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Knitted fabric specifications and axilla odour retention characteristics

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This study focuses on the role of bacteria and the effect of textile structure on the odour formation. Cotton knitted fabric made of three different structures are selected based on their commercial importance. The knitted samples are given for human wear trial and the effect of structure on odour formation is analysed. It is found that the rib structure has the high odour intensity rating and the least value is observed for plain jersey. This is explained in terms of thickness and mass per square meter of the fabric. Sensory evolution test is performed by the expert team and it is confirmed that the higher the mass and loop density, the higher is the odour formation. The thicker fabric enhances the optimum environment in the axilla region for better bacterial growth. This is confirmed by the bacterial isolation process and swab analysis, the thicker the structure (rib) the higher is the presence (CFU/ml) of *corynebacterium* Sp., *Bacillus* Sp. and *Staphylococcus* Sp. groups than in the thinner structure (single jersey). Higher amount of carboxylic acid is formed in the axilla region as a metabolic byproduct of bacteria. The formation of carboxylic acid in the textile material after wear trial is further confirmed objectively by PTR-MS and FTIR studies, where fragments of butyric, valeric and isobutryic acid along with acetates groups are identified. Response surface methodology is adapted to study the effect of fabric parameter on odour formation. Using this experimental design, the general relationships relating the properties with variables as well as the significant terms in these relationships are computed.

Keywords: Axilla, Bacterial metabolism, Knitted fabric, FTIR Spectra, Proton transfer reaction-mass spectrometry

1 Introduction

Strong body odours associated with an individual is a socially embarrassing problem. The characteristic musky, urinous or acidic odours commonly emanating from the axillary regions of humans are due to the bacterial metabolism of the milky, protein-rich fluid secreted by the apocrine and sebaceous glands located in this area[1]. Clothing has been implicated in contributing to body odour intensity, possibly even increasing the intensity[2] by the transfer of secretions, skin debris and bacteria from the body to the fabric substrates[3]. The findings of Shelley *et al*.[2], show that the apocrine sweat is odourless and sterile, when it initially appears on the skin and that typical axillary odour are produced by the action of microorganisms on apocrioc sweat *in- vitro*. It was found that pure apocrine sweat collected from a "sterile" axilla failed to develop any odour throughout the fourteen-day period of incubation. Tubes containing apocrine sweat from an "unsterile" axilla developed a strong odour within 6 h which became very strong in 24 h. These findings were confirmed in an *in-vivo* experiment by Leyden *et al*.[4] and Ferguson and Edward[5].

Even though odour research has been performed in the cosmetics and food industries, odour measurement in textiles is very meager. The recent advancement in textile industry creates awareness among the customers about hygienic and odour free textiles. But, the current research trend focused only on the antimicrobial effect of various agents on textile material considerably. Textiles have always been playing a major role in the odour propagation. Bacteria can multiply rapidly in textile when basic requirements are met, such as warm temperature, humidity and nutrients[6]. McQueen *et al.*[7] studied the importance of textile material on the odour formation and propagation. They have studied the effect of various fibre materials and their effects on odour formation. Hence in this study, an attempt has been made to analyse the effect of structure on the odour formation in terms of bacterial population. Here knitted cotton material with three different structures and different mass/square meter have been taken and the subjective and objective analyses are performed to measure the intensity of the odour formed. The effect of structure on the odour formation is also discussed.

2 Materials and Methods

2.1 Sample Selection and Preparation

Commercially available knitted cotton fabrics in three basic structures, namely plain, rib and interlock, commonly used for men's vests as undergarment, were used for the study. The fabrics were laundered

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and laid flat to dry prior to cutting sample specimens. Fabric sample specimens were cut to a size of 225mm × 225 mm and their edges were over locked. The fabric specimens were fixed to the underarm area of the 100% cotton vests with the help of velcro. So, the centre of the fabric specimen was close to axilla when the vest is worn by the wearer[8]. The fabric specifications are shown in Table 1.

2.2 Wear Trial and Orientation of the Subjects

The wear trial and orientation of subjects were adopted as mentioned by Mc Queen et al[7]. The subjects selected were in the age group of 27-35. Five male participants involved in non-sedentary jobs were selected. Before the experimental study, the subjects were advised not to use any cosmetic, deodorants and other antibacterial products. They were advised to follow these instructions for 7 days as conditioning phase. Further, they were also advised not to consume any spicy foods for 48 h before the experiments[8]. The normal working hours (8 h) were allotted for each subject. The subjects were also advised to wear the same fabric specimen for two days consecutively. After the trial phase the samples were separated and put into an air tight poly bags, with the details of the sample.

