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Statistical Model of Pesticide Penetration Through Woven Work Clothing Fabrics

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Abstract. Statistical models estimating the level of protection and thermal comfort performance of woven fabrics were developed using simple fabric and liquid parameters. Eighteen woven fabrics were evaluated against three pesticide mixtures of atrazine and pendimethalin at different concentrations. Using three mixtures that represent a range of both surface tension and viscosity, percentages of pesticide penetration are measured, along with fabric thickness, fabric cover factor, yarn twist factor, yarn packing factor, solid volume fraction, wicking height, and air permeability. Statistical analyses are performed to examine the relationship between liquid/fabric parameters and pesticide penetration. Statistical analyses show that fabric cover factor, yarn twist factor, viscosity of pesticide mixture, critical surface tension of solid, and wicking height are significant parameters affecting pesticide penetration. For this purpose, cover factor and twist factor are better parameters in describing the geometry of woven fabrics than solid volume fraction. Modeling of comfort performance of woven fabric based on simple textile parameters shows that the combination of fabric thickness, cover factor, yarn twist factor and yarn packing factor can be used to estimate air permeability of woven fabric. These findings could be used for developing selection charts or tools as guidelines for the selection of personal protective equipment for use in hot, humid environments.

Use of pesticides in the United States continues at a high level, and workers occupationally involved in handling and application risk possible health effects due to exposure to these chemicals. According to the U.S. Environmental Protection Agency, 1.23 billion pounds of conventional pesticides (excluding disinfectants and wood preservatives) are used annually in the United States, a figure that accounts for more than one fifth of global pesticide use (Donaldson et al. 2002). The primary route by which pesticides enter the body is dermal absorption (Wolfe *et al.* 1967). Contact with these toxic chemicals is linked to the rise in cancer-related health problems and a growing number of occupational skin diseases. Thus, protection afforded by clothing is vital for minimizing dermal exposure of workers to pesticides.

Various protective clothing materials are used to reduce dermal exposure, ranging from everyday clothing to impermeable polymeric suits. Selecting the type of personal protective equipment (PPE) depends on the toxicity of pesticides being handled and exposure situation. For pesticides of low toxicity, many pesticide manufacture labels recommend long-sleeved shirt and long pants for PPE. In practice, many agricultural workers and household users of pesticide wear their everyday clothing during pest control operations because of its comfort and low cost. Surveys of 707 agricultural workers in New York, Michigan, and Iowa, on the type of PPE used when handling or spraying pesticides (Charlotte Coffman, personal communication 2004) confirm that regular work clothes in conjunction with chemical-resistant gloves are the predominantly used PPE over all other. Traditional work-clothing fabric has been shown to reduce skin exposure to pesticides (Welch and Obendorf 1997, Obendorf et al. 2003). To provide necessary information on selecting appropriate woven work clothing with sufficient level of protection, there is a need for a predictive model estimating pesticide penetration through woven fabrics.

Liquid movement in porous medium is a complex phenomenon determined by various liquid and material properties. Fiber wetting is a prerequisite for the occurrence of liquid transport into the medium and is determined by fiber surface properties and liquid properties. Critical surface tension data have been useful in evaluating wettability of fibers (Bascom 1992). Liquid surface tension and viscosity are influential factors in liquid penetration of a porous medium.

Yarn/fabric structural properties are also important in barrier performance of woven fabric (Raheel and Gitz 1985; Leonas 1991). Level and rate of wicking are determined by the size of interfiber and interyarn capillaries, which strongly depend on degree of twist in yarns and compactness in fabric weave.

In a previous work, a statistical model was developed to predict pesticide penetration through nonwoven chemical protective fabrics, using 14 nonwoven fabrics and a range of pesticide mixtures (Lee and Obendorf 2001). In the modeling, using simple pesticide and textile parameters in estimating the protection performance was attempted so that they would be usable for developing selection charts or tools as guidelines for choosing PPE in field situations. The model developed was

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based on three significant parameters: liquid/fabric surface tension difference, solid volume fraction of fabrics, and fabric thickness, which are easily measurable or readily available from the literature. Using those liquid and textile parameters and adding air permeability as another factor, Jain and Raheel (2003) developed statistical models for woven and nonwoven fabrics, based on eight woven and eight nonwoven fabrics and a range of pesticide mixtures. They suggested that separate models are needed for woven and nonwoven fabrics, and their model for woven fabrics was based on three factors: fabric thickness, solid volume fraction, and air permeability of fabrics.

