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Effect of Fabric Geometry on Resistance to Pesticide Penetration and Degradation

Mastura Raheel and Elizabeth Craig Gitz

Department of Textiles, Apparel, and Interior Design, University of Illinois, 905 South Goodwin, Urbana-Champaign, Illinois 61801

Abstract. Cotton is a standard washable fabric for garments and is preferred for workclothing. Agricultural workers' clothing may become contaminated with pesticides. Among other factors, the rate of pesticide solution penetration and transport from the garment to the underlayers, such as undergarments or skin, depends on fabric geometry. In 100% cotton fabrics, the ease of wettability as measured by the drop absorbency rate is higher in fabrics with large interfiber and interyarn capillaries, while the level and rate of wicking is higher in fabrics with smaller interfiber and interyarn capillary radii, due to fine, highly twisted yarns and dense weave. The implication of these results is that contrary to the U.S. Federal Register specifications for closely woven fabrics as body covering for pesticide applicators, a tightly woven fabric may transport pesticide solution to the undergarments or skin more rapidly and to a greater extent, due to a wicking action.

Cotton is a standard washable fabric for garments and coveralls, as well as undergarments. Cotton and cotton-containing fabrics are preferred for work clothing because of the comfort factor and good washability characteristics associated with cotton. Agricultural pesticide applicators and field workers, however, may frequently come into contact with pesticides during the course of their work. Contaminated clothing presents a hazard through continuing dermal exposure long after the pesticide application operation has ended. Human exposure and absorption of pesticides occur by three routes: dermal, respiratory, and oral. It is believed that the primary factor in the intoxication of agricultural workers is dermal exposure to pesticides. Studies by Wolfe *et al.* (1966) have shown that considerably more pesticide is deposited on the skin instead of the respiratory tract.

Minimizing dermal exposure to pesticides may best be achieved through the appropriate use of clothing as a body covering. Various types of protective garments and respirators for spray applicators have been developed, including disposable protective clothing based on plastic-covered paper and non-woven plastic discussed by Kawar *et al.* (1978). The specific protective measures required by the National Institute of Occupational Safety and Health (NIOSH) vary according to the degree of potential exposure and body area most likely to be contaminated. Nevertheless, the standards developed by NIOSH (1976, 1978) apply only to the processing, manufacture, or other workplace exposure to pesticides. Many agricultural workers and household users of pesticides, however, use their usual everyday clothing during pest control operations.

This study examines the effects of fabric geometry on resisting pesticide penetration and fabric degradation.

Experimental

A randomized block design with three replications was developed. Analysis of variance and F ratios were used to discriminate significant difference. In addition, t-tests were performed to discriminate differences between pairs of treatments.

Fabrics

One hundred percent cotton in three fabric geometries were obtained from Testfabrics, Inc., Middlesex, NJ. These were cotton broadcloth (Style 419A), twill (Style 423), and poplin (Style 407). The fabric characterization data are given in Table 1.

Pesticides

Three classes of pesticides were selected based on their broad application. These constituted a carbamate insecticide (carbaryl) in liquid formulation and wettable powder form; a benzoic acid derivative herbicide (chloramben) in liquid formulation; and a hetrocyclic nitrogen derivative herbicide (atrazine) in flowable liquid, as well as wettable powder form (Table 2).

Methods

The fabrics were laundered to remove any traces of sizing which may have been left, using a low phosphate detergent, a wash temperature of 60°C and rinse temperature of 49°C. The desized fabric specimens were treated with pesticide/acetone solutions. Acetone was used as a common solvent for all three pesticides, because atrazine and carbaryl had low solubility in water. In addition, acetone offered ease of handling, compatibility with pesticides and minimum adverse effects on cotton fabrics. Two concentrations of pesticide solution were used: 1.25% a.i. (active ingredient) representing field strength, and 5.0% a.i. simulating repeated exposure of garments that could occur during the pesticide application process. The fabrics were saturated in 500 ml of pesticide solution according to procedures used by E.I. DuPont De Nemours & Co. (1966) in sealed glass containers for 8 and 100 hr at 22°C and for 8 hr only at 50°C. The 100 hr exposure at 50°C was attempted but discarded due to acetone vapor pressure buildup in sealed jars, whereas in unsealed jars constant pesticide/acetone concentration could not be maintained for 100 hr. The glass jars were placed in a Precision Shaker Bath to maintain proper agitation and thermal regulation.

