Doctoral Dissertation

Resources protection: towards replacement of cotton fiber with polyester

By

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Declaration

I hereby declare that, the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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Edwin Kamalha
Turin, May, 2019

Abstract

In 2006/2007, and later in 2008/2009, the world experienced a peak in the global production of cotton. However, there is increasing annual demand for cotton due to world population growth and changes in consumers' purchasing behavior. Cotton fiber has the widest acceptance in apparel due to several desirable properties (e.g mass and heat transfer, and sensory properties among others) compared to synthetic fibers. The growing demand in consumption continuously exerts pressure on resources for natural fibers, especially cotton. Apart from ecological concerns with conventional cotton production and engineering (such as land requirements, use of pesticides, water requirements and wet processing and finishing), there is more concern as more cotton farmland is being rechanneled to more profitable ventures such as real estate, transport and settlements. Other natural fiber options such as wool, flax, linen and silk among others, are produced in very meager proportions, globally that they cannot fill the gaps in demand and the unpredictable future of cotton supply. Polyester, in the form of poly(ethylene terephthalate) (PET) has qualities that could address this concern. With several desirable properties such as tenacity, strength, light weight, and easycare, polyester brings interesting properties for apparel purposes as well as furnishing. Unfortunately, except for sportswear, consumers are reluctant to wear 100% polyester clothing mainly because of its inferior sensory comfort, touch and sometimes appearance.

This study seeks to find ways of improving polyester fabric characteristics in order to decrease the gap between human perception of cotton vs. PET; specifically the sensory perception and hydrophilic performance in comparison with similar aspects of cotton fabrics. This study focuses on three main subjects:

1. Sensory study of cotton and polyester fabrics to identify the main distinguishing attribute between PET and cotton fabrics, using sensory analysis.
2. Chemical functionalization of PET fabrics to introduce a sensory perception similar to that in cotton fabrics (bridging between PET and cotton fabrics).

3. Sensory evaluation of cotton fabrics, untreated PET fabrics and chemically functionalized PET fabrics
4. Enhancement of the hydrophilic property of PET fabrics through photo-initiated polymer grafting.

First, using sensory analysis, the sensory patterns of knitted and woven fabrics were studied to determine the suitability of samples. The fabric samples included plain and twill fabrics (for woven) of different structures, and interlock and single jersey fabrics (for knitted) of different structures. It was found that knitted fabrics are profiled differently from woven fabrics. Thus, approaches to enhance the sensory perception of knitted fabrics would be different from those of woven fabrics. For a manageable scope, this study proceeds to experiment with woven fabrics of different structures. Objective measurements were also performed for properties defining sensory attributes. The influences of yarn and fabric construction were factored in the analysis of sensory perception and the measured attributes. For example, the weave density, which compounds the yarn fineness and threads per inch were found to significantly ($p \leq 0.05$) influence the stiffness properties of woven fabrics.

To determine the disparity between cotton and PET woven fabrics, a multisensory study was undertaken. A 12 judges' panel was used to rank six cotton and polyester woven fabrics for 11 sensory descriptors. Rank aggregation and weighting were performed using cross-entropy Monte Carlo (CE) algorithms, Genetic algorithms (GA), and the Borda count (BK) technique. The quality of the sensory panel was studied using ANOVA and consonance analysis. Principle component analysis (PCA) and unsupervised agglomerative hierarchical clustering (AHC) were used to study and profile sensory relationships. The largest Euclidean distance (dissimilarity) was found between fabrics of dissimilar generic. The descriptor *crisp* accounted for the highest variability between PET and cotton fabrics ($p \leq 0.05$). To replace cotton with PET via this sensory approach, the modification of stiffness of polyester fabrics was judiciously suggested. For the fabrics studied, it was deduced that visual aesthetics can be used to distinguish between PET and cotton fabrics. It is also underscored that cotton and polyester fabrics can be distinguished via their sensory attributes and that the sensory behavior of fabrics can be predicted on the basis of fiber content. However, fiber content does not influence sensory perception independently, but rather with other factors such as weave type and type of finishing.

To bridge between the perceived sensory properties of polyester and cotton fabrics, the stiffness of polyester fabrics was modified. NaOH and an amino-functional polysiloxane softener, with atmospheric air plasma pre-oxidation were used. Sensory evaluation was then carried out using a panel of 14 judges, for 11 sensory descriptors. Rank aggregation, sensory clustering, dissimilarity analysis

and profiling were then carried out. NaOH and softening treatment of polyester bridged between cotton and one of the three polyester fabrics studied.

Polyester fabrics treated with NaOH and the silicon softener were perceived *soft*, *smooth*, *less crisp*, and *less stiff* compared to untreated polyester fabrics. However, cotton fabrics were still perceived *natural* compared to any polyester fabrics. Using the Ciro-FAST system and other appropriate testing equipment, objective measurements were carried out on all fabrics studied. The Moisture Management Tester was also used to study the in-plane moisture behavior of the fabrics. Although NaOH-treated PET fabrics had enhanced air permeability and hydrophilicity, they also presented degradation; loss in weight— accompanied with reduced abrasion resistance and bursting strength. As expected, NaOH-treated polyester fabrics later became hydrophobic and less air-permeable when the silicon based softener was added. It is deduced that characterization of human perception can play a vital role in human centered production of fabrics, particularly in finishing. A better understanding of fabric sensory perceptions was realized by integrating sensory analysis data with objective measurements data.

Using correlation analysis, clustering and profiling, the relationship between instrumental (objective) measurements was studied. Only a few sensory attributes were precisely expressed by instrumental measurements. Hand attributes were more expressed by fabric mechanical and surface attributes. The profiling of fabrics indicates that conventional PET fabrics can be distinguished from conventional cotton fabrics using both subjective and objective evaluation, by selected attributes. It is also argued that human evaluation and objective measurements present varying dimensions for sensory analysis. It is further deduced that textile human sensory perception cannot be directly represented by instrumental measurements.

The final part of the study investigates and compares the hydrophilic potential and efficacy of two vinyl monomers applied by photo-grafting on the surface of polyethylene terephthalate (PET) fabric. Two monomers: Poly-(ethylene glycol) diacrylate (PEGDA) and [2-(methacryloyloxy) ethyl]-trimethylammonium chloride (METAC) were used separately, with 2-hydroxy-2-methyl-1-phenyl-1-propanone (HMPP) as the radical photo initiator. Surface study of the grafted PET was confirmed using X-ray photoelectron spectroscopy (XPS) and Energy Dispersive Spectroscopy (EDS). Water contact angle (WCA) measurements and dynamic moisture management tests (MMT) indicate that PEGDA and METAC induce complete wetting of PET at concentrations 0.1-5% (V:V). The grafted PET fabrics remain hydrophilic following testing by washing, crocking drycleaning tests. PEGDA grafted fabrics perform better than METAC grafted fabrics, as static water contact angles of METAC grafted fabrics increase after washing. Colorimetric measurements (K/S and CIELAB/CH) and color on dyed PET fabrics suggest that both monomers greatly improve the dyeing efficiency of PET.

Grafted PET fabrics presented strong fastness properties, slightly better than the reference PET fabric. The hand and appearance of grafted PET fabrics remains largely unchanged, following drycleaning and laundering procedures. This study demonstrates the potential of PEGDA and METAC for a hydrophilic function in conventional textiles utilizing UV grafting. It is suggested that PEGDA and METAC generate hydrophilic groups on PET; the macroradicals are in a form of vinyl structures which form short chain grafts and demonstrate hydrophilic function at the tested concentrations.

This study contributes to research on hydrophilic functionalization of PET. The studied monomers have not been used elsewhere in the hydrophilic enhancement of fabric for apparel purposes. The results of this research can play a practical guiding role in the design of fabrics, sensory property design and contribute to the development of cotton-like polyester fabrics.

Keywords

Polyester (PET) and cotton, woven fabrics, knitted fabrics, photo-grafting, wettability, contact angle, moisture management, photo-initiator, hydrophilicity, polyester dyeing, sensory evaluation, knitted fabrics, ranking, rank aggregation, principal component analysis (PCA), clustering, dissimilarity, Euclidean distance, softening, alkali hydrolysis, stiffness, performance, agglomerative hierarchical clustering (AHC), FAST, surface modification, subjective evaluation, objective evaluation, finishing, chemical finishing, NaOH treatment, EDX/EDS, XPX, SEM, MMT, water contact angle

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To my beloved parents, my wife, and children, you are such a blessing to me.

Edwin Kamalha

I would like to dedicate this thesis to my loving family and parents

Contents

List of Abbreviations

PET- Poly (ethylene terephthalate)

CI- Cotton Incorporated

CCI- Cotton Council International

GA- Genetic algorithim

CE- Cross Entropy

BK-Borda Kendall Borda Count)

METAC- (methacryloyloxy) ethyl]-trimethylammonium chloride

PEGDA- Poly-(ethylene glycol) diacrylate

HMPP- 2-hydroxy-2-methyl-1-phenyl-1-propanone

XPS- X-ray photoelectron spectroscopy

EDS- Energy Dispersive Spectroscopy

WCA- Water contact angle

MMT- Moisture management tester

FAST- Fabric assurance by simple testing

Chapter 1

General introduction and aim

1.1 Background

In 2006/2007 and later in 2008/2009, the world experienced a peak in the global production of cotton. However, there is increasing annual demand for cotton due to world population growth and changes in consumers' purchasing behavior. Cotton fiber has the widest acceptance in apparel due to several desirable properties (e.g mass and heat transfer, and sensory properties among others) compared to synthetic fibers. It was recently reported in the Sourcing Journal that cotton demand would hit an all-time high in late 2018[1]. The growing demand in consumption continuously exerts pressure on resources for natural fibers, especially cotton. Apart from ecological concerns with conventional cotton production and engineering (such as land requirements, use of pesticides, water requirements and wet processing and finishing), there is more concern as more cotton farmland is being rechanneled to more profitable ventures such as real estate, transport and settlements. Other natural fiber options such as wool, flax, linen and silk among others, are produced in very meager proportions, globally that they cannot fill the gaps in demand and the unpredictable future of cotton supply. Polyester, in the form of poly(ethylene terephthalate) (PET)has qualities that could address this concern. With several desirable properties such as tenacity, strength, light weight, and easycare, polyester brings interesting properties for apparel purposes as well as furnishing. Unfortunately, except for sportswear and sometimes in Fast Fashion, consumers are reluctant to wear 100% polyester clothing mainly because of its inferior sensory comfort, touch and sometimes appearance.

Therefore, this study seeks to improve polyester fabric characteristics in order to decrease the gap between human sensory perception and hydrophilic character of PET against cotton.

1.2 Global fiber market; the fluctuating and reducing share of cotton

As the global demand for cotton fiber grows annually, supply statistics point to a declining market share for cotton. Despite a steady production, the proportion of global fiber consumption of cotton has gradually fallen from over 80% in the early 1950's, to about 32% presently, in favor of polyester (PET), currently at about 58%[2]. Figure 1.1 shows global fiber production and forecast through 1980-2025.

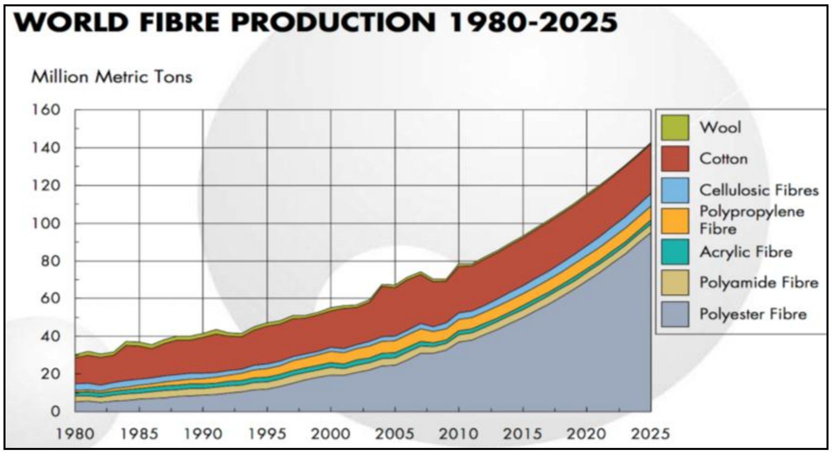
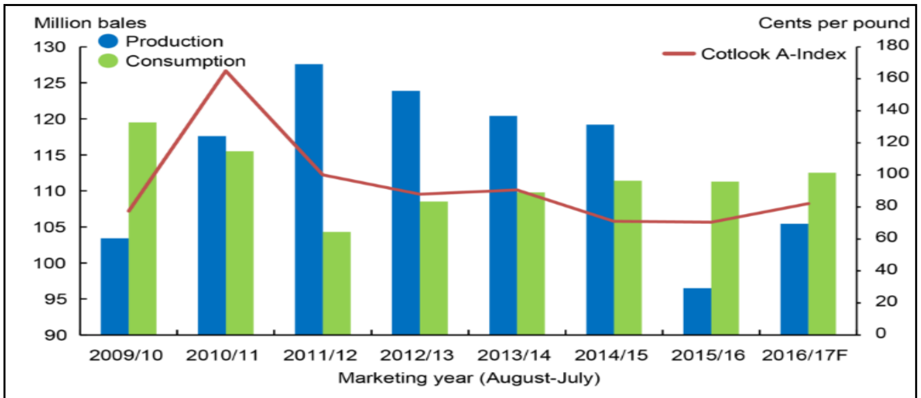


Figure 1.1 Projection of global fiber production through 1980-2025[3]. Copyright Tecnon OrbiChem; Reproduced with permission.

This demonstrates the growing prominence of polyester and the gradual substitution of cotton in several applications. For decades, polyester has also had the largest share of the global synthetic fiber market, peaking at 82% in 2015[2].

Polyester also competes with cotton in global apparel market share, both averaging between 31% and 36% since 2010[4,5]. As pressure on farming land increases, the future of cotton could be uncertain, with a predicted decline in the global market share to about 21%, while polyester is anticipated to peak to about 70% by 2025[3,5,6]. For four consecutive marketing years, global cotton demand was lower than actual supply, until 2015/16 when a deficit of 15 million bales was recorded. A further decrease in production was recorded for the 2016/2017 marketing year. These were argued on reduced cotton prices, poor farming conditions and excess stocks[7]. Global cotton consumption in 2017-18 is also projected to rise by 5%, to 120.4 million bales, according to latest US Department of Agriculture (USDA) statistics. The rise in cotton demand is attributed to the reduction in global polyester production, the rising cotton mill use, and expanding global economy[8,9]. Figure 1.2 presents trends and forecasts for global cotton production and consumption, along with price.



Note: 1 bale = 480 pounds. F=Forecast. Cotlook A-index is a global cotton reference price used by industry analysts.
Source: USDA, Economic Research Service using World Agricultural Supply and Demand Estimates reports and Cotlook A-index.

Figure 1.2 Global cotton production, consuption, and prices

USDA has projected a new record high in world cotton mill use in the 2018/19 marketing year[1], with a 3.9% increase in global consumption from the 2017/2018 period. Compared to the 2015/16 cotton year, cotton mill use is projected to increase in China (18%), India (2%), Pakistan (4%) and Bangladesh (27%). The projection is very remarkable for Vietnam at 67%.

The versatility in applications, in addition to some performance properties (such as high abrasion resistance, tensile strength, lightweight, resistance to attack by many chemicals, dimensional stability, high degree of resistance to creasing, and excellent resistance to photochemical degradation[10,11], account for polyester's grown prominence. Polyester is also well priced compared to many other synthetic and natural fibers including cotton[12]

1.3 Consumer apparel perceptions and preference; cotton against manmade fibers

Today's competitive apparel market calls for manufacturers to recognize changing patterns in consumer preferences. Today's interpretation of quality compounds important associated elements of total quality of apparel materials such as a fabric's ability to provide protection from cold or hot weather, tactile sensation, fit, lifecycle details, and several varying consumer emotional or psychological needs.

When apparel users talk about their preferred wear, they mention comfort, fit and that the item makes them look or feel good; and that usually, their favorite apparel is made of cotton[13]. The wider application of cotton in a range of apparel products is partly due to the desirable physiological and sensory comfort perceived with cotton fabrics. According to a Cotton Incorporated's 2015 *Lifestyle Monitor* survey carried out in the US, 29% of respondents cited jeans as their favorite apparel[13]. These were followed by tees, active bottoms and casual pants by 15%, 9%, and 8% respectively. Comfort was mentioned by 47% of the wearers, as the main reason for their choices. 14% said they preferred the garments for the fit, while 14% said that they made them look and feel good. In the same *Lifestyle Monitor* survey, a similar question revealed that over respondents favored cotton and cotton blends for the making of their jeans

(96%), tees (96%), socks (93%), casual shirts (91%), underwear (89%), pajamas (86%), dress shirts (78%), casual slacks (74%), and activewear (65%). A significant proportion of respondents generally asserted that quality garments are made from all natural fibers like cotton. Consistently over time, and recently it has been reported that most global wearers say cotton and cotton blends are best suited for today's fashions.

Earlier in 2004, a *Global Lifestyle Monitor* survey carried out by Cotton Incorporated (CI) and Cotton Council International (CCI), with respondents from Brazil, China, Colombia, Germany, Hong Kong, India, Italy, Japan, and the United Kingdom, found an overwhelming preference for cotton fiber[14]. Compared to a their preceding survey of 2001, it was noted that fiber type/content had gained more prominence as an important factor in apparel purchase; 50% of the interviewed consumers preferred clothing made of natural fibers, and that 60% of the consumers cited preference for apparel made of cotton rather than other fibers. Two-thirds of respondents said they prefer to avoid synthetic fibers, and that 67% would find out the fiber content of clothing before purchasing. Followed by India, Hong Kong had the highest percentage of consumers with cotton preference among the surveyed countries.

According to a market survey by CCI and CI, growth in consumer interest in fiber content had surged by 2011, especially in the fast growing markets[15]. With interviewee sample sizes above 500, for each country, Italy and India posted 95% and 86% respectively, for consumers interested in fiber content. In Brazil, 85% of respondents indicated this interest, while Chinese consumers stood at 83%. The 2011 survey indicated that 85% of global consumers preferred cotton and cotton blends for their garments, and that the majority of consumers in all countries surveyed preferred cotton clothing. 96% of Chinese consumers associated cotton garments with comfort and softness, while 92% associated cotton clothing with natural and breathable. In India, cotton was found in 87% of men's clothing compared to 83% in women's clothing. The survey also noted that 75% of apparel on US retail stalls contained cotton, and that cotton was higher in men's garments (85%) compared to women's (68%). Jeans, shorts and knitted shirts accounted for the highest cotton presence with 99%, 92% and 82% respectively. The lowest cotton presence was in outerwear (46%), skirts (46%), athletic apparel (37%), and dresses (34%). Price was not a hindering factor for cotton clothing purchases. More than half of global consumers are willing to pay an extra to keep cotton from being substituted for synthetic fibers in their clothing. Even in apparel where synthetics dominate, such as sports apparel, several consumers would pay extra for cotton moisture management athletic apparel. 90% of consumers are willing to purchase cotton athletic apparel that wicks moisture like synthetics. However, the market survey found that of the 35% of athletic apparel with moisture management properties, only 12% of cotton athletic apparel contained moisture management properties. With a slogan that "cotton is the enemy" the brand Under Armour was established and succeeded on synthetics, thriving on moisture management, especially for wicking[15].

Overall, consumers consider quality as the most popular deciding factor during clothing purchase. The proportion of American consumers willing to pay for a premium for better quality was at 68% in 1999 and 70% in 2001. More than six in every ten consumers associated cotton clothing with higher quality compared to synthetic clothing[15].

1.4 Cotton versus polyester; ecological and economic sustainability

In light of continued exploitation of resources and disposal of used items, it is also important that cleaner methods are used to minimize environmental impacts. Economic sustainability in terms of costs is also considered. Some consumers and economies are keen to promote these aspects. The use of pesticides and herbicides in the cotton value chain, the usage of chemicals in manmade fibers and the composition of textile dyes has increasingly come under scrutiny. A growing number of consumers prefer their clothing produced close to home[16,17]. Polyester fiber and apparel are relatively priced lower compared to many other synthetics and natural fibers; posting a ratio of about 0.6-0.8 compared to cotton[12].

Studies on life cycle assessment of cotton and polyester fabrics have reported findings in favor of polyester, against cotton for, natural resources requirements- land, water, and location. Since most of the global cotton is produced conventionally; entailing the use of irrigation, fertilizers and pesticides, there are adverse ecological implications[18,19]. Polyester can be produced in many locations, and seasons unlike cotton, thus reducing the supply chain time and eco-footprints associated with transport. The energy requirement to produce 1 Kg of cotton fabric requires less energy and impacts less on fossil fuels compared to polyester, with an estimated ratio of about 1.5 (polyester to cotton). However, the production of a unit of 1 Kg of polyester fabric was found to emit less carbon dioxide compared to cotton with a ratio of 0.8[18–21]. Moreover, the spinning of polyester for fabrics provides a re-use medium for polyester waste from food and beverage packaging, and waste fabrics among others. Polyester of several grades is obtained from recycling of these waste materials. For instance, most PET extruded from PET waste is used for coarse fibers utilized in fabrics for bags, denim, footwear and composites lately[18,19,22,23]. Therefore, the promotion of PET spinning is an avenue to cater for sustainable end-of-life applications for PET waste from fabrics and other industries.

From the reviewed literature, the mass and heat transport behavior (breathability, wicking, porosity, absorbance) of clothing, along with sensory attributes (such as soft feel, fit), among others, have been largely found as preferred by consumers. Despite the several positives with polyester fiber, the use of polyester in apparel is only common in blends, (mostly with cotton, rayon, and wool), fast fashion-wear and sportswear. This is, among others, due to inferior sensorial comfort and poor heat and mass transfer attributes of polyester[24]. While there are several other requirements of apparel, this study focuses on the enhancement of the user sensory perception and moisture management of polyester fabrics through chemical functionalization. Sensory evaluation and sensory data mining were used to identify the key sensory attributes that distinguish cotton fabrics from polyester fabrics, and to also determine the gap between cotton and polyester fabrics. NaOH and an amino functional polysiloxane softener were used to modify the hand property of polyester fabrics in comparison with cotton fabrics. Radical photo-grafting was used to modify the surface of polyester fabrics using two monomers, separately, to introduce hydrophilicity.

1.5 The hand and wetting of polyester fabrics

Polyester is a synthetic fiber composed of at least 85 percent by weight of an ester of dihydric alcohol and terephthalic acid (TPA). Poly(ethylene terephthalate) (PET) , the most globally used polyester, is produced from ethylene glycol (EG) and dimethyl terephthalate (DMT) or terephthalic acid (TPA) by polycondensation (Figure 1.3).

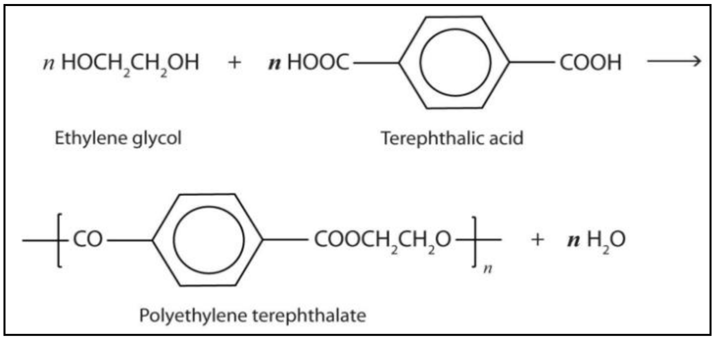


Figure 1.3 Polycondensation process for polyethylene terephtahaletesynthesis

The linear polymer, PET, is composed of an alternating unit of flexible aliphatic segments and stiff interactive benzene rings.

The hand of fabrics has been reported to depend on fiber type, fabric construction and mechanical properties among others. The stiffness properties such as bending length and flexural rigidity have pronounced effect on the hand feel properties such as softness, drape, bending and flexibility. Although PET is non-crystalline, during the fiber spinning, crystallization occurs during drawing of the fiber, as the chains are aligned[25,26]. PET is known to be among the stiffest and strongest commercial melt-spun fibers. This stiffness in addition to the hydrophobic and oleophilic nature of polyester gives an undesirable hand and an inferior reputation of comfort when compared to cotton fabrics[22,27,28].

Again, due to its crystalline structure, PET is hydrophobic and shows a moisture regain as low as 0.6-0.8%[26,29,30]. Due to these reasons, and the absence of chemically reactive groups, it is also difficult to dye PET fabrics with dyestuffs other than disperse dyes. The hydrophobic character of PET is responsible for inferior sensory properties and discomfort to wearers, especially skin sensorial discomfort. Such sensory attributes and interventions in apparel have been reviewed[31,32].

1.6 NaOH hydrolysis of polyester

The simplicity and economic viability of alkaline hydrolysis has been exploited for the wide use in imparting hydrophilicity and enhanced handle to polyester fabrics[33]. Hydrolysis is the chemical degradation of a compound using water. Polyester fibers are comprised of poly(ethylene terephthalate) (PET), which is an organic ester, and potent to cleavage and hydrolysis when treated with strong sodium hydroxide. Water in the form of its hydrogen and hydroxyl ions, adds to the cleaved compound. The addition of water is increased by increasing the concentration of hydrogen or hydroxyl ions through the addition of acid or base— which increases the rate of hydrolysis[25,34]. Acidic or basic catalysts can enhance the hydrolysis of esters. The hydrolysis reaction of NaOH with PET is commenced by an attack of a hydroxyl ion on the electron deficient carbonyl carbon atom of the ester linkages. The carboxyl group formed then converts into a carboxylate anion and the reaction goes on until complete hydrolysis is reached. It is suggested that the alkali randomly acts at the surface of the fiber, attacking carboxyl groups of the polymer molecule and hydrolyses them as short chains of disodium terephthalate[11,35]. Owing to the removal of fiber material in the form of short chains, the fiber suffers a loss in weight.

A cotton-like or silky hand has particularly been noted after NaOH treatment of polyester fabrics, associated with morphological changes, although maintaining a circular cross-section of fibers, while also creating polar groups at the fiber surface[11,33,35–38]. Treatment with NaOH reduces the regular filaments of fabrics to finer deniers, leaving scars on the surface of the filament. This gives fabrics with a silky appearance and touch. Polyester fabrics produced by this treatment exhibit irregularity comparable to natural silk fabrics; with a silk-like soft touch, good drape and reduced stiffness. Previous studies have also deeply examined, among others, the morphological, physiochemical, and mechanical changes associated with NaOH treatment of polyester. The concentration and duration of NaOH treatment on polyester have been noted as the main parameters that influence the treated fabric properties[39].

Application of softeners after NaOH treatment of polyester has been found to enhance the smoothness, softness, and to reduce associated harshness[40]. Softeners for fabrics exist in a wide range of classes and also offer added functionality, in addition to handle modification. Many anionic, cationic and non-ionic softeners also add anti-static or hydrophilic properties. Nonionic softeners are argued for stability to temperatures, and resistance to yellowing[41,42]. They are thus suitable for finishing bleached or whitened fabrics[40,43]. The substantivity of nonionic softeners is not distinctive since they do not carry any electrical charge. Padding, followed by curing is the main process of applying nonionic softeners onto fabrics. Amino functional silicones are known for distinct smoothening and softening properties compared to all other groups of softeners[43]. They can be made into micro and semi-micro emulsion recipes using specially selected emulsifying combinations. Additionally, softeners have been found to enhance some performance properties of polyester fabrics, such as the elastic resilience, crease recovery, abrasion resistance, sewability, and tear strength. Silicone softeners particularly enhance durable press performance and maintain mechanical properties and durability, compared to cationic softeners[40]. The elastic silicone polymer network entraps fibers within its matrix— thus improving the fabric's wrinkle recovery ability. The high molecular flexibility of the silicone chain confers low glass transition temperature (about –100 °C) and unique softness to fabrics finished with silicone softeners. During curing, silicone bonds with fabric and also forms a cross-linking network due to self-polymerization[44]. The pretreatment of polyester with atmospheric air plasma was fund to increase the reactivity with NaOH and the substantivity of softeners; and also improves the wrinkle recovery angles much more than in the absence of plasma pre-treatment[40,44–46].

The use of heat (boiling or heat-setting), enzymes[33,47–51] and oxidizing chemicals[52] has also been explored to produce polyester fabrics with a cotton-like hand and enhanced wettability.

However, these methods have been found less effective and costly as they consume large quantities of reagents and require longer treatment times[44].

Earlier studies on the modification of polyester largely focused on the production of ‘silk-like’ fabrics. Recently, ‘cotton-like’ fabrics have also been produced but the application has been on a limited scope. The sensory evaluation of polyester fabrics, towards the replacement of cotton fiber, has not been studied. Attempts have mainly focused on objective measurements, which hardly reflect end-user perception. Understanding the human sensory perception of NaOH hydrolyzed polyester fabrics would aid in optimizing process parameters. Considering the several desirable properties of polyester fabrics, ‘cotton-like’ polyester fabrics with enhanced comfort would transform the chemical fiber and apparel industry in view of replacement of cotton fiber with polyester. A most recent publication on alkali treatment of PET for cotton-like properties reported on four aspects of the wearable ability[53]. Through objective and subjective tests, the handle and luster of treated fabrics were found close to those of cotton fabrics. Optimal parameters were noted to be: an alkali concentration of 25 g/*l*, treatment time of 50 min, bath ratio of 1:15 and treatment temperature of 110 °C. In 2013, Laijiu’s group[10] reported on the porosity of knitted fabrics made from chemically modified polyester fibers, for cotton-like properties.