2.3 Subjective Analysis

The odour test was performed with reference to SNV 195651 (ref. 9). The test specimen was placed on top of 300mL sodium carbonate solution and kept in a closed container. The container was put into oven set to a temperature of 37 +/-2°C for 15 h.

Six people (minimum) are required to independently judge the odour intensity and rate it according to the following Scale:

Intensity Scales

Grade 1 – odourless
Grade 2 – weak odour
Grade 3 – tolerable odour
Grade 4 – annoying odour
Grade 5 – intolerable odour

The mean value of the grades for the odour intensity must be a grade < 4.

Table 1—Fabric Specifications

Fabric structure	Wales/inch	Courses/ inch	Thread density/inch^2	Mass, g/m^2	Thickness mm
Single jersey	40	54	2160	145	0.42
1 × 1 Rib	36	24	864	325	1.22
Interlock	46	36	1656	157	0.64

2.4 PTR-MS Studies

PTR-MS provides absolute quantitative analysis in real-time (response time < 100 ms). The determination of absolute concentration is possible without the use of Gas standards. H_3O + ions do not react with any of the major components present in clean air due to their low proton affinity. PTR-MS (Ionicon Analytik GmbH, Innsbruck, Austria) is based on the ionising reactions of H_3O+ with volatile organic compound detected by non- dissociative proton transfer. The claimed advantages of PTR-MS as a volatile compound measuring instrument include that it is extremely sensitive and offers real-time analysis requiring no pre treatment of the sample. Due to the low fragmentation resulting from the PTR-MS, compounds in a mixture can be detected and quantified without the necessity of complex extraction and separation of pre treatment process. The fundamental process in a PTR-MS instrument can be written as

$$H_3O^+ + R \rightarrow RH^+ + H_2O \quad \ldots (1)$$

This means that protonated water (H_3O +) interacts with the trace gas (R). During this interaction a proton transfers from the hydronium to the trace gas molecule, which leads to a protonated and therefore ionized molecule (RH +) and a neutral water molecule (H_2O). The proton transfer reaction [Eq.(1)] is energetically possible for all VOCs with a proton affinity higher than that of water (166.5 kcal/mol). Some other compounds with proton affinities below that of H_2O can be detected using new switchable reagent ion option[10,11].

2.5 Bacterial Isolation from Worn Cotton Sample

The test samples were collected aseptically and stored in air tight pouches. A part of the sample was taken and allowed to grow in Tryptic soy broth. In a test tube, 10 mL of sterile Tryptic soy broth was taken and test fabric sample was kept in the broth. Then the broth was incubated at 37°C for a time period of 24-48 h. After incubation, the broth becomes turbid due to the presence of bacterial strains present in the test fabric. The broth may constitute more than one species of bacterial strain[12].

The bacterial isolation procedure was carried out by the Gram straining[13,14], catalase test[15], biochemical test[16] and citrate utilisation[17,18] test methods.

2.6 FTIR Analysis

The worn samples were analysed for FTIR spectra with a SHIMADZU Spectrophotometer to identify the

presence of chemical compound in the fabric. The spectra were obtained in the range of 400-4000 cm^{-1}.

2.7 Statistical Analysis

Response surface methodology (RSM) is an empirical modelization technique devoted to the evaluation of relationship of a set of controlled experimental factors and observed results. It requires a prior knowledge of the process to achieve statistical model. Basically this optimization process involves three major steps, namely performing the statistically designed experiments, estimating the coefficients in a mathematical model, and predicting the response and checking the adequacy of the model[19], as shown below:

$$q = b_0 + \sum_{i=1}^{n} b_1 x_1 + \left(\sum_{i=1}^{n} b_{ii} x_i \right) 2 + \left(\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_j x_j \right) \quad \ldots (2)$$

where q is the predicted response; b_0, the constant coefficients; b_i, the slope or linear coefficients of the input factor; x_i and b_{ii}, the linear by linear interaction coefficients or quadratic coefficients between the input factor x_i and x_j; and b_{ij}, the interaction coefficients of input factor x_i[20]. The most important parameters of a knitted cloth which affect the odour formation in textile material has been selected based on the literature and Initial experiments. In order to study the combined effect of these factors, experiments were performed at different combinations of the physical parameters using statistically designed experiments[21].

The intervals of all three independent variables have been selected based on the preliminary studies and survey, where the commercially available different knitted foundation garments were analysed and their gram per square meter (GSM), thickness, loop density and Bulk density were identified. Based on that, the minimum and maximum levels were assigned to Design Expert software (Trial version – 8.0.7.1). The central point is assigned automatically by the design software. The factors levels were coded as –1 (low), 0 (central point) and +1 (high)[22]. Table 2 shows the input parameters and experimental design levels used in the present work. A total of 15 experiments were necessary (Table 3) to estimate the 10 coefficients of the model using multiple linear regression analysis[21].