Following pesticide treatments, the fabric specimens (36 × 20 cm) were decontaminated with three rinses of 500 ml acetone. The samples were then laundered in an Atlas Launderometer according to AATCC test method 61-1980 II A (1983), using 60°C temperature and 0.2% detergent solution (Tide®) for 9 min to remove the last traces of pesticides. The fabrics were rinsed in warm water (49°C), air dried, and conditioned for at least 24 hr prior to testing.

To assess the ease with which pesticide solutions would penetrate the fabric and induce chemical degradation, the following physical tests were performed:

Drop Absorbency: Drop absorbency was performed according to AATCC test method 79-1979 (1983). A drop of liquid (distilled water or pesticide solution) was delivered from a burette on the taut surface of the fabric mounted in an embroidery hoop. The tip of the burette was kept at 1 cm distance from the taut surface of the fabric. The time for the specular reflection of light to disappear from the surface of the flattened drop was recorded in seconds. The average of ten tests per replication was recorded.

Wicking: Wicking levels were determined in both warp and filling directions in fabrics by allowing a 2.5 × 15 cm specimen to hang vertically above a liquid (distilled water or pesticide solution) reservoir. The fabric was marked at 1 cm intervals with a water-soluble ink. The weighted specimen was immersed 1 cm into the liquid which was taken as the starting line. The wicking height after 1 min, 5 min, and 10 min was recorded in centimeters. The average of five warp and five filling tests was taken for each treatment per experiment replication.

Tensile Strength: Tensile strength measurements were performed in the warp and filling directions in fabrics according to ASTM test method D-1682-75 (1983), using an Instron Table Tensile Tester.

All physical tests were performed after the specimens were allowed to equilibrate for at least 24 hr at 21 ± 1°C and 65 ± 2% RH (relative humidity).

Results and Discussion

To insure evaluation of chemical degradation due to pesticides, fabrics were treated with the solvent acetone under similar conditions as with pesticide/acetone solutions to establish the effect of acetone as a control. At 0.05 level of probability, no significant differences were found in the physical properties between the original untreated fabrics and those exposed to acetone, implying that any deviations in physical properties may indeed be attributed to the effects of pesticide treatments.

The cotton fabrics were different in weight, yarn count, yarn linear density and yarn twist factor. Twill fabric was the heaviest among the three fabrics. Twill and poplin were closer to each other in weight and yarn characteristics compared to cotton broadcloth, which was lightweight, had finer yarns with a higher twist factor and was more tightly constructed (Table 1).

Drop Absorbency

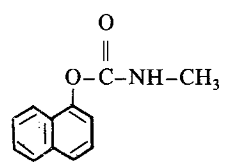
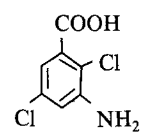
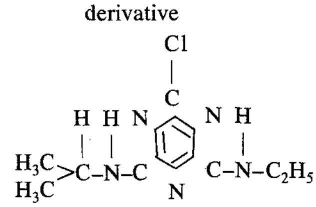
The drop absorbency rate of all three fabrics was very high and ranged from less than one sec to 1.8 sec. Cotton twill exhibited the highest rate of drop absorbency before and after pesticide treatments (Table 3), closely followed by poplin and broadcloth in that order. The changes in rate of absorbency due to pesticide treatments were too small for any reasonable deductions. Nevertheless, the absorbency rate exhibited relevance to the geometric attributes of fabrics. Cotton broadcloth, which had dense fabric construction, higher yarn count, and finer yarns with higher twist factor exhibited a relatively low rate of drop absorbency compared to twill and poplin fabrics. Cotton twill, which had the lowest yarn interlacings, hence greater yarn mobility and interfiber and interyarn spaces, exhibited the highest rate of drop absorbency, closely followed by poplin fabric.