Although there are other stages (fiber or yarn) at which cotton-like effects could be introduced in polyester textiles, the costs of producing special raw fibers, combining and modifying filaments may be incomparable to the processing costs of NaOH treatment, on fabrics. Again, most often, specially processed fibers and yarns undergo alkaline treatment as a cleaning stage. In this study, NaOH treatment, preceded by plasma oxidation was carried out on three polyester woven fabrics. The concentration and temperature of treatment were fixed; however, varied for the different fabric structures, following an experimental pilot. A commercial amino functional silicon softener was applied on selected NaOH treated polyester fabrics. The functionalized and untreated (reference) PET fabrics were then subjected to a sensory evaluation and objective measurements, along with cotton fabrics evaluated.

1.7 Surface photo-grafting of polyethylene terephthalate

At industrial scale, alkaline treatment of PET has been used for decades to improve PET fabric wettability and wicking. However, alkaline hydrolysis of PET induces a controlled degradation of the fabric usually accompanied by loss in fabric strength and weight[33,54]. Alternative treatments with less profound effect on PET mechanical properties are thus preferable. Graft copolymerization offers an approach to functionalize polymers such as PET. For grafting on a polymer surface, ionic chemical groups or free radicals are formed either on the polymer backbone, or on the monomer to be grafted. This may be achieved by decomposition of a chemical initiator triggered by ultraviolet light or high energy radiation[55].

Photo-grafting possesses several advantages over conventional thermal, oxidative, and evaporative methods. The advantages of photo-grafting include: reduced overall costs, high productivity, less space requirement, enhanced safety with omission of volatile reagents, lower energy requirements, and environmental sustainability[56,57]. In photo-grafting, UV irradiation in the presence of a radical photo-initiator generates free radicals which can abstract hydrogen atoms from the substrate polymer, yielding active sites for grafting and initiating a chain growth from the substrate surface. At the same time, the generated free radicals can also promote homopolymerisation of the monomers[55,58]. Several examples of photo-initiated grafting reactions have been reported for different purposes, such as: photo-grafting of poly(ethylene glycol methacrylate) and glycidyl methacrylate on PTFE for reduced surface adsorption and increased conductivity respectively;[59,60] poly(3-hydroxyoctanoate) and methoxy poly(ethylene glycol) for antitumor drug delivery of paclitaxel;[61]. A review by Neugebauer[62] focused on PEO graft copolymers and their applications. The graft density and yield were reported to increase with increasing UV irradiation time and the macro-monomer concentration[63]. With UV-initiated grafting, hydrophilic and antistatic properties of PET fabrics were greatly enhanced using acrylamide, poly(ethylene glycol) methacrylate, 2-acrylamide-2-methyl propane sulfonic acid, and dimethyl aminoethyl methacrylate vinyl monomers[64].

In this research, UV-grafting of two vinyl monomers, separately, on PET fabric was attempted. The potential to enhance wetting and dyeing of PET by the selected monomers has been studied. The monomers selected were PEGDA ($H_2C{=}CHCO(OCH_2CH_2)_nO_2CCH{=}CH_2$) and METAC ($H_2C{=}C(CH_3)CO_2CH_2CH_2N(CH_3)_3Cl$). PEGDA is a PEG-based monomer with an acrylate function as end group of the PEG linear chain[65,66]. In the presence of a photo-initiator and UV light, PEGDA gels quickly, at room temperature. PEGDA gels are hydrophilic, elastic, of high modulus and are inert. Common applications of PEGDA include: adhesives, coatings, sealants, photoresists, solder masks and photopolymers[65,67]. METAC is a quaternary ammonium salt that contains one acrylic reactive function. METAC is commonly used as an intermediary in the production of polymers such as polyelectrolites. METAC also possesses antimicrobial properties; thus, METAC functionalized fabrics could offer an associated antimicrobial function that could inhibit control odor associated with PET fabrics [68,69]. The changes in wetting and dyeing of PET, following photo-grafting of PEGDA and METAC were evaluated. This study was motivated by: i) the merits of using UV as a cure method compared to other conventional methods already mentioned ii) the use of PEGDA and METAC, which have never been used in hydrophilic functionality of textiles; iii) as a basis to study other similar monomers, and sustainable techniques to enhance wetting of polyester. The study findings suggest that PEGDA and METAC are potential monomers for hydrophilic functionalization of PET with profound enhancement of color depth.

1.8 Sensory analysis in textiles

In apparel design and development, sensory value addition isn't an exception; it engulfs end-user requirements with designers' constraints. To perceive a quality of clothing, customers engage in touch, vision and try-on of garments. This process generates and integrates various multi-sensory, sentimental and cognitive experiences that partly inform buying decisions[17,70]. When appropriately defined, user preferences, sensory, hedonic and practical user requirements can be integrated in product design and quality evaluation. Textile sensory attributes may relate to tactility, moisture, pressure, temperature, aesthetics, acoustic, and olfaction[71,72]. Sensory properties of textile products are a function of fiber, yarn and fabric characteristics, as well as the type of dyeing and finishing processes[73].

Sensory evaluation is premised on the competence of trained or experienced human beings (usually called judges) to execute objective measurements of sensations[74]. Sensory analysis involves the evaluation of products through descriptors linked to human senses (sight, hearing, taste, smell, touch). From the sensory analysis of food, cosmetics, and pharmaceuticals, methods tailored to textiles have been developed[75–77]. Attempts have been made to develop and standardize terminologies and scales to describe subjective sensory experiences; but also found to vary with individuals[78]. Objective sensory evaluation, which involves physical tools, has also been developed. They include the works of Kawabata in the early1970's through the late 80's[79], and other innovations with computer programs[80,81]. However, instrumental methods do not represent the in-use textile experience since the measured mechanical parameters cannot directly reflect human sensations in a precise way. The use of humans as tools for sensory evaluation exploits and integrates the non-uniform perception of sensory attributes; which is also consumer representative[82]. Park and Hong[83] and Kim et al[84] recently noted a variation in sensory perception across selected nationalities and cultures. A study by Zeng and Koehl[85] argued that sensory evaluation of fabrics was cultural-independent since it is preference-independent; and that a well trained panel should deliver credible scores.

Rank-based and score-based methods are popular in textile sensory evaluation[86–88]. The rank-based system accords a distinct position to an item, in a *rank list* based on the perceived magnitude of the attribute assessed. The score-based system utilizes a scale to estimate the magnitude for each item. Rank lists from a sensory session are usually aggregated and object ranks can be transformed into scores[89,90]. In this study the rank-based system was applied.

1.9 Mining of textile sensory data

The multidimensional and non-linear nature of sensory data is often analyzed using advanced multivariate statistics[91] and intelligent algorithms— such as neural networks and fuzzy logic[71,92]. Such methods have provided new frontiers for modeling and predicting sensory relationships, using sensory data. Jeguirim's team[93] utilized multiple factor analysis (MFA) and principal component analysis (PCA) in studying the effect of fabric finishes on low stress mechanical properties and sensory parameters. The study noted significant correlation between the sensory attributes; thick, heavy, soft, elastic and crumple-like; and the measured attributes— resilience, and the geometrical and frictional roughness. Fuzzy logic and neural networks were found to yield better prediction results when used together[94,95].

Analyzing assessors' performance helps to discover any significant variations in sensory ratings and consequently to decide on assessors who may have challenges in discriminating samples. For example, non-perceivers may fail to perceive an attribute. Also, non-discriminators may fail to discriminate between some samples for one or more attributes. Reproducibility errors are also common as panelists may fail to replicate assessments. In other cases, a panelist may use the rating scale in opposition to the rest of the panel (crossover effects) or use a varying interval of magnitudes compared to other panelists (magnitude error). Crossover errors are said to contribute largely to poor panel consistency[96,97]. Errors in sensory evaluation may be due to individual assessors or by agreement within a sensory panel. One way analysis of variance (ANOVA) can show the relative importance of attributes, identify assessor errors, and class the total variation of sensory data into sources that affect sensory returns[98]. Exploratory multivariate techniques also give a robust overview of the panel performance. Consonance analysis (CA) using PCA across variables may be used along with ANOVA[99]. Consonance analysis entails a PCA run on individual assessors' evaluations for the set of samples. The variance explained by the first principle component represents the panel agreement for the descriptor in question. Visualization of factor loadings, correlations, squared cosines, and percentage contributions presents an exploratory image and facilitates the identification of outlying assessors and reproducibility errors[71,86,99].

1.9.1 Principal component analysis (PCA)

In principal component analysis **(**PCA), observations are defined by inter-correlated quantitative dependent variables with an aim of extracting the most relevant information. Output from PCA is presented as a collection of new *orthogonal* variables called principal components. PCA utilizes components along which the variation in the data is maximal. PCA is commenced and explained by the *Eigen decomposition* of positive semi-definite matrices and upon the singular value decomposition (SVD) of rectangular matrices[100]. PCA then linearly merges original variables to yield principal components (F1+F2.....+Fn). The ensuing components are orthogonal to preceding components. Onto the principal components, variables are projected geometrically as factor scores of the observations[100,101]. Further analysis yields more relationships between variables/observations and factors, and between observations and variables; such as correlations, factor scores, squared cosines, and contributions to factors. These constraints have relative meaning and importance to the variability. For instance, the magnitude of the squared cosines indicates the relative significance of variables or observations to the variability[102,103]. In this study, PCA was used to study sensory patterns between different kinds of fabrics.

1.9.2 Agglomerative hierarchical clustering (AHC)

Hierarchical (connectivity) clustering establishes a hierarchy of clusters of objects on a set of quantitative attributes, yielding multiple levels of abstraction of the original data set. AHC clusters objects by combinations that minimize a given agglomeration criterion. A metric, together with a linkage criterion is often used to indicate the distance between pairs of observations. The Manhattan, Euclidean, and squared Euclidean distances are some common metrics. Linkage criterion include minimum within class variance, mean linkage clustering, weighted pair group method with arithmetic mean, and centroid linkage clustering among others[104,105].

AHC outputs a binary clustering tree known as a *dendrogram* (Figure 1.4), a hierarchy from which appropriate clusters may be selected.

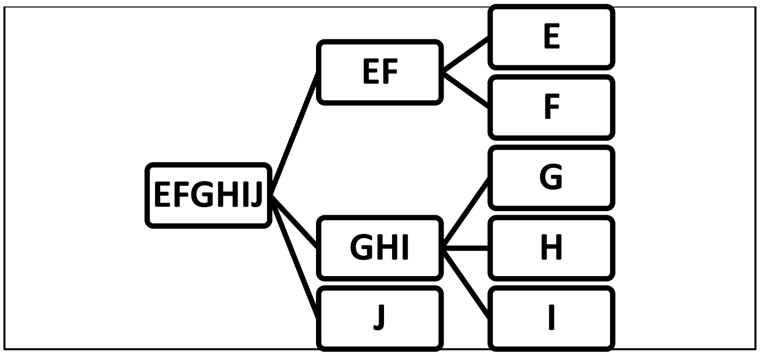


Figure 1.4 A sample dendrogram from AHC of objects EFGHIJ

Graphically, the y-axis of the *dendrogram* represents the dissimilarity distance, while the x-axis represents items or observations. In this study, AHC was performed to profile fabrics according to sensory attributes defined by assessors. The *squared Euclidean distance and the weighted pair-group average* were used as metric and linkage criteria respectively.

1.10 Aim of the study

Through the reviewed literature, it is presented that the future of cotton fiber supply is quite uncertain as there is growing global demand. It is also noted that consumers prefer apparel made from cotton fabrics, especially due to the perceived sensory comfort and moisture properties attributed to cotton fabrics. Due to several desirable properties of PET, it is envisaged that polyester could serve as a surrogate to cotton, if certain inferior properties were addressed. The literature also presents that NaOH treatment of PET textiles has been widely used to enhance the moisture and hand properties of PET fabrics. Although previous studies have carried out objective measurements on NaOH-treated PET textiles, sensory evaluation has not been undertaken on such fabrics. A sensory comparison between functionalized PET fabrics and cotton fabrics has neither been undertaken as well. Such reflection of end-user perception is a knowledge gap in these researches. There is no evidence of previous research to investigate and identify sensory attributes that distinguish polyester fabrics from cotton fabrics. The use of UV irradiation and surface grafting is not a new phenomenon. However, the potential of METAC and PEGDA, enhancing hydrophilicity of fabric was the focus of this study. These monomers have been used for other non-conventional applications but not for apparel.

Chapter 2

The sensory disparity between cotton and polyester woven fabrics

2.1 Overview

The aim of this study was to determine the disparity and identify the most discriminating sensory attribute between cotton and polyester (poly(ethylene terephthalate))— PET woven fabrics. A multisensory evaluation was used to explore the potential of PET as a surrogate to cotton in woven fabrics. A panel of 12 judges was used to evaluate and rank six cotton and polyester woven fabrics for 11 sensory descriptors. Rank aggregation and weighting were performed using cross-entropy Monte Carlo and Genetic algorithms, and the Borda count technique. The quality of the sensory panel was studied using ANOVA and consonance analysis. Principle component analysis (PCA) and unsupervised agglomerative hierarchical clustering (AHC) were used to study and profile sensory relationships. The largest Euclidean distance was found between fabrics of dissimilar generic. The descriptor *crisp* accounted for the highest variability between PET and cotton fabrics ($p \leq 0.05$). To replace cotton with PET via this sensory approach for woven fabrics, the modification of stiffness of polyester fabrics has been judiciously suggested. For the fabrics studied, it was deduced that visual aesthetics represent the vast of sensory perception and that PET and cotton fabrics can be distinguished by appearance via vision.

2.2 Materials and Methods

2.2.1 Materials

2.2.1.1 Test fabrics and experimental conditions

Six fabrics of 20x30 sq cm and basic parameters shown in Table 2.1 and Figure 2.1 were used in this study. The experimental room was maintained at ambient temperature with day-lighting and with no interference from external sounds/noise. The test fabrics were labeled and then conditioned in standard atmosphere (according to *ISO 139:2005* Textiles— Standard atmospheres for conditioning and testing)[106] for 48 hours at 20^oC (±2°C) and *65%* RH (±4%). The sample fabrics had neither coloring nor patterning.

Table 2.1 Basic parameters and structure of woven fabrics used in the study

Fabric	Fiber content	Weave	Finish	Warp count	Weft Count	Weave density	Weight g/m2	Thickness mm
SA	PET	plain	Bleach	31	28	847	149	0.276
SK	PET	twill 5	Bleach	38	38	1021	230	0.325
SC	Cotton	plain	Bleach	19	20	702	136	0.348
SE	PET microfiber	plain	Bleach	18	10	710	94	0.17
SG	PET/cotton;33/67	twill 5	None	36	32	1182	258	0.76
SX	Cotton	plain	Bleach+calendar	21	20	738	131	0.216

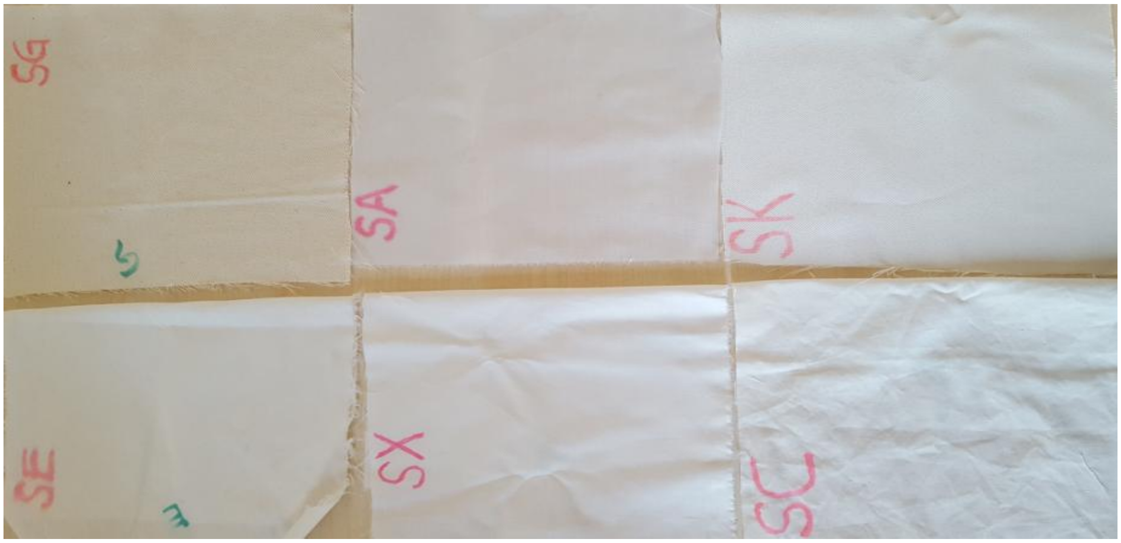


Figure 2.1 PET and cotton woven fabric samples used in the sensory study

2.2.2 Methods

2.2.2.1 Sensory panel, descriptors and sensory evaluation

The multicultural sensory panel comprised of six male and six female adults aged between 20 and 52 years. These included three college professors, five Doctorate scholars, two master's students and two undergraduate students. Figure 2.2 shows the sensory evaluation session.

Figure 2.2 Assessors in the sensory evaluation session

The racial distribution included: four European natives, two African natives, three Asian natives, and three Middle-Eastern natives. All panelists had background training/experience in textiles/apparel, except the two undergraduate students. Prior to the experiment, training was carried out by the principal investigator for all the panelists, in one session. Training involved presentation of objectives, materials, evaluation criteria, and estimates for sensory evaluation. A pilot sensory evaluation for selected descriptors was carried out for illustration.

The experimental room was maintained at ambient temperature with day-lighting and with no interference from external sounds/noise. Before commencement of the sensory evaluation, panelists were required to wash and rinse their hands ten minutes in advance. Each panelist received one specimen for each of the six fabric samples, randomly without revealing specifications. Free choice profiling (FCP)[107] was adopted; each panelist independently listed descriptors of sensations perceived as one examined the fabrics randomly. FCP was followed by a focused discussion of all panelists with an aim of extracting and integrating the most frequent sensations and their common descriptors. Based on the frequency, panelists consensually agreed on 11 sensory descriptors with antonyms and synonyms. A frequency of at least eight was considered for a descriptor adopted. Evaluation criterion/protocols (Appendix) and illustration for each attribute were then discussed, printed and given to each panelist. For each descriptor, each panelist nominally ranked the six fabrics in descending order according to the magnitude of the perceived sensations.

2.2.2.2 Rank aggregation and rank weighting

Three methods were used and compared to aggregate the 12 rank lists into one *super list* (fused list), for each descriptor. The aggregation methods used were: the Borda count method also known as the Borda-Kendall (BK) method[108], a genetic algorithm (GA) and a cross-entropy Monte Carlo (CE) algorithm. On the basis of frequency and agreement with the modal list, fused lists from only one method were adopted for further computations. The BK method was then used to convert ranks into weights.

The Borda count (BK) method awards weights to objects based on their position in a rank list. For a rank list $T=[x_1, x_2,.... x_k]$ *w.r.t.* universe U; $x_i \in T$; $i \in N$ (N is a set of integers of ranks of objects in (T); $T(i)$ is the rank of i in T; a low-numbered position indicates a higher magnitude of a sensory sensation, $\omega^T(i)$ (Eq 2.1) is the normalized weight (score) of item $i \in T$.

$$\omega^T(i) = 1 - \frac{(T(i)-1)}{|T|}\ ;\ \omega^T(i) = \left\{1, \frac{1}{|T|}\right\} \dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.1)$$

The BK method may yield more than one fused list in case of ties in weights. The GA and CE in this study are intelligent algorithms run under the function *RankAggreg* in software R[109]. The GA and CE may be weighted or without weights. The objective function of the GA or CE (Eq 2.2)[109–111] aims to search for an "optimal" list or *super list*, close as possible to all individual ordered lists concurrently.

$$\phi(\delta) = \sum_{i=1}^{m} w_i d\ (\delta L_i) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.2)$$

where δ is the suggested ordered list of length $k = |L_i|$; w_i is the importance weight; *d is* the distance function; and L_i is the ith ordered list. Hence, these iterative algorithms aim at finding δ^* (Eq 2.3) that would minimize the total distance between δ^* and L_i's [109,110]:

$$\delta^* = \arg min \sum_{i=1}^{m} w_i d\ (\delta L_i) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.3)$$

Distance functions utilized by GA and CE are based on Spearman's footrule distance or Kendall's tau. Considering scores $M_i(1)$,...,… $M_i(k)$ for an ordered list L_i; $M_i(1)$ being the highest (first rank) score, followed by $M_i(2)$. If A has rank $r^{L_i}(A)$ in the list L_i, given that A is in the top k; or, $k+1$ if not in the top k, the Spearman's footrule distance between L_i and any ordered list δ, is the sum of the absolute differences between the ranks of all unique elements from all ordered lists combined (Eq 2.4).

$$S(\delta, L_i) = \sum_{t \epsilon L_i \cup \delta} \left| r^{\delta}(t) - r^{L_i}(t) \right| \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.4)$$

The Weighted Spearman's footrule distance (Eq 2.5)[109,110] between L_i and any ordered list δ utilizes further quantitative information pertinent to the rank lists.

$$WS(\delta, L_i) = \sum_{t \epsilon L_i \cup \delta} \left| M\left(r^{\delta}(t)\right) - M\left(r^{L_i}(t)\right) \right| \times \left| r^{\delta}(t) - r^{L_i}(t) \right| \dots\dots\dots\dots\dots (Eq\ 2.5)$$

The Kendall's tau distance (Eq 2.6 and 2.7)[109] utilizes pairs of elements from the union of two lists. It is based on award of penalties accruing from differences in ordering in lists compared.

$$K(\delta, L_i) = \sum_{t,u \epsilon L_i \cup \delta} K_{tu}^{p} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.6)$$

where,

$$K_{tu}^{p} = \begin{cases} 0 \text{ if } r^{\delta}(t) < r^{\delta}(u), r^{L_i}(t) < r^{L_i}(u) \text{ or } r^{\delta}(t) > r^{\delta}(u), r^{L_i}(t) > r^{L_i}(u) \\ 1 \text{ if } r^{\delta}(t) > r^{\delta}(u), r^{L_i}(t) < r^{L_i}(u) \text{ or } r^{\delta}(t) < r^{\delta}(u), r^{L_i}(t) > r^{L_i}(u) \dots\dots\dots\dots (Eq\ 2.7) \\ p \text{ if } r^{\delta}(t) = r^{\delta}(u) = k+1 \text{ or } r^{L_i}(t) = r^{L_i}(u) = k+1 \end{cases}$$

A penalty p; $0<p<1$, is imposed if two elements t and u do not have the same relative ordering in the compared lists. In the package *RankAggreg*, $p=0$. The weighted Kendall's tau is computed as in Eq 2.8[109,110]:

$$WK(\delta, L_i) = \sum_{t,u \in L_i \cup \delta} \left| M\left(r^{L_i}(t)\right) - M\left(r^{L_i}(u)\right) \right| \times K_{tu}^{P} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.8)$$

Before weighting, scores from each rank list Li are normalized (Eq 2.9)

$$M_i^{*} = \frac{M_i - min\,(M_i)}{Max(M_i) - min\,(M_i)},\ i = 1, \dots\dots, n \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (Eq\ 2.9)$$

Further studies provide more theoretical understanding of the GA and CE algorithms[111–113]. An input program for the GA and CE is specified by the main arguments; data matrix (x) of the rank lists, length of the rank lists (k), number of elements being ranked (n), number of iterations for the algorithms to converge (convIn), N given by $10k^2$ or 10kN if n>>k, rho (rarity parameter- the "quantile" of candidate lists sorted by the function values). N and rho apply to only the CE algorithm. Other arguments and details have been presented by Pihur[109]. Both the GA and CE apply a convergence mechanism; repetition of the same minimum value of the objective function in convIn consecutive iterations. Based on six fabrics and 12 rank lists for each descriptor, the eight rank aggregation programs below were written and used for aggregation, in separate runs:

1. CEKnoweights <- RankAggreg(table_matrix, 6, method="CE", distance="Kendall", N=1440, convIn=30, rho=.1)
2. CESnoweights <- RankAggreg(table_matrix, 6, method="CE", distance="Spearman", N=1440, convIn=30, rho=.1)
3. CEK <- RankAggreg(table_matrix, 6, w, "CE", "Kendall", N=1440, convIn=30, rho=.1)
4. CES <- RankAggreg(table_matrix, 6, w, "CE", "Spearman", N=1440, convIn=30, rho=.1)
5. GAKnoweights <- RankAggreg(table_matrix, 6, method="GA", distance="Kendall", convIn=30)
6. GASnoweights <- RankAggreg(table_matrix, 6, method="GA", distance="Spearman", convIn=30)
7. GAS <- RankAggreg(table_matrix, 6, w, "GA", "Spearman", convIn=30)
8. GAK <- RankAggreg(table_matrix, 6, w, "GA", "Kendall", convIn=30)

A total of nine (or ten in case of ties with the BK method) aggregated lists from the BK, GA and CE methods were tabulated and compared simultaneously. Since the methods yielded different aggregated rank lists in some cases, the modal aggregated lists were extracted for each descriptor. Only lists from the method with the highest agreement with other methods were then taken for consistency in further analyses. The BK method was then used to compute rank weights for subsequent analyses.

2.2.2.3 Performance of the sensory panel

The quality of the sensory panel was studied using ANOVA, and CA with PCA of assessors and fabrics/attributes, performed on ranks' data transformed into scores. PCA in this study was performed with R software using packages *prcomp* and *princomp*[114]. The significance of assessors' ratings for a descriptor was inferred from individual assessors' total contribution (%) on principal components F1 and F2. If C1 and C2 are the contributions of an assessor on F1 and F2 respectively, the total contribution of an assessor, on explanation of variability by F1 and F2 is computed as: (C1*Eig1) + (C2*Eig2)[115]; Eig1 and Eig2 are the eigenvalues of F1 and F2 respectively. Hence, if the contributions of the 12 assessors were uniform, the expected average contribution on a given principal component would be 1/12 = 8.3%. In this case, the average contribution of assessors for F1 and F2 would be: (8.3*Eig1) + (8.3*Eig2). Thus, significant assessors for any descriptor are those with contribution higher than the average contribution. The percentage contribution was also used in determining the number of descriptors that assessors were able to effectively perceive and use for discriminating fabrics. In PCA, variables presenting higher variability of the first principal component (denoted as the percent agreement), and/or those with higher contribution (%) carry more importance. PCA of descriptors was also used to identify atypical assessors and peculiar patterns; errors such as lack of sensitivity and cross-over.

2.2.2.4 Significant attributes, dissimilarity, and sensory profiles

Using ANOVA, factor contribution of descriptors, correlation between descriptors, squared cosines of descriptors, and our prior knowledge of textile fabric properties, the number of sensory descriptors were reduced from eleven to six. PCA was then used to study sensory patterns between fabrics and sensory attributes. Also, using PCA, the most significant sensory attribute in discriminating between cotton and polyester fabrics was identified. The Euclidean distance was then computed to estimate the dissimilarity between different pairs of fabrics. With the squared Euclidean distance and the weighted pair-group average as metric and linkage criterion respectively, unsupervised AHC was used to create fabric sensory classes and profiles. Algorithms for AHC was performed using XLSTAT, an add-in for Excel[116].

2.3 Results and Discussion

2.3.1 Descriptors generated by the sensory panel

The sensory panel recorded 98 descriptors, from which the eleven below, were found to be the most frequent and were consensually retained:
***Stiff**/inflexible, **Soft**/not hard, **Smooth**/not rough, **Heavy**/not light, **Noisy**/pitchy/harsh/not quiet sound, **Crisp**/brittle/firm/fresh/crushable/crumbly, **Stretchy**/elastic/not rigid, **Drapy**/hang/enclose, **Regular**/uniform/even, **Natural**/not synthetic/not artificial, and **Compact**/packed/dense*. These descriptors comprise taxonomy of aesthetic/tactile, visual, physical, generic, acoustic, mechanical, and dynamic perceptual attributes of fibers and fabrics.

2.3.2 Ranks and rank aggregation

Twelve raw ranks lists were obtained for each descriptor. The aggregated rank lists from the BK, CE and GA methods, and the modal list for each descriptor are shown in Table 2.2.