Table 2—Variables and their levels used in experimental design

Variable	Coded level		
	+1	0	-1
GSM of fabric (X_1)	150	235	325
Thickness of fabric, mm (X_2)	0.42	0.82	1.22
Loop density, loops/inch^2 (X_3)	860	1510	2160

3 Results and Discussion

3.1 Effect of Structure on Odour Intensity

The subjective analysis is performed as per SNV 195651. The average ratings of the results of the subjective analysis are shown in the Fig. 1. The subjective analysis results reveal that the average odour intensity is high in the rib fabric followed by interlock fabric and plain fabric ($p<0.05$). Since all the fabrics selected are of cotton with different structures, the differences in odour intensity may be because of the structural changes like thickness and mass per area. The rib fabric has double GSM to that of plain knitted, and the interlock material has double layered structure and high thermal resistance, it provides the favourable microclimate required for bacterial manipulation and hence shows high odour intensity.

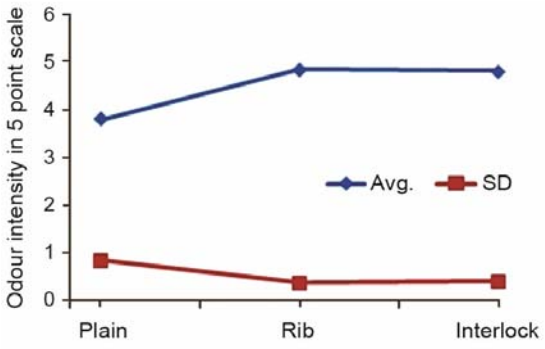

Fig. 1—Average rating for different structures along with standard deviation

Table 3—Process conditions according to Box-Behnken method

Exp No	Fabric GSM	Fabric thickness	Loop density
1	0	1	-1
2	-1	0	-1
3	0	-1	1
4	1	0	1
5	-1	0	1
6	0	0	0
7	0	0	0
8	1	0	-1
9	1	1	0
10	1	-1	0
11	0	1	1
12	0	-1	-1
13	-1	1	0
14	-1	-1	0
15	0	0	0

Guanxiong *et al*.[23] stated that the water vapour permeability values of single jersey are higher than rib and interlock and this difference is most probably due to the thinner structure. Oğlakcioğlu *et al*.[24] mentioned that as the fabric thickness increases the thermal resistance increases. Thermal resistance is a measure of the fabrics ability to prevent heat from flowing through it. The cotton fabric sample shows the lowest thermal resistance values for the single jersey structure, and the highest values are obtained for the interlock structure. The differences between the values of the three structures are found statistically significant[24].

3.2 Influence of Subject

Differences are apparent in odour intensity depending upon the subjects as shown in Fig. 2. In general, all participants rated plain single jersey fabric as less odour intensity ($p<0.05$). Subject number 7 alone got higher rating of 4.6 (Average of 6 assessors) for plain fabric relatively nearer to the other structure 1×1 rib (4.8) and interlock (4.6). This may be because of the fact that odour intensity of individuals differ from one to another. Therefore, sources of variation such as individual's level of activity, environment temperature, humidity and physiological difference[2] are unavoidable. Their influence on the odour formation is insignificant[25].

3.3 Analysis of Odour Intensity Based on PTRMS Test Results

The masses associated with the axillary volatiles and possibly axillary odour is identified by comparing the non-worn fabric sample with those that have been worn, matching fibre types. There are thirteen masses ranging from 60 to 175 were present in the worn fabric, which are significantly higher in concentration than that of the non-worn fabric of the same. PTR-MS does not enable absolute identification of specific compounds, but the source of the volatile emission in axilla can be identified. Hence, from the literature, potential axillary volatile components were identified and listed in Table 4.