Unlike nonwoven textiles, which are relatively homogeneous and isotropic in structure, woven textiles have far more complex geometric configurations because of the fabric weave and yarn structure. Woven fabrics have capillaries directed along the warp, filling, and thickness direction of the fabric. Pores in woven fabrics can be interfiber and interyarn. In general, woven fabrics give bimodal distributions in pore volume distributions (Miller and Tyomkin 1994). Typically two peaks are found in the pore volume distributions for woven fabrics: the larger pore sizes reflect interyarn space, whereas the smaller pores reflect interfiber space. Pore structure and dimension are extremely important parameters in capillary action. Structure and dimension of these inter- and intrayarn pores strongly depend on hardness of twist in yarn structure and compactness in the woven structure; hence these would have a considerable effect in determining liquid transport in woven textiles. Capillary flow is one of the major mechanisms of liquid transport in porous medium and is especially important in well-aligned capillary systems such as woven structures. Thus, parameters that could describe capillary geometry of woven textiles should be included in modeling in order to have a better representation of structural properties of textiles in the penetration process. To be usable in field situations, these parameters should not only describe complex yarn/fabric structures of woven fabrics but also be simple and easily derived from basic fabric characteristics. In this study, fabric cover factor was selected to quantify the relative magnitude of interyarn space, and yarn twist factor and yarn packing factor to represent the relative magnitude of interfiber space, as possible predictor variables for modeling.

Nonbarrier materials such as woven fabrics provide protection against chemical contaminates, through absorption and retention of chemical in the fabric (Obendorf *et al.* 2003). For nonbarrier fabrics in which capillaries are formed between fibers and yarns, liquids are held or retained by means of capillary forces, which could be influential in the protection performance of the material. Level of wicking could give further information on capillary sorption/retention of liquid in materials, and protection performance; hence, it could act as a possible predictor variable in modeling.

Predictive models are needed to estimate PPE protection performance and eventually to provide necessary information for users in choosing appropriate materials related to the chemical being handled. Theoretical studies have been made on the wetting behavior of fibrous structures, developing theoretical models to predict the wetting process, which were approached mostly from solid planar surface wetting. Lukas *et al.* (1997) pointed out the differences in wetting a solid planar surface and a fiber mass, which is heterogeneous and anisotropic, and applied Ising's model combined with Monte Carlo simulation to study liquid–fiber interactions and resulting wetting behavior of fiber networks. As described by previous researchers, the complexity of a fabric structure makes it hard to simulate pore structure in theoretical modeling of liquid penetration of porous materials. Furthermore, fiber swelling from absorption of liquid or the complex interactions of fibers with liquid can cause shifting of fibers and changes of the pore structure, which makes modeling even more difficult (Miller and Schwartz 2001, Rajagopalan *et al.* 2001). From the aspect of providing information for field situations, a statistical model would be useful as a supplement to theoretical modeling. As another step to practical application, a statistical model can be used for developing selection charts or tools as guidelines for selecting appropriate materials and serve as the basis for recommendations for pesticide applicators. To be practical, statistical modeling should cover a sufficient number of samples to represent the population of typical woven work clothing, and parameters should be readily available or simple to measure for a wide range of pesticide-woven combinations.

The main reasons that pesticide applicators are reluctant to wear conventional chemical-resistant garments are discomfort and potentially serious heat stress under hot, humid conditions. Breathability of material is extremely important in terms of wearer comfort for working in these environments. Fabric air permeability, which reveals the breathing or ventilation functions of the material, is closely related to comfort performance of fabric (Sun *et al.* 2000). Thus, it would be very useful to estimate fabric air permeability based on simple fabric measurements, along with the protection performance.

The objectives of this study are to characterize fabrics that represent the population of typical woven work clothing, to explore physicochemical factors affecting penetration of pesticide mixture through woven fabrics, and to develop a generally applicable and easily implemented statistical model to estimate the protection performance, using simple pesticide and fabric parameters. Also, a statistical model that predicts air permeability of fabric from basic textile parameters is developed to estimate comfort performance.

Materials and Methods

Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) and pendimethalin (*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine) were chosen based on their usage, type of formulation, and chemical properties. From a practical standpoint, commercially available pesticide formulations were used for the study: atrazine as wettable dispersible granules and pendimethalin as an emulsifiable concentrate. They were chosen based on differences in chemical solubility. Atrazine 90WDG, from United Agri Products/Platte Chemical Company, Greeley, CO, contains 85.5% active ingredient. Prowl® 3.3 EC, which consists of 37.4% active ingredients of *N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine, comes from American Cyanamid Company, Parsippany, New Jersey.