Table 2.2 Aggregated Rank Lists from the BK, GA and CE methods

Attribute	BK	CEKN	GAKN	CESN	GASN	CES	GAS	CEK	GAK	Modal list
Stiff	SA,SK,SC, SE,SG,SX	SA,SK,SC,SE, SG,SX	SA,SK,SC,SE, SG,SX	SA,SK,SE,SC, SX,SG	SA,SK,SC,SE, SX,SG	SA,SK,SE,SC, SG,SX	SA,SK,SC,SE, SG,SX	SA,SK,SC,SE, SG,SX	SA,SK,SC,SE, SG,SX	SA,SK,SC,SE, SG,SX
Soft	SX,SE,SC, SG,SA,SK	SX,SE,SC,SG, SA,SK	SX,SE,SC,SG, SA,SK	SX,SE,SC,SG, SK,SA	SX,SE,SC,SG, SK,SA	SX,SE,SC,SG, SA,SK	SX,SE,SC,SG, SA,SK	SX,SC,SE,SG, SA,SK	SX,SC,SE,SG, SA,SK	SX,SE,SC,SG, SA,SK
Smooth*	SX,SE,SC, SG,SA,SK; SX,SC,SE, SG,SA,SK	SX,SE,SC,SG, SK,SA	SX,SE,SC,SG, SK,SA	SX,SE,SC,SG, SK,SA	SX,SE,SC,SG, SK,SA	SC,SX,SE,SG, SA,SK	SC,SX,SE,SG, SA,SK	SX,SC,SE,SK, SA,SG	SX,SC,SE,SK, SA,SG	SX,SE,SC,SG, SK,SA
Heavy	SG,SK,SC, SA,SX,SE	SG,SK,SC,SA, SX,SE	SG,SK,SC,SA, SX,SE	SG,SK,SA,SC, SX,SE	SG,SK,SA,SC, SX,SE	SG,SK,SC,SA, SX,SE	SG,SK,SC,SA, SX,SE	SG,SK,SC,SA, SX,SE	SG,SK,SC,SA, SX,SE	SG,SK,SC,SA, SX,SE
Noisy*	SK,SA,SE, SX,SC,SG; SK,SA,SE, SC,SX,SG	SK,SA,SE,SX, SC,SG	SK,SA,SE,SC, SX,SG	SK,SA,SE,SX, SC,SG	SK,SA,SE,SX, SC,SG	SK,SA,SE,SC, SX,SG	SK,SA,SE,SC, SX,SG	SK,SA,SE,SX, SC,SG	SK,SA,SE,SX, SC,SG	SK,SA,SE,SX, SC,SG
Crisp	SA,SK,SE, SC,SX,SG	SA,SK,SE,SC, SX,SG	SA,SK,SE,SC, SX,SG	SA,SK,SE,SC, SX,SG	SA,SK,SE,SC, SX,SG	SA,SK,SE,SC, SX,SG	SA,SK,SE,SC, SX,SG	SA,SK,SE,SC, SX,SG	SK,SA,SE,SC, SX,SG	SK,SA,SE,SX, SC,SG
Stretchy	SK,SX,SA, SC,SE,SG	SK,SA,SX,SC, SE,SG	SK,SA,SX,SC, SE,SG	SK,SA,SX,SE, SC,SG	SK,SA,SX,SE, SC,SG	SK,SA,SX,SC, SE,SG	SK,SA,SX,SC, SE,SG	SK,SX,SA,SC, SE,SG	SK,SX,SA,SC, SE,SG	SK,SA,SX,SC, SE,SG
Drapy	SX,SG,SC, SE,SK,SA	SX,SG,SC,SE, SK,SA	SX,SG,SC,SE, SK,SA	SX,SC,SG,SE, SK,SA	SX,SC,SG,SE, SK,SA	SX,SG,SC,SE, SK,SA	SX,SG,SC,SE, SK,SA	SG,SX,SC,SE, SK,SA	SG,SX,SC,SE, SK,SA	SX,SG,SC,SE, SK,SA
Regular	SE,SX,SA, SK,SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SA,SK, SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SK,SA, SC,SG	SE,SX,SK,SA, SC,SG
Natural	SG,SC,SX, SA,SE,SK	SG,SC,SX,SA, SE,SK	SG,SC,SX,SA, SE,SK	SG,SC,SX,SA, SE,SK	SG,SC,SX,SA, SE,SK	SG,SC,SX,SA, SE,SK	SG,SC,SX,SA, SE,SK	SC,SG,SX,SA, SE,SK	SC,SG,SX,SA, SE,SK	SG,SC,SX,SA, SE,SK
Compact	SK,SG,SC, SX,SA,SE	SK,SG,SC,SX, SE,SA	SK,SG,SC,SX, SA,SE	SK,SG,SC,SX, SE,SA	SG,SKSC,SX, SA,SE	SK,SG,SC,SX, SE,SA	SK,SG,SC,SX, SE,SA	SK,SG,SE,SX, SC,SA	SK,SG,SE,SX, SC,SA	SK,SG,SC,SX, SE,SA

*Descriptors with two super lists from the BK method, Descript- Descriptor, BK- Borda Kendal, CEKN- Unweighted cross entropy Kendall, GAKN- Unweighted genetic Kendall, CESN- Unweighted cross entropy Spearman, GASN- Unweighted genetic Spearman, CES- Weighted cross entropy Spearman, GAS- Weighted genetic Spearman, CEK- Weighted cross entropy Kendall, GAK- Weighted genetic Kendall

Due to ties in the weighted score for SE and SC (for *smooth*), and SX and SC (for *noisy*), there were two optimal rank lists by the BK method for *smooth* and *noisy*. This demerit associated with the BK method has been reported elsewhere[117,118]. The unweighted CE utilizing Kendall’s tau (CEKnoweight) was the most closest to other methods, returning the modal fused list in 100% of the descriptors. While the descriptor *crisp* presented the highest agreement (89%) within the rank aggregation methods, the descriptor *smooth* recorded the lowest agreement (40%), followed by *drapy* and *stretchy*, both with 44%.

By observing positions in rank lists, polyester fabrics presented a strong dominance in magnitude for permutations of *stiff, noisy, crisp,* and *stretchy*. While, cotton fabrics, were prominent in magnitude for *soft, drapy, smooth*, and *natural*. The positioning of SX, SE and SG fabrics does not present a precise pattern with respect to some attributes. This could be attributed to the micro fiber nature of SE, the blended composition of SG, and the calendared finish on SX. Aggregated rank lists did not give precise conclusions about the influence of the fiber generic on the magnitudes of the perceived sensations. Since different rank fusion methods yielded different aggregated rank lists, it was judged that the outcome of each method was a function of the constraints (distance function, weighted or un-weighted). Hence, it was judiciously thought to adopt aggregated lists from one method for consistency in further computations, rather than the modal lists. The unweighted CE rank lists were selected on the basis of similarity to the modal list for all the descriptors. Table 2.3 presents rank BK scores computed from the selected aggregated rank lists.

Table 2.3 Weighted and normalised BK scores $\omega^T(i)$ of fabrics for each descriptor

Fabric	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
SA	1.00	0.33	0.17	0.50	0.83	0.83	0.83	0.17	0.50	0.50	0.17
SK	0.83	0.17	0.33	0.83	1.00	1.00	1.00	0.33	0.67	0.17	1.00
SX	0.17	1.00	1.00	0.33	0.50	0.50	0.67	1.00	0.83	0.67	0.50
SE	0.50	0.83	0.83	0.17	0.67	0.67	0.33	0.50	1.00	0.33	0.33
SC	0.67	0.67	0.67	0.67	0.33	0.33	0.50	0.67	0.33	0.83	0.67
SG	0.33	0.50	0.50	1.00	0.17	0.17	0.17	0.83	0.17	1.00	0.83

$$\omega^T(i) = \left\{1, \frac{1}{|T|}\right\}; |T| = 6; \omega^T(i) = 1 - \frac{T_i - 1}{6}; T_i = \{1,6\}$$

2.3.3 Performance of the sensory panel

The analysis of the performance of the sensory panel was based on datasets of weighted ranks of assessors before rank aggregation. The univariate plots (Figure 2.3) present a visualization of the relative subjective estimation of magnitudes of perceptions by panelists for each descriptor. Magnitude and crossover (inversion of ratings) errors can be observed where the minimum and maximum scores of ranks for a particular fabric are far apart.

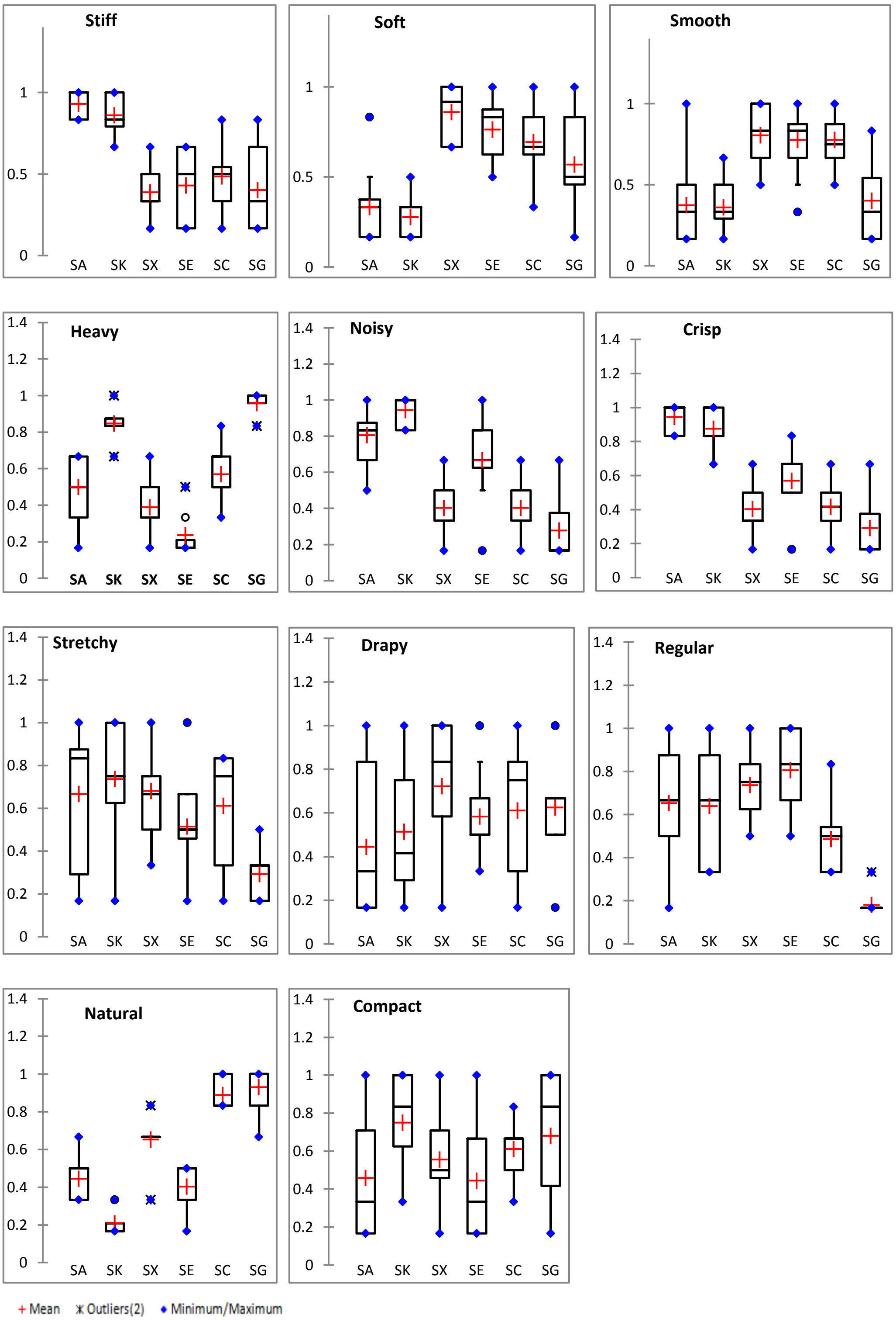


Figure 2.3 Univariate plots of panelists' scores for the 11 descriptors

For instance, SC and SG for *stiff*, SG for *soft*, SA for *smooth*, SA, SK and SC for *stretchy*, SA, SK, SX, SC and SG for *drapy*, SA for *regular*, and all fabrics, except SC for *compact*. From the box plots, outlying scores were identified in five descriptors; with *heavy* having the highest (4). The univariate plots also present some visible responsive patterns for some fabrics and sensory descriptors; polyester fabrics follow in sequence for some mechanical related attributes, and there was an inverted relationship between *stiff* and *soft*, especially with polyester fabrics.

Using ANOVA on dataset for each descriptor, it was possible to identify descriptors for which there was no product (fabric) effect (descriptors with p-values higher than our specified threshold of 0.05) and such were left out in ensuing analyses. For each descriptor, a table of Type III sum of squares (SS) of the ANOVA was obtained with a regression model: Y=mu+P+J+P*J (J and P*J are random factors). For example, Table 2.4 corresponds to the ANOVA for the descriptor *Stiff* which had a p-value less than 0.001.

Table 2.4 Type III SS of the ANOVA with descriptor Stiff as dependent variable at 5% significance level

Source	**Type**	**DF**	**Sum of squares**	**Mean squares**	**E(Mean squares)**	**Pr > F**
Fabrics	Fixed	5	3.6	0.72	$\text{sigma}^2 + 1 * \text{sigma}^2(\text{Fabrics*Assessors}) + 12 * Q(\text{Fabrics})$	< 0.0001
Assessors	Random	11	0.00	0.00	$\text{sigma}^2 + 1 * \text{sigma}^2(\text{Fabrics*Assessors}) + 6 * \text{sigma}^2(\text{Assessors})$	1.00
Fabrics*Assessors	Random	55	2.22	0.04	$\text{sigma}^2 + 1 * \text{sigma}^2(\text{Fabrics*Assessors})$	
Error		0	0.00		sigma^2	

One way ANOVA was followed by PCA of each descriptor's weighted ranks (fabrics/assessors dataset) to further compare the relative significance of descriptors in discriminating the fabrics. The significance of descriptors' p-values and the percentage agreement are discussed further after this section.

Figure 2.4 presents, for each pair (of assessor, descriptor), the percentage of variance carried by the two principal axes (F1 and F2) of the PCA plot. For all descriptors, only the first two principal components F1 and F2 were retained as they carried significant variability ($p \leq .05$). Figure 2.5 presents a visualization of assessors' correlations on F1 and F2.

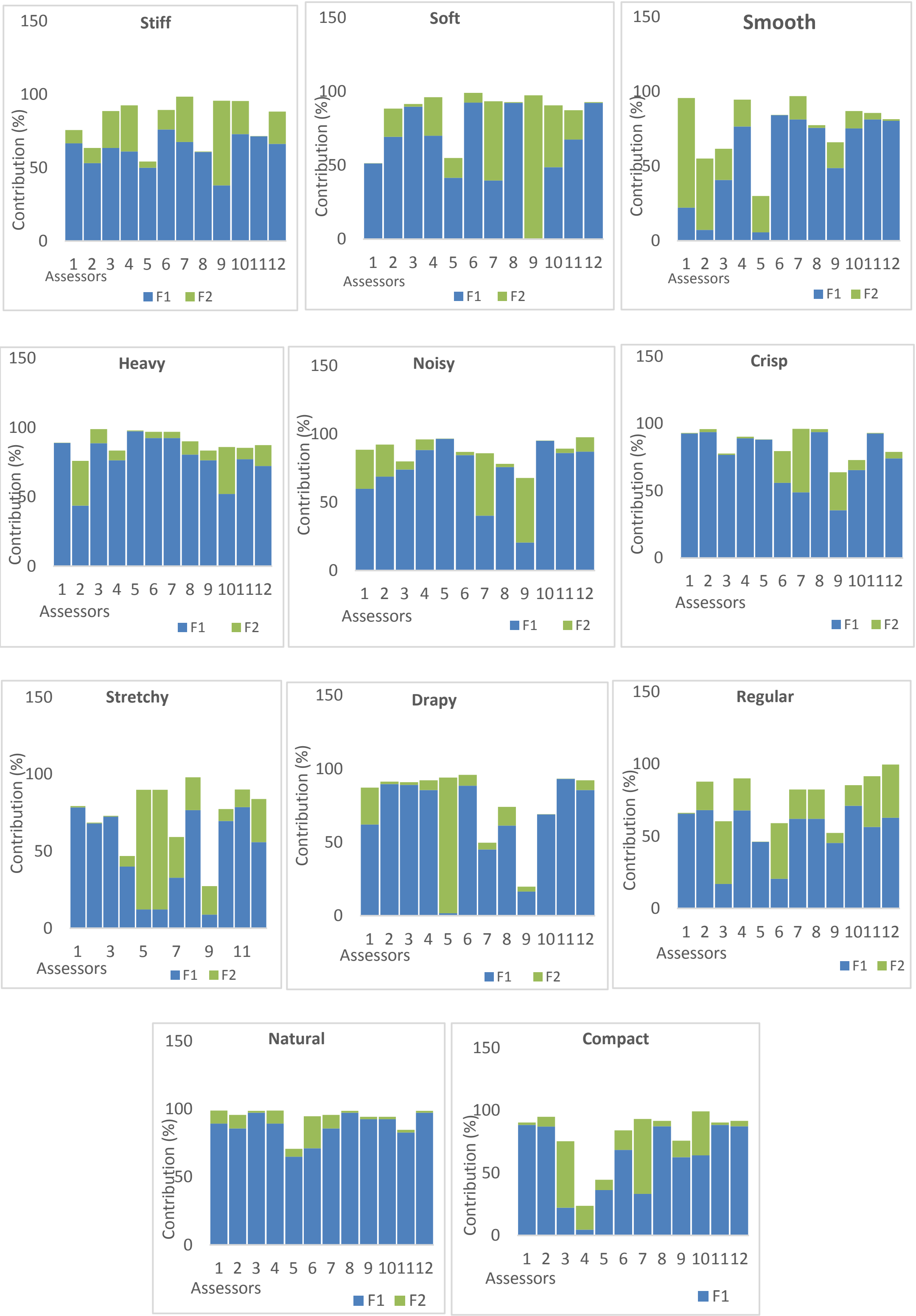


Figure 2.4 Percentage of variance carried by the two principal axes (F1 and F2) of the PCA plot

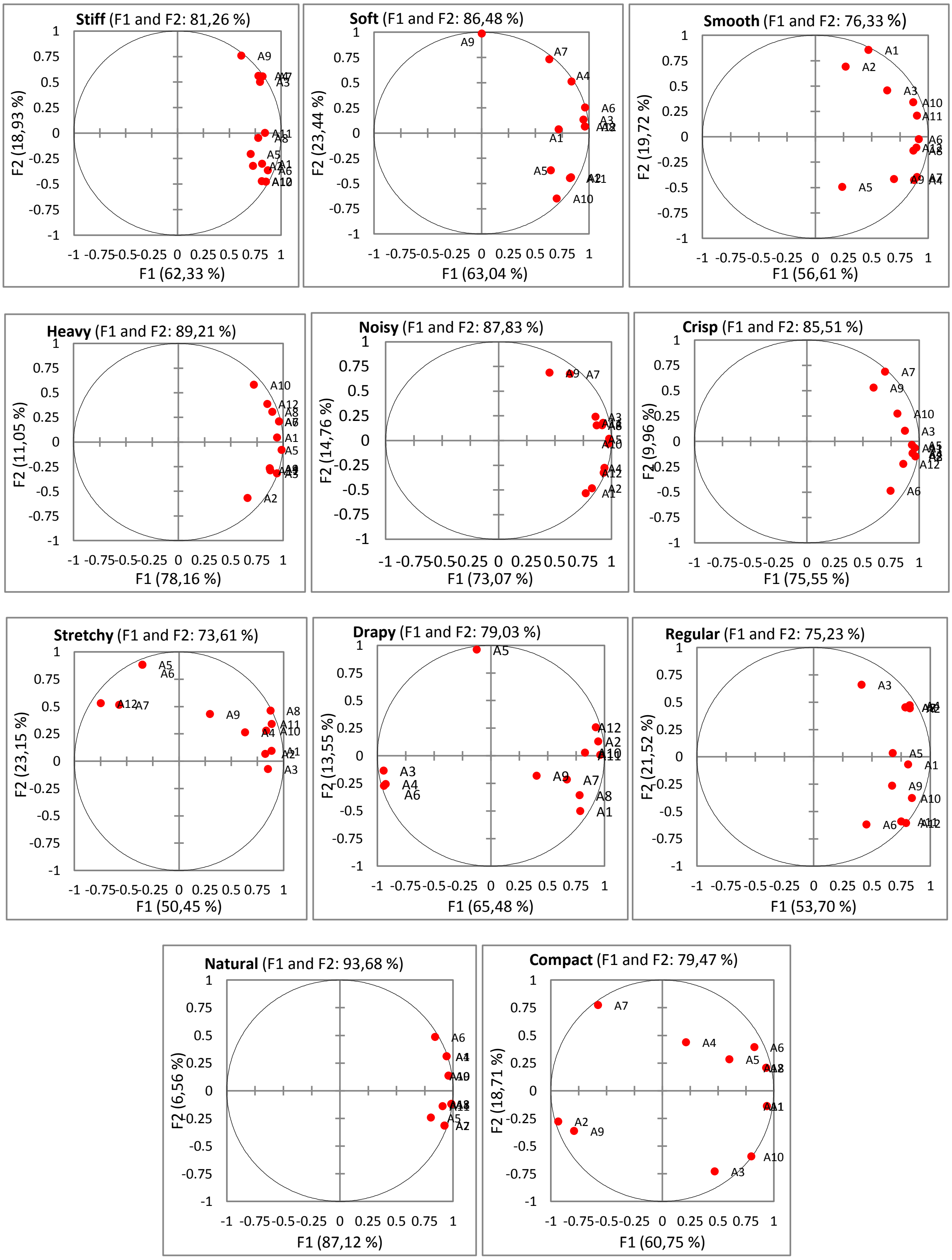


Figure 2.5 Correlations plot of assessors on F1 and F2 for 11 descriptors

The oriented factor loadings of assessors towards either F1 or F2 (Figure 2.4 and Figure 2.5) present valuable information on variations and errors in assessors' ranks. While a pair or group of assessors may have their largest loading on the same principal component, they may also load in opposition (negative correlation), on the same principal component. This pattern was noted between assessors 1, 2 and 5 loading more on F1 (Figure 2.4), with assessor 5 in opposition to assessors 1 and 2 (Figure 2.5) for *smooth*. Similarly, the largest factor loadings of assessors 5, 6, and 9 are on F2 (Figure 2.4) whilst assessors 5 and 6 load in opposition to assessor 9 (Figure 2.5), for *stretchy*. Assessors showing outlying perceptions and low sensitivity can be identified by their isolated loading and low contribution (%) relative to the rest of the panel. Sensitivity errors are characterized by very low contributions of assessors on F1 and F2. In our analysis, a total contribution (%) on F1 and F2, below 50% indicates that an assessor had low sensitivity for the particular descriptor. Magnitude errors can be noticed when the factor loading of an assessor is significantly lower or larger than the vast of the panel members, on the same principal component. Magnitude errors imply that some assessors' subjective magnitudes of sensory perceptions differ significantly compared to the rest of the panel members. Crossover errors were noted by identifying assessors scoring in opposition to the vast of the panel. For example, in Figure 2.5, assessors 5, 6, 7, and 12 exhibit this effect for *stretchy*. Table 2.5 presents a summary of the panelists' errors based on Figure 2.4 and Figure 2.5, p-values from one way ANOVA of descriptors, the percent agreement from PCA of assessors' scores, and the average contribution (%) of assessors on F1 and F2.

Table 2.5 Summary of assessor/fabric effect: p-values, percent agreement of assessors, and assessors' errors

Descriptor	***Pr > F**	***Percent agreement**	**Average contribution (%) of assessors on F1 and F2**	**Assessors below average contribution on F1 and F2**	**Assessors with crossover errors**	**Assessors with a magnitude error**	**Assessors with a sensitivity error**
Stiff	<0.0001	62	81	1,2,5,8,11	-	9	-
Soft	<0.0001	63	86	1,5	-	7,9	-
Smooth	<0.0001	57	76	2,3,5,9	-	1,2	1(5)
Heavy	<0.0001	78	89	2,4,9,10,11,12	-	-	-
Noisy	<0.0001	73	88	3,6,7,8,9	-	7,9	-
Crisp	<0.0001	76	86	3,6,9,10,12	-	7,9	-
Stretchy	0.0032	50	74	2,3,4,7,9,10	5,6,7,12	-	2(4,9)
Drapy	0.3471	66	79	7,8,9,10	3,4,6	5	2(7,9)
Regular	<0.0001	54	75	1,3,5,6,9	6	3	1(5)
Natural	<0.0001	87	94	5,11	-	-	-
Compact	0.0981	61	79	3,4,5,9	2,7,9	-	2(4,5)

*The values were computed at significance level 0.05, figures in bold are higher than the threshold

The percent agreement shows that the descriptor *natural* carried the largest variability, while, *stretchy* accounted for the lowest variability. *Drapy* and *compact* were the least significant, considering their p-values. We introduced the *discriminating power,* which represents the percentage of descriptors an assessor was able to effectively perceive to discriminate fabrics. An assessor was recorded to have effectively perceived a descriptor if the assessor's contribution (%) for that descriptor was higher than the panels' average contribution (%) for the same descriptor. For example, from Table 2.5, considering the average contribution (%) on F1 and F2, assessor 1 was able to effectively perceive eight descriptors. Hence, the discriminating power for assessor 1 is 73%. The average discriminating power was 63%, with 50% of the panel attaining 72%. Assessor 9 exhibited the lowest discriminating power (27%). With 82%, assessor 12 had the highest discriminating power. The coefficient of variation for the discriminating power was 25%. It is inferred and underscored that further training was needed by at least two assessors for each descriptor. This analysis of the sensory panel performance was utilized in selecting and retraining panelists for the second sensory evaluation, which is presented in Chapter 3 of this work.

2.3.4 Reducing the sensory descriptors to a significant six

To determine the most significant discriminating attribute between polyester and cotton fabrics, it was essential to reduce the number of descriptors systematically and objectively. From Table 2.5, it is deduced that there was no precise relationship between p-values, percent agreement and the average contribution of descriptors. For example, by p-values, the descriptors *stiff*, *soft*, *regular*, and *smooth* were more significant compared to *drapy*. However, the same descriptors with lower values of percent agreement compared to *drapy*. We thus utilized rank correlation coefficients, together with the test for significance, and the percent agreement simultaneously. First, we identified highly positively correlated descriptors (Table 2.6). Basing on the percent agreement, p-values, and the average contribution (in Table 2.5), the least significant descriptors were discarded.

Table 2.6 Pearson rank correlation matrix of 11 descriptors

	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
Stiff	1.00	**-0.77**	**-0.83**	0.14	0.66	0.66	0.60	**-0.94**	-0.14	-0.49	-0.14
Soft	**-0.77**	1.00	**0.94**	-0.66	-0.49	-0.49	-0.49	**0.71**	0.43	0.31	-0.37
Smooth	**-0.83**	**0.94**	1.00	-0.54	-0.43	-0.43	-0.43	**0.77**	0.49	0.20	-0.09
Heavy	0.14	-0.66	-0.54	1.00	-0.26	-0.26	-0.03	0.03	**-0.83**	0.37	**0.77**
Noisy	0.66	-0.49	-0.43	-0.26	1.00	**1.00**	**0.83**	**-0.77**	0.54	**-0.94**	-0.14
Crisp	0.66	-0.49	-0.43	-0.26	1.00	1.00	**0.83**	**-0.77**	0.54	**-0.94**	-0.14
Stretchy	0.60	-0.49	-0.43	-0.03	**0.83**	**0.83**	1.00	-0.54	0.26	-0.66	0.03
Drapy	**-0.94**	**0.71**	**0.77**	0.03	**-0.77**	**-0.77**	-0.54	1.00	-0.09	0.66	0.26
Regular	-0.14	0.43	0.49	**-0.83**	0.54	0.54	0.26	-0.09	1.00	**-0.71**	-0.37
Natural	-0.49	0.31	0.20	0.37	**-0.94**	**-0.94**	-0.66	0.66	**-0.71**	1.00	0.09
Compact	-0.14	-0.37	-0.09	**0.77**	-0.14	-0.14	0.03	0.26	-0.37	0.09	1.00

Values in bold are different from 0 with a significance level alpha=0.05

Additionally, we also utilized our knowledge of textile properties considering the broader objective of this study; to enhance the properties of polyester in relation to cotton. Particularly, we were also interested in descriptors that could be objectively measured and modified. With an assumption that highly positively correlated attributes possess a common causality, we retained either of the descriptors basing on significance. From Table 2.6, *noisy* and *crisp* are 100% correlated; *crisp* was retained on account of the percent agreement since they both have p<0.0001. Considering *smooth* and *soft*, we retained *soft* based on its higher percent agreement. The descriptor *stretchy* was also discarded on the basis of a high correlation with *crisp*, which a higher percent agreement and a lower p-value compared to *stretchy*. Between *heavy* and *compact*, the former was retained on account of a lower p-value and a higher percent agreement. With a correlation coefficient of 0.71 between *soft* and *drapy*, we discarded the descriptor *drapy* due to a much higher p-value 0.347 compared to the set threshold 0.05. The descriptors *natural* and *stiff* were also retained as they both had $p<0.0001$ and percent agreement 78% and 62% respectively. With the rest of the descriptors already evaluated, we finally retained *regular* with $p<0.0001$. Therefore, the descriptors retained include: *crisp, soft, heavy, natural, stiff*, and *regular*; herein termed as *the leading sensory attributes*. Consequently, the next analyses involved computations based on these six descriptors. This list comprises of attributes that mainly describe tactility/hand, visual/appearance, and generic properties of fabrics.

2.3.5 Correlation and PCA of the leading sensory attributes

Analyses of correlations and PCA were used to investigate the clustering relationships between cotton and polyester woven fabrics, and to identify the main sensory attribute that most precisely discriminates cotton and polyester fabrics. The correlation matrix (Table 2.7) presents the proximity of the six leading sensory attributes.