The dominant mass observed are 61m/z which is the protonated acetic acid, 71.05 m/z is the fragments of butyric and isobutyric acids and 79.04 represents

Table 4—Prominent mass found in PTR-MS study for worn sample at 1 day

Protonated mass m/z	Expected component
61.028	Acetic acid
69.08	Ethylene glycol, Cyto pentane and Isoprene
71.05	Fragments of butyric and Isobutryic acid
79.04	Dimethyl ether and Ethyl alcohol.
81.07	Unknown
83.09	Unknown
85.03	Unknown
102.01	Valeric acid cyclo octadiene and Isovaleric acid
111.08	Unknown
124.04	Isonicotinic acid, Niacin, and Picolinic acid
129.07	Heptonic acid, Naphthalene 3-methyl-2-hexenoic acid and Azolene
143.14	2-heptyloxirane and 4-propylcyclohexan-1-ol, Nonanal
171.12	2,3,6-trimethylnaphthalene and 4,6,8-trimethylazulene

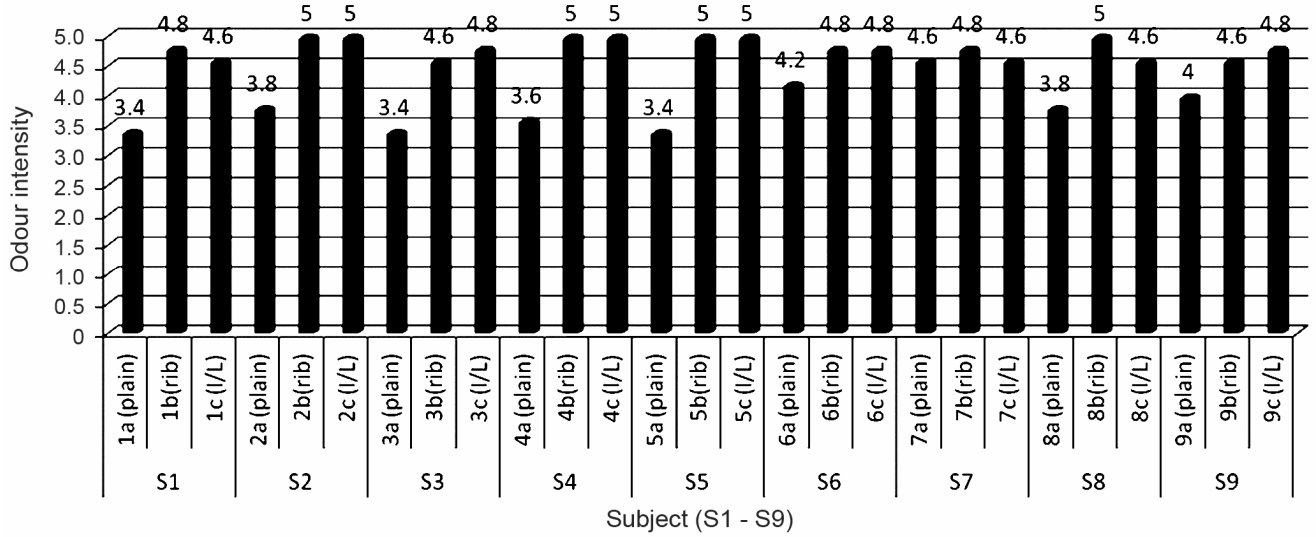

Fig. 2—Odour intensity of individual subjects

the ethyl alcohol. The short chain carboxylic acid also recognized to be a component of axillary malodour, which is also mentioned by the Hartungena *et al.*[26] and Bernier *et al.*[27].

3.4 Bacterial Isolation Test Results

The bacterial isolation has been done for all samples, which are worn by the subjects in the axilla. The day to day variations were kept insignificant. The microflora was quantitatively and qualitatively the same in right and left hand axilla and was not affected by handedness or sex as reported by Leyden *et al.*[4]. The day to day flora of a subject was also kept very stable Hence in this study, the aforementioned factors were ignored and the analysis was performed invariantly. However, differences among participants were expected, as the types and numbers of bacteria are highly variable among individuals.

The results from bacterial isolation process of worn samples indicate (Fig. 3) that all the samples worn at axilla region consist of *Bacillus* Sp. along with *corynebacterium* Sp.. Other than this, there are many *Staphylococcus* Sp., *Enterococci* Sp., *E.coli,* and *Pseudomonas* Sp. found in the axilla. Five out of ten subjects (%) are having *Corynebacterium* Sp. a major contributor for the axillary malodour present in the axilla region as mentioned by Rennie *et al.*[28].