Eighteen woven fabrics commonly used for work clothing for agricultural workers, or having the potential for such use, with various

Table 1. Fabric descriptions

Code	Fiber	Fabric count yarns/in; W × F	Fabric weight g/m^2	Fabric thickness mm	Construction
1	Cotton	73 × 43	337 (2)	0.627 (0.012)	Twill
2	Cotton	64 × 55	191 (0.9)	0.381 (0.001)	Plain
3	Cotton	86 × 71	108 (1)	0.206 (0.005)	Plain
4	Cotton	34 × 28	540 (4)	1.000 (0.022)	Plain
5	Cotton	59 × 53	350 (2)	0.712 (0.007)	Herringbone
6	Nylon 6,6	50 × 45	125 (0.9)	0.323 (0.011)	Plain
7	Dacron®	52 × 52	126 (2)	0.301 (0.006)	Plain
8	Dacron®	40 × 32	179 (2)	0.402 (0.006)	Plain
9	Polypropylene	40 × 33	189 (3)	0.552 (0.007)	Plain
10	Cotton	78 × 29	316 (2)	0.615 (0.008)	Rib
11	Cotton	88 × 29	209 (2)	0.474 (0.008)	Rib
12	Cotton	55 × 41	359 (3)	0.601 (0.010)	Plain
13	Cotton	115 × 52	278 (2)	0.480 (0.008)	Twill
14	Tencel®	92 × 68	148 (3)	0.254 (0.014)	Plain
15	Tencel®	70 × 52	205 (1)	0.421 (0.008)	Plain
16	Cotton	74 × 49	358 (2)	0.683 (0.008)	Twill
17	Cotton	87 × 27	445 (8)	0.813 (0.036)	Rib
18	Cotton	45 × 45	474 (2)	0.972 (0.008)	Twill

Standard deviations in parentheses.

Table 2. Pesticide amounts, surface tension, and viscosity of pesticide mixtures

Pesticide	Sample code	Pesticide amounts used in mixtures				Surface tension dynes/cm	Viscosity mPa s
		Water g	Atrazine 90 WDG or Prowl 3.3 EC g	Oil g	Nonionic surfactant g		
Atrazine 90 WDG	M1	246.10	2.50	—	—	38.00 (0.57)	0.93 (0.01)
	M2	96.30	2.00	85.00	1.03	28.81 (0.22)	5.77 (0.28)
Prowl® 3.3 EC	M3	55.00	40.00	65.00	—	20.57 (0.08)	20.80 (0.05)

Standard deviations in parentheses.

fabric thicknesses, weight, fabric construction, and fiber type were selected. Fabric descriptions are given in Table 1.

Chemical Challenge

Pesticide Mixtures. Based on the previous study on liquid penetration modeling on nonwoven fabrics (Lee and Obendorf 2001), two pesticide mixtures were selected and another mixture was formulated to represent a range of viscosity and surface tension. Nonionic surfactant or oil concentrates were added for some mixtures to vary the surface tension or viscosity of each mixture. Nonionic surfactant was LI 700® from Loveland Industries Inc., Greeley, CO. Oil concentrate was All Seasons® Spray Oil Concentrate, which consists of 98.8% petroleum oil, manufactured by Bonide Products Inc., Yorkville, New York. Pesticide concentrations of selected mixtures are shown in Table 2.

Surface Tension. Surface tension of the pesticide mixtures was measured according to ASTM D 1331-89, Standard Test Methods for Surface and Interfacial Tension of Solutions of Surface-Active Agents. Four replicate measurements were taken with a surface tensiometer, model 21, Fisher, at 21°C.

Viscosity. Kinematic viscosity of pesticide mixtures was measured according to ASTM D 445-96, Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids for three replicates at 25°C ± 0.05°C. Dynamic viscosity was obtained by multiplying measured kinematic viscosity by density of the liquid.

Woven Fabrics

Fabric Thickness. Fabric thickness was measured according to ASTM D 1777-96, Standard Test Method for Thickness of Textile Materials. Measurements were taken with a Frazier Compressometer using a 0.375-inch diameter presser foot at 1.0 psi of pressure at 10 randomly selected areas.

Mass per Unit Area. Mass per unit area (weight) was measured according to ASTM D 3776-96, Standard Test Method for Mass per Unit Area (Weight) of Fabric, Option C, Small Swatch of Fabric. Measurements were taken for four randomly selected samples.

Fabric Count. Fabric count, number of yarns per inch, was measured according to ASTM D 3775-03, Standard Test Method for Fabric Count of Woven Fabric. Measurements were taken at five randomly selected areas.

Yarn Number. Yarn number was measured according to ASTM D 1059-01, Standard Test Method for Yarn Number Based on Short-Length Specimens. Measurements were taken from 10 warp samples and 10 filling samples for each fabric.