Table 2.7 Pearson correlation matrix of the six leading sensory attributes

Variables	Stiff	Soft	Crisp	Regular	Natural	Heavy
Stiff	**1**	-0.7714	0.6571	-0.1429	-0.4857	0.1429
Soft	-0.7714	**1**	-0.4857	0.4286	0.3143	-0.6571
Crisp	0.6571	-0.4857	**1**	0.5429	-0.9429	-0.2571
Regular	-0.1429	0.4286	0.5429	**1**	-0.7143	-0.8286
Natural	-0.4857	0.3143	-0.9429	-0.7143	**1**	0.3714
Heavy	0.1429	-0.6571	-0.2571	-0.8286	0.3714	**1**

Values in bold are different from 0 with a significance level alpha=0,05

At significance level of 0.05, there were no significantly positively correlated attributes. The highest positive correlation (0.66) was recorded between *stiff* and *crisp*. Significantly negative correlations were noted between *natural* and *crisp,* and, *heavy* and *regular;* suggesting possible opposing relationships in perception. Table 2.8 shows eigenvalues representing contributions to the variability by five principal components, F1-F5.

Table 2.8 Eigenvalues and variability of the five principal components

	F1	F2	F3	F4	F5
Eigenvalue	3.0082	2.5435	0.3955	0.0360	0.0168
Variability (%)	50.1366	42.3919	6.5920	0.6002	0.2793
Cumulative %	50.1366	92.5285	99.1206	99.7207	100.0000

Principal components F1 and F2 were retained for further analysis since they explained a significant percentage (93%) of the variability. Figure 2.6 presents correlations between attributes and the relationship between factors and sensory attributes.

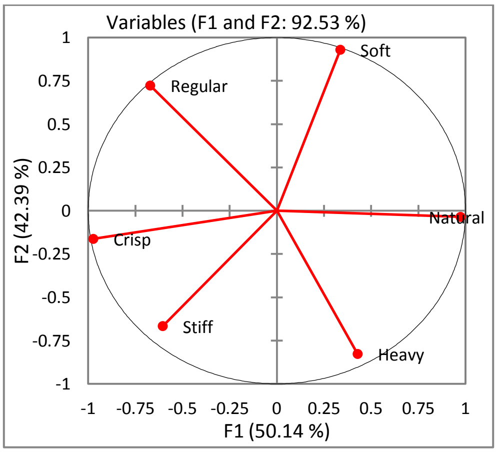


Figure 2.6 Correlation circle of the Leading sensory attributes

From the correlation circle (Figure 2.6) and Table 2.9, it is observed that attributes with the highest factor loadings, in descending order, are: *natural*, *crisp*, *soft* and *heavy*. This finding was also replicated with the squared cosines of the sensory attributes.

Table 2.9 Factor loadings and squared cosines of attributes on principal components

	Factor loading		Squared cosines		Contribution (%) to F1 and F2
Attribute	F1	F2	F1	F2	
Stiff	-0.605	**-0.6663**	0.366	**0.4439**	81
Soft	0.3367	**0.9299**	0.1133	**0.8647**	98
Crisp	**-0.9729**	-0.1625	**0.9465**	0.0264	97
Regular	-0.6712	**0.7231**	0.4506	**0.5229**	97
Natural	**0.9738**	-0.0354	**0.9482**	0.0013	95
Heavy	0.4284	**-0.8272**	0.1835	**0.6843**	87

Values in bold indicate figures for which the factor loadings and squared cosines of attributes are the largest

From Table 2.9, n*atural* and *crisp* were identified closely, as the two most significant sensory attributes accounting for the variability between cotton and polyester woven fabrics. This implies that cotton and polyester fabrics can be distinguished via vision as well. Considering the contribution (%), and measurability, *crisp* was selected as the most significant. The evaluation panel defined *crisp* as being synonymous to *firm*, *dry*, *crushable*, and *brittle*. These adjectives define visual and hand aesthetics.

To measure the disparity between cotton and polyester fabrics on the basis of sensory profiling, we studied the relationship between the fiber generic and sensory attributes. In the biplot (Figure 2.7), the loading of fabrics shows a clustering defined by fiber generic and sensory attributes. Polyester fabrics SA, SK and SE load closely and strongly with *stiff*, *crisp* and *regular*; in opposition to cotton fabrics with stronger perceptions of *natural* and *soft*. The observed loading of SG fabric closer to 100% cotton fabrics may be attributed to the high content (67%) of cotton fiber in SG.

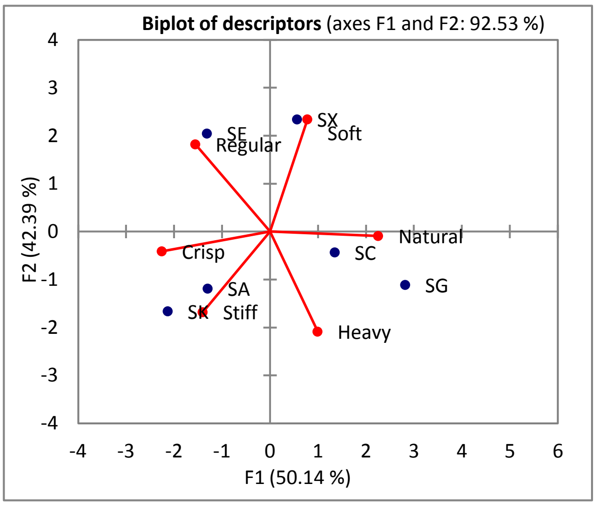


Figure 2.7 Biplot showing the clustering of fabrics with attributes

2.3.6 Dissimilarity of PET and cotton woven fabrics

The Euclidean distance was used as a metric to measure the disparity between polyester and cotton fabrics. Table 2.10 and Figure 2.8 show the dissimilarity between fabrics, on the basis of the leading sensory attributes.

Table 2.10 Dissimilarity (Euclidean distance) between fabrics

Fabric 1	SE	SK	SK	SA	SA	SX	SK	SK	SE	SA	SX	SA	SA	SX	SC
Fabric 2	SG	SG	SX	SG	SX	SG	SC	SE	SC	SE	SC	SC	SK	SE	SG
Dissimilarity	1.49	1.42	1.38	1.24	1.19	1.18	1.14	1.12	1.05	0.96	0.88	0.80	0.58	0.58	0.58

The most dissimilar fabrics are SE and SG, followed by SK and SG. Generally, the dissimilarity is lower among fabrics of the same or closer fiber generic composition.

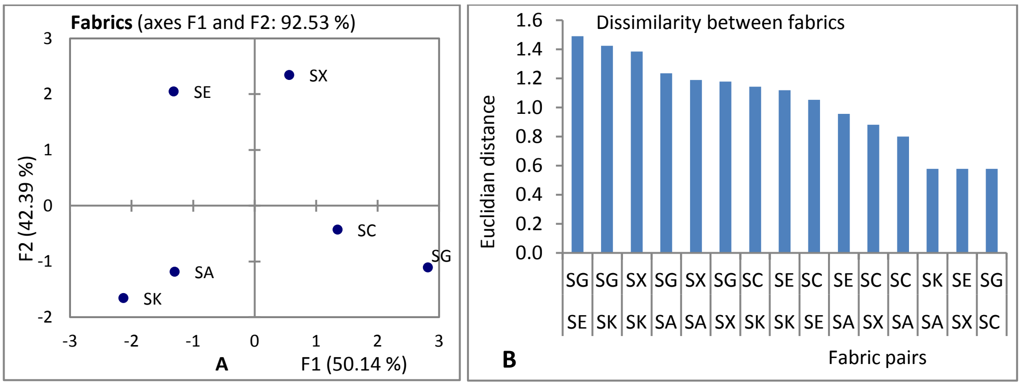


Figure 2.8 Visualization of the Euclidean distance between fabrics: **A**- Map, **B**- Graph of distances

SE and SX present unique clustering behavior probably due to their uncommon characteristics. SE is composed of microfibers which are often finer and may possess different hand and aesthetic properties compared to conventional fibers. SX has a particular physical finish— *calendered*, that also offers a modification to the visual and hand aesthetics. Especially, the sheen and softness are greatly enhanced by this finish. It is also important to note the influence of fiber blending on sensory attributes of SG. With controlled blending, a cotton-like perception may be optimized since SG clustered closer to cotton fabrics and shows heightened dissimilarity with PET fabrics. The Euclidean distance between unconventional fabrics (SG, SE and SX) and the conventional fabrics (SA, SK and SC) is thus subject to the modified characteristics of the unconventional fabrics.

2.3.7 Sensory profiles of woven fabrics

Three classes of fabrics were identified each containing two fabrics. Figure 2.9 shows defining profiles and a dendrogram for the sensory taxonomic relationship of the six fabrics.

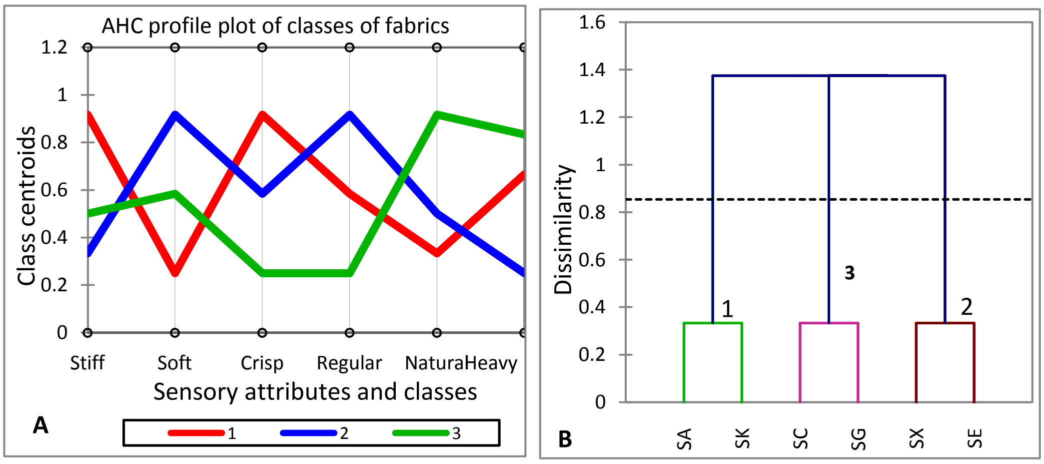


Figure 2.9 A- AHC profiles of fabrics by leading attributes; **B**- Dendrogram of fabrics for the different classes

The clustering behavior of fabrics in AHC was similar to results in Figure 2.7 from PCA; there is a recognizable clustering of fabrics— SA with SK, SE with

SX, and SG with SC. This pattern is associated with fiber generic and shared sensory characteristics. The presented profiles indicate that polyester fabrics are generally perceived *stiff, crisp, regular, not heavy, not natural* and *not soft*. On the other hand, cotton fabrics are generally perceived *soft, heavy, natural, not regular, not stiff, and not crisp*. Fabrics SE and SX may not be the adequate reference to reduce the disparity between cotton and polyester fabrics. However, they present an interesting profile as their perceived sensory attributes seem to transition between those of 100% cotton and 100% polyester fabrics. Thus, class 1, which contains only regular PET fabrics, is the appropriate reference to compare cotton and polyester fabric sensory attributes. Additionally, fabrics in class 1 present consistent profiles with respect to opposing attributes. For example, while they are perceived as the *stiffest* and *crispiest*, they are also the least *soft* and least *natural*.

From Table 2.11, fabrics (SA and SK) in class 1 stand out as strongly *stiff* and *crisp*, and fairly *heavy*, with SK as the central object. Fabrics (SX and SE) in class 2 are strongly *soft* and *regular*, with SE as the central object. While fabrics (SG and SC) in class 3 on the other hand, are strongly *natural* and *heavy*, with SG at the centre.

Table 2.11 Class centroids and central objects (fabrics) by AHC of leading attributes

Class	Stiff	Soft	Crisp	Regular	Natural	Heavy
1 (SK)	0.92	0.25	0.92	0.58	0.33	0.67
2 (SE)	0.33	0.92	0.58	0.92	0.50	0.25
3 (SG)	0.50	0.58	0.25	0.25	0.92	0.83

The distance between class central objects was directly related to the Euclidean distance between fabrics, influenced by their fiber generic. For instance, SK was closer to SE (1.12) than it is to SG (1.42). Also, SE is closer to SK than it is to SG (1.49).

The influence of yarn and fabric structure and properties cannot be ignored. The fabric weight and yarn count are of prominence among others. The yarn count is integrated in the computation of the weave density. The weave density (WD) was computed from the formula:
$\mathrm{WD} = \left(\mathrm{ppi} * \sqrt{\mathrm{C}_1 * 1.22}\right) + \mathrm{epi} * \sqrt{\mathrm{C}_2 * 1.22}$, where, ppi is picks per inch, epi is ends per inch, C1 and C2 are the weft count and warp count respectively. The Pearson rank correlation coefficient between the measured fabric weight and the perceived weight (*heavy*) was 0.9. Except for fabrics SC and SA, panelists were able to rank other fabrics nominal to their weight. Despite PET fabric SA being heavier by 13 GSM, panelists perceived cotton fabric SC as heavier. The perception of compactness, which is related to the weave density, was disproportionate to the calculated values. The Pearson's rank correlation coefficient between the perceived compactness and the weave density was 0.4. Although the weave density was generally higher for PET fabrics, the perceived compactness was highest in cotton fabrics. Thus, these fabric and yarn properties had no direct influence on perceived attributes. Other inherent properties, such as mechanical can deeply be evaluated with a study on objective sensory measurements, which is not within the scope of this specific work.

To realize the main objective of the study; which is to determine and reduce the disparity between cotton and polyester fabrics, the identified most distinguishing attribute (*crisp*) needs to be measured objectively. Sensory crispness in fabrics/textiles has not been explored nor deeply defined by sensory researchers including the objective evaluation. Objective measurements and definitions of crispness may differ from the subjective approach. As presented earlier in Table 2.6 and Table 2.7, *crisp* was found to correlate positively with *stiff* (0.67) and negatively with *natural* (-0.94). While, *stiff*, negatively correlated with *soft* (-0.77). In the sensory evaluation protocol, *crisp* was also defined by *brittleness, firmness,* and *crumbliness*— which attributes are related to *stiffness*. Therefore, reducing the *stiffness* of polyester would reduce the *crispness* while enhancing the *soft* and *natural* perception. Although haptic attributes were found to be significant, visual sensory attributes were more pronounced and represented the vast of sensory perception. This finding is similar to findings by Xue's research team[119] on fabric visual tactility and perception. Thus, polyester and cotton fabrics can also be perceived and discriminated via vision, by their appearance attributes. In food products, sensory crispness has been defined and associated with fracture mechanics, micro and macrostructure, and acoustic properties of food among others[120–123].

2.4 Conclusions

Using sensory analysis, discrimination between cotton and polyester woven fabrics was achieved using the panel's descriptors. For the studied fabrics, six key sensory attributes (*crisp*, *stiff*, *soft*, *heavy*, *natural*, and *regular*) that discriminate between cotton and polyester woven fabrics were identified; c*risp* was found to be the most distinguishing attribute. The disparity between cotton and PET fabrics was also determined; dissimilarity was larger between fabrics of dissimilar generic. Polyester fabrics have particular sensory profiles distinct from those of cotton fabrics; polyester fabrics are especially perceived *crisp, stiff, regular* and are *not natural*. Assessors strongly perceived cotton fabrics as *natural*, *not crisp*, *not stiff*, and *not regular*. Also, for the fabrics studied, this study demonstrates that appearance attributes dominate sensory perception and that cotton and polyester fabrics can be distinguished via vision. This study also underscores the significance of other fabric and fiber characteristics such as finishing and structure in sensory perception. The study of the performance of the sensory panel indicates that all assessors needed re- training for at least two sensory attributes. The limitation of these findings includes potential bias that could arise from the use of panelists with the subject background and any bias that fabric samples may present in their non uniform appearance. Part II of this study will deal with functional techniques to reduce the disparity between polyester and cotton fabrics based on sensory analysis.

Chapter 3

Sensory analysis of cotton and functionalized polyester woven fabrics

3.1 Overview

This study builds on results in Chapter 2, in which the modification of the stiffness of polyester fabrics was suggested, to reduce the perceived disparity between cotton and polyester woven fabrics. In this study, the use of sodium hydroxide (NaOH) and an amino-functional polysiloxane softener, with atmospheric air plasma pre-oxidation, to modify the stiffness of polyester was attempted. Sensory evaluation of 20 fabric samples (which included cotton fabrics and untreated and treated polyester fabrics) was then carried out using a panel of 14 judges, for 11 sensory descriptors. Rank aggregation, sensory clustering, dissimilarity analysis and profiling were carried out. NaOH and softening treatment of polyester bridged between cotton and one of the three polyester fabrics studied. NaOH and softener treated fabrics were perceived *soft*, *smooth*, *less crisp*, and *less stiff* compared to untreated polyester fabrics. However, cotton fabrics were still perceived *natural* compared to any polyester fabrics. Although NaOH-treated polyester fabrics had enhanced air permeability and hydrophilicity, they also presented loss in weight— accompanied with loss in abrasion resistance and bursting strength. NaOH-treated polyester fabrics became hydrophobic and less air-permeable when the silicon based softener was added. It is deduced that characterization by human perception can play a vital role in human centered production and processing of fabrics. A better understanding of fabric sensory perceptions was realized by integrating sensory analysis data with objective measurements data.

3.2 Materials and methods

3.2.1 Materials

3.2.1.2 Fabric samples and laboratory reagents

A total of twenty fabrics, each of 20x30 sqcm dimensions were used in this study. The fabrics include two cotton woven fabrics (SC and SX), three untreated PET woven fabrics (SE, SA and SK) and the cotton/PET blended fabric (SG) used in Chapter 2 (section 2.2.1.1, Table 2.1) of this thesis. Fourteen fabric samples resulted from the functionalization of PET fabrics (SA, SK and SE) with different parameters and treatments.

Siligen softener SIO, cross-linker Fixapret NF, Condensol N as catalyst, and Kieralon JET-B Conc wetting agent were supplied by BASF Chemicals (Ludwigshafen- Germany). Siligen SIO is a non-ionic, slightly opaque emulsion of an amino functional poldimethylsiloxane (Figure 3.1) nature that offers softening, smoothening, and antistatic properties to cellulosic and synthetic fibers and their blends[44].

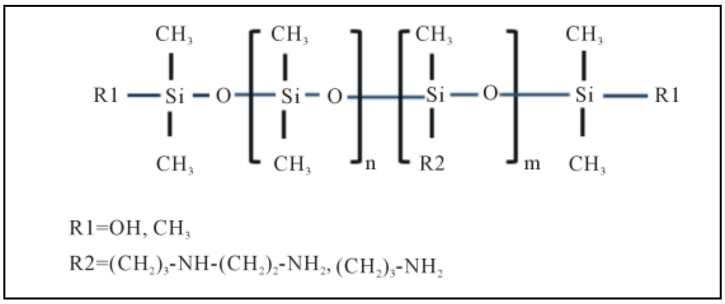


Figure 3.1 Chemical structure of dimethyl polysiloxane containing amino group[124]

Fixapret NF is a formaldehyde-free aqueous solution of 1,3-dimethyl-4,5-dihydroxyethylene urea (DMeDHEU. Condensol N is a synergetic mixture of inorganic salts. Other reagents such as NaOH, acetic acid, and petroleum ether were used in their original laboratory form without modification.

3.2.2 Methods

3.2.2.1 Determination of stiffness properties of cotton and untreated PET woven fabrics

Since the stiffness of PET fabrics was identified for modification, in order to reduce the gap between cotton and PET fabrics, it was imperative to adopt an objective measurement for the stiffness of fabrics. Stiffness was measured for both cotton and untreated PET fabrics to guide on optimum parameters to achieve PET functionalization. The stiffness of fabrics was determined by the SiroFAST system[125,126] using the FAST-2 Bending Meter (CSIRO, Sydney, Australia). The system uses the Cantilever bending principle described in the British Standard- *BS-3356*[127] , and *ASTM D1388- 14e1*[128]; methods for determining the bending length and flexural/bending rigidity of fabrics. Three specimens of 50 mm by 200 mm were cut in each of the two fabric directions; machine (MD) and cross-machine (CD) for each sample. For each specimen, two measures of the bending length were taken so that six measures in total were obtained for each sample in each fabric direction. From the average bending length and mass per unit area for the different fabrics, the bending rigidity in MD and CD were then calculated from Eq 3.1.

$$B = Wc^3 \times 9.81 \times 10^{-6} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq\ 3.1$$

where B is the bending rigidity (μNm), W is the fabric mass per unit area (g/m^2), and c is the bending length (mm).

3.2.2.2 Preparation of PET woven fabrics for functionalization

Functionalization treatments for PET fabrics were preceded by Soxhlet extraction in order to eliminate any surface active agents and prior spinning and weaving oils. Extraction in petroleum ether was carried out using a *Soxhlet-* apparatus (Carlo Erba Reactifs- DS Chausseedu Vexin-BP France) for 4 hours, in the weight ratio of 1:5 (fabric:petroleum ether) at 65^{o}c. Samples for plasma treatment were 50cm wide, owing to the width of electrodes on the plasma machine.

3.2.2.3 Plasma pre-treatment of PET woven fabrics

All PET fabrics intended for NaOH treatment and softening were plasma treated to increase the surface energy and polarity; thus improving the action of NaOH and softening on PET fabrics. Plasma oxidation was carried out on an atmospheric air plasma machine Coating Star (Ahlbrandt System, Lauterbach- Germany) equipped with a pair of ceramic (dielectric) electrodes that create a glow discharge (Dielectric Barrier Discharge) when subjected to a potential difference. The fabric samples for plasma treatment were o.5 m in width (equivalent to the electrode length).

The electrical power, sample velocity, frequency, electrode length and distance between electrodes were kept at 500 W, 2m/min, 26 kHz, 0.5 m and 1.5 mm respectively, delivering a plasma power 30 kJ/m^2. The plasma power delivered during plasma oxidation is defined as:

$PP = \left(\frac{P}{V \times L}\right) \times 0.06$; P is the electrical power (W), V is velocity (m/min) and L is the electrode length (m). To select an optimal electric power and velocity, a study on the effect of plasma power and velocity on wetting of PET fabrics was carried out. PET fabric samples SK and SE were treated at varying velocity (1 m/min, 2 m/min, 3 m/min, 5 m/min, 7 m/min and 10 m/min) and electrical power (200 W, 300 W, 400 W, 500 W, 700 W, and 1000 W). Plasma treatment was done on both sides of the fabrics. To prevent ageing effects, all plasma treated fabrics were protected from light using aluminum foil, and stored in an enclosed dark cabinet. Then, water contact angles using the tensiometry approach were determined using a tensiometer 3S (GBX, Romans sur Isere- France). A 5 cm x 3cm strip of fabric was clamped so as to hang in the weighing position of the tensiometer, and the weight reading adjusted to zero. The fabric was gradually lowered until it just touched the surface of water placed in a container. A meniscus formed on the surface of the fabric triggers an immediate weight gain (Mm). As wicking progresses, the weight gain reached a total (Mt) g. The capillary weight (Mc) g was then determined two minutes after the fabric had been raised from the water surface. The WCA was computed from Eq 3.2:

$$Cos\theta = \frac{(Mt-Mc)g}{\gamma_{L}p} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..Eq\ 3.2\ ;$$

where, $Mt - Mc$ is the meniscus liquid weight Mm, γ_L and p are the water surface tension (mN/m) and perimeter (mm) of the fabric surface in contact with water, respectively. The perimeter of the fabric is estimated to be $2L$; where L is the length. Leroux[29] presented a detailed discussion on these computations.

Following a study on the effect of plasma oxidation on the wetting of the PET samples under study, we opted to fix the electrical power and velocity at 500 W and 2 m/min respectively, for subsequent plasma treatments. Plasma treatment was carried out on both sides of the fabric samples. Since ageing affects the durability of hydrophilic species induced by plasma oxidation[46,129], NaOH and softening treatments commenced immediately after plasma treatment.

3.2.2.4 NaOH treatment of PET woven fabrics

NaOH treatment of plasma treated PET fabrics was carried out in 3% (W/V) aqueous NaOH, in steel beakers of an AHIBA IR high temperature laboratory machine (datacolor, Lawrenceville, New Jersey, USA). The fabric:NaOH ratio was 1:5 at fixed temperature of 100°C or 120°C depending on the fabric weight. The NaOH treatment time was varied between 10 and 30 min. NaOH treatment parameters were adopted following trials and a factorial experimental design. Treatment temperatures above 120°C were avoided as they were prone to PET degradation. Treatment parameters were drawn to optimize the reduction of the stiffness of PET fabrics with minimum loss in weight and strength.

3.2.2.5 Application of the softener on PET woven fabrics

The softening recipe was prepared with 10 g/l of Siligen SIO, 50 g/l of Fixapret NF, and 0.5 g/l Kieralon JET-B Conc. Using acetic acid, the pH of the mixture was adjusted to 5. The ratio of the softener liquor to fabric was 10:1 giving a wet pickup range of 70%-80%. The softening process was realized by impregnation and squeezing with a laboratory padder (MSV textile machinery Lodz, Poland), and then drying and curing in a stenter (MSV textile machinery Lodz, Poland). The drying and curing processes were carried out at at100°C (for 60 s) and 170°C (for 45 s) respectively, in hot air.

Table 3.1 summarizes the parameters for plasma oxidation, NaOH treatment and softener application on selected PET fabrics.

Table 3.1 Experimental parameters for plasma treatment, NaOH treatment and softening of PET fabrics

Substrate fabric	Treated fabric	Electric Power (W)	NaOH Conc (W/V %)	NaOH treatment Temp (˚C)	NaOH treatment Time (Min)	Softener Applied
SK	SK10	500	3	120	10	
SK	SK10S	500	3	120	10	✓
SK	SK15	500	3	120	15	
SK	SK15S	500	3	120	15	✓
SK	SK20	500	3	120	20	
SK	SK20S	500	3	100	20	✓
SK	SK25	500	3	100	25	
SK	SK30	500	3	120	30	
SA	SA10	500	3	120	10	
SA	SA10S	500	3	120	10	✓
SA	SA20	500	3	100	20	
SA	SA20S	500	3	120	20	✓
SE	SE20	500	3	100	20	
SE	SE30	500	3	100	30	

The coding for treated fabrics e.g SK20S represents PET fabrics from which they were obtained, the temperature at which they were treated, and S at the end if the softener was applied to the fabric

3.2.2.6 Determination of the stiffness of NaOH and softener treated fabrics

The stiffness properties of PET fabrics after NaOH and softening treatments were determined by the SiroFAST system[125,126] already described, using the FAST-2 Bending Meter (CSIRO, Sydney, Australia).

3.2.2.7 Sensory panel, descriptors and sensory evaluation

Following the study of the performance of the sensory panel in Chapter 2 (section 2.3.3) of this research, retraining and replacement of some panelists was carried out. Also, the number of assessors was increased from 12 to 14. The sensory panel comprised of eight male and six female adults aged between 24 and 52 years. They included three college professors and eleven Doctoral scholars. The racial distribution was: six European natives, two African natives, four Asian natives, and two Middle-Eastern natives. All panelists had background training/experience in textiles/apparel.

Eleven descriptors realized in Chapter 1 (section 2.3.1) of this research by free choice profiling (FCP)[107]: ***Stiff**/inflexible, **Soft**/not hard, **Smooth**/not rough, **Heavy**/not light, **Noisy**/pitchy/harsh/not quiet sound, **Crisp**/brittle/firm/fresh/crushable/crumbly, **Stretchy**/elastic/not rigid, **Drapy**/hang/enclose, **Regular**/uniform/even, **Natural**/not synthetic/not artificial, and **Compact**/packed/dense* were utilized for this sensory evaluation. Again the six identified *leading attributes- Stiff, Soft, Heavy, Crisp, Regular,* and *Natural,* from the first study, were considered for computations in clustering, and measure of changes in disparity between cotton and PET fabrics.

Prior to the sensory evaluation, training was delivered by the researcher for all the panelists, in one session regarding the objectives, materials, evaluation criteria, and rank estimation. The evaluation criterion and illustration for each descriptor were discussed, printed and given to each panelist. Panelists washed and rinsed their hands ten minutes before the sensory experiment. Each panelist received one specimen for each of the 20 fabric samples, randomly without revealing their specifications. The panelists nominally ranked the 20 fabrics in descending order of perceived magnitudes for each of the 11 sensory descriptors.

3.2.2.8 Rank fusion and weighting

The unweighted cross-entropy Monte Carlo (CE) algorithm utilizing Kendall's tau (CEKnoweight)[109–111]was used to aggregate the 14 rank lists into one *super list* (fused list), for each descriptor. The CE method, under the function *RankAggreg* in software R[109] has been explained in Chapter 2 (section 2.2.2.2). Based on 20 fabrics and 14 rank lists for each descriptor, the rank aggregation program below was written and used for aggregation lists for each descriptor, in separate runs:

CEKnoweights <- RankAggreg(table_matrix, 20, method="CE", distance="Kendall", N=1960, convIn=30, rho=.1)

The Borda count, also known as the Borda-Kendall (BK) method[108] already described in Chapter 2 (section 2.2.2.2) was then used to convert ranks into weights.

3.2.2.9 Performance of the sensory panel

A brief analysis of the panel's performance was carried out using ANOVA and consonance analysis with PCA. The percentage agreement of assessors, assessors' contribution (%) to variability, and potential errors in assessment were identified. The percent agreement is the variability carried by the first principal axis of a descriptor's PCA (Assessors/Fabrics PCA). The performance of the present sensory panel was compared to that of the panel utilized in Chapter 2 (section 2.2.2.1) of this thesis.