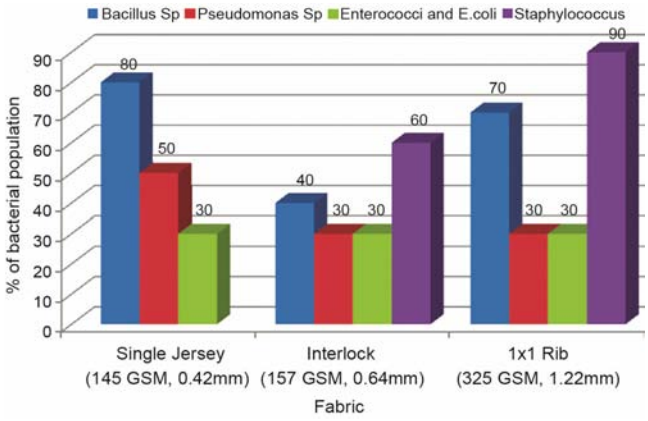

Fig. 3—Bacterial propagation percentage with respect to structural mass and thickness

All the fabric structures have the *Bacillus* Sp. and *corynebacterium* Sp. as major along with the *Staphylococcus* Sp., *Pseudomonas* Sp., and *Enterococci* Sp. However, the percentage of bacterial strain varies between persons and structures. In general, eight out of ten subjects (80%) are having *Bacillus* Sp. and six out of ten subjects having *Staphylococcus* Sp. (60%), The *Corynebacterium* Sp. and *Pseudomonas* Sp. (50%) are found only in five out of ten subjects. The *Enterococci* Sp. are found in three subjects as (30%) the lowest amount as compared to other bacterial strains

It is observed that the high odourous rib sample consists of more amount (CFU/ml) of *Bacillus* Sp., *Staphylococcus* Sp. and *corynebacterium* Sp., than other structures like interlock and plain single jersey. With respect to the textile structure the microflora of the axilla is not found stable and no single group of organisms is found continuously dominated the population. But it is identified that the difference between structures has influence in terms of both population density and group dominance. The changes observed in the colonization of axillae are most likely due to changes in environmental conditions in the axilla because of the mass and thickness of fabric, which, in turn, determine the growth rate of the organisms.

3.5 Metabolic Byproducts of Microorganisms

The studies on bacterial isolation from the worn samples reveal that few types of bacterial strains are found in all fabric types, invariant of the fabric structure. In the point of view of odour analysis, it is necessary to find the causes for the odour formation. Bacteria themselves do not smell bad, it is the result of their decomposing activity and byproducts end up smelling in the cloths. Hence, Table 5 lists the various possible metabolic byproducts of the identified bacteria[29-31]. These microorganisms generate a variety

Table 5—Metabolic byproducts of microorganisms

Species	Metabolic byproducts of microorganisms
Bacillus Sp.	Butyric acid, Valeric acid and Pyruvate compounds.
Corynebacterium Sp.	Propionic acid, Amino acids, Acetic acid (Acetate compounds), Formate and Succinate compounds
Staphylococcus Sp.	Butyric acid, Acetate compounds (Acetic acid) and Propionic acid (Carbohydrate sources)
Enterococci Sp.	Propionic acid and Methane gas production
E.coli	Ammonia compounds, Acetoin from Tryptophan and Putrifactive odour producing valereic acid from carbohydrate sources
Pseudomonas Sp.	Dodecanol , Hydrogen sulphide gas from triple sugar medium, Ammonia and Methane rarely
Bacteroids Sp.	Putrefactive smell producing gases, Ammonia and Ether compounds

of odouriferous compounds that characterize the axillary region. *In vivo* correlations of odour quality and axillary bacterial populations have also been demonstrated by Leyden *et al*.[4].

The bacterial isolation process result reveals that the fabrics mostly consist of *Corynebacterium* Sp, *Bacillus* Sp., *Pseudomonas* Sp. and *Staphylococcus* Sp., for all structures invariantly, which, in turn, produces propionic acid, amino acids**,** butyric acid, acetic acid and valeric acid. The molecular mass findings in the 'PTR-MS' results also confirm the presence of various carboxylic acids (Table 2) in the sample. Taylor *et al*.[32] show that *Corynebacterium* Sp. is one of the most found isolates in human skin, in specific to the axilla region. The production of acetate, formate and succinate compounds in the axilla region due to the metabolic byproduct of *corynebacterium* Sp. is the major cause for odour formation. In contrast to the results of Ara *et al*.[33], it is observed from our results that the presence of *Bacillus* Sp. also is found to be more in the axilla region and is also one of the contributors of axilla malodour. The metabolic byproduct of *Bacillus* Sp. (butyric acid and valeric acid) is observed as one of the major mass deviations in PTR-MS results of axilla worn sample while comparing to the control fabrics. Next to the *Corynebacterium* Sp. and *Bacillus* Sp., *Staphylococcus* Sp. is also found in axilla region. The presence of the *Staphylococcus* Sp. generates the acetate and carbohydrate sources which also result in malodour formation.