Yarn Twist. Yarn twist was measured according to ASTM D 1423-99, Standard Test Method for Twist in Yarns by the Direct Counting Method. Measurements were taken from 25 warp samples and 25 filling samples for each fabric.

Yarn Diameter. Yarn diameter was measured using a microscope equipped with a calibrated micrometer (Continuµm™, Thermo Nicolet Co., Madison, Wisconsin). Measurements were taken from 50 warp samples and 50 filling samples for each fabric.

Wicking. Three samples for both warp and filing direction were cut into 2.54 × 20.3 cm specimens. Each sample was hung vertically by a clamp, and the free end was dipped 1 inch into a bath containing a pesticide mixture with 0.2% Sudan Red 7B dye (Sigma Chemical Co., St. Louis, Missouri), at 21°C and 65% RH. After 10 minutes, the sample was removed from the pesticide solution, and the length that the liquid front moved up the samples from the 1-inch line was measured. The test was performed in triplicate for each combination of pesticide mixtures and woven fabrics.

Air Permeability. Air permeability was measured according to ASTM D 737-96, Standard Test Method for Air Permeability of Textile Fabrics, using a Frazier Air Permeability Tester for four samples.

Pesticide Repellency, Retention, and Penetration

Percentages of repellency, pesticide retention, and penetration were measured according to ASTM F 2130-01, Standard Test Method for Measuring Repellency, Retention, and Penetration of Liquid Pesticide Formulation Through Protective Clothing Materials, using 0.1 mL of contamination load. For collector layers, absorbent paper backed with polyethylene film (Whatman® Benchkote™ Plus with polyethylene backing, Whatman 3 mm cr, Whatman plc, Whatman House, Kent, United Kingdom) was used. HPLC-grade acetone (AlliedSignal Inc., Burdick & Jackson, Muskegon, Michigan) was used for extraction. The test was performed in triplicate for each combination of pesticide mixtures and woven fabrics.

A Hewlett Packard model 5890 gas chromatograph (Hewlett-Packard Company, Wilmington, Delaware) equipped with a nitrogen–phosphorus detector and automatic injector was used for pesticide analysis. Separation was achieved on a 30-m × 0.25-mm i.d. capillary column (5% phenyl substituted methylpoly-siloxane, HP-5, Hewlett-Packard Company) with a nitrogen flow of 1.7 mL/min. Column temperature was maintained 50°C for 1 minute, then programmed at 25°C/min to 260°C and held 1 minute. Injector port and detector temperatures were 250°C.

Statistical Analyses

Statistical analyses were performed on textile and pesticide mixture measurements and penetration data using the SAS® system (SAS Institute Inc., Cary, North Carolina). Multiple linear and multiple polynomial regressions were performed using a general linear model analysis. Before the analyses, data were centered by subtracting the mean for each predictor variable to reduce the degree of multicollinearity.

Results and Discussion

Liquid Parameters

Surface tension and viscosity of pesticide mixtures were measured for use as predictor variables for liquid penetration modeling (Table 2). Surface tension ranged from 20.57 to 38.00 dynes/cm, and viscosity ranged from 0.93 to 20.80 mPa seconds. Three mixtures were selected to cover and extend the range of both viscosity and surface tension for the eleven mixtures in the previous study (Lee and Obendorf 2001).

Textile Parameters

Fabric weight and thickness were measured for each specimen. Mass per unit area ranged from 108 to 540 g/m^2 and thickness ranged from 0.206 to 1.000 mm. Weight and thickness are presented in Table 1.

Yarn/fabric geometry is an important factor affecting liquid penetration through woven fabrics. Capillary action, which drives liquid transport in a porous medium, depends on geometric configurations of the porous medium as well as properties of the liquid and fiber surface wetting characteristics (Raheel and Gitz 1985; Hsieh 1995). In the previous study on liquid penetration modeling on nonwoven fabrics (Lee and Obendorf 2001), solid volume fraction was used to describe geometric configurations of the medium and was found to be a significant factor affecting the liquid penetration process. However, in woven textiles, geometric configurations are far more complex because of complicated interaction of fabric weave and yarn structure, and cannot be described by a single descriptor.