3.2.2.10 Sensory relationships and the dissimilarity between cotton and functionalized PET woven fabrics

Using PCA, analysis of correlations, and the Euclidean distance, sensory patterns and dissimilarities between fabrics were elucidated. In particular, the Euclidean distance was used to determine the changes in the disparity between cotton and PET fabrics following the NaOH and softening treatments. The Euclidean distance computed in the first sensory study, based on six fabrics, was compared with the current distance computed with 20 fabrics. The type of functionalization and corresponding parameters that yielded the highest bridging between cotton and PET fabrics were then identified. Using the squared Euclidean distance and the *weighted pair-group average*, unsupervised AHC was used to create sensory clusters and profiles. The algorithm for AHC was executed using XLSTAT, an add-in for Excel[116]. The dissimilarity and agglomeration method used for AHC were the squared Euclidean distance and weighted pair-group average respectively. Regression models (Nonlinear and partial least squares) were computed to predict the descriptor *crisp*, as a response variable with *soft, natural*, *regular* and *heavy* as predictors.

3.2.2.11 Performance and physical properties of functionalized PET fabrics

NaOH and softener treated PET fabrics were characterized for selected properties to study the impact of the applied functionalization on sensory and performance attributes. Comparisons were also done with both cotton and untreated PET fabrics. All fabric tests were preceded by standard conditioning according to *ISO 139:2005* Textiles— Standard atmospheres for conditioning and testing[106] at *20^{o}C (*±2^{o}C) and *65%* RH (±4%) for 24 hours.

3.2.2.11.1 Fabric weight (mass per unit area)

The fabric weight was determined according to *ASTM D3776 / D3776M - 09a(2017)*: Standard Test Method for Mass Per Unit Area (Weight) of Fabric, Option C(on swatches)[130]. A circular fabric cutter of area 100 cm^2 was used to cut five specimens which were weighed on an electronic balance MS205DU (Mettler-Toledo, France) to the precision 0.01 mg. The final weight was the average of the five specimens recorded in g/m^2.

3.2.2.11.2 Thickness and surface thickness

The thickness of fabrics was determined according to *ASTM D1777 - 96(2015)*-Standard test method for thickness of textile taterials[131]. Ten specimens were measured on a K094 thickness gauge (SDL Atlas, Rock Hill, USA) of foot area 20 cm^2 with an applied pressure of 1kPa and the average thickness was recorded in mm (±0.02 mm). The surface thickness of the fabrics was determined by the SiroFAST (Fabric assurance by simple testing) sytem[125], using the FAST-1 Compression Meter (CSIRO, Sydney, Australia). Using three obtained thicknesses T_2, T_{20} and T_{100}; T_2 is thickness measured with a pressure load of 2 gf/cm^2 (196 Pa), T_{20} is the thickness measured with a pressure load of 20 gf/cm^2 (1.96 kPa), T_{100} is the thickness measured with a pressure load of 100 gf/cm^2 (9.81 kPa). The surface thickness is expressed as T_2-T_{100} in mm. The surface thickness can provide information about the handle and appearance of a fabric, and also on the quality of a surface finish; large values of surface thickness imply that a fabric is rough, while large changes after washing indicate poor adhesion of a finish.

3.2.2.11.3 Abrasion resistance

The abrasion resistance of fabrics was determined according to ASTM D4966 - 12(2016) Standard Test Method for Abrasion Resistance of Textile Fabrics (Martindale Abrasion Tester Method), Option n 1(revolutions needed for breakage)[132] using a Martindale Healink (James H. Heal & Co. Ltd, Halifax England) at an applied pressure of 9kPa, with felt wool of weight 750 g/m^2 and thickness of 3 mm as the abradant. The method records the number of revolutions taken for two or more yarn breakages to be detected.

3.2.2.11.4 Bursting strength and strain/elongation at break

The bursting strength of fabrics was determined according to *ASTM D6797 - 15* Standard Test Method for Bursting Strength of Fabrics Constant-Rate-of-Extension (CRE) Ball Burst Test using an Instron 6021/5500 tensile strength tester (Instron, Norwood, USA) with a Ball Burt Attachment. The balls and ring clamps used were of diameter 20 mm and 25 mm respectively. The average bursting strength (N) for five specimens was recorded for each tested sample. Strain values were also recorded along in mm, indicating the elongation at break.

3.2.2.11.5 Fabric extensibility

The FAST-3 Extension Meter (CSIRO, Sydney, Australia) was used to directly measure the extension (%) in the warp and weft directions according to the CiroFAST system[125]. Six specimens of 200 mm by 50 mm were used for each fabric. The instrument measures the length increase in a gauge length of 100 mm when loads are exerted. A weight of 98.1 N/m was used to deliver a force of 100 gf/cm. The average extension in the warp and weft was recorded.

3.2.2.11.6 Air permeability

The air permeability ($cm^3/s/cm^2$) was measured according to *ASTM D737-96*[133]*; 1SO 9237(11)* using a Textest *FX 3300 Air Permeability* Tester (*Textest* AG, Switzerland). The test volume was 10 l with a pressure drop of 100 Pa against a test surface of $20cm^2$. The average of ten measurements made on each sample was recorded.

3.2.2.11.7 Moisture management

Moisture management properties of fabrics were studied using the moisture management test (MMT) device (SDL Atlas LLC, Charlotte, NC, USA) in accordance with *AATCC Test Method (TM) 195-2011*– Liquid moisture management properties of textile fabrics[134–136]. The MMT provides objective measurements and gives an overall evaluation of in-plane and off-plane wettability of fabrics. A predetermined amount of conductive liquid dropped on the top surface of the test fabric is evaluated for 120 seconds. The top and bottom radial spreading and absorption behavior is recorded due to changes in the electrical resistance of the specimen. Predetermined indices are used to grade and classify the fabrics according to their moisture management behavior.

3.3 Results and discussion

3.3.1 Wetting of plasma modified PET

The average water contact angles (WCAs) of untreated PET fabrics SE and SK were 79^o and 101^o respectively. Regardless of the plasma power and sample velocity, the WCAs following plasma oxidation averaged at 49^o and 89^o for SE and SK respectively. The microfiber fabric SE experienced increased wetting compared to the twill weave fabric SK, of conventional filament yarn. Any decrease in speed or increase in plasma power was of negligible consequence on these WCAs. However, the capillary weight of plasma-treated PET samples increased with respect to plasma power; the highest values of Mc (300 mg) were obtained at the lowest velocities (1-3 m/min). This is because at low speeds, fabrics stay longer between electrodes and allow higher plasma power to be delivered per unit area, on fiber surfaces inside the fabric structure. Electrical power between 400 W and 100 W at speeds between 1 m/min and 10 m/min was sufficient enough to impart moisture polar groups to the surface of PET in order to facilitate wetting. Plasma oxidation partially breaks chemical bonds and creates polar groups, and facilitates the creation and growth of reactive free end radicals[137] which react with reactive species with a resulting increase in surface energy. Particularly, plasma oxidation has been noted to increase the concentration of oxygen atoms on the surface of PET fabrics[138], consequently, enhancing the wetting of PET woven fabrics. Thus, plasma re-treatment preceded the NaOH and softening treatments in order to enhance the absorption.

3.3.2 Stiffness of PET and cotton fabrics

The guiding objective of this study was to alter the stiffness of PET fabrics in relation to cotton fabrics. Following the treatment of PET fabrics (SK, SE and SA) with NaOH and Siligen softener SIO, 14 fabrics were realized by varying the NaOH treatment temperature and time. The stiffness properties of NaOH treated and softener treated fabrics are presented in Table 3.2 along with untreated PET fabrics (SK, SA and SE), cotton fabrics (SC and SX) and blended fabric SG.

Table 3.2 Stiffness properties of NaOH and softener treated PET fabrics compared with cotton and untreated PET fabrics

Fabric	Weight g/m^2	C warp (mm)	C weft (mm)	B Warp (µNm)	B Weft (µNm)
SK	229.5	24.5	20	33.1	18.0
SK10	165.2	17.0	15	8.0	5.5
SK10S	169.8	18.0	15	9.7	5.6
SK15	141.0	17.0	14.5	6.8	4.2
SK15S	144.0	16.5	15.1	6.3	4.9
SK20	141.0	19.1	18.3	9.6	8.5
SK20S	148.0	16.3	15.8	6.3	5.7
SK25	94.9	15.0	13	3.1	2.0
SK30	80.4	12.5	11.1	1.5	1.1
SA	149.8	25.1	20.5	23.2	12.7
SA10	97.9	12.1	11.8	1.7	1.6
SA10S	96.0	12.0	11.5	1.6	1.4
SA20	67.5	11.9	10.9	1.1	0.9
SA20S	70.7	11.0	11	0.9	0.9
SE	96.0	21.3	16.1	9.1	3.9
SE20	86.4	14.2	12.2	2.4	1.5
SE30	84.7	16.7	12.2	3.9	1.5
SC	136.5	17.0	15.5	6.6	5.0
SX	131.5	18.0	17.5	7.5	6.9
SG	257.8	15.0	16	8.5	10.4

C is the bending length, B is the bending rigidity. The coding for treated fabrics e.g SK20S represents PET fabrics from which they were obtained, the temperature at which they were treated, and S at the end if the softener was applied to the fabric. SC and SX are cotton fabrics; SG is a blend of cotton (67%) and PET (33%)

At 130°C, PET degrades and disintegrates in NaOH at the experimental concentration of 3%. By comparison, untreated PET fabrics generally had higher bending length, both for warp and weft, compared to cotton fabrics. Except SK30, NaOH and softener treatment of SK yielded fabrics with bending lengths close to values for cotton fabrics and the blended fabric SG. Further, the bending rigidity for SK-derived fabrics were much closer to those of cotton fabrics compared to other PET samples. NaOH treatment of SE yielded only SE30 with only the warp bending length close to values for cotton fabrics. The weft bending lengths for SE derived fabrics and the ensuing bending rigidity were much lower compared to cotton fabrics. Sample SA had the most pronounced response to NaOH treatment. The bending lengths, in both fabric directions and the bending rigidity of all SA-derived fabrics were the lowest. The stiffness values reduced with increasing NaOH treatment time. Application of the softener slightly lowered the bending rigidity. Low values of bending rigidity (below 5 µNm) have been associated with cutting difficulties during garment making. These measured values, however, may not represent the perceived relative stiffness when judged with human assessors.

In an earlier study, Dave's research team[35] found that the flexural rigidity of PET fabrics decreased with concentration and time of NaOH treatment; the decrease was higher at the initial treatment times and lowered as weight loss progressed. Mousazadegan[36]noted that the bending length related non-linearly with fabric weight loss, and predicted that the yarn/fiber diameter was pertinent to the bending length; and that bending stiffness decreased by the second order of weight reduction rate during NaOH treatment. NaOH and softening treatment of PET fabrics effectively altered the stiffness properties of PET fabrics, bridging close to cotton fabric stiffness properties. A sensory analysis to evaluate the impact of these treatments on the perceived difference between cotton and PET fabrics was necessary.

3.3.3 Rank lists and rank aggregation

The sensory evaluation yielded 14 rank lists for each of the 11 descriptors. Table 3.3 shows, in descending order of magnitudes of sensations, the optimal rank lists for all 11 descriptors obtained by the unweighted cross-entropy Monte Carlo (CEKnoweight) algorithm.

Table 3.3 Aggregated rank lists of 20 fabrics; treated PET, cotton and untreated PET fabrics

Rank	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
1	SA	SK30	SK30	SG	SK	SA	SE30	SA20	SK	SG	SK
2	SK	SA20S	SK25	SK	SA	SK	SE20	SA20S	SK10	SC	SG
3	SC	SA20	SK15S	SA	SE	SE	SK30	SA10	SK20	SA10S	SK10
4	SG	SA10	SK20S	SK10	SX	SC	SK20S	SK30	SE	SA20	SK15S
5	SX	SK25	SE30	SX	SK10	SG	SK25	SA10S	SK25	SA10	SK20
6	SE	SA10S	SE20	SK10S	SC	SX	SE	SK25	SK15	SA20S	SK10S
7	SK10	SK15S	SK15	SC	SG	SK10	SA10S	SE20	SK20S	SX	SK15
8	SK10S	SE30	SA20S	SK20	SK20	SK20	SK15S	SK15S	SK10S	SK30	SK20S
9	SK20	SE20	SA20	SK20S	SE20	SK10S	SK15	SK15	SK15S	SK25	SK25
10	SK20S	SK20S	SK10S	SK15S	SK10S	SK15	SA20S	SE30	SK30	SK15	SX
11	SK15	SK15	SA10S	SK15	SE30	SE30	SK10	SK20S	SA10	SK15S	SE20
12	SE20	SK20	SA10	SE	SK20S	SE20	SK10S	SK10	SX	SE30	SK30
13	SK15S	SK10S	SK20	SK25	SK15S	SK20S	SK20	SK20	SA10S	SK20S	SE
14	SE30	SK10	SK10	SE20	SK15	SK15S	SA20	SK10S	SA	SK20	SC
15	SK25	SX	SX	SE30	SK25	SK25	SA10	SX	SA20	SK10	SE30
16	SA10	SE	SE	SA10S	SK30	SA10	SK	SG	SE30	SE20	SA
17	SA10S	SC	SC	SA10	SA10	SA10S	SA	SC	SE20	SA	SA20
18	SK30	SG	SK	SK30	SA10S	SK30	SC	SE	SA20S	SK10S	SA10
19	SA20	SK	SG	SA20S	SA20	SA20S	SX	SK	SG	SE	SA10S
20	SA20S	SA	SA	SA20	SA20S	SA20	SG	SA	SC	SK	SA20S

The coding for treated fabrics e.g SK20S represents PET fabrics from which they were obtained, the temperature at which they were treated, and S at the end if the softener was applied to the fabric. SC and SX are cotton fabrics; SG is a blend of cotton (67%) and PET (33%)

One prominent observation is that untreated PET fabrics lead in permutations of stiff, crisp, noisy, regular and compact. Cotton fabrics were still perceived as more natural, despite trailing in expected descriptors, such as soft, as was deduced in the first part of this study. For several descriptors of tactility, treated PET fabrics are perceived *softer*, *smoother* and *drapy*. These are explored further in the section on clustering and profiling of fabrics. Softened fabrics were particularly perceived *soft* (more for SA derived) and *smooth* (more for SK derived).

Table 3.4 presents the BK weights $\omega^T(i)$ of ranks; ($\omega^T(i) = \left\{1, \frac{1}{|T|}\right\}$; $|T| = 20$.

Table 3.4 Weighted and normalised BK scores $\omega^{T}(i)$ of fabrics for 11 sensory descriptors

Fabric	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
SA	1	0.05	0.05	0.9	0.95	1	0.2	0.05	0.35	0.2	0.25
SK	0.95	0.1	0.15	0.95	1	0.95	0.25	0.1	1	0.05	1
SC	0.9	0.2	0.2	0.7	0.75	0.85	0.15	0.2	0.05	0.95	0.35
SG	0.85	0.15	0.1	1	0.7	0.8	0.05	0.25	0.1	1	0.95
SX	0.8	0.3	0.3	0.8	0.85	0.75	0.1	0.3	0.45	0.7	0.55
SE	0.75	0.25	0.25	0.45	0.9	0.9	0.75	0.15	0.85	0.1	0.4
SK10	0.7	0.35	0.35	0.85	0.8	0.7	0.5	0.45	0.95	0.3	0.9
SK10S	0.65	0.4	0.55	0.75	0.55	0.6	0.45	0.35	0.65	0.15	0.75
SK20	0.6	0.45	0.4	0.65	0.65	0.65	0.4	0.4	0.9	0.35	0.8
SK20S	0.55	0.55	0.85	0.6	0.45	0.4	0.85	0.5	0.7	0.4	0.65
SK15	0.5	0.5	0.7	0.5	0.35	0.55	0.6	0.6	0.75	0.55	0.7
SE20	0.45	0.6	0.75	0.35	0.6	0.45	0.95	0.7	0.2	0.25	0.5
SK15S	0.4	0.7	0.9	0.55	0.4	0.35	0.65	0.65	0.6	0.5	0.85
SE30	0.35	0.65	0.8	0.3	0.5	0.5	1	0.55	0.25	0.45	0.3
SK25	0.3	0.8	0.95	0.4	0.3	0.3	0.8	0.75	0.8	0.6	0.6
SA10	0.25	0.85	0.45	0.2	0.2	0.25	0.3	0.9	0.5	0.8	0.15
SA10S	0.2	0.75	0.5	0.25	0.15	0.2	0.7	0.8	0.4	0.9	0.1
SK30	0.15	1	1	0.15	0.25	0.15	0.9	0.85	0.55	0.65	0.45
SA20	0.1	0.9	0.6	0.05	0.1	0.05	0.35	1	0.3	0.85	0.2

3.3.4 Performance of the sensory panel

Figure 3.2 presents, the variability by the two principal components (F1 and F2) of PCA of panelists for each descriptor.

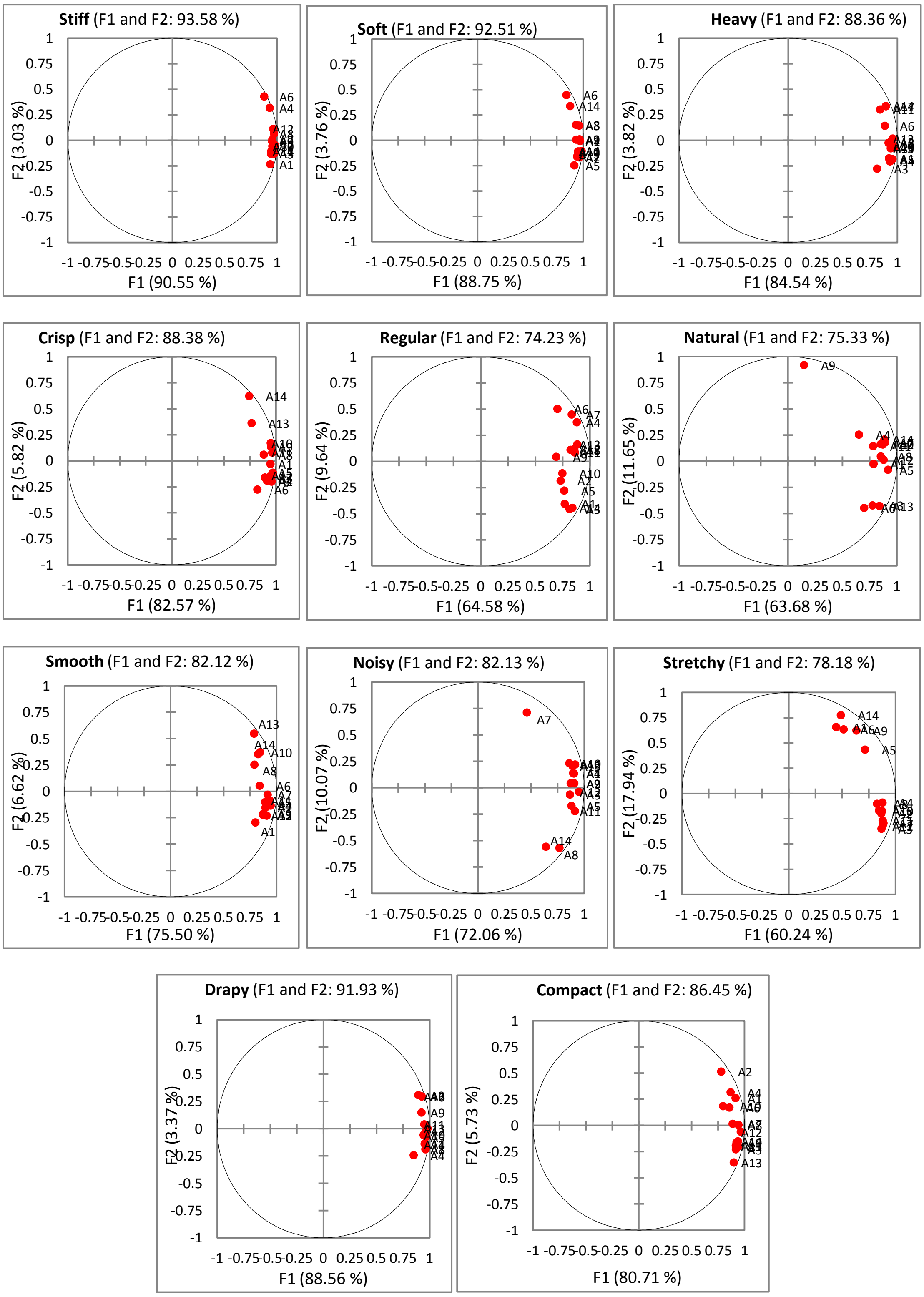


Figure 3.2 PCA plots of 11 descriptors showing factor loadings and relative correlation between assessors

For all the descriptors, significant proportions of assessors' contributions were carried by F1. In 55% of the descriptors, F1 carried more than 80% of the variability. Moreover, in 67% of the descriptors, the variance for F1 was above 70%. Hence, it was also reasonable to retain the first principal component alone, for further analysis. In this analysis however, F1 and F2 were considered to compute other analyses. The highest percent agreement (93.6%) was recorded with descriptor *stiff*. Table 3.5 presents a summary of the panel's performance; errors based on Figure 3.2, ANOVA, the percent agreement from PCA of assessors, and the average contribution (%) of assessors on F1 and F2. Included also, is the percent agreement from the first sensory evaluation (section 2.2.2.1).

Table 3.5 Summary of assessors' performance: percent agreement, and assessors' errors

Descriptor	F	*Pr > F	% agreement	Initial % agreement	Average contribution (%) of assessors on F1 and F2	Assessors below average contribution on F1 and F2	Assessors with crossover errors	Assessors with a magnitude error	Assessors with a sensitivity error
Stiff	124	<0.0001	91	62	93.5	1,2,3,9,10,14	-	-	-
Soft	101	<0.0001	89	63	92.5	5,6,8,9,11,12,14	-	-	-
Smooth	40	<0.0001	76	57	82.1	1,5,6,8,9,14	-	-	-
Heavy	70	<0.0001	85	78	88.4	3,6,8,11	-	-	-
Noisy	31	<0.0001	72	73	82.1	3,5,7,9,10,14		7	-
Crisp	59	<0.0001	88	76	92.5	4,6,7,8,13	-	13,14	9
Stretchy	18	<0.0001	60	50	78.2	1,5,6,8,13		1,6,14	-
Drapy	100	<0.0001	89	66	91.9	3,4,9,10,11		-	-
Regular	23	<0.0001	65	54	74.2	2,5,8,9,10	-	6,9	-
Natural	20	<0.0001	64	87	75.3	1,4,6,8,11	9	6	-
Compact	54	<0.0001	81	61	86.4	4,6,7,10	-	-	-

*The values were computed at significance level 0.05

The type III Sum of Squares analysis from ANOVA with a regression model Y=mu+P+J+P*J (J and P*J are random factors) showed that, all the 11 descriptors were significant and had product (fabric) effects at a significance level of 5%; as all p-values were <0.0001 (Table 3.5).

Compared to the first sensory panel evaluation, the percent agreement notably increased for eight attributes. The statistical significance for *drapy* and *compact* also improved. The reduction in the percent agreement for *natural* and *compact* could arise from the increased number of PET fabric samples with only a little variation in the functionalization parameters. It appears that panelists well evaluated hand attributes compared to appearance related attributes.

Cross-over errors (ratings' inversion) are identified by observing assessors clustering in opposite quadrants from the rest of the panel. There was no cross-over error detected among panelists. Magnitude errors apply where a panelist seems to use lower or higher estimations compared to other assessors. Magnitude errors were noticed by large margins of variations in factor loading for some panelists compared to the vast of the panel. However, in rank-based evaluations, it is complex to identify magnitude errors since assessors do not use a rating scale. Sensitivity errors are characterized by very short vectors or low total percent contribution and low factor loading. Compared to the first sensory evaluation, the number of errors was significantly reduced by 88%, 18% and 92% for sensitivity, magnitude and crossover respectively.

Since each judge only evaluated each fabric once for a descriptor; as the panel regression is based on ANOVA, it would require at least two observations of the same product (a second session) for each judge in order to discriminate between the fabrics. Thus, the average contribution to F1 and F2 was used to analyze assessors' ability to discriminate the fabrics with the various descriptors. The *discriminating power*, which represents the percentage of descriptors effectively perceived by an assessor to discriminate the fabrics, was computed. An assessor was recorded to have effectively perceived a descriptor if the assessor's contribution (%) for that descriptor was higher than the panels' average contribution (%) for the same descriptor. From Table 3.5, the average discriminating power was 63.6%, which was also the mode, obtained by 45% of the panelists. The highest discriminating power was 81.8%, by assessor 2 and assessor 13. Assessor 9 exhibited the lowest discriminating power (36.4%). The standard deviation and coefficient of variation (%) were 16% and 25.3% respectively.

The current study demonstrates an improved performance of the sensory panel compared to the panel in Chapter 1 of this research. The general improvement in the performance of the sensory panel can be attributed to the added training, as well as the number of judges added to the panel. The introduction of chemical treatments also added samples with interesting profiles.

3.3.5 Sensory relationships and the dissimilarity between cotton and functionalized PET woven fabrics

3.3.5.1 Sensory clustering of sensory descriptors and woven fabrics

In this analysis, the six leading attributes (*stiff*, *soft*, *heavy*, *crisp*, *natural*, and *regular*) earlier identified in part 1 were used to study sensory relationships. PCA was used to analyze correlations between sensory descriptors and the 20 fabrics. Table 3.6, derived from the BK weights in Table 3.4, shows the correlation coefficients of the six sensory descriptors.

Table 3.6 Correlation matrix (Pearson (n)) based on the six initial significant descriptors

Descriptor	Stiff	Soft	Heavy	Crisp	Natural	Regular
Stiff	**1.00**	-0.98	0.92	0.97	-0.40	0.17
Soft	-0.98	**1.00**	-0.90	-0.98	0.39	-0.14
Heavy	0.92	-0.90	**1.00**	0.86	-0.34	0.25
Crisp	0.97	-0.98	0.86	**1.00**	-0.46	0.20
Natural	-0.40	0.39	-0.34	-0.46	**1.00**	-0.62
Regular	0.17	-0.14	0.25	0.20	-0.62	**1.00**

Values in bold are different from 0 with a significance level alpha=0.05

Unlike the initial study, there was very high correlation between several attributes. For example, there was initially very low correlation (0.14) between *stiff* and *heavy*, which, drastically increased to 0.92. This was similar to the increased correlation between *cris*p and *heavy*. These changes reflect the altered relationships introduced with more samples and altered sensory attributes of PET fabrics. The descriptors *natural* and *regular* appear more independent and less correlated to other attributes. *Stiff*, *crisp* and *heavy* were highly interdependent. The Eigen decomposition (Table 8) and Figure 3 show that F1 and F2 carried a significant amount of variability (91.1%) of the PCA to represent data on the six descriptors.

Table 3.7 Eigenvalues and variability of five principal components

	F1	F2	F3	F4	F5	F6
Eigenvalue	4.11	1.35	0.39	0.122	0.02	0.01
Variability (%)	68.52	22.53	6.44	2.03	0.26	0.22
Cumulative %	68.52	91.05	97.50	99.53	99.78	100

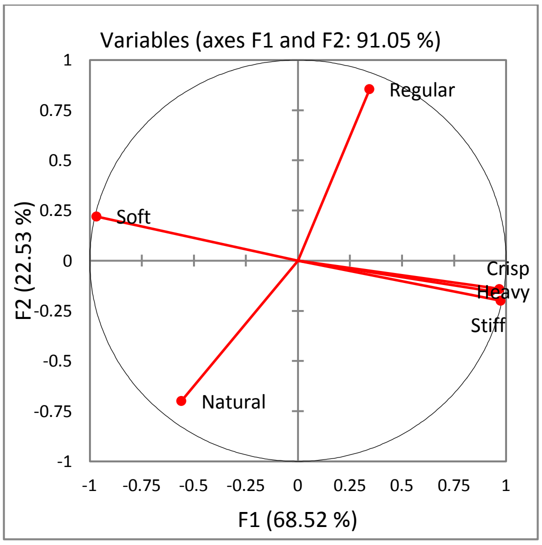


Figure 3.3 Visualization of correlations between descriptors and principle components F1 and F2

From Table 3.6 and Table 3.7, the factor loadings (correlation between descriptors and factors), and squared cosines of descriptors were computed as in Table 3.8.

Table 3.8 Factor loadings and squared cosines of attributes on principal components F1 and F2

	Factor loading		Squared cosines		Contribution (%) to F1 and F2
Descriptor	F1	F2	F1	F2	
Stiff	0.9744	-0.1992	0.9495	0.0397	98.9
Soft	-0.9671	0.2205	0.9354	0.0486	98.4
Crisp	0.9682	-0.1413	0.9374	0.0200	95.8
Regular	0.3439	0.7231	0.1183	0.7318	85.0
Natural	-0.5595	0.8554	0.3130	0.4887	80.2
Heavy	0.9261	-0.1524	0.8577	0.0232	88.1

Values in bold indicate figures for which the factor loadings and squared cosines of attributes are the largest

The large values of the squared cosines as well as the factor loadings indicate that the three descriptors; *stiff*, *soft* and *crisp* were very significant or the most significant in the variability. The descriptor *natural* lost the initial position of significance discovered in part 1 of this research. *Natural* and *regular* contributed more on F2 than for F1, compared to other descriptors. Hence, it can be said that F1 represents hand descriptors, while F2 represents visual/appearance descriptors. Figure 3.4 is a biplot showing the clustering of fabrics and descriptors.

