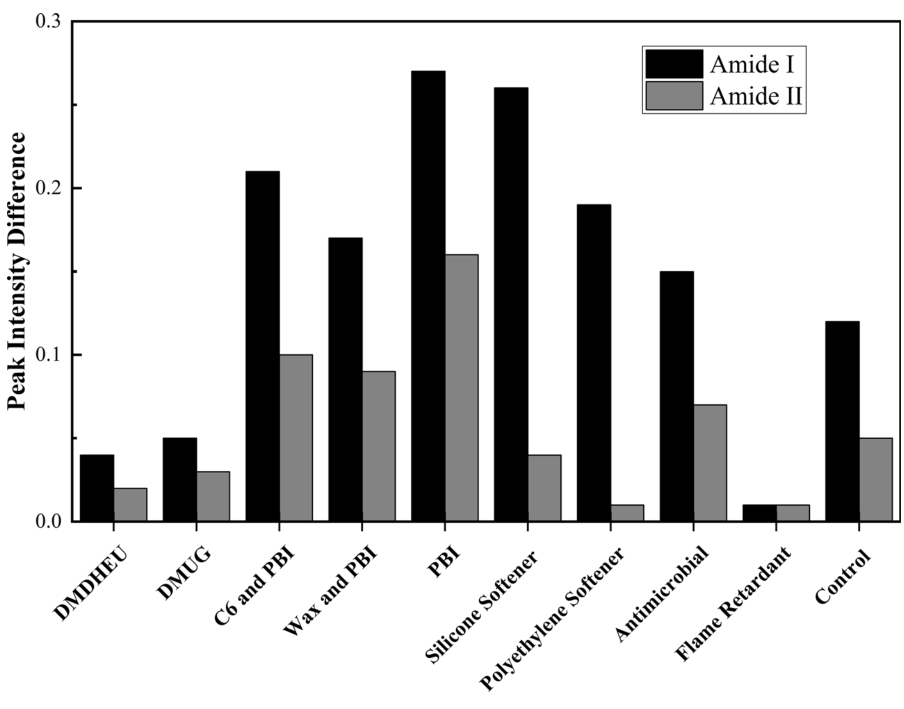

Fig. 5 Difference of normalized spectra peak intensity for each fabric finish at 1640 cm^{-1} (Amide I) and 1548 cm^{-1} (Amide II) from day 0 to day 154

nanoparticles were shown to agglomerate which limited the Ag^{+} cation release from the surface. In contrast, silver chloride finishes released a much higher amount of Ag^{+} cations upon the dissociation of the silver salt. As previously mentioned, degradation of cotton occurs when microorganisms attack the polymer bonds (Blackburn 2005) of the cellulose chain; however silver exhibited biocidal activity limiting the fiber exposure to such organisms (Lazić et al. 2015). Non-crosslinked fibers without this biocidal tendency showed CO_2 production similar to the control fabric.

CO_2 production shown in Fig. 2 cannot be relied on solely to examine cotton biodegradation. Though the PBI only finish falls in the middle of the pack for the CO_2 production, it has the highest measured weight loss percentage, exceeding the weight loss of the control fabric by 13%. This behavior was unexpected since PBI is a crosslinking agent which should hinder biodegradation. During the first 60 days we see that PBI has among the lowest average weight loss due to the hydrophobic nature of the finish. However, there was a significant jump in weight loss between day 60 to 90, from $\sim$ 1% to 40%. The large weight loss of the PBI fiber can be attributed to the brittle nature of the PBI only coating and leaching of the finish into the surrounding soil. Incorporating water repellent finishes such as PBI can lead to hard brittle surface film on the fibrous material after the chemicals polymerizes, thus increasing the brittleness of the overall fabric. This increase in brittleness of the fabric can lead to disintegration, which would account for the high weight less but average CO_2 production of the PBI only. The brittle nature of the coating can also lead to the breakdown of the finish coating over time making the fabric more susceptible to water uptake and microorganism growth. As the PBI finish leaches out into the surrounding soil, the fabric became more hydrophilic, leading to high uptake of water into the amorphous regions and swelling. Swelling could lead to microcracks on the surface of the fiber leading to defects and higher surface area available to microorganisms. The increase in microorganism activity will lead to higher biodegradation and hence facilitating weight loss. In addition, the microcracks formed can facilitate more rapid colonization of microorganisms within the fabric, further accelerating degradation (Yaacob et al. 2016; Sülar and Devrim 2019). Cracks in the fabric structure were clearly seen in Fig. 4, with frayed and broken pieces observed in the SEM image. Photographs of the PBI fabric showed the extensive degree of fiber degradation with most of the fabric missing after 154 days. Finishes that couple PBI with another finish such as C6 or wax showed a much slower rate of weight loss as time progresses. As previously noted, C6 and wax are also water repellent finishes (Table 1). This increased measure of hydrophobicity allows these finishes to withstand the soil burial conditions of this study. Looking at Fig. 4f, the C6&PBI finish had maintained the original twisted morphology of the fibers with some signs of fraying. This fraying was mostly attributed to the PBI present in the finish.