In this study on liquid penetration modeling on woven fabrics, fabric cover factor, yarn twist factor, and yarn packing factor were calculated to be used as possible predictor variables, in an attempt to describe the complex capillary geometry of woven textiles with parameters that can easily be derived from basic fabric characteristics. Cover factor is a measure of fabric tightness and describes compactness of the weaving of a given yarn system, which could represent the relative magnitude of interyarn space of a given fabric. Cover factor was calculated from fabric counts and yarn diameters using the following equation:

$$C = ed_1 + pd_2 - epd_1d_2 \tag{1}$$

where C represents cover factor of the fabric; e is number of warp yarns over 1 inch of fabric width; p is number of filling yarns over 1 inch of fabric width; d_1 is diameter of the warp yarn (inch); and d_2 is diameter of the filling yarn (inch). Cover factors for the specimens, which ranged from 0.71 to 1.00, are shown in Table 3.

Relative magnitude of interfiber space could be quantified by textile parameters such as yarn twist factor or yarn packing factor. Twist factor is a measure of "twist hardness" of yarn and describes compactness in yarns of the same size. Twist factor was calculated using the following equation:

$$t_w = \frac{tpi}{\sqrt{N_e}} \tag{2}$$

where t_w represents twist factor of the yarn; tpi is the twist in turns per inch; and N_e is yarn number in the cotton system. Average twist factors of warp and filling yarns for each specimen, which ranged from 2.53 to 5.30, are presented in Table 3.

Table 3. Fabric parameters

Fabric code	Cover factor	Twist factor	Packing factor	Solid volume fraction
1	0.95	3.89	0.53	0.354
2	0.81	4.06	0.57	0.329
3	0.71	3.65	0.62	0.345
4	0.96	5.30	0.41	0.355
5	0.87	4.57	0.81	0.323
6	0.78	2.92	0.46	0.340
7	0.87	3.08	0.30	0.303
8	0.88	3.83	0.26	0.322
9	0.91	2.53	0.37	0.369
10	1.00	4.12	0.53	0.338
11	0.90	3.61	0.55	0.290
12	0.88	5.10	0.66	0.394
13	1.00	3.86	0.64	0.381
14	0.78	3.64	0.70	0.386
15	0.86	3.67	0.50	0.322
16	0.94	4.11	0.56	0.345
17	1.00	4.37	0.55	0.360
18	0.94	4.38	0.48	0.321

Yarn packing factor, which describes the ratio of the total fiber area to actual yarn area in the cross-section of a multifilament yarn, was calculated as follows:

$$\phi = \frac{4N_t}{\pi \cdot d^2 \rho \cdot S} \tag{3}$$

where ϕ represents the packing factor of the yarn; d is the diameter of the fiber (cm); ρ is the density of the fiber (g/cm^3); N_t is the linear density of the yarn (tex); and S is the constant, 10^5. Densities for cellulose, nylon, polypropylene, and polyester were obtained from Physical Properties of Textile Fibres (Morton and Hearle 1993). Average packing factors of warp and filling yarns for each specimen, which ranged from 0.26 to 0.81, are presented in Table 3.

Solid volume fraction of fabric, which has been shown to be a significant parameter in liquid penetration modeling on nonwoven fabrics (Lee and Obendorf 2001), was used as a possible predictor variable as well, using the following equation:

$$S = \frac{m/\rho}{at} \tag{4}$$

where S represents solid volume fraction of the fabric; m is mass of the specimen at standard condition (g); ρ is density of the fiber (g/cm^3); a is area of the specimen (cm^2); and t is thickness of the specimen (cm). Solid volume fractions for the specimens, which ranged from 0.290 to 0.394, are shown in Table 3.

Wicking height was measured for each combination of pesticide mixtures and woven fabrics to reflect the complex fabric/liquid interactions. Average wicking heights of warp and filling direction for each combination ranged from 0.2 to 8.8 cm (Table 4).

Surface energy of the solid, γ_S, is a property that reflects the chemical nature of the solid surface, and such inherent fiber characteristics contribute to wetting and liquid transport properties. In this study, critical surface tension of fiber was used as a predictor variable to represent surface free energy of the solid. Critical surface tensions for cellulose, nylon, polypropylene, and polyester were obtained from Physical Properties of Polymers Handbook (Mark 1996).

Parameters Influencing Fabric Protection Performance

Pesticide penetration for selected pesticide mixtures M1, M2, and M3 was tested for the 18 woven fabrics. Penetration percentages for each set of fabric/liquid parameters tested are presented in Table 4.