The growth and byproducts formation of micro organism strongly depends on the environment of the axilla, moisture, dampness of the contact fabric and their structure. It is observed from this study that the change in fabric structure is also one of the main reasons for high microflora generation. This is because of the microclimate inside the clothing. Among the selected most commonly used structures, the rib fabric has more thickness and fabric density, and hence the bacterial population percentage is also high in this case. It is found that the thickness and mass per square meter has significant influence on odour intensity, which may be because of the bacterial population and their moisture management properties. It is also in line with the findings of Guanxiong *et al.*[23] and Oğlakcioğlu *et al*.[24]. The correlation between the thickness and odour intensity is higher (r^2= 0.73) than the mass per square meter (r^2= 0.57).

3.6 FTIR Analysis for Odour Intensity

The axilla worn sweat samples were analysed with the help of FTIR, to identify the chemical components present in the worn sample and the absorbance peaks of worn samples were compared with unworn samples. The results shown in Figs 4 (a) and (b) indicate that most of the worn samples have higher amount of carboxylic acids the major source of odour. The FTIR spectrum of various worn trial samples indicates that the prominent absorbance wavenumber is in the range 3400-2400 cm^{-1}, which represents the OH stretching of carboxylic acids. Further the amide group is found to be the second major compound in the range of 3500-3180 cm^{-1} and 1680-1630 cm^{-1}. The spectra of amines are also found in the range 3500-3300 cm^{-1}. Other than these groups, few alkyl halides in the region of 600-485 cm^{-1} and 650-510 cm^{-1}, alcoholic groups in the

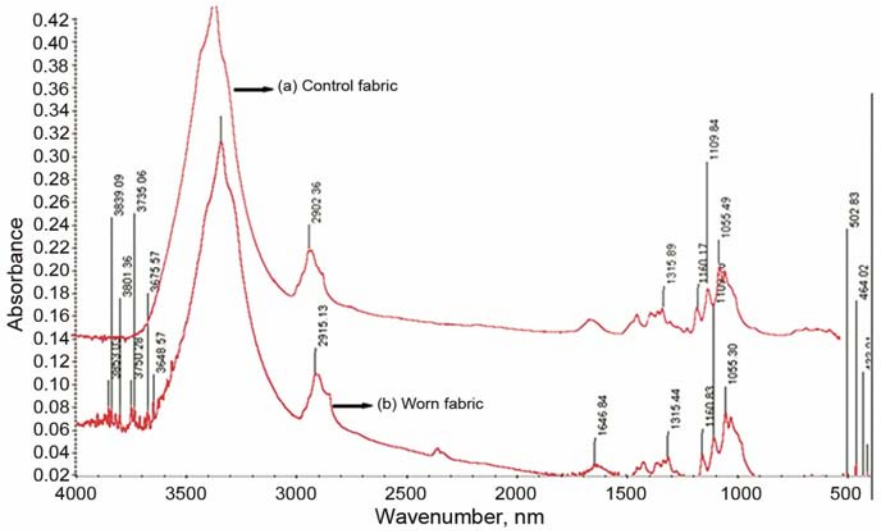

Fig. 4—FTIR Spectra of control (a) and worn (b) samples

range of 1260-1000 and 3400-3300 cm^{-1} are also found in the worn sample.

Hence, it can be understood from the study that the presence of carboxylic groups with amide and alcoholic groups in worn sample over control fabric is a representation of odour formation. It is found that the major mass deviation in the worn sample is in the range of 61.028, 71.05 and 79.04. It represents the protonated acetic acid and butyric acids fragments. This research identifies that the fabric with higher mass and thickness produces more odour because of its higher ability to absorb the sweat and at the same time the increment in thickness reduces the water vapour permeability and air permeability, which helps the formation of microclimate in the axilla region and aids the odour formation.

3.7 Model Building and Response Surface Analysis

Moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body which is maintained by perspiring both in vapor and liquid form[34]. When the perspiring liquid and vapour are not transmitted properly, the humidity of the air in the space between the skin and the fabric increases. This increased humidity prevents rapid evaporation of liquid water on the skin and gives the body the sensation of heat that triggers the sweating in the first place.

Consequently, the body responds with increased sweating to dissipate excess thermal energy. This forms a suitable microclaimatic condition for the bacterial growth in terms of moist environment. The structure and the fabric construction parameters have great influence on the microclaimate of moist environment and hence causes odour formation. This analysis is aimed to identify the inter relationship between the fabric construction paramaters like loop density, fabric GSM and thickness with odour formation. The samples have been prepared as per experiment requirement and the odour formation indensity is assessed subjectively. The methametical model is developed to correlate the fabric parameter along with odour formation.