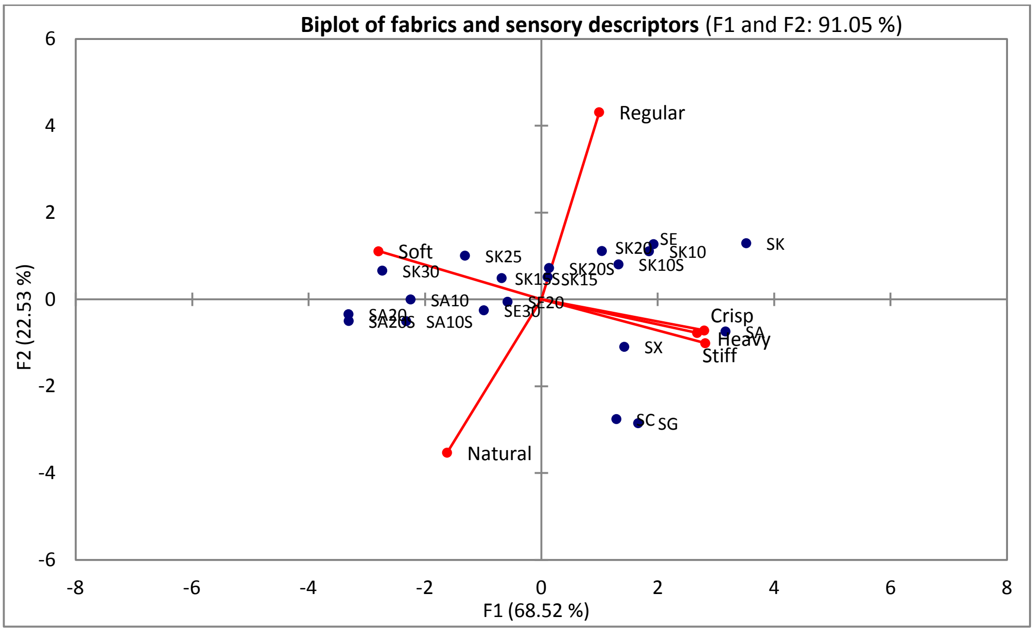


Figure 3.4. A biplot showing the clustering of 20 fabrics and the six sensory attributes on F1 and F2 of PCA

Fabrics SG and SC are more pronounced for *natural*, while several PET fabrics treated with NaOH and the softener load strongly with *soft*. Fabrics SA, SK, SX, SG and SC are perceived *heavier*, *stiffer* and *crispier*. Fabrics of SK derivative are clustered closer, as so are fabrics of SA and SE derivative. This implies that functionalized fabrics still shared their generic sensory attributes. This clustering shows that despite the modified/enhanced attributes of PET through NaOH treatment and softening to alter the *crispiness*, judges still perceived cotton fabrics as more *natural*. NaOH treated PET fabrics were also perceived lighter, which might correspond to their actual weight permutations. The perceived softness of NaOH treated fabrics is, especially due to their reduced objective stiffness already observed in the earlier sections. However, compared to untreated PET fabrics, cotton fabrics were still perceived less *stiff* and less *crisp*. It appears that cotton and PET fabrics have unique appearance that judges are able to decipher the natural appeal for each fiber generic. Hence, there are intricate visual perceptual differences beyond the tactile cognition of PET and cotton fabrics. These relationships are further presented under sensory profiling with AHC.

3.3.5.2 Dissimilarity (Euclidian distance) between untreated PET and cotton woven fabrics

In Chapter 1 (section 2.3.6, Table 2.10) of this research, the Euclidean distance between cotton and untreated PET woven fabrics was determined. The Euclidean distance between treated PET woven fabrics and cotton woven fabrics was also determined. Using linear regression and nonlinear regression, two models linking the distances computed with the two different panels were computed. Table 3.9 shows the proximity between untreated PET and cotton woven fabrics; D_1 obtained by the sensory panel in Chapter 2 and D_2 obtained by the current sensory panel.

Table 3.9 Euclidean distance between cotton and untreated PET fabrics computed with the two different panels

Fabric 1	SE	SK	SK	SA	SA	SK	SE	SA	SX
Fabric 2	SG	SG	SX	SG	SX	SC	SC	SC	SE
D_1	1.49	1.42	1.38	1.24	1.19	1.14	1.05	0.80	0.58
D_2	1.31	1.32	0.92	0.89	0.66	1.34	1.21	0.86	0.82

D_1 is the Euclidean distance with the 1st sensory panel; D_2 is the Euclidean distance with the 2nd sensory evaluation

From Table 3.9, the Euclidean distance computed from the two sensory panels is different, for all sets of fabrics; despite the number of descriptors and criteria for evaluation being the same. A Pearson correlation coefficient of 0.45 was found between D_1 and D_2. The equation of the linear regression model (Eq 3.3) and nonlinear regression models (Eq 3.4) were computed to relate the two distances D_1 and D_2.

$D_1 = 2.072 - 2.464D_2 + 1.434{D_2}^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Eq\ 3.3$ (Nonlinear regression)

$D_1 = 0.6104 + 0.515D_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Eq\ 3.4$ (Linear regression);

The observed inter panel differences could stem from the introduction of new samples and some variation in the panel performances. Following the discovery of discrepancy in the untreated PET fabric-cotton fabric distances from these two sensory panels, our measure of the changes in the disparity between cotton and PET woven fabrics was based on the second sensory panel.

3.3.5.3 Dissimilarity between fabrics after NaOH and softening treatments

In this analysis, dissimilarities were computed and treatments that bridged more between PET and cotton fabrics were identified. Figure 3.5 shows the proximity mapping of fabrics.

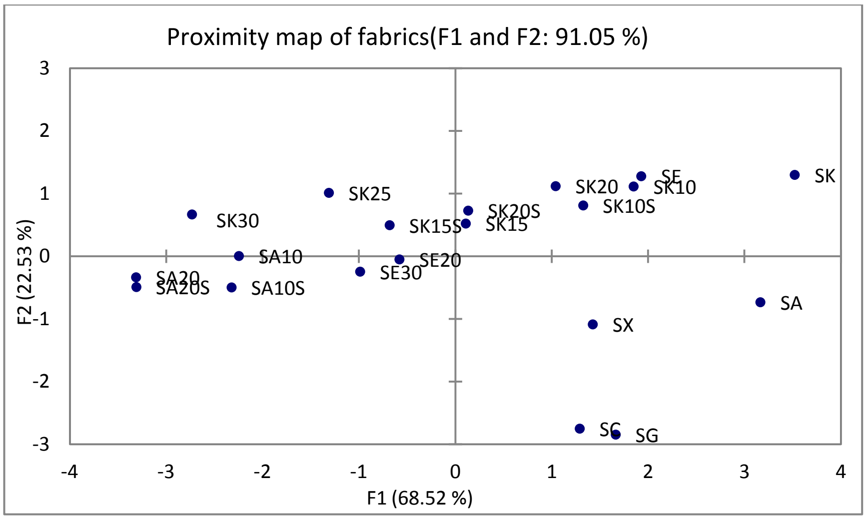


Figure 3.5 Mapping of the dissimilarity between fabrics based on the Euclidean distance

The mapping of fabrics (Figure 3.5) shows that generally, the disparity between some PET fabrics and cotton fabrics was reduced by NaOH treatments or the combination with softening. The largest Euclidean distance was between untreated PET fabric SK and SA. The NaOH and/or softening treatment of SA increased the disparity between SA and cotton fabrics. Cotton fabrics and the blended fabric SG remained closely related, and in one cluster, while treated PET fabrics also formed clusters with respect to their generic sources. The changes in the Euclidean distance after functionalization of PET fabrics can be visualized by the bar plots in Figure 3.6.

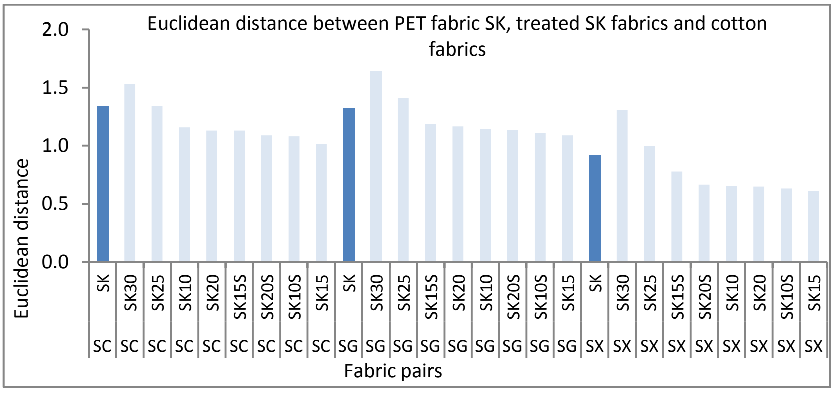


Figure 3.6 Euclidean distance: between untreated PET fabric SK and cotton fabrics, and between SK-derived fabrics and cotton fabrics. The dark bars represent the Euclidean distance between SK and cotton fabrics (SC and SX) and the blended fabric (SG)

The relative changes in the proximity due to the different treatment parameters can be estimated by comparing the untreated fabrics' bar plots with the treated fabrics' bar plots, for each fabric. Table 3.10 shows the percentage reduction in the Euclidean distance between SK and cotton fabrics due to NaOH and softening treatments.

Table 3.10 Percentage reduction in the Euclidean distance between cotton fabrics and SK, with functionalization

SK-derived fabric	Temp (°C)	Time (min)	Softener	Reduction (%) SK/SC	Reduction (%) SK/SG	Reduction (%) SK/SX
SK15S	120	15	✓	15.65	10.04	15.45
SK20	120	20		15.65	11.65	29.56
SK10	120	10		13.61	13.37	28.93
SK20S	120	20	✓	18.85	13.96	27.90
SK10S	120	10	✓	19.36	15.98	31.25
SK15	120	15		24.26	17.62	33.66

The temperature and time represent the conditions during the NaOH treatment of SK

Treated PET fabric SK15 had the lowest disparity with all cotton fabrics, and the blended fabric SG. Thus, the NaOH treatment of SK at 120°C, for 15 minutes was more effective in bridging between cotton fabrics and PET fabric SK. Fabric SK15 was closely followed by SK10S and SK20S. The introduction of the softener onto NaOH treated fabrics did enhance the reduction in the disparity between cotton fabrics and PET fabric SK. For instance, with NaOH treatment time of 10 minutes, the dissimilarity between SK and SC reduced by13.61% (with fabric SK10). When the softener was added, the dissimilarity reduced by a further 6% (with SK10S). The dissimilarity between SC and SK also reduced with NaOH treatment at 120°C for 20 minutes; reducing further upon softening. The trend of changes in the Euclidean distance between SK and SG, and SX are not different from trends with SC. Fabric SX has the closest proximity to SK treated fabrics, compared to SC and blended fabric SG. The reduction in the proximity was also highest with SX fabric, following funcionalization of SK fabric. As shown in Figure 3.7, the functionalization of PET fabric SA did not reduce, but rather increased the disparity with cotton fabrics.

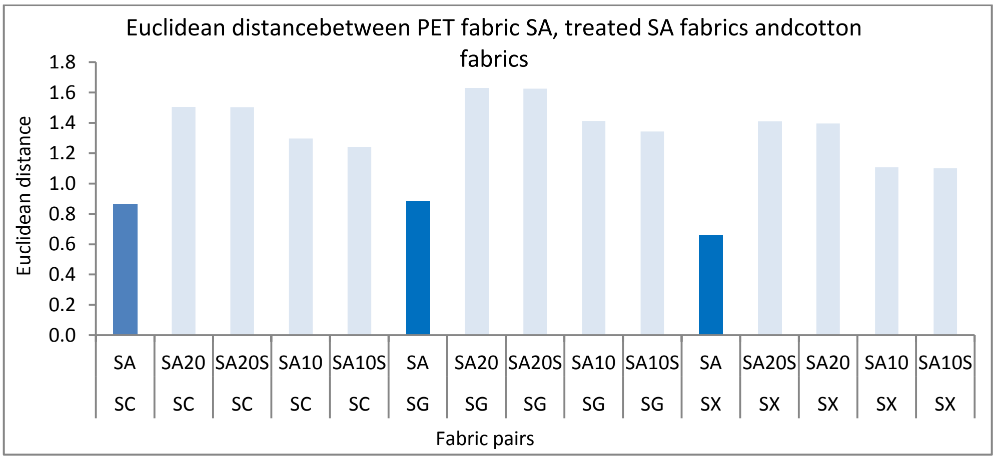


Figure 3.7 Euclidean distance: between untreated PET fabric SA and cotton fabrics, and between SA-derived fabrics and cotton fabrics. The dark bars represent the Euclidean distance between SA and cotton fabrics (SC and SX) and the blended fabric (SG)

As earlier noted, SA-derived fabrics presented very low stiffness values, compared to cotton fabrics. In contrast, SK-derived fabrics had stiffness values in ranges close to those of cotton fabrics. This, in addition to structural, physical and mechanical differences could explain these wide sensory differences. The section on performance properties deeply explores these differences that might account for different perceptions.

Regardless of the treatment parameters on SA, the Euclidean distance between the resulting treated fabrics and cotton fabrics, increased consistently. This finding is unique and exclusive to SA, suggesting differences in the interaction of the substrate fabrics with the applied treatments. Especially, the structure and physical properties of the substrate fabrics may have an impact. Figure 3.8 shows the changes in the Euclidean distance between SE and cotton fabrics.

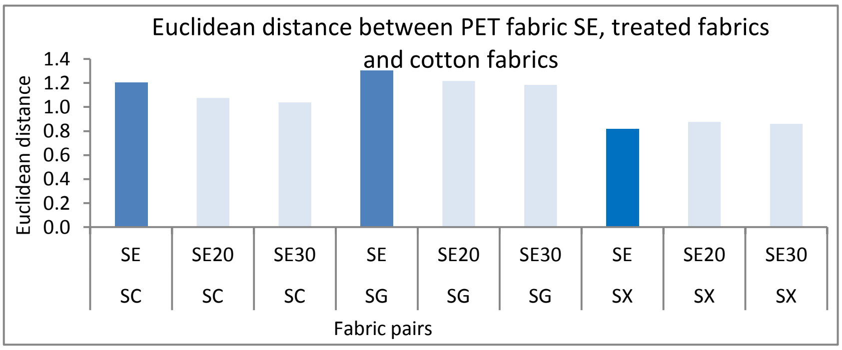


Figure 3.8 Euclidean distance: between untreated PET fabric SE and cotton fabrics, and between SE-derived fabrics and cotton fabrics. The dark bars represent the Euclidean distance between SA and cotton fabrics (SC and SX) and the blended fabric (SG).

The treatment of SE with NaOH at 100°C for 20 and 30 minutes reduced the dissimilarity between SE and SC cotton fabric. A slight decrease in the Euclidean distance between SE and blended fabric SG was also achieved by NaOH treatment of 20 and 30 minutes. However, the dissimilarity between SE and cotton fabric SX slightly increased for all NaOH treatment times.

The dissimilarity between cotton fabrics and PET fabric SK was generally consistently reduced by all NaOH and softening treatments, except for the NaOH treatment lasting 25 and 30 minutes. Irrespective of the treatment parameters, PET fabric SA got distant from all cotton fabrics, and the cotton/PET blended fabric. The gap between cotton fabric SC and PET fabric SE reduced by about 18%, with NaOH treatment for 20 and 30 minutes. The reduction in the Euclidean distance between SE and SG was about 8% irrespective of the duration of the NaOH treatment. It seems that, to achieve a systematic bridging between cotton and PET fabrics, using NaOH treatment and softening, processes need to be optimized for the different fabrics. Even at a macro scale, fabrics with different structures would need to be processed differently.

3.3.5.4 Fabric sensory classes and profiles with AHC

Considering the lowest within-class variance and the highest inter-class variance, three classes from unsupervised AHC were realized (Table 3.11).

Table 3.11 AHC results by class

Class	Within-class variance	Average distance to centroid	Fabrics
1 (6)	0.1899	0.3838	SA,SK,SE,SK10,SK10S,SK20
2(3)	0.1075	0.2634	SC,SG,SX
3 (11)	0.2101	0.4239	SK15,,SK15S,SK20S,SK25,SK30,SE20,SE30,SA10,SA10S,SA20,SA20S

The fabrics were agglomeratively clustered by integrating the six sensory attributes using the squared Euclidean distance between fabrics. Hence, fabrics in the same class have close attributes. From Table 3.11, fabrics in class 2 have the lowest variance within them. Apart from three fabrics (SK10, S10S and SK20), all functionalized PET fabrics were classified together. Figure 3.9 shows the class profiles and a dendrogram of the fabrics.

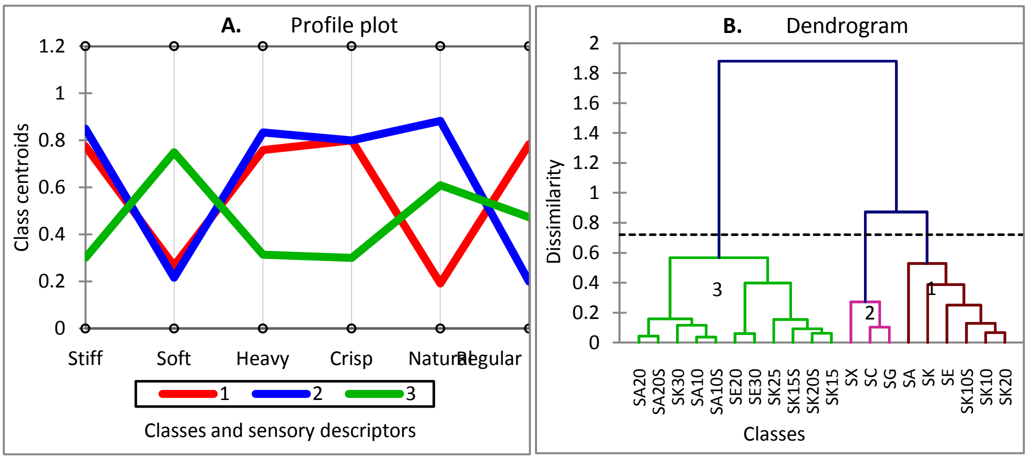


Figure 3.9 AHC profile plot (**A**) and dendrogram (**B**) of fabric sensory classes

The class centroids indicate that fabrics in class 1, which include all untreated PET fabrics and three SK-derived PET fabrics (mainly treated at the lowest temperatures), were closer to cotton fabrics (Class 2) for *stiff*, *soft*, *crisp*, and *heavy*. This observation was obvious especially for *stiffness*; the use of ranks rather than scores implies that for a pair of samples, one is treated as presenting the largest sensation without an estimate of the difference. Hence, panelists felt cotton fabrics *stiffer*, next to untreated PET fabrics, despite some larger differences in the measured stiffness between cotton and untreated PET fabrics. The main distinguishing attributes between class 1 and class 2 were *natural* and *heavy*. It is also evident that treated PET fabrics generally overtook cotton fabrics as the *softest, least crispy,* and *least stiff*. However, panelists still perceived treated PET fabrics as *not natural*. Cotton fabrics also stood out as the least *regular*. This appearance attribute indicates that cotton fabrics present lower surface *evenness* compared to PET fabrics, even after the functional treatment on PET fabrics. However, NaOH treated PET fabrics were perceived more *irregular* than pristine PET fabrics. This can be attributed to the surface alteration as alkali treatment of PET causes partial hydrolysis and at physical etching at the PET surface[139], creating convolutions that might be irregularly distributed.

The perceived enhanced softness after PET NaOH treatment results from the reduced inter-fiber bond strength, enhanced fabric matrix freedom due to lower bending and shear rigidity and reduced yarn pressure at crossover points; which promote flexibility and formability under small forces. Softening of fabrics adds to this flexibility, reducing yarn-yarn friction. As already presented, the perceived *crispness* is lowest in treated PET fabrics, even compared to cotton fabrics. Hence, the judicious choice to control the *crispness* of PET fabrics via *stiffness* was effective.

The global aim of the study, which was to reduce the gap between cotton and polyester woven fabrics, was successfully carried out on two PET fabrics SK and SE. The limitation in experimental controls could have led to the observed increase in the dissimilarity between cotton fabrics and some treated PET fabrics, especially with fabric SA. With series of experiments and subsequent sensory evaluations, optimized process parameters to standardize the reduction in PET-cotton dissimilarities can be achieved.

3.3.5.4 Statistical modeling of crisp with other five descriptors

To model the sensory data, nonlinear regression and partial least squares regression was performed on the six leading descriptors, with *crisp* as the dependent variable. Table 3.12 shows residuals and results for the test of fitness for the obtained models.

Table 3.12 Goodness of fit statistics for variable crisp

Regression	Observations	DF	R²	SSE	MSE	RMSE
Nonlinear regression	20	9	0.985524	0.024066	0.002674	0.05171
Partial least squares (PLS) regression	20	18	0.9150	NA	0.0071	0.841

The corresponding equations of the models are:

$$C = 1.191 + 1.004S - 2.356M + 0.006H + 0.472N - 0.306R - 0.870S^2 + 1.157M^2 - 0.250H^2 + 0.476N^2 + 0.305R^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq\ 3.5$$

(Nonlinear regression)

$$C = 0.426 + 0.308S - 0.309M + 0.272H + 0.146N + 0.062N \ldots\ldots\ldots\ldots... Eq\ 3.6$$

(PLS regression);
where, C is *crisp*, S is *stiff*, M is *soft*, H is *heavy*, N is *natural*, R is *regular*. Considering the residuals for the two models, the R^2 value suggests significant quality and fitting to support the data.

3.3.6 Physical and performance properties of functionalized PET fabrics

NaOH and softening treatment of PET fabrics as an attempt imitate cotton sensory experiences involved several trade-offs which impact on performance and sewing properties of PET fabrics. Fabric properties such as weight, thickness, strength, dimensional stability and cohesiveness are bound to be affected. For instance, too low values of stiffness, formability, and thickness would make it difficult to sew-up garments. Also, pronounced loss in fabric weight would make the final product costly as well as impact on product usability and durability. In this section, the effect on selected performance properties of NaOH and softener treated PET fabrics are reported. A comparison with cotton fabrics was also done for selected properties.

3.3.6.1 Weight loss with NaOH treatment PET fabrics

Following NaOH and softening treatments on SK, SA and SE, the weight and accompanying weight loss of fabrics are presented in Table 3.13.

Table 3.13 Weight and weight loss (%) of functionalized PET fabrics from SK, SA and SE.

	SK fabrics								SA fabrics				SE fabrics	
Fabric	SK10	SK10S	SK15	SK15S	SK20	SK20S	SK25	SK30	SA10	SA10S	SA20	SA20S	SE20	SE30
Weight (g/m^2)	165	170	141	144	141	148	95	80	98	96	68	71	86	85
Temperature	120	120	120	120	120	120	120	120	100	100	100	100	100	100
Weight loss (%)	28	26	39	37	39	35	59	65	35	36	55	53	10	12
Time (mins)	10	10	15	15	20	20	25	30	10	10	20	20	20	30

NaOH concentration was fixed at 3%.

The weight loss increased with treatment time and varied with the fabric structure. The microfiber fabric, which had the lowest basis weight (96 g/m^2) and lowest thickness (0.25 mm), exhibited a much lower weight loss compared to SA (of 150 g/m^2, 0.31) treated at the same temperature and same duration. It thus appears that, fabric weight did not influence the resulting weight losses during NaOH treatment. The yarn and fiber structure might have impacted on the weight loss. Accelerated weight loss occurred with further heating. Application of the softener added insignificant weight to the NaOH treated fabrics. Figure 3.10 shows the variation of weight loss with NaOH treatment time as well as the impact of the softener.

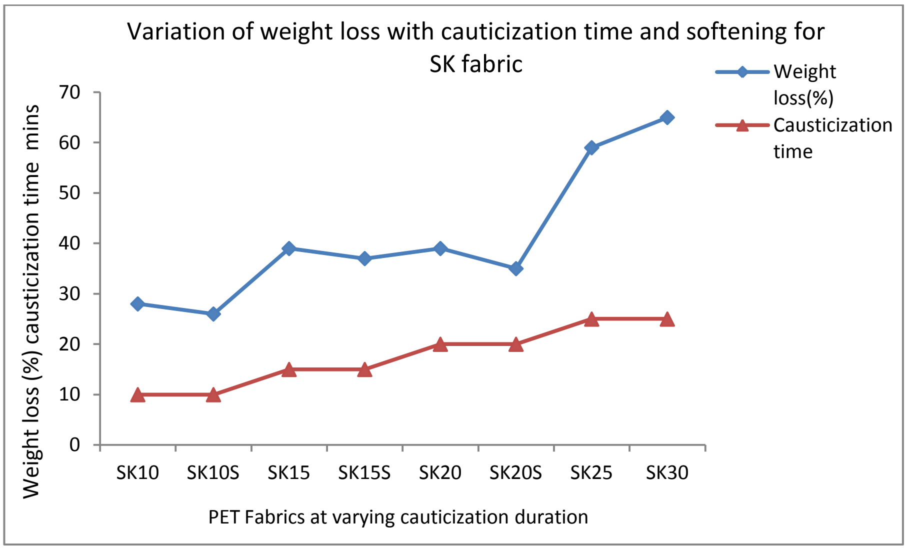


Figure 3.10 Loss in fabric weight with NaOH and softener treatment of SK fabric

In an earlier study, the specific area or thickness of fibers was found to impact on the weight loss during the hydrolysis of polyester fibers with NaOH[140]; and as the process continued, further weight loss depended on the temperature, alkaline concentration, specific area of fiber, and previous treatment or structure of fibers[37–39]. Weight loss of NaOH treated textured PET fabrics was found to vary linearly with treatment time and temperature, and exponentially with concentration. The temperature of the reaction was also found more impactful on weight loss compared to time and concentration.[35] The crystallinity and orientation of polyester fibers have been found to remain unchanged during alkaline hydrolysis[38,141], suggesting that hydrolysis takes place at the fiber surface and thus it is topochemical[33,142]. Weight losses in PET fabrics, during NaOH treatment, can be explained by the pitting into the fabric surface as hydrolysis continues. New surfaces are created with continuous erosion at the fiber surface. Earlier studies[35,39] noted that new surfaces are exposed due to chain scission that leads to dissolution of emerging. The fiber diameter, consequently, gradually diminishes.

Numerous studies on NaOH hydrolysis of PET have emphasized that fabric weight losses are often accompanied by large losses in fabric strength[11,37,143]. Therefore, depending on costs and the final application, the weight loss of fabrics can be a factor of concern to fabric producers. Costs of reagents and input fabric, and performance expectations would have to be considered against the final product. Large weight losses can be utilized in producing top-weight and some bottom weight fabrics that often demand great suppleness, and liveliness.

3.3.6.1 Thickness and surface thickness

The thickness of fabrics is useful during garment make up as it is important for handling purposes as well as for particular applications. The surface thickness of fabrics can give information about the roughness or smoothness of a fabric, and garment sewability. According to the FAST system, fabrics with surface smoothness below 0.2 mm are considered to be smooth. Also, the released surface thickness can help in evaluating the quality of a finish, such as coating; by assessing changes in the surface thickness when in-use testing is carried out. Figure 3.11 presents the thickness and surface thickness of treated and untreated PET fabrics, as well as cotton fabrics.

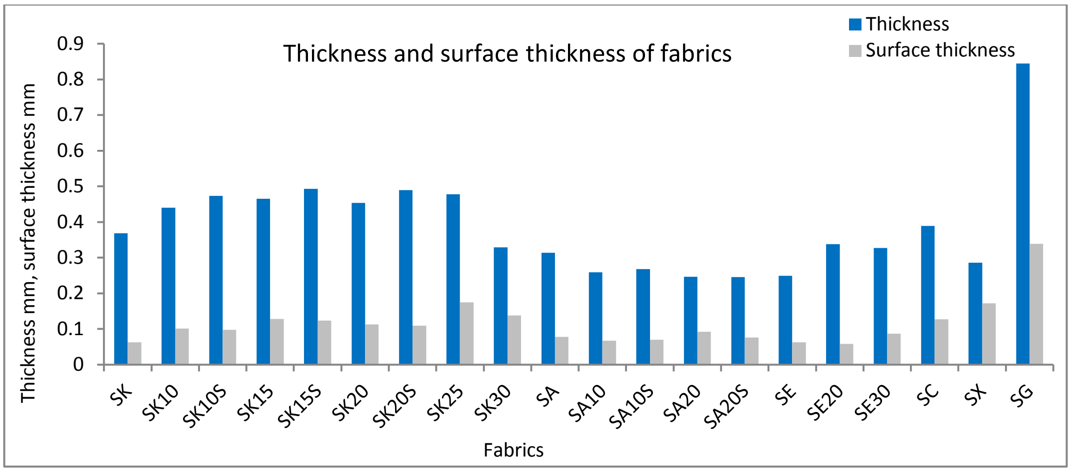


Figure 3.11 Thickness (mm) and surface thickness (mm) of treated and untreated PET fabrics and cotton fabrics

The thickness of SK fabrics increased by between 19% and 33% with NaOH treatment time and weight loss, up to 25 minutes, when it suddenly decreased by 11% at NaOH treatment time of 30 minutes. NaOH treatment of SE also led to an increase in the fabric thickness by about 33% for both treatment times of 20 minutes and 30 minutes. However, the thickness of fabric SA decreased by an average of 20% for all the NaOH treatment durations. The thickness of NaOH treated PET fabrics slightly increased when the softener was added. The surface thickness of PET fabrics generally increased with NaOH treatment time and weight loss, thus. Generally, cotton fabrics had higher surface thickness compared to PET fabrics— indicating that PET fabrics are relatively smoother than cotton fabrics. However, the blended fabric SG had the highest surface thickness. This is expected of fabric SG, being made of spun yarns that are often characterized by short fibers and fuzzy appearance. NaOH treatment of PET fabrics increased the surface thickness to almost that of the cotton fabrics.