Drop absorbency measures the ability of a fabric

Table 1. Characterization of fabrics

Fabric	Fabric weight $(g/m)^2$	Yarns per cm		Yarn number (Tex)		Yarn twist (Turns/cm)	
		Warp	Filling	Warp	Filling	Warp	Filling
						singles Z	
Cotton broadcloth #419A	115	57	25	14	14	9.0	9.0
Cotton twill #423	295	33	24	39	40	7.0	5.0
Cotton poplin #407	222	44	23	25	41	7.0	5.0

Table 2. Pesticides used in treatment of fabrics

	Insecticide	Herbicides	
Name	Carbaryl (Sevin®)	Chloramben (Amiben®)	Atrazine (Aatrex®)
Class	Carbamate	Benzoic acid	Heterocyclic nitrogen derivative
			
Chemical formula	1-Naphthyl N-methyl carbamate	3, Amino-2, 5-dichloro-benzoic acid	2-Chloro-4 ethylamino-6-isopropylamino-s-triazine
Commercial formulation	A. Flowable liquid (Sevin 4L) B. Wettable powder (Sevin 50W)	A. Flowable liquid	A. Flowable liquid (Aatrex 4LC) B. Wettable powder (Aatrex 80W)

to transport water from the surface into the interior of the fabric. This ability depends upon the hydrophilicity of the fiber, the availability and accessibility of the polar groups in the polymer chain, as well as fiber morphology, and interfiber and interyarn spaces in fabrics. Since all three fabrics were bleached and mercerized cotton with no special functional finish, it is reasonable to assume that the hydrophilicity, accessibility of the hydroxyl groups in cellulose chains, and fiber morphology were similar. Thus, the differences noted in drop absorbency were due to the geometric attributes of fabrics. Washburn (1921) discussed the parameters affecting the rate of capillary flow for movements of liquids in horizontal capillaries which describe the term wetting, as in drop absorbency, and derived an equation:

$$dl/dt = (\gamma r/4ln) \cos \theta$$

Where dl/dt describes the rate of liquid transport, r the capillary radius, n the viscosity of the liquid, and θ the liquid contact angle on the fiber. This equation establishes that in wetting action (horizontal transport of liquid where gravitational force can be neglected) an increase in capillary radius (or surface tension of the liquid or decrease in contact angle θ) would result in increased rate of wetting. Thus, cotton broadcloth having finer and tightly twisted yarns and closely woven construction exhibited a relatively slow rate of wetting. On the other hand, twill fabric with larger diameter yarns, less yarn interlacings, hence larger interfiber and interyarn capillary radii exhibited higher wetting rate. Cotton poplin exhibited an intermediate wetting rate but was closer to twill than broadcloth. It follows that twill and poplin fabrics would transport water and pesticide solution into the fabric interior more rapidly than broadcloth. Based on fabric weight data, it also follows that cotton twill and poplin may retain larger quantities of pesticide solution within the fabric spaces rather than transporting it to the secondary surfaces such as under-

Table 3. Drop absorbency rate in seconds

Fabrics	Initial value (control)	Pesticide treatments: Carbaryl Liquid formula	Carbaryl Wettable powder	Chloramben Liquid formula	Atrazine Liquid formula	Atrazine Wettable powder
		100 hr exposure at 22°C				
Cotton broadcloth	1.3	1.2[a]	1.3	1.5	1.4	1.3
		1.3[b]	1.3	1.8	1.2	1.4
Cotton twill	0.5	0.6	0.3	0.4	0.4	0.3
		0.5	0.4	0.4	0.4	0.5
Cotton poplin	0.6	1.5	0.7	1.3	0.4	0.6
		0.8	0.6	0.8	0.7	0.7
		8 hr exposure at 50°C				
Cotton broadcloth	1.3	1.8	1.2	1.2	1.3	1.1
		1.5	1.5	1.9	1.3	1.5
Cotton twill	0.5	0.3	0.4	0.6	0.4	0.3
		0.4	0.3	0.6	0.3	0.3
Cotton poplin	0.6	0.9	0.4	0.6	0.5	0.6
		0.9	0.6	0.5	0.6	0.4

[a] 1.25% a.i.
[b] 5.0% a.i.

Table 4. Level of wicking in cms

Fabrics	Warp (min) 1	Warp 5	Warp 10	Filling (min) 1	Filling 5	Filling 10
Cotton broadcloth	3.4	7.3	10.0	2.9	6.9	9.0
Cotton twill	4.3	7.4	9.4	3.7	6.5	8.0
Cotton poplin	3.5	6.0	7.6	3.4	6.1	7.6

garments or skin, thus limiting dermal intoxication compared to cotton broadcloth.

Wicking Level

There were no significant differences ($\alpha = 0.05$) between the initial wicking level of a specific fabric and after exposure to all three pesticides under various conditions. Therefore, wicking data are given at different time intervals rather than for each condition of pesticide treatment (Table 4).