The empirical relationships for odour formation (Y) and the tested variables are obtained by application of response surface methodology. The final mathematical model in terms of coded factors as determined by Design-expert software is shown in the Table 4. The regression coefficient (R^2) value indicates a good correlation of selected experimental region with the physical properties of fabric. In general, the p values are used as a tool to check the significance of each coefficient, which also indicates the interaction strength between each independent variable. The smaller the p values, the bigger is the significant difference[35]. R^2 represents the proportion that the model can explain for the variation in the response. The model with the $R^2 \geq 0.6$ (60%) can be considered as a valid model[36].

The goodness of the model can be checked by the determination coefficient R^2 and the adjusted R^2 (multiple correlation coefficient R). The R^2 value of 0.9402 represents that the selected variables are in good agreement with the odour generation. The adjusted R^2 of 0.8326 suggests that the total variation of 83.26% of odour formation is attributed to the selected independent variables and only about 16.74% of the total variation cannot be explained by the developed model respectively. The closer the value of adjusted R^2 to 1, the better is the correlation between the experimental and predicted values[37]. Here, the predicted R^2 (0.6413) of odour formation is in reasonable agreement with the adjusted R^2. The regression equation of the developed model is shown below:

$$Y = +3.33+1.25X_1 - 0.13X_2 + 0.38X_3 - 0.25X_1X_2 + 0.25X_1X_3 + 0.0\ X_2\ X_3 - 0.17X_1^2 - 0.083X_2^2 + 0.0836X_3^2 \quad \ldots (3)$$

The adequacy measures in total are found to be in reasonable agreement and indicate adequate models. The adequate precision compares the range of the predicted value at the design points to the average prediction error. The value of adequate precision is found significantly greater than four. An adequate precision ratio above 4 indicates adequate model efficacy as reported by Wang and Lu[38].

The ANOVA results of the selected model on odour formation is given in Table 6. The Model F-value of 8.74 implies that the model is significant. There is only a 1.40% chance that the developed model could deviate due to noise. The lack-of-fit can also said to be insignificant.

3.8 Effect of Process Parameter on Odour Formation

Figure 5 represents the contour plots of GSM, thickness and loop density on odour intensity. It is observed that the GSM of the fabric has the direct influence on the subjectivly assesed odour intensity. The increment in fabric GSM increases the odour

Table 6—ANOVA for response surface quadratic model

[Response-Odour intensity]

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	14.41667	9	1.601852	8.737374	0.0140
GSM (A)	12.5	1	12.5	68.18182	0.0004
Thickness (B)	0.125	1	0.125	0.681818	0.4466
Loop density (C)	1.125	1	1.125	6.136364	0.0560
AB	0.25	1	0.25	1.363636	0.2956
AC	0.25	1	0.25	1.363636	0.2956
BC	0	1	0	0	1.0000
A^2	0.102564	1	0.102564	0.559441	0.4882
B^2	0.025641	1	0.025641	0.13986	0.7238
C^2	0.025641	1	0.025641	0.13986	0.7238
Residual	0.916667	5	0.183333	-	-
Lack of fit	0.25	3	0.083333	0.25	0.8576
Pure error	0.666667	2	0.333333	-	-
Cor eotal	15.33333	14	-	-	-

formation drastically. This may be explained by the fact that in the fabric with higher GSM, sweat may not pass through simply as in the case of lighter fabric, due to their thick structure and higher mass per square meter. This difference in odour intensity may also be because of the easy evaporation of sweat in lighter fabric due to their easy transmission than in heavy fabric. Onofrei *et al.*[39] motioned that thinner and less dense fabrics have improved diffusion ability.

Figure 5 (b) shows that the thickness increment in fabric structure increases the odour formation, This is because the heat and water vapour resistance increase with the increment of material thickness and air entrapped in the fabric. Analysis of the computational and experimental results of Li *et al.*[40] showed that the heat transfer process is influenced by fabric thickness and porosity, which also significantly impacts moisture transport processes. The thermal insulation and water vapor resistance of clothing systems are determined not only by fabric properties but also by construction factors. Hence, the increment in thickness changes the microclimate as a suitable place for bacterial growth and odour formation. These results are also supported by McQueen *et al.*[7]

Figure 5 (c) shows that the increase in loop density has less influence on odour intensity relatively. Loop density is another factor which has direct correlation with the odour intensity rating. During moisture transport process, water vapour diffusion and liquid water diffusion will occurs through the air filling and the inter fibre voids of yarn by saturation and