The increase in thickness can be explained by the reduced compactness as the fabric swells in the matrix and at the surface, increasing the yarn crimp. Mousazadegan[36] noted that the thickness, at low pressure, of micro fiber fabric treated with NaOH increased with weight loss. The increased thickness is also attributed to bulk resulting from swelling and crimping. Important to note are the variations in the changes of thickness of the PET fabrics with respect to NaOH treatment and weight loss for SA against SK and SE. The micro fiber fabric SE presented increased thickness with NaOH treatment time and low weight loss; also, the twill weave fabric SK recorded a positive linear increase in the thickness, which suddenly dropped after 25 minutes of NaOH treatment. However, SA showed reduced thickness with NaOH treatment time and weight loss. The history of handling/processing of the yarns, and the individual fabrics, such as partial of full orientation of yarns, and other inherent properties might be responsible for the isolated response by fabric SA. Figure 3.12 shows a comparison, for PET fabrics, of the changes in surface thickness with thickness and NaOH treatment time, and therefore, with weight loss.

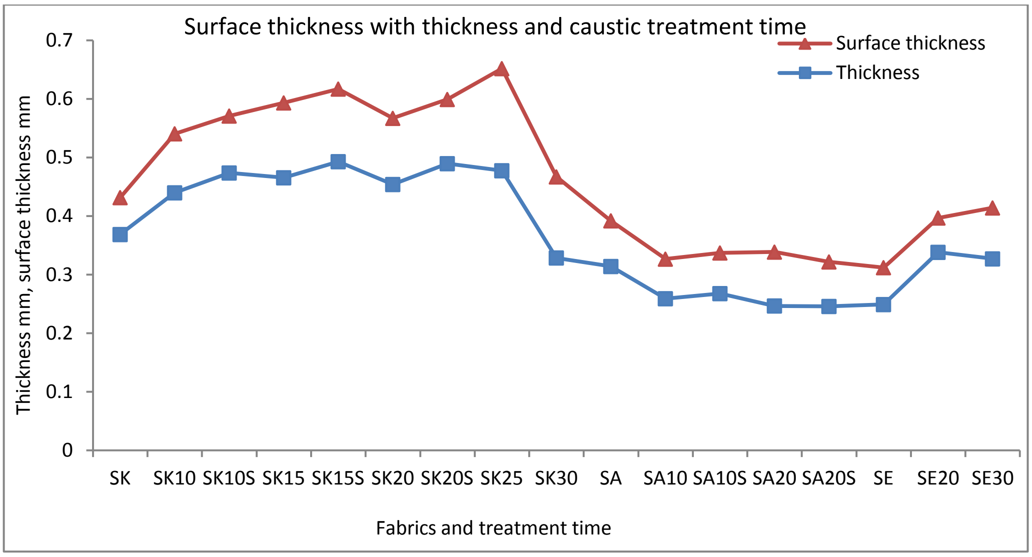


Figure 3.12 Variation of surface thickness (mm) with respect to thickness (mm) of untreated and treated PET fabrics

The drop in the thickness and surface thickness of SK at a certain time of cauticization could result from irreversible degradation of the PET surface. The large weight loss comes with heightened erosion of the PET surface such that upon washing, the surface fibers fall off and leave a much smoother surface, leading to low surface thickness as well. The application of the softener by, and by padding, reduces the surface thickness of NaOH treated PET fabrics. The micro-emulsion silicon softener is able to penetrate into the fabric and yarn matrices, forming a smooth hydrophobic adhesion. During curing, the softener cross-link entraps fibers within its matrix, thus improving the fabric smoothness further. As shown in Figure 3.13, the surface roughness increased with surface thickness, both representing the smoothness or roughness estimate of fabrics.

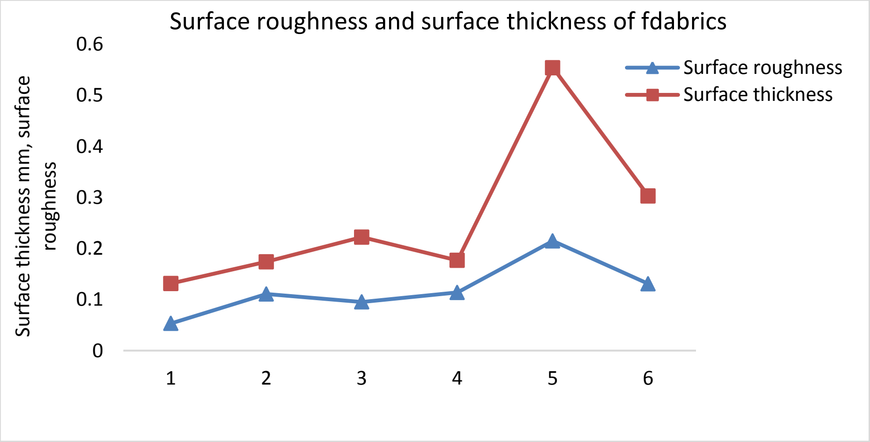


Figure 3.13 Variation of surface roughness with respect to surface thickness of fabrics

3.3.6.2 Abrasion resistance

The abrasion resistance values of PET fabrics after NaOH and softening treatments are shown in Table 3.14. The method records the number of cycles taken to wear a fabric sample by a rotating abrading cloth, denoted in Martindale. The test equipment works in intervals of 5000 cycles totaling the wear number of abrasion cycles that lead to the cloth being worn to a specific degree.

Table 3.14 Abrasion resistance of selected treated and untreated PET fabrics

	SA fabrics				SK fabrics				SE fabrics		
Fabric	SA	SA10	SA20	SA20S	SK	SK20	SK20S	SK30	SE	SE20	SE30
Abrasion resist (Martindale)	23333	1000	1000	1000	50000	46667	25000	4333	21667	20000	20000
CV(%)	12.4	0	0	0	0	12.4	0	26.7	13.3	0	0
Loss (%)	NA	96	96	96	NA	6.7	50	91	NA	7.7	7.7

Following NaOH treatment of SA for 10 and 20 minutes- with a weight loss of 35% and 55% respectively, the abrasion resistance diminished significantly, for both treatment times. According to results in Table 15, addition of the softener to SA20 did not yield quantitative improvement in the abrasion resistance. However, a visual analysis and weighing of specimens after the abrasion resistance test indicated that SA20S performed better than SA20, but lower than SA10. Hence, the addition of the softener did improve the abrasion resistance of NaOH treated fabrics. It should also be noted that a slight pill of the softener could easily be interpreted as a breakage by the automated equipment; making the interpretation unreliable. At a weight loss of 35%, the abrasion resistance of SK remained close to the original value; considering fabric SK20. Figure 3.14 presents a plot of the abrasion resistance for treated and untreated PET fabrics.

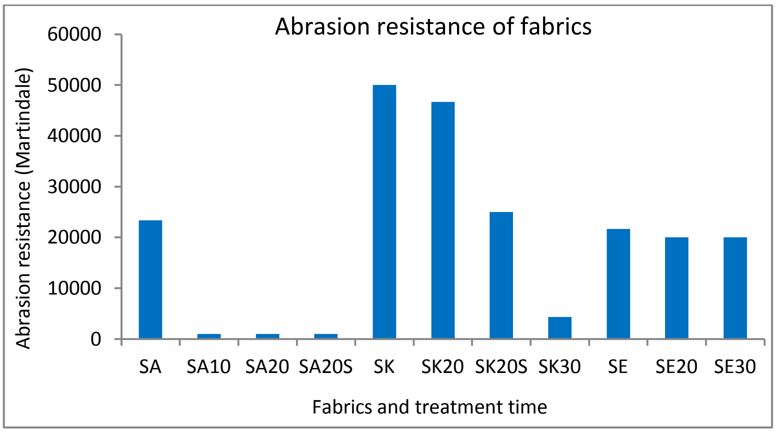


Figure 3.14 Abrasion resistance (Nartindale) of untreated and treated PET fabrics

The lowest abrasion resistance for SK was exhibited at the largest weight loss (65%). Fabric SE exhibited the highest resistance to abrasion, after NaOH treatment, losing about 8% of the original value. It is evident that the abrasion resistance of PET fabrics reduced with weight loss due to NaOH treatment. As hydrolysis of the PET surface takes place, the diameter is also affected, with surface pitting at several points. Hence, the fiber surface is easily eroded, and more susceptible to abrasion with further NaOH treatment. Musale and Shukla[11] recently found similar results about abrasion resistance and weight loss of NaOH treated PET fabrics; However, Dave's group[35] found that the flex abrasion life of fabrics peaked at 8-9% of weight loss after which it sharply decreased as weight loss increased. They argued that at lower levels of weight loss, alkaline hydrolysis erodes the PET filaments' surface with less pitting, exposing a relatively more plastic inner layer, and thereby increases abrasion resistance. At higher weight losses, increased pits at the fiber surface enhance flaws and cracking[144], hence increased abrasion effect. The abrasion resistance was found to vary linearly with weight loss and that fabric thickness was the main determinant in such behavior[36].

3.3.6.3 Bursting strength and strain/elongation at break

The bursting strength was used to estimate the changes in strength of PET fabrics with NaOH and softening treatments. Table 3.15 shows the bursting strength and strain values of selected PET fabrics after NaOH and softening treatments. The strain is a measure of the elongation at the point of break for the fabrics.

Table 3.15 Bursting strength and strain of selected untreated and treated PET fabrics

	SK fabrics				SA fabrics				SE fabrics		
Fabric	SK	SK20	SK20S	SK30	SA	SA10	SA20	SA20S	SE	SE20	SE30
Bursting strength N	1386	800	723	291	306	124	62	58	554	256	223
CV (%)	2.8	5.0	13.1	26.5	13.6	13.5	20.2	16.7	12.6	18.5	16.6
Loss (%)	NA	42	48	80	NA	59	80	81	NA	54	54
Strain (%)	11	7.5	7.9	5.8	7.3	6.8	4.9	3.1	8.4	7.4	7.9

The strength of SK PET fabric decreased by about 57%, and 80% respectively at treatment time of 20 S and 30 S. The strength of SA fabric lowered by 59% and 81% after 10 minutes and 20 minutes respectively, of NaOH treatment. While, the strength of SE degraded by 54% and 81% after NaOH treatment time of 20 minutes and 30 minutes respectively. The rate of strength loss for all PET samples was more pronounced during the initial NaOH treatment times. With softening treatment, the strength of SK20 and SA20 reduced by 10% and 6.5% respectively.

The origin and mechanism of fabric strength degradation due to NaOH treatment is most probably due to hydrolytic scission of ester linkages of the PET chains on the fiber and the spreading of concentrated tensile stress at several flaws/pits on the fiber surface. This, with reducing fiber denier, leads to rupture at much lower total force. Core cavitations may also emerge in fibers— suggesting weakening in the fiber interior. And, in woven PET fabric assembly, sequential tensile ruptures contribute to overall lower fabric strength. The relative fabric strength loss due to NaOH treatment of PET fabrics ranged from magnitudes of 0.9-2.3 times the relative weight loss._A study on alkaline hydrolysis of PET[35] found a linear dependence of strength loss with weight loss and that weight loss and strength loss were very strongly (r= 0.989); weight loss increased faster than weight loss.

3.3.6.4 Fabric extensibility

The changes in the extensibility of PET fabrics after NaOH treatment and softening are shown in Figure 3.15.

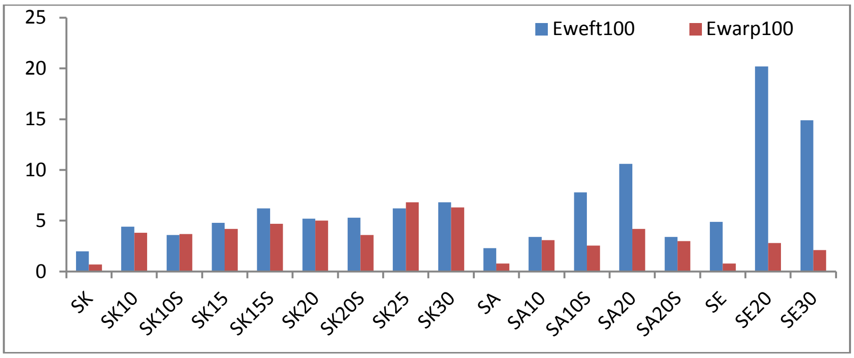


Figure 3.15 Extensibility values for untreated and treated PET fabrics

Fabric extensibility increased with NaOH treatment, more pronounced in the weft direction. This means that PET fabrics became more elastic. The introduction of the softener on already NaOH treated PET generally reduced the extensibility, except for a meager increase, on SK NaOH treated for 15 minutes (SK15S). Fabric extensibility and bending rigidity do affect the formability of fabrics. Particularly, extensibility above 5% has been noted to affect the laying-up, requiring extra work, such as use of pins during sewing. Extensibility also has impact on fabric cutting, sewing and appearance. During laying-up, highly extensible fabric can lead to distorted, stretched or compressed fabric affecting the final cutting. Poor pattern matching has been noted during the sewing of long seams with patterned highly extensible fabric; a hindrance that requires time and costly special approaches. Extensibility below 2% is associated with overfeed moulding during sewing. Moreover, variations in fabric extensibility also affect the consistency of fabric overfeed for seams in automatic overfeed machines. Although designing seams off the weft and warp directions has been found an effective solution[77,125].

3.3.6.5 Air permeability

Results in Figure 3.16 show that air permeability of PET fabrics increased with NaOH treatment; surpassing cotton fabric values. Air permeability increased with NaOH treatment time.

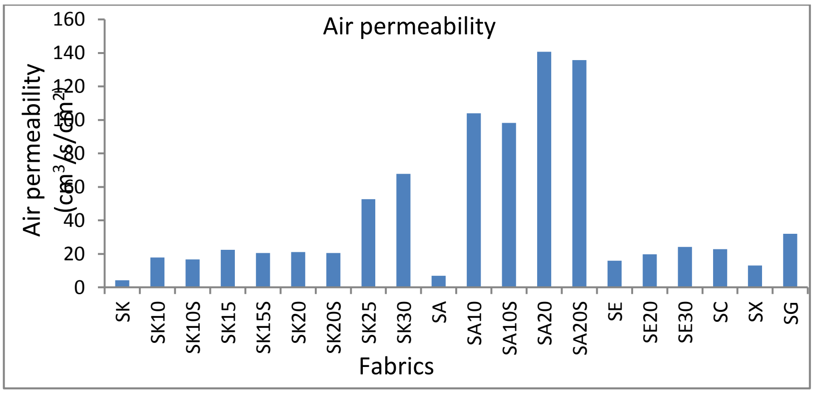


Figure 3.16 Air permeability of PET and cotton fabrics

Since air passes through fabric, the volume of fibers in the fabric matrix is important. When PET fabrics are treated with sodium hydroxide, the fiber/filaments diameter, volume and specific surface reduce[36] yielding a more revealing fabric structure. Inter fiber and inter yarn spaces in the fabric increase; hence, increasing porosity gradually. The air permeability of the fabric consequently increases. However, fabrics may also become too open/loose for other performance properties if the openness is severe.

The softener slightly decreased the air permeability of NaOH treated fabrics as shown by SK10S, SK15S, SK20S, SA10S and SA20S. This decrease may result from softener particles binding onto fiber surfaces and partially blocking some fiber pores within fibers and the fabric matrix. Umut and Sena[4343] found that softeners negatively affected the air permeability of PET knitted fabrics. This was similar to a very recent finding by Badr[145] who studied the effect of several silicon softeners on air permeability of several fabrics. The study also noted that the air permeability reduced with the concentration of the softener, and that micro emulsion softeners had a higher impact compared to macro emulsion softeners. On the other hand, Parthiban and Kumar[146] found less effect on the air permeability of polyester fabrics compared to cotton fabrics when studied after repeated launderings. The exhaustion rate and applied process may contribute to nature of results, with softening treatment.

3.3.6.6 Moisture management properties

Table 3.16 presents moisture management profiles of all PET and cotton fabrics.

Table 3.16 Moisture management/wetting and wicking properties of PET and cotton fabrics

Fabric	TWT (sec)	BWT (sec)	TAR (%/sec)	BAR (%/sec)	TMWR (mm)	BMWR (mm)	TSS (mm/s)	BSS (mm/sec)	AOWTI (%)
SK	3.2	120	40.9	0.0	5.0	0.0	1.5	0.0	-840.9
SK10	2.1	1.8	39.6	56.6	25.0	25.8	8.0	7.7	312.7
SK10S	3.5	120	41.6	0.0	5.0	0.0	1.4	0.0	-808.6
SK15	1.7	1.9	43.9	59.4	24.2	25.8	7.6	7.2	252.7
SK15S	3.4	120	46.4	0.0	5.0	0.0	1.4	0.0	-777.9
SK20	1.8	1.9	31.1	41.0	25.0	25.0	7.7	7.8	177.1
SK20S	3.9	120	42.1	0.0	5.0	0.0	1.3	0.0	-784.2
SK25	2.2	2.3	56.5	68.9	23.0	24.0	5.9	5.1	132.6
SK30	1.7	1.7	57.9	67.5	28.8	28.8	7.2	6.6	100.3
SA	2.9	6.5	38.0	9.8	10.0	10.0	2.2	1.7	-415.7
SA10	2.3	2.5	17.4	48.2	30.0	30.0	4.9	4.8	382.6
SA10S	3.7	10.6	71.5	60.6	8.8	7.5	1.4	0.6	454.6
SA20	2.0	2.2	22.3	41.9	30.0	30.0	6.7	6.5	273.4
SA20S	3.6	7.3	78.9	53.3	10.0	10.0	1.7	1.6	324.0
SE	3.2	9.2	45.4	24.3	21.3	23.8	3.4	3.6	-156.8
SE20	2.2	2.0	53.2	81.8	26.7	26.7	7.0	6.7	168.8
SE30	2.2	2.2	49.6	87.0	28.3	29.2	7.6	6.9	185.7
SC	1.9	1.7	59.2	71.7	30.0	25.0	7.3	7.1	191.4
SX	1.7	1.5	60.5	71.7	25.0	25.8	7.5	7.3	191.8
SG	4.7	5.0	49.1	63.5	18.0	18.0	3.6	3.3	174.4

TWT- Top wetting time, BWT- Bottom wetting time, TAR- Top absorption rate, BAR- Bottom absorption rate, TMWR- Top maximum wetted radius, BMWR- Bottom maximum wetted radius, TSS- Top spreading speed, BSS- Bottom spreading speed, AOWTI- Accumulative one way transport index.

After NaOH hydrolysis, the top and bottom wetting time of all PET fabrics reduced by at least 40%, for all treatment temperatures and time. However, the addition of the softener imparted moisture proofing on SK NaOH treated fabrics such that there was no bottom wetting, for the total test period (120 S). On the other hand, the bottom wetted radius for SA NaOH treated fabrics reduced by over 60% upon addition of the softener, reducing their moisture spreading ability. This indicates that the silicon softener had a hydrophobic or repelling function. Hence, it is preferable to apply such hydrophobic softener after dyeing in case of goods to be colored. Untreated fabrics; SA, SK and SE were graded as: fast absorbing slow drying, water proof, and fast absorbing quick drying respectively, according to the MMT indices. Overall, NaOH treated fabrics, without the softener, were graded as, moisture management, moisture penetration or fast absorbing quick drying fabrics. The accumulative one way transport index for NaOH-treated PET fabrics, without a softener, was comparable to or even higher (better) than cotton fabrics SC and SX, and the blended fabric SG. Therefore, NaOH treatment generally enhanced the wetting and moisture management capability of PET fabrics. Similar to our finding, Parthiban and Kumar[146] also found that wicking properties of PET were negatively affected by silicon softener treatments. A similar study by Chinta and Pooja[147,148] found that the hydrophilic ability of cotton and polyester fabrics decreased as the concentration of silicon softener treatments. Hence, an alternative of using hydrophilic silicon softeners would be preferable.

Some garments such as swim and bathing suits become completely wet while being worn. Also, some localized areas of garments (such as arm pit and groin regions) accumulate high moisture concentrations, compared to other garment parts. Thus, fast wicking and quick drying would be important to keep the wearer comfortable.

The hydrophilicity of sodium-hydroxide-treated polyester fabric has been argued on: (a) enhanced surface roughness, increase in the number of hydrophilic groups on the fiber surface due to chain scission, and increased accessibility of hydrophilic groups on the fiber surfaces due to hydrolysis[142]. Carboxyl and hydroxyls are the eminent hydrophilic groups found in polyester. The ability of polyester fabrics to transmit moisture through in-plane wicking is also improved as carboxyl and hydroxyl groups increase at the surface. Consequently, PET fabrics also attain faster drying ability when treated with NaOH. The imparted hydrophilicility to PET, through NaOH reduction can be attributed to a function of the chemical change in the surface of the fiber. The improved polyester fabric moisture transport and holding properties can also be attributed to the increased porosity of the hydrolysed fabric[149].

In several studies, it has been reported that the moisture-related properties of NaOH treated polyester textiles indicated by water vapor transport, vertical wicking height, water retention liquid water transport, drop absorbency, and contact angle[30,150–154], exhibit significant improvements. However, it has been reported in various research articles[30,35] that the moisture regain of NaOH-treated polyester fabric remains close to that of untreated fabric. Narita and Okuda[149] reported contradicting results; that the moisture regain at 100% relative humidity increased from 0.4% to 1.8%. This was attributed to an increase in carboxyl end-groups of the NaOH-treated polyester from 25.4 to $67 \mathrm{xl0}^6$ mol/g. Shenai and

Nayak[155–157] noted an increase in the moisture regain of polyester fabrics with increasing concentration of alkali, in the presence of quaternary ammonium compounds.

Earlier investigations reported that NaOH-treated polyester fabrics exhibited an increased dyeability which attributed to increased surface area after NaOH treatment[158]. Dave's research team[35] noted that at lower weight loss (1-2%), the dye uptake of NaOH-treated polyester fabrics reduced; the dye uptake increased to match the untreated fabric at 6-10% weight loss, and thereafter, the dye uptake steadily increased. The low dye uptake at lower levels of weight loss was attributed to the removal of some oligomer during the onset of hydrolysis. At higher percentage of weight loss, the fiber surface is etched and pitted further, creating more boundary areas between the dye solution and fibers. A related study on dyeability of NaOH-treated polyester posted conflicting results, noting that the coefficient of diffusion of dye, decreased as weight loss increased[159].

3.4 Conclusions

This study focused on two main areas: (1) the use of sensory analysis to determining the reduced gap between cotton and polyester fabrics following the reduction of the stiffness of polyester fabrics by NaOH and softening treatments; (2) examining the effect of NaOH and softening treatment on PET fabrics.

The attempted functional treatments yielded changes in stiffness properties of fabrics; particularly, the bending length and flexural rigidity. These modifications to PET fabrics were reflected in both objective measurements and subjective sensory evaluations. By the descriptor *natural*, panelists were still able to decipher cotton fabrics from PET fabrics regardless of the functionalization. However, by classification and clustering, some functionalized PET fabrics closely related with cotton fabrics, unlike untreated PET fabrics. The gap between cotton and some PET fabrics was effectively reduced, through the combined function of NaOH and softening treatments. However, for reproducibility, series of trials and careful management of NaOH hydrolysis would be needed.

At different levels of weight loss with NaOH hydrolysis, several properties of polyester are significantly modified. The weight loss has bearing on most performance and surface properties of NaOH hydrolyzed fabrics. While thermal comfort properties (air permeability, wicking and absorption) may improve, reduced strength and abrasion properties might be a concern. The observed increase in thickness of some NaOH treated PET fabrics implies more volume and bulk of fabrics; hence a lofty hand. The silicon softener enhanced the *soft* and *smooth* perception of NaOH-treated polyester fabrics, depicted in the raw ranks. The softener also added hydrophobicity to NaOH-treated PET fabrics.

Although some observed effects of NaOH treatment may be undesirable, the modified fabrics may serve in some clothing such as ladies' tops and night wear where the performance would be acceptable. NaOH hydrolysis and softening treatments are not new phenomenon. The main contribution of this study is the application of these methods to the sensory evaluation and bridging between polyester fabrics and cotton fabrics. Quantification of human perception can thus be utilized in industrial design of fabrics with sensory function.

Chapter 4

Sensory analysis of cotton and polyester knitted fabrics

4.1 Overview

In this chapter, the sensory analysis of knitted fabrics was undertaken, with an aim of comparing results to woven fabrics' sensory patterns. The study focuses on the fabric macro-scale, including a brief look at the impact of the basic physical parameters and structural properties on sensory perception. Ranks of fabrics against sensory attributes were analyzed and relationships between various fabrics and perceived attributes were drawn. Correlations, PCA and AHC were the main tools used in this study. It is deduced that sensory perception of knitted fabrics is divergent from that of woven fabrics. However, mechanical related perceptual attributes are significant in both knitted and woven fabrics.

4.2 Materials and methods

4.2.1 Materials

4.2.1.2 Test fabrics and experimental conditions

Five knitted fabrics (three 100% cotton, two 100% PET) of 20x30 sqcm, as shown in (Figure 4.1) and of basic parameters as shown in Table 4.1 were labeled and then conditioned in standard atmosphere (according to ISO 139:2005 Textiles—Standard atmospheres for conditioning and testing)[106] for 48 hours at 20°C (±2°C) and 65% RH (±4%). The sample fabrics were either bleached or grey (untreated), without coloring or patterning.

Figure 4.1 Pictorial of the five knitted fabrics used in the study

Table 4.1 Basic structure and characteristics of five knitted fabrics used in the study

Fabric	Structure	Wales/ in	Courses/ in	Stitch density(in^{-2})	Thickness (mm)	Weight (g/m^2)	Fiber	Finish
SB	Single Jersey	33	52.2	1723	0.58	1.56	Cotton	None
SI	Interlock	31.4	29.2	917	1.18	2.55	Cotton	None
SF	Single Jersey	38.2	46.6	1780	0.43	1.63	Cotton	Bleach
SZ	Interlock	30	33	990	1.13	2.38	PET	Bleach
SH	Interlock	31.6	35	1106	0.74	2.19	PET	Bleach

4.2.2 Methods

4.2.2.1 Sensory panel, descriptors and sensory evaluation

The sensory panel, sensory descriptors and sensory evaluation were composed of details described in Chapter 2 (section 2.2.2.1). The 12 judges ranked the five knitted fabrics for the 11 sensory descriptors (*Stiff, Soft, Smooth, Heavy, Noisy, Crisp, Stretchy, Drapy, Regular, Natural, and Compact),* in ascending order according to magnitudes of perceived sensations. Ranking of fabrics was done using consensually discussed protocols already explained in 2.2.2.1 and the Appendix.

4.2.2.2 Rank aggregation and rank weighting

The unweighted cross-entropy Monte Carlo (CE) algorithm with Kendall’s tau (CEKnoweight)[109–111] already presented in Chapter 2 (section 2.2.2.2) was used to aggregate the 12 rank lists, for each descriptor. The program below was used in separate runs for each descriptor:
CEKnoweights <- RankAggreg(table_matrix, 5, method="CE", distance="Kendall", N=250, convIn=30, rho=.1). The Borda-Kendall (BK) method[108] was then used to convert ranks into weights.

4.3.3 Significant attributes, dissimilarity, and profiles

Using the percent agreement with PCA and correlation analysis, the number of sensory descriptors was reduced to a significant five. The most distinguishing attribute between cotton and PET knitted fabrics was identified using the squared cosines of variables and factor analysis. At the same time, further relationships and profiles were realized using AHC and PCA. The Euclidean distance between different pairs of knitted fabrics was then computed to estimate the dissimilarity.

4.3 Results and discussion

4.3.1 Ranks and rank aggregation

Table 4.2 shows, in descending order of magnitudes of sensations, the optimal rank lists from the CEKnoweights algorithm, for the 11 descriptors.

Table 4.2 Aggregated rank lists of the five knitted fabrics

Rank	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
1	SI	SH	SH	SI	SI	SI	SI	SF	SF	SI	SI
2	SB	SF	SF	SZ	SB	SB	SZ	SH	SZ	SB	SZ
3	SZ	SZ	SZ	SH	SF	SZ	SH	SZ	SH	SF	SH
4	SH	SB	SB	SB	SZ	SF	SB	SB	SB	SH	SB
5	SF	SI	SI	SF	SH	SH	SF	SI	SI	SZ	SF

For subjective assessment, interlock fabrics presented the largest perception for *heavy*, *stretchy*, and *compact*. Interlock fabrics also ranked high for stiff and crisp, and low for soft. On the other hand, single jersey fabrics were perceived strongly for *soft*, *smooth*, *drapy* and *regular*. The influence of fiber content can be argued by the ranks of fabrics in several permutations where either cotton or PET fabrics are closely ordered. For instance, cotton fabrics led in *stiff*, *noisy*, *crisp* and *natural*, while trailing in *smooth*, *soft*, *regular* and *compact*. For further computations, the fabric ranks transformed in weights by the BK technique are presented in Table 4.3.