Cotton broadcloth and twill exhibited higher wicking levels in the warp direction than in the filling direction of fabrics. Cotton poplin exhibited highly uniform wicking levels both in warp and filling directions. After 1 min of immersion time, twill fabric exhibited a higher wicking level in both warp and filling directions compared to the other two fabrics (Table 4). After 5 min, twill and broadcloth were very close and exhibited higher levels than poplin. However, after 10 min, cotton broadcloth exhibited a statistically significant ($\alpha = 0.05$) higher wicking level in both warp and filling directions compared to twill and poplin. Wicking determines how rapidly a fabric transports liquid water (or solutions) from one surface to the other. It involves migration of liquid vertically through the interfiber and interyarn capillaries of the fabric. According to our results, the fabric with fine capillary radii (broadcloth) transported water the farthest, in contrast to Washburn's equation which holds true in horizontal water transport as in the wetting action. However, the Washburn equation does not seem to hold after one min of immersion time in this study, which supports the findings of Saunders and Zeronian (1982). In contrast to wetting, the wicking action is affected by gravitational forces, and larger capillary radii may not promote movement of liquids as opposed to smaller capillary radii. In addition, large capillaries increase the liquid holding capacity of the fabric rather than transporting it to other surfaces.

Hydrophillic fibers such as cotton exhibit good wicking qualities, because as the fiber preferentially absorbs water in its interior, causing swelling of fiber, the interfiber and interyarn capillaries decrease in diameter, hence an increase in the capillary action. On the other hand, a tightly constructed fabric geometry, with finer, smoother yarns (due to high twist) would also decrease interfiber and interyarn capillaries. The combined action of cotton fiber swelling and a closely woven construction would increase the wicking characteristic of the fabric. This explains the higher wickability of cotton broadcloth compared to twill or poplin. It follows that cotton broadcloth will transport water or pesticide solution to the secondary layer of fabric or skin to a greater extent than twill or poplin.

The Federal Register (1974) defined protective clothing as "at least a clean hat with a brim, a clean long sleeved shirt and long legged trouser or a coverall type garment, all of closely woven fabric." Except for the specification of being closely woven, little attention has been given to other characteristics of fabrics. In contrast to the Federal Register recommendation of closely woven fabric, the results suggest heavier weight and less tightly woven cotton twill and poplin may afford better dermal protection from pesticide solutions compared to tightly woven cotton broadcloth.

Resistance to Degradation

Resistance of fabrics to degradation when exposed to pesticide chemicals was assessed by tensile strength measurements, which were carried out in the warp and filling directions. In general, there was greater strength reduction in the filling yarns than the warp yarns in fabrics. All three fabrics exhibited tensile strength reduction in varying degrees, indicating chemical degradation of fibers due to pesticide exposure.

In the warp direction, cotton broadcloth suffered approximately 2% strength reduction when exposed to carbaryl in wettable powder formulation for 100 hr at room temperature and was not significantly different ($\alpha = 0.05$) from the reference specimens. After 8 hr exposure, the differences were negligible, therefore only 100 hr exposure data are reported.

The strength loss was significantly greater at higher temperature (50°C) exposure even for a shorter duration of 8 hr (Table 5). The effect of pesticide concentration was not significant. There was no strength reduction due to liquid formulation exposure at room temperature; however, at 50°C cotton broadcloth suffered approximately 2% strength loss in liquid formulation of carbaryl at 5% a.i. concentration. Strength reduction in atrazine was not statistically significant. Cotton twill suffered much greater strength reduction in the chlorinated benzoic acid pesticide chloramben than in carbaryl or atrazine at 100 hr exposure, but not at 8 hr exposure time, even at 50°C. Cotton poplin exhibited similar behavior as cotton broadcloth and exhibited strength reduction in all three pesticides, which was 3–4%.

The filling direction strength reductions were significantly greater ($\alpha = 0.05$) than warp strength losses. In general, longer exposure time was the overriding factor in strength reduction rather than pesticide concentration or exposure temperature. Cotton broadcloth suffered strength reduction ranging from 1 to 15% and was degraded by all three pesticides. Cotton twill suffered less strength reduction than broadcloth or poplin and was in the range of 1–6%.

Cotton poplin, on the other hand, exhibited significantly higher strength reduction than the other two fabrics in all three pesticides at 100 hr exposure time which ranged from 2 to 20%. However, at 8 hr exposure time strength loss was minimal or none.