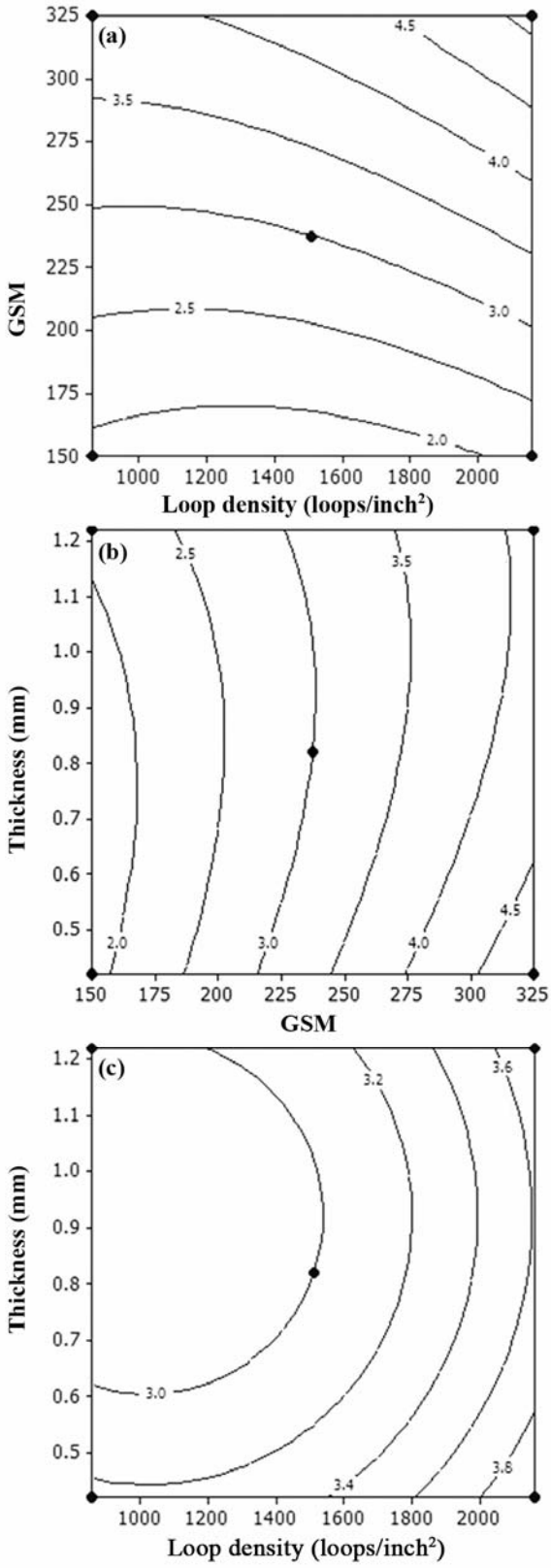

Fig 5—Contour plots showing effect of fabric GSM, loop density and thickness on odour formation

capillary wicking. When the fabric structure with high loop density absorbs moisture, the diffusion ability of the water vapor through the fibre is restricted due to the construction. Zhang *et al.*[41]. found that the geometrical distribution of capillaries in fibre assemblies affects the volume of liquid and the wicking time by capillary action. Our study results are in line with the findings of Dai *et al*.[42], and confirmed that the moisture transport of fabric (fabric construction parameter) has significant influence on the microclimate between body surface and garments which helps the growth of bacterial population. Increased amount of bacterial population leaves more metabolic byproducts (acids) and this helps in odour formation.

4 Conclusion

The odour formation in human body especially in axilla region is due to the short chain carboxylic acids produced by the bacterial metabolic activity. The studies show that the textile material also has its major responsibility in the odour formation; this is supported by the PTR-MS and FTIR results. The growth of bacteria and formation of fatty acids as their byproduct on the surface of the textile material is confirmed objectively by bacterial isolation with respect to the source bacteria in CFU/ml. It is found that there is a strong positive correlation between fabric thickness and odour formation observed. Thicker structure (r^2= 0.73) and high mass/square meter (r^2= 0.57) cause more odour in axilla regions (Single jersey < Interlock < 1×1 Rib). This may be attributed to the restriction for the air and water vapour permeability through the fabric with heavy structure, which produces suitable microclimate and helps in the effective growth of bacteria, thereby forming the higher odour intensity. The bacterial population in axilla is not stable and that no single group of organisms continuously dominates the population. But it is identified that the differences in structure has a major influence in terms of both population density and group dominance.

The statistical results of the designed experiments have identified that the material thickness and GSM are the major influencing factor on odour formation. The R^2 value (94%) of the developed model confirms the importance of selected variables on response. Hence, the result suggests that the fabric construction parameters (GSM, thickness and loop density) are the major factors, which affect the body microclimate changes. The microclimate change in the axilla is major cause for odour intensity by enhancing the bacterial growth on textile material.

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