Statistical analyses were performed to determine the characteristics for each parameter that influences the penetration phenomenon. Table 5 shows the correlation coefficients between percent penetration and fabric and liquid parameters. Cover factor has the highest correlation coefficient, followed by fabric thickness, yarn twist factor, wicking, viscosity, and surface tension of pesticide mixture. For textile parameters, fabric cover factor, thickness, and yarn twist factor are negatively related to pesticide penetration, whereas critical surface tension of fiber is positively related to penetration. In other words, pesticide penetration decreases with increased cover factor, fabric thickness, and twist factor, whereas penetration increases with increased critical surface tension of fiber. For liquid parameters, viscosity of pesticide mixture has a positive relationship with penetration, whereas surface tension of pesticide mixture shows a negative relationship with penetration. That is, pesticide penetration increases with increased viscosity and decreased surface tension of pesticide mixture.

To develop a statistical model for pesticide penetration through woven fabrics, regression analyses were performed using those fabric/liquid parameters. Table 6 shows the coefficients for pesticide and fabric parameters with R^2 values for models developed. The final model selected to predict pesticide penetration through woven fabrics was a polynomial model with linear terms of cover factor, twist factor, critical surface tension of fiber, viscosity of pesticide mixture, and wicking, and quadratic terms of cover factor, twist factor, critical surface tension of fiber, and wicking, keeping only significant terms at a 5% significance level (Table 6, Model 4). Thus, a regression equation to predict pesticide penetration through woven fabrics is as follows:

$$\begin{aligned} \mathrm{P} = {} & 11 - 97\mathrm{C} - 22\mathrm{t_W} + 0.7\eta - 5\gamma_{\mathrm{S}} - 4\mathrm{w} + 874\mathrm{C}^2 \\ & + 13\mathrm{t_w^2} - 0.6\gamma_{\mathrm{s}}^2 + 1.5\mathrm{w}^2 \end{aligned} \tag{5}$$

where C is fabric cover factor; $\mathrm{t_W}$ is yarn twist factor; η is viscosity of pesticide mixture (mPa second); γ_S is critical surface tension of fiber (mN/m); and w is wicking height (cm). The R^2 value is 0.72. Influence of surface tension of liquid, solid volume fraction, and yarn packing factor were shown to be insignificant at the 5% significance level for these experimental conditions. There was no significant difference between models 2, 3, and 4 in terms of R^2 at the 5% significance level. Thus, the final model selected is the one showing higher R^2 with the fewest number of significant variables. A previous study (Jain and Raheel 2003)

Table 4. Fabric/liquid parameters: wicking and percentage penetration of pesticide

Fabric code	Wicking height cm			Penetration %		
	Mixture 1	Mixture 2	Mixture 3	Mixture 1	Mixture 2	Mixture 3
1	8.2	2.5	3.1	0	0	3
2	8.2	2.7	3.1	19	2	20
3	3.9	2.6	2.7	65	54	62
4	0.3	2.8	3.2	0	0	1
5	0.2	2.3	2.7	26	0	13
6	1.4	1.8	2.4	81	78	45
7	6.3	2.4	2.8	5	47	81
8	3.4	2.5	3.3	2	20	59
9	5.6	2.6	3.2	10	9	5
10	6.7	2.4	3.0	8	0	0
11	7.6	2.4	2.8	31	3	20
12	5.8	2.4	2.1	7	0	13
13	6.7	2.9	2.9	4	0	33
14	2.3	1.5	1.5	1	62	80
15	5.3	2.6	3.1	22	15	31
16	0.8	2.1	2.3	33	0	0
17	7.8	3.0	3.5	0	1	2
18	8.8	2.8	3.3	0	1	1

Table 5. Correlation coefficients between percentage penetration and fabric/pesticide parameters

Fabric/pesticide parameters	Correlation coefficient
Fabric cover factor	−0.67
Fabric thickness	−0.65
Yarn twist factor	−0.46
Wicking height	−0.26
Viscosity of pesticide mixture	0.16
Surface tension of pesticide mixture	−0.14
Solid volume fraction of fabric	−0.10
Critical surface tension of fiber	0.09
Yarn packing factor	−0.05

showed a statistical model for woven fabrics using three parameters, fabric thickness, solid volume fraction, and air permeability of fabrics. In this modeling, it was attempted to describe the complex capillary geometry in woven structure by adding fabric cover factor, yarn twist factor, and wicking height as possible predictor variables, and found that these additional parameters contributed significantly to the woven model.

In the statistical modeling processing, fabric thickness was one of the highly influential factors affecting liquid penetration of woven fabric as a singular parameter (Table 5). As shown in Figure 1, fabrics of thickness above 0.8 mm showed very little or no penetration regardless of other fabric/liquid parameters for the experimental conditions, which assures that fabric thickness is a dominant factor in the penetration phenomenon of woven work clothing fabrics as a single factor. However, further statistical modeling processing to find a model with multiple variables for a better fit revealed that influence of fabric thickness decreases once other fabric parameters are entered into the model, which indicates that fabric parameters are interrelated. Consequently, influence of fabric thickness was insignificant at the 5% significance level when other textile parameters are present, thus replaced by a combination of fabric cover factor and yarn twist factor in the final model (Table 6).