Based on the initial strength of fabrics, the twill fabric exhibited greater strength reduction than broadcloth or poplin in the warp direction; probably, because in twill fabric there is less yarn interlacings and warp yarns are exposed on the surface to a greater extent than the other two fabrics making penetration of pesticide solution easier, hence greater chemical degradation. This reasoning explains greater strength reduction in poplin fabric in the filling direction, since in poplin the filling yarns are more exposed to the surface, hence to degradation due to pesticide chemicals. Although cotton broadcloth exhibited higher strength reduction than twill in the filling direction on percentile basis, its initial strength was one-third that of twill or poplin. Thus, in actual fact, fabrics with projected yarns, *i.e.*, poplin and twill, suffered greater degradation in that order, compared to the tightly woven cotton broadcloth. Chemical degradation and strength loss seems to be directly related to the wetting and wicking properties of fabrics. Higher wettability seems to promote pesticide solution penetration and retention, hence greater chemical degradation and strength loss.

Table 5. Percent change in tensile strength. Warp direction

Fabrics	Initial value (newtons)	Pesticide treatments: Carbaryl Liquid formula	Carbaryl Wettable powder	Chloramben Liquid formula	Atrazine Liquid formula	Atrazine Wettable powder
		100 hr exposure at 22°C				
Cotton broadcloth	285.5	+3.1[a]	−1.9	−0.3	+0.8	+1.9
		+2.5[b]	−2.1	+1.7	+1.2	−2.2
Cotton twill	632.5	+1.6	−1.9	−6.8	+2.0	−0.4
		+1.1	−1.3	−6.6	+11.7	+1.2
Cotton poplin	320.2	+2.5	−2.2	+4.0	−0.8	−1.4
		+9.0	+9.0	−4.0	+2.6	−3.1
		8 hr exposure at 50°C				
Cotton broadcloth	285.5	+0.1	−4.0	+2.5	−1.5	+5.1
		−1.9	−3.3	+2.6	+2.34	−0.8
Cotton twill	632.5	+2.2	+4.7	+1.3	+7.2	+2.1
		+4.8	+3.6	+7.4	+2.6	+2.1
Cotton poplin	320.2	−0.7	−3.1	+4.2	−4.2	+4.1
		−0.7	−1.2	+2.0	−3.6	−1.3

[a] 1.25% a.i.
[b] 5.0% a.i.

Table 6. Percent change in tensile strength. Filling direction

Fabrics	Initial value (newtons)	Pesticide treatments: Carbaryl Liquid formula	Carbaryl Wettable powder	Chloramben Liquid formula	Atrazine Liquid formula	Atrazine Wettable powder
		100 hr exposure at 22°C				
Cotton broadcloth	130.7	−1.7[a]	−15.6	−7.1	−7.5	+0.3
		−0.7[b]	−11.9	−1.0	−7.9	−3.7
Cotton twill	367.4	+6.0	+6.6	−4.9	+2.9	−0.1
		+0.6	+1.0	−4.9	−3.1	+2.4
Cotton poplin	389.6	−7.0	−5.0	−8.0	−4.8	−2.5
		−1.8	−2.1	−20.2	+1.1	−2.7
		8 hr exposure at 50°C				
Cotton broadcloth	130.7	+1.0	−3.0	−0.7	+0.4	−1.0
		+5.1	+2.0	−4.5	−4.8	−1.7
Cotton twill	367.4	+2.4	+0.1	+3.0	−0.4	+0.4
		−6.5	−4.4	−1.0	+3.2	−1.2
Cotton poplin	389.6	+5.3	+8.0	+2.1	+3.0	−0.2
		+2.8	+7.6	−5.2	+3.6	−2.1

[a] 1.25% a.i.
[b] 5.0% a.i.

Conclusions

Chemical degradation of cotton fabrics due to pesticide chemicals is related to the ease of wetting and water or pesticide solution holding capacity. Thus, cotton twill and poplin which had larger diameter yarns and more yarn exposure on the surface of the fabric than broadcloth exhibited greater strength reduction. On the other hand, the ability of twill and poplin fabrics to hold liquids and transport them to a lesser extent from one surface to the other (wicking) compared to cotton broadcloth may enhance the dermal protection afforded by these fabrics. The amount of pesticide solution transmitted from the contaminated fabrics of various fiber contents and fabric geometries to the secondary surfaces needs further investigation.

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