Fabrics that showed the lowest weight loss also showed the fewest signs of visible degradation. For example, the DMDHEU crosslinked fabric showed the least amount of color change or hole formation. Unlike PBI only fabric, this result agreed with the carbon dioxide and weight loss data. As noted above, the degradation of fabrics with some finishes such as the flame retardant and antimicrobial finishes (Fig. 3) was not homogenous. This non-homogeneity could be attributed to a combination of factors such as: (1) non-homogeneity of the finish application during production (2) position of fabric within the soil and (3) the orientation of the fabric (whether its folded or not completely flat). All these factors could affect the ease of microorganism attack degradation of the fabric.

Important information regarding the chemical structure differences in the fabrics at day 0 and day 154 was provided by infrared spectra data. In Fig. 5, we presented the change in peak intensity at 1640 cm^{-1} (Amide I) and 1548 cm^{-1} (Amide II). The existence of these peaks was explained by the presence of secondary polyamides from proteins that formed when microorganism growth became irreversibly bonded to the fibers (Tomšič et al. 2011). The Amide I band was the result of C=O stretching vibrations of the β-sheet of the peptide bonds, while the Amide II band shows interactions between C=O and N–H deformation coupling (Kong and Yu 2007; Gupta et al. 2015). The largest increase in peak intensity was seen in PBI only finish fabric; this confirms that the drastic increase in weight loss and visual degradation seen was due to the presence of microorganisms. The C6&PBI and wax&PBI fabrics show a smaller increase in peak intensity, indicating these finishes provide some protection against microorganism growth. Most finishes see an increase in both the Amide I and Amide II peaks with the increase of the Amide II peaks usually half that of the Amide I. However, softener finishes showed primarily a large increase in the Amide I peak and little change for the Amide II peak. This indicated the softener finishes influence how the polyamides bind to the fabric.

Although microorganism activity is often credited with the biodegradation of cellulose fabrics, the flame-retardant finish shows this is not always the case. Though there was observed change in CO_2 production and weight loss after 154 days, there was very little evidence of polyamides bound to the surface from the FTIR data. Flame-retardant finish fibers showed little activity at the relevant FTIR bands after 154 days, indicating the degradation was caused by something other than microorganism attachment. A large change in peak intensity occurred at approximately 3340 cm^{-1} which was not seen for the other fabrics (Figure S16). Changes in peak intensity in this region are explained by changes in intramolecular forces of the O–H vibrations (Fengel 1992; Zghari et al. 2018). The increase indicates an increase in intramolecular hydrogen bonding strength due to enzymatic hydrolysis which causes disintegration of the amorphous regions of the cotton fabric most notably in the lignin and hemicellulose (Guo et al. 2014; de Aguiar et al. 2020). In addition, the FTIR spectra of the control fabric and the other finished fabrics (excluding flame retardant) indicated little change in the characteristic cellulose peaks around 1000–1200 cm^{-1}. However, for the flame-retardant finish there is substantial increase in peak intensity further indicating a disruption in the hydrogen bond network and the cellulose structure.

Conclusions

As the world develops more fabric finishes to address some of the perceived shortcomings of untreated cotton, it is important to understand how these finishes affect the biodegradability of cotton fabrics once they are discarded. Initial results show crosslinked finishes show less biodegradation than the non-crosslinked finishes. Outcomes of this experiment showed wrinkle recovery finishes slow the degradation of cotton as they strengthen the disordered area of the fiber leading to less degradation by microorganisms. DMDHEU finish fabrics showed the lowest CO_2 production, weight loss and microorganism activity. While PBI only finish fabrics showed the largest degradation caused by microorganism present in the soil. This is owed to the disintegration of the fabric finish reducing the fabric hydrophobicity due to the brittle PBI coating disintegrating during the tests. Interestingly, the biodegradation of flame-retardant finish fabric was evidenced by changes in intramolecular forces as a result of enzymatic hydrolysis instead of the presence of bound polyamides as with the other fibers. Silicone treatments show little impact in the soil biodegradation of the cotton fabrics which supports previous results seen from this lab.

Acknowledgments This work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1719875).

Author contributions **Soshana Smith**: formal analysis, writing—original draft, visualization; **Mehmet Ozturk**: conceptualization, methodology, data curation; **Margaret Frey**: supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding This work was financially supported by Cotton, Inc [grant number 18–266].

Compliance with ethical standards

Conflict of interest None.

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