It is also noteworthy that cover factor and twist factor are better parameters in describing the geometry of woven fabrics than solid volume fraction. For this purpose, cover factor and twist factor were the two most influential factors affecting pesticide penetration through woven fabrics, and their contribution to penetration is illustrated in a three-dimensional plot (Figure 2). It clearly shows that pesticide penetration increases as fabric cover factor and yarn twist factor decrease.

Parameters Influencing Fabric Comfort Performance

Fabric air permeability is a characteristic closely related to comfort performance of fabric. To develop a statistical model predicting air permeability from basic textile parameters, regression analyses were performed using fabric thickness, fabric cover factor, yarn twist factor, yarn packing factor, and solid volume fraction as independent variables. Table 7 shows the coefficients for fabric parameters with R^2 values for models developed. The final model selected to predict air permeability of fabric was a polynomial model with linear terms of fabric thickness, cover factor, twist factor, and packing factor, and quadratic terms of fabric thickness, cover factor, and packing factor, keeping only significant terms at a 5% significance level (Table 7, Model IV). The regression equation resulted in an R^2 of 0.91:

$$\begin{aligned}\text{Air permeability} = 17 - 127\text{C} - 130\text{t} - 12\text{t}_\text{W} - 161\phi \\ + 957\text{C}^2 + 229\text{t}^2 + 904\phi^2\end{aligned} \tag{6}$$

where C is fabric cover factor; t is fabric thickness (mm); t_W is yarn twist factor; and ϕ is yarn packing factor. The influence of solid volume fraction might already be ex-

Table 6. Summary of coefficients and R^2 values for regression models for protection

	Regression coefficients																			R^2
	Intercept	C	t	t_W	ϕ	υ	γ_S	η	γ_L	w	C^2	t^2	$t_W{}^2$	ϕ^2	υ^2	$\gamma_S{}^2$	η^2	$\gamma_L{}^2$	w^2	
Model 1	20	−152	−2	−18	−30	137	2.7	1.6	2	−2	—	—	—	—	—	—	—	—	—	0.66
	(2)	(45)	(21)	(7)	(21)	(104)	(0.9)	(0.9)	(1)	(1)										
Model 2	8	−149	38	−25	−26	48	−5	1.0	0.3	−5	1406	−91	12	98	3418	−0.6	0	0	1.6	0.74
	(10)	(93)	(63)	(11)	(37)	(126)	(8)	(0.9)	(1)	(2)	(774)	(120)	(8)	(141)	(4068)	(0.6)			(0.6)	
Model 3	11	−96	—	−22	—	—	−6	0.8	—	−5	1007	−36	15	—	—	−0.7	—	—	1.6	0.73
	(4)	(33)		(5)			(3)	(0.3)		(2)	(360)	(44)	(5)			(0.2)			(0.5)	
Model 4	11	−97	—	−22	—	—	−5	0.7	—	−4	874	—	13	—	—	−0.6	—	—	1.5	0.72
	(4)	(32)		(4)			(3)	(0.3)		(2)	(320)		(5)			(0.2)			(0.5)	

C (fabric cover factor); t (fabric thickness); t_W (yarn twist factor); ϕ (yarn packing factor); υ (solid volume fraction); γ_S (critical surface tension of fiber); η (viscosity of pesticide mixture); γ_L (surface tension of pesticide mixture); w (wicking height).
Standard errors of coefficients in parentheses.

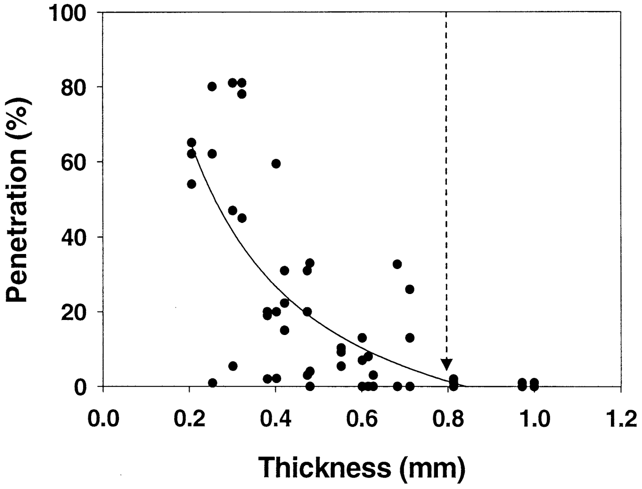

Fig. 1. Relationship between fabric thickness and pesticide penetration.

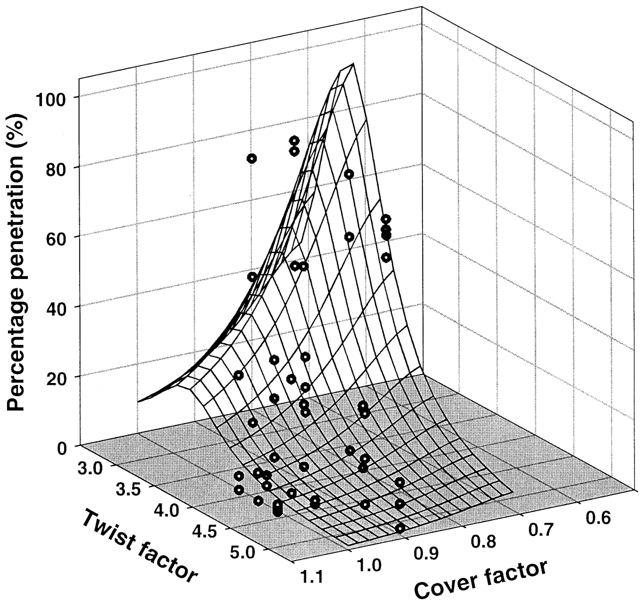

Fig. 2. Effect of fabric cover factor and yarn twist factor on pesticide penetration.

plained by other factors, and thus shown to be not significant. There was no significant difference between models II, III, and IV in terms of R^2 at the 5% significance level. Thus, the final model selected is the one showing the higher R^2 with the fewest number of significant variables. This model could be useful as an estimate of thermal comfort based on simple measurements of fabric parameters, which could be provided by fabric manufacturers.

Conclusions

The objectives of this research were to explore physicochemical factors affecting pesticide penetration through woven fabrics and to develop a statistical model to serve as the basis for recommendations on the selection of woven work clothing for pesticide applicators, using basic characteristics of fabric and challenge liquid. Also, a statistical model was developed to predict fabric air permeability as an estimate of thermal comfort, based on simple fabric measurements.

Liquid penetration of woven textiles is complex, involving the inherent nature of fiber, geometric configurations of the porous medium, liquid properties, and their interaction. An empirical model was presented to estimate pesticide penetration through woven fabrics. Fabric cover factor, yarn twist factor, critical surface tension of solid, viscosity of pesticide mixture, and wicking are shown to be significant parameters affecting pesticide penetration. The correlation coefficients show that, in general, penetration increases with decreased fabric cover factor, decreased yarn twist factor, decreased wicking height, increased liquid viscosity, and increased critical surface tension of fiber.

A statistical model predicting air permeability of fabric was developed based on fabric cover factor, fabric thickness, yarn twist factor and yarn packing factor. This can be used to estimate thermal comfort based on simple fabric measurements.

Table 7. Summary of coefficients and R^2 values for regression models for air permeability

	Regression coefficients[a]											R^2
	Intercept	C	t	t_W	ϕ	υ	C^2	t^2	$t_W{}^2$	ϕ^2	υ^2	
Model I	53	−253	−116	−2	−195	12	—	—	—	—	—	0.75
	(4)	(68)	(34)	(9)	(38)	(169)						
Model II	16	−143	−120	−13	−167	−17	1081	213	−0.8	909	1537	0.91
	(7)	(91)	(50)	(7)	(40)	(145)	(525)	(96)	(7)	(124)	(4641)	
Model III	17	−126	−130	−12	−160	−22	972	228	—	903	—	0.91
	(5)	(63)	(32)	(6)	(29)	(108)	(405)	(83)		(119)		
Model IV	17	−127	−130	−12	−161	—	957	229	—	904	—	0.91
	(5)	(62)	(31)	(6)	(28)		(394)	(82)		(117)		

Standard errors of coefficients in parentheses.

C = fabric cover factor; t = fabric thickness; t_w = yarn twist factor; ϕ = solid volume fraction.

Textile and pesticide parameters measured by simple tests or readily available in the literature can be used in the statistical model to estimate the level of protection and thermal comfort. This could be used for developing selection charts or tools as guidelines for selection of PPE for use in hot, humid environments. The series of liquid penetration modeling on woven and nonwoven textiles shows that different textile parameters are needed in describing the geometric configurations depending on the manner in which fibers are assembled into a given fibrous structure. In this application, fabric cover factor and yarn twist factor are better parameters in describing the geometry of woven fabrics than solid volume fraction.

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