Table 4.3 Normalized weights of ranks of five knitted fabrics

Fabric	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
SI	1	0.2	0.2	1	1	1	1	0.2	0.2	1	1
SZ	0.6	0.6	0.6	0.8	0.4	0.6	0.8	0.6	0.8	0.2	0.8
SF	0.2	0.8	0.8	0.2	0.6	0.4	0.2	1	1	0.6	0.2
SB	0.8	0.4	0.4	0.4	0.8	0.8	0.4	0.4	0.4	0.8	0.4
SH	0.4	1	1	0.6	0.2	0.2	0.6	0.8	0.6	0.4	0.6

$$\omega^T(i) = \left\{1, \frac{1}{|T|}\right\}; |T| = 5; \omega^T(i) = 1 - \frac{T_i - 1}{5}; T_i = \{1,5\}$$

4.3.2 Relationship between knitted fabric parameters and subjective evaluation

Table 4.4, presents Spearman's correlation coefficients between descriptors of sensory perception and parameters of the knitted fabrics.

Table 4.4 Correlation coefficients between perceived attributes and knitted fabric parameters

Variables	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
Wales/in	-0.5	0.3	0.3	-0.9	0.1	-0.3	-0.9	0.5	0.3	0.3	-0.9
Courses/in	-0.4	0.3	0.3	-0.9	-0.1	-0.3	-0.9	0.4	0.3	0.0	-0.9
Stitch density	-0.7	0.5	0.5	**-1.0**	-0.2	-0.5	**-1.0**	0.7	0.6	-0.1	**-1.0**
Thickness	0.7	-0.5	-0.5	**1.0**	0.2	0.5	**1.0**	-0.7	-0.6	0.1	**1.0**
Weight	0.4	-0.3	-0.3	0.9	0.1	0.3	0.9	-0.4	-0.3	0.0	0.9

Descriptors *heavy*, *stretchy*, and *compact* were very strongly associated with all the five knitted fabric parameters in Table 4.4. *Noisy* and *natural* were hardly associated with any fabric parameters. Hand and visual descriptors- *soft*, *smooth*, *crisp*, *drapy* were mainly associated with stitch density and thickness. The wales per inch were averagely correlated with *stiff* and *drapy*. It appears that compared to the fiber content, the structure of knitted fabrics has more influence on sensory perception of knitted fabrics.

4.3.3 Significant sensory descriptors

To reduce the number of sensory descriptors to a few most significant, the percent agreement and correlation analysis were used. The F1 variability (percent agreement) extracted from PCA performed on fabrics/assessors for each descriptor is shown in Table 4.5

Table 4.5 Percent agreement of sensory descriptors

Descriptor	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
%agreement	65	74	82	68	78	69	63	70	56	68	68

A summary of Pearson correlation coefficients between sensory attributes is also shown in Table 4.6.

Table 4.6 Proximity matrix (Pearson correlation coefficient) of descriptors

	Stiff	Soft	Smooth	Heavy	Noisy	Crisp	Stretchy	Drapy	Regular	Natural	Compact
Stiff	1.0	-0.9	-0.9	0.7	0.7	0.9	0.7	-1.0	-0.9	0.6	0.7
Soft	-0.9	1.0	1.0	-0.5	-0.9	-1.0	-0.5	0.9	0.7	-0.7	-0.5
Smooth	-0.9	1.0	1.0	-0.5	-0.9	-1.0	-0.5	0.9	0.7	-0.7	-0.5
Heavy	0.7	-0.5	-0.5	1.0	0.2	0.5	1.0	-0.7	-0.6	0.1	1.0
Noisy	0.7	-0.9	-0.9	0.2	1.0	0.9	0.2	-0.7	-0.6	0.9	0.2
Crisp	0.9	-1.0	-1.0	0.5	0.9	1.0	0.5	-0.9	-0.7	0.7	0.5
Stretchy	0.7	-0.5	-0.5	1.0	0.2	0.5	1.0	-0.7	-0.6	0.1	1.0
Drapy	-1.0	0.9	0.9	-0.7	-0.7	-0.9	-0.7	1.0	0.9	-0.6	-0.7
Regular	-0.9	0.7	0.7	-0.6	-0.6	-0.7	-0.6	0.9	1.0	-0.7	-0.6
Natural	0.6	-0.7	-0.7	0.1	0.9	0.7	0.1	-0.6	-0.7	1.0	0.1
Compact	0.7	-0.5	-0.5	1.0	0.2	0.5	1.0	-0.7	-0.6	0.1	1.0

By concurrently considering the percent agreement, the correlation coefficients between pairs of descriptors, and the objective measurability of the sensory attributes, five descriptors were retained for further computations. When two descriptors were strongly positively correlated, the descriptor with the largest variability would be retained. However, the possibility that such a descriptor could be measured or expressed objectively was also considered. The descriptors- *Stiff, smooth, heavy, drapy,* and *natural* were subsequently retained.

To identify the most distinguishing perceived sensory attribute, the Eigen decomposition of PCA for the five attributes was analyzed. The factor loadings and squared cosines of descriptors were then computed (Table 4.7).

Table 4.7 Squared cosines and factor loadings of the significant descriptors

	Squared cosines		Factor loadings	
Descriptor	F1	F2	F1	F2
Stiff	**0.9685**	0.0062	**0.9841**	0.1328
Smooth	**0.8805**	0.0292	**-0.9384**	0.2145
Heavy	**0.4784**	0.4514	0.6917	-0.0863
Drapy	**0.9685**	0.0062	**-0.9841**	-0.1328
Natural	**0.4740**	0.4443	0.6885	-0.0007

Values in bold correspond for each descriptor to the factor for which the factor loading and squared cosine is the largest

Descriptors *stiff* and *drapy* accounted for the largest variability of PCA. This finding is similar to an earlier one in woven fabrics in which hand properties were more significant. Hence, towards replacement with polyester, a precise profile would be needed to determine the direction of modification of the drape or stiffness of PET knitted fabrics.

4.3.4 Clustering and dissimilarity of knitted fabrics

The biplot in Figure 4.2 shows the clustering of the knitted fabrics with sensory attributes on principal factors F1 and F2.

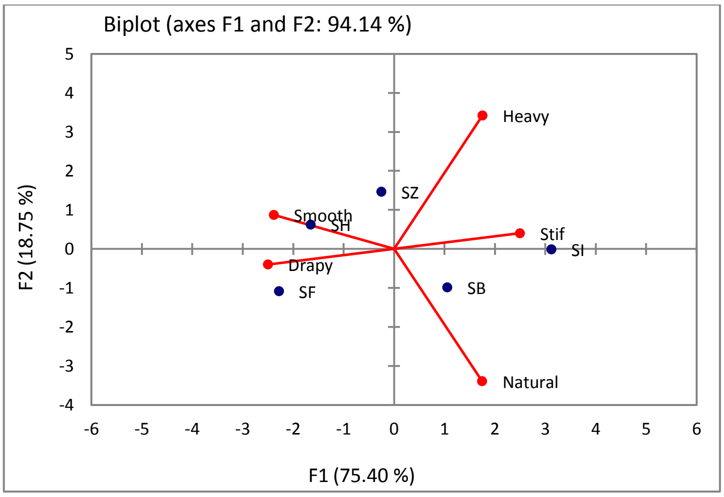


Figure 4.2 Biplot of five knitted fabrics and five sensory descriptors

With F1 and F2 accounting for 94% of variability, two factors were sufficient to represent the knitted fabrics' data. Except SZ, all the other fabrics contributed largely on F1. Cotton fabrics SB and SI are grouped together and share common attributes— *natural* and *stiff*. While, cotton fabric SF is grouped closer with PET fabric SH for *drapy* and *smooth* perceptions. SB is a single jersey while SI is an interlock structure. SF is a single jersey while SH is an interlock fabric. This implies that the structure had no obvious influence on the sensory clustering of the knitted fabrics. The fiber content and other physical parameters, especially thickness and weight were significant. A factor for clustering cotton fabric SF with PET fabric SH could arise from the added finishing (bleaching) that adds luster and further softness to fabrics, which could enhance the perception of drape and smoothness. It is also possible for a bias by assessors due to the difference in appearance between cotton fabrics SI and SB and the rest of the fabrics.

The Euclidean distance (Table 4.8) shows the dissimilarity between different pairs of fabrics, by subjective sensory evaluation.

Table 4.8 Proximity matrix (Squared Euclidean distance)

Fabric1	SI	SI	SI	SF	SZ	SB	SZ	SI	SZ	SF
Fabric2	SF	SH	SZ	SB	SF	SH	SB	SB	SH	SH
Dissimilarity	1.56	1.37	1.08	0.98	0.94	0.94	0.80	0.72	0.57	0.57

SB, SI, SF- 100% Cotton, SH,SZ- 100% PET

The largest dissimilarity between cotton and PET knitted fabrics exists between SI and SH. The dissimilarity between different fabrics can be reduced by profiling fabrics with sensory attributes in order to determine the direction of modification. AHC profiles of the five fabrics are presented in Figure 4.3.

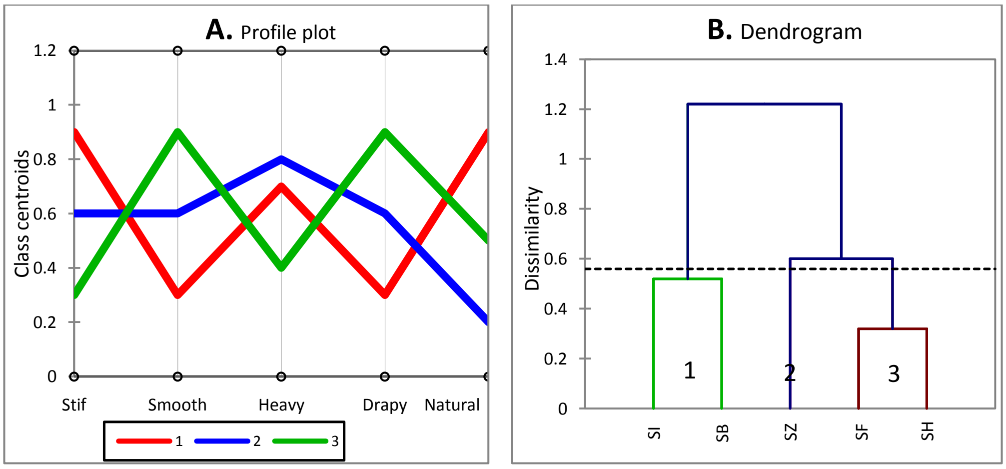


Figure 4.3 Sensory profiles (**A**) and a dendrogram (**B**) from subjective evaluation of the five knitted fabrics

Unlike cotton woven fabrics, cotton knitted fabrics were ranked and profiled highest for *stiff*, and lowest for *drapy* and *smooth*. Also, PET knitted fabrics ranked highest for *drapy* and *smooth*, and lowest for *stiff* unlike with PET woven fabrics. Hence, approaches towards the replacement of cotton with polyester would be different when considering woven fabrics and knitted fabrics. For instance, while the reduction of the stiffness of PET woven fabrics was suggested, an increase in the stiffness would be the approach for PET knitted fabrics. It can be deduced that the sensory perception of woven fabrics is different from the sensory perception of knitted fabrics. Via vision and touch, PET knitted fabrics can be distinguished from cotton knitted fabrics.

4.4 Conclusions

A sensory study of knitted fabrics was undertaken. In addition to the fiber content, the knitted fabric structure and physical properties are argued to influence the sensory perception of knitted fabrics. Perceived sensory attributes of knitted fabrics were found to mostly correlate with the stitch density and thickness. Similar to woven fabrics, the visual and hand attributes were found dominant and significant in differentiating between polyester and cotton knitted fabrics. The sensory perception of knitted fabrics was noted to be distinct from that of woven fabrics. Towards the replacement of cotton fiber with polyester, the modification (increase) in the stiffness or drape of PET knitted fabrics has been suggested.

Chapter 5

Subjective Vs objective valuation of cotton and polyester woven fabrics

5.1 Overview

Previous studies have largely focused on the effect of fabric construction, finishing and mechanical properties on the perception of selected sensory properties. Less emphasis has been directed towards the influence of fiber content on sensory properties of fabrics. This study focuses on the relationship between subjectively evaluated sensory attributes and objectively measured parameters that relate to sensory behavior of PET and cotton woven fabrics. Correlation analysis and classification to compare subjective and objective evaluation was performed. This study utilized sensory evaluation descriptors, fabric samples, protocols and some data already presented in Chapter 2. Through correlation analysis, only a few sensory attributes were found to be precisely expressed by instrumental measurements. Particularly, hand attributes were more expressed by fabric mechanical and surface attributes. It is deduced that human perception cannot be directly represented by instrumental measurements. The profiling of fabrics indicates that conventional PET fabrics can be distinguished from conventional cotton fabrics using selected subjective and objective attributes.

5.2 Materials and Methods

5.2.1 Materials

5.2.1.1 Woven fabric samples

The six woven fabric samples used in this analysis, and their specifications have been presented in Chapter 2 (section 2.2.1.1; Table 2.1 and Figure 2.1); cotton fabrics- SC and SX; PET fabrics- SA, SK and SE; and cotton/polyester blended fabric SG

5.2.2 Methods

5.2.2.1 Sensory panel and sensory data

The sensory panel described in Chapter 2 (section 2.2.2.1) and the ensuing aggregated rank lists as presented in section 2.3.2, were used in this chapter. Table 2.3 in Chapter 2 was referred to for this analysis.

5.2.2.2 Objective measurements related to sensory perception

5.2.2.2.1 Bending length and flexural rigidity

The bending length of fabrics was determined using the Cantilever bending principle described in British Standard- BS3356[127] and ASTM D1388-14e1[128]; methods for determining the bending length and flexural/bending rigidity of fabrics. A KFG-2000 Cantilever device (JA King, Charlotte, NC) was used to measure the bending length in the warp and weft directions. The rigidity was computed from the formula in Eq 5.1, for both the warp and weft directions:

$$G = MC^3 \times 9.81 \times 10^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq\ 5.1$$

where G is the flexural rigidity (μNcm), M is the fabric mass per unit area (g/m^2), and C is the bending length (mm).

5.2.2.2.2 Elongation/ extensibility

The fabric elongation was measured as extensibility, both in the warp and weft directions, using the method and device already described in Chapter 3; (section 3.3.11.5).

5.2.2.2.3 Drape coefficient

Drape is used to describe how a fabric or garment hangs and shapes gracefully under its own weight. Fabric drape is a pertinent fabric feature, that affects clothing appearance and comfort attributes such as handle. The drape coefficient is used to express the drape of fabrics. The standard method BS5058, 1974[160,161] was used to determine the drape coefficient, using a Cusick Drapemeter (Rotrakote Converting Limited, New York, N.Y). In this method, a form of overhead projector is used. A 10-in-diameter fabric specimen is draped over a 4-in-diameter circular platform. A shadow of the specimen shape is then cast by light and a lens situated below the specimen. The image is then traced onto a paper and cut out. The Drape coefficient is expressed as the percentage of the area of the annular ring of fabric (less the supporting ring) obtained by vertically projecting the shadow of the drape specimen (less the supporting ring). Some recent studies have used digital methods with image processing and reported results statistically comparable to those obtained by conventional drape testing[161–164].

5.2.2.2.4 Roughness and waviness coefficients

The surface texture was characterized by the waviness and roughness coefficients (RC and WC respectively) on a five 5 sq cm samples using a 3D surface profiler— Profilm3D (Filmetrics, San Diego, CA).

5.2.2.2.5 Warp density, weft density and weave density

The warp, weft and weave densities were computed from the equations below:

$$Warp\ density = Ei * \sqrt{(Warp\ count * 1.22)} \ldots\ldots\ldots\ldots\ldots Eq\ 5.2$$

$$Weft\ density = Pi * \sqrt{(Weft\ count * 1.22)} \ldots\ldots\ldots\ldots\ldots Eq\ 5.3$$

$$Weave\ density = Warp\ density + Weft\ density \ldots\ldots\ldots Eq\ 5.4$$

5.2.2.2.6 Fabric weight

The fabric weight was determined using ASTM D3776 / D3776M- Standard Test Methods for Mass per Unit Area (Weight) of Fabric, option A.

There were no objective measurements related to the descriptors *natural* and *noisy*

5.2.2.2.7 Ranking of fabrics with objective measurements

For each measured parameter, the six fabrics were ranked, in descending order according to the magnitude. Then, weights were computed for each fabric, for each parameter according to the position/rank in the rank lists.

5.3 Results and discussion

5.3.1 Objective measurements

Table 5.1 and Table 5.2 show results of objectively measured fabric parameters. Weights of ranks of fabrics are based on magnitudes of objective measurements.

Table 5.1 Characteristics of the six fabrics measured objectively

Fabric	C1	C2	Ei	Pi	D1	D2	WD	Th	Wt	FM	FC	EM	EC	DC	RC	WC	BC	BM
SA	31	28	76	65	467	380	847	0.28	149	3.56	2.30	13.3	21.6	0.77	0.05	0.07	2.49	2.88
SK	38	38	97	53	660	361	1021	0.33	230	8.97	3.51	13.4	26.1	0.72	0.11	0.15	2.48	3.39
SC	19	20	84	75	366	335	702	0.35	136	2.39	1.17	5.3	20.0	0.51	0.10	0.12	2.05	2.60
SE	18	10	103	65	483	227	710	0.17	94	1.30	0.64	18.6	28.3	0.63	0.11	0.14	1.89	2.40
SG	36	32	98	102	597	586	1182	0.76	258	5.18	3.46	13.6	8.8	0.59	0.22	0.26	2.39	2.74
SX	21	20	82	81	376	362	738	0.22	131	1.25	1.37	9.7	15.8	0.55	0.13	0.17	2.19	2.12

C1- Warp Tex, C2- Weft Tex, Ei- Ends/inch, Pi- Picks/inch, D1-Warp density, D2-Weft density, WD- Weave density, Th- Thickness (mm), Wt- Weight (g/m2), FM- Flexural rigidity (mNcm) in the warp direction, FC- Flexural rigidity (mNcm) in the weft direction, EM- Elongation (%) in the warp direction, EC- Elongation (%) weft direction, DC- Drape coefficient, RC- Roughness coefficient, WC- Waviness coefficient, BC- Bending length (cm) in the weft direction, BM- Bending length (cm) in the warp direction

Table 5.2 Weighted and normalized ranks ($\omega^T(i)$) of fabrics using objectively measured parameters

Fabric	T1	T2	Ei	Pi	D1	D2	WD	Th	Wt	FM	FC	EM	EC	DC	RC	WC	BC	BM
SA	0.67	0.67	0.17	0.33	0.50	0.83	0.67	0.50	0.67	0.67	0.67	0.50	0.67	1.00	0.17	0.17	1.00	0.83
SK	1.00	1.00	0.67	0.17	1.00	0.50	0.83	0.67	0.83	1.00	1.00	0.67	0.83	0.83	0.50	0.67	0.83	1.00
SX	0.50	0.50	0.33	0.83	0.33	0.67	0.50	0.33	0.33	0.17	0.50	0.33	0.33	0.33	0.83	0.83	0.50	0.17
SE	0.17	0.17	1.00	0.50	0.67	0.17	0.33	0.17	0.17	0.33	0.17	1.00	1.00	0.67	0.67	0.50	0.33	0.33
SC	0.33	0.33	0.50	0.67	0.17	0.33	0.17	0.83	0.50	0.50	0.33	0.17	0.50	0.17	0.33	0.33	0.17	0.50
SG	0.83	0.83	0.83	1.00	0.83	1.00	1.00	1.00	1.00	0.83	0.83	0.83	0.17	0.50	1.00	1.00	0.67	0.67

C1- Warp Tex, C2- Weft Tex, Ei- Ends/inch, Pi- Picks/inch, D1-Warp density, D2-Weft density, WD- Weave density, Th- Thickness (mm), Wt- Weight (g/m2), FM- Flexural rigidity (mNcm) in the warp direction, FC- Flexural rigidity (mNcm) in the weft direction, EM- Elongation (%) in the warp direction, EC- Elongation (%) weft direction, DC- Drape coefficient, RC- Roughness coefficient, WC- Waviness coefficient, BC- Bending length (cm) in the weft direction, BM- Bending length (cm) in the warp direction; $\omega^T(i) = \left\{1, \frac{1}{|T|}\right\}; |T| = 6; \omega^T(i) = 1 - \frac{T_i - 1}{6}; T_i = \{1,6\}$

5.3.1 Correlation between objective and subjective attributes

Table 5.3 shows correlations between instrumental and human evaluation.

Table 5.3 Correlation between objective measurements and descriptors of human sensory perception

Objective/ Sensory	Stiff	Soft	Smooth	Heavy	Crisp	Stretchy	Drapy	Regular	Compact
C1									**0.60**
C2									**0.60**
FM	**0.54**	**-0.94**			0.26				
FC	0.26	**-0.77**			0.26				
BC	0.49	**-0.71**			**0.54**				
BM	**0.77**	**-1.00**			0.49				
RC			**0.54**						
WC			0.37						
Wt				**0.9429**					
EM						-0.37			
EC						0.37			
DC							**-0.83**		
RC								0.03	
WC								-0.09	
D1									0.49
D2									0.09
WD									0.49

C1- Warp Tex, C2- Weft Tex, Ei- Ends/inch, Pi- Picks/inch, D1-Warp density, D2-Weft density, WD- Weave density, Th- Thickness (mm), Wt- Weight (g/m2), FM- Flexural rigidity (mNcm) in the warp direction, FC- Flexural rigidity (mNcm) in the weft direction, EM- Elongation (%) in the warp direction, EC- Elongation (%) weft direction, DC- Drape coefficient, RC- Roughness coefficient, WC- Waviness coefficient, BC- Bending length (cm) in the weft direction, BM- Bending length (cm) in the warp direction

Softness, stiffness, elasticity and smoothness define fabric hand [165]. In this study, the descriptor *stiff* was associated with stiffness properties of fabrics. As shown in Table 5.3, only the bending length in the warp direction (BM) and the flexural rigidity in the warp direction (FM) were significantly correlated (r=0.77 and r=0.54 respectively) to the descriptor *stiff*. The weights of *stiff* increased as the values of BM and FM increased. PET fabrics were generally perceived and measured stiffer compared to cotton fabrics.

The descriptor *soft* was also associated with stiffness properties of fabrics. From Table 5.3, it is also evident that there was strong negative correlation between the perception of *soft* and all the measured stiffness properties; BM, BC, FM, and FC. Objective and subjective evaluations generally presented PET fabrics, except microfiber fabric SE, as stiffer and least soft than cotton fabrics. The ranking of the cotton/polyester blended sample SG by subjectivity presented the largest variation among objective measurements and human evaluation.

Representing the surface texture, the fabric roughness and waviness coefficients were related to the descriptor *smooth.* RC was more correlated (r=0.54) to *smooth* compared to WC (r=0.37). The ordinal ranking of fabrics for descriptor *smooth* listed cotton fabrics and the microfiber fabric SE as the *smoothest* compared to conventional PET fabrics SA and SK. Contrastingly, the roughness and waviness measures had a random listing, with some cotton fabrics exhibiting more roughness than PET fabrics. However, the roughness and waviness measurements were closely related with r= 0.94.

Fabric weight was used to directly assess the perceptual evaluation of the descriptor *heavy*. With a correlation coefficient of 0.94, it is deduced that assessors' perception of *heavy* was representative of objective measurements. Moreover, the actual rank lists of fabrics by descriptor heavy and the objective measurement (weight) were very close. Thus, fiber content was of inferior significance on the perception of weight.

The descriptor *crisp* was also associated with stiffness properties of fabrics in the warp and weft directions. Only the bending length in the weft direction (BC) was significantly correlated (r=0.54) to the descriptor *crisp*. Correlations between *stiff* and other stiffness properties were insignificant. Therefore, objective measurements of stiffness were not representative of the perception by the panelists.

Elongation measurements in the warp and weft directions (EM and EC) were used to evaluate the descriptor *stretchy.* Findings show that there was low correlation between the measured values and the human perception of *stretchy*. Moreover, the fabric ranks for elongation measured in the warp and weft directions were also different. Due to several interlacing points in plain weaves, threads in plain weave fabrics portray extra length and stretch compared to twill weaves.

Behery[165,166] reported about correlations between human perception of hand attributes and objective measurements, considering different cotton and cotton/polyester blended fabrics. The tensile linearity was negatively correlated with the perception of softness, silkiness, smoothness, and thickness. Bending rigidity was highly positively correlated with the perception of stiffness, crispness, hardness and harshness. Fabrics with the highest cotton proportion in the blend ratio presented the highest general hand factor (GHF). Correlation among measured sensory attributes indicated that both shear rigidity and shear hysteresis

were highly correlated with weight and surface roughness, and negatively correlated with compression resilience. The roughness (static friction coefficient) of plain fabrics increased with the weft density.
Table 5.3 further shows that mechanical properties associated with hand, varied in different directions. Bending rigidity has previously been reported to vary in the warp and weft direction of the fabric due to variations in the warp and weft densities. Particularly, the warp density is often higher than the weft density, for example, bending rigidity in denim fabric can be different in the warp and weft directions [167]. Yarn fineness may also differ for the weft and warp, leading to different hand profiles in the two fabric direction. Chen et al[168] reported low values of roughness for plain weave silk and satin structure, but slightly different in warp and weft directions.

The correlation coefficient between the descriptor *drapy* and the drape coefficient (DC) was highly significant (r=-0.83). Fabrics with higher drape coefficients were perceived less *drapy*; the draping quality of fabrics lowers with drape coefficient. This implies that subjectively perceived drape was closely related to measured drape values. This result is similar to findings by a number of studies[169–174]; drape values obtained instrumentally had significant correlation with subjective evaluation. Fabric drape has been found to depend on fabric, yarn and fiber properties. Other factors include, the environmental conditions as well as the shape of the wearer/object[175]. The current study noted that cotton fabrics exhibited lower DC and were subjectively perceived strong for *drapy* compared to PET fabrics. This study thus underscores the influence of fiber content on the drape coefficient as well as on the human perceived drape of fabrics. For example, PET micro fiber fabric SE had lower values of flexural rigidity and bending lengths compared to some cotton fibers; however, the drape coefficients for all cotton fabrics, and the cotton/PET blended fabric were still lower than for SE. Similar findings on fiber content and drape were reported elsewhere[175,176]. Ning's group [177] classed 40 fabrics into three categories, according to their drape coefficient: 15 of pure cotton, 19 of cotton blend, and 6 synthetics fibers (5 PET and 1rayon). The resulting correlations were: r = 0.838 within the pure cotton group, r = 0.554 for the cotton blend group and r = 0.545 for the synthetic group. They concluded that fabric linear density was a better parameter to classify fabrics based on fabric parameters influencing drape, compared to fiber content. Other studies recorded that the drape coefficient highly correlates with; bending length and shear stiffness [170], fabric weight and shear hysteresis[178], bending rigidity and weight[179] and bending resistance[173].

The surface waviness and roughness were also used to evaluate the descriptor *regular*. In the evaluation protocol, *regular* was also defined as *even.* Computed correlations indicate that there was a negligible correlation relationship between the measured values and the perceived sensations for *regular* by panelists. The descriptor *compact* was associated with the yarn count and the fabric weave properties; warp/weft density, and weave density. These attributes also represent the fabric cover factor. The warp density and the weave density presented low correlations, below average, with the perceived sensation for *compact*. The weft density, however exhibited very low correlation with the human perception of *compact*. However, the linear density of yarns was more related to the perception of compactness. The correlation coefficient between *compact* and the warp count and weft count (Tex) was significant (r=0.6). Descriptors *Natural* and *noisy* could not be represented with measurable attributes. The closest objective representation of *natural* would be by the percentage of cotton fiber content. However, five fabrics had ties in the cotton or PET fiber composition.

5.3.2 Sensory clustering and profiling by subjective versus objective data

Considering the nine sensory descriptors used to identify sensory objective measurements, PCA was carried out. Similarly, PCA was performed on objective measurements that represent fabric sensory behavior. Table 5.4 shows the main principal components needed to attain at least 80% of variability.

Table 5.4 Summary of variability of subjectively and objectively measured sensory parameters

PCA parameter	Subjective PCA		Objective PCA		
	F1	F2	F1	F2	F3
Eigenvalue	4.51	2.96	8.56	4.28	3.09
Variability (%)	50.09	32.85	47.55	23.77	17.17
Cumulative %	50.09	82.94	47.55	71.31	88.48

Table 5.4 shows that the PCA variability was more significant with subjective data. Only F1 and F2 were sufficient for subjective evaluation, compared to objective evaluation, where three principal factors were needed. The analysis of significant attributes was done by the squared cosines of variables (Table 5.5 and Table 5.6), from PCA.

Table 5.5 Squared cosines of subjectively assessed sensory attributes

	Stiff	Soft	Smooth	Heavy	Crisp	Stretchy	Drapy	Regular	Compact
F1	**0.86**	**0.86**	**0.84**	0.12	**0.51**	**0.48**	**0.79**	0.04	0.01
F2	0.02	0.12	0.07	**0.85**	0.37	0.14	0.11	**0.79**	**0.49**

Figures in bold indicate values for which the squared cosine is largest at p=0.05

From Table 5.5, it is evident that the descriptors of fabric hand (*stiff* and *soft*) are the most significant, followed by heavy. Table 5.6 presents squared cosines of objective measurements.

Table 5.6 Squared cosines of objectively evaluated fabric properties

	C1	C2	Ei	Pi	D1	D2	WD	Th	Wt	FM	FC	EM	EC	DC	RC	WC	BC	BM
F1	**0.94**	**0.94**	0.00	0.04	**0.55**	**0.46**	**0.88**	0.31	**0.85**	**0.80**	**0.94**	0.07	0.04	0.29	0.01	0.11	**0.66**	**0.69**
F2	0.00	0.00	0.03	**0.90**	0.02	0.18	0.04	0.18	0.04	0.04	0.00	0.01	**0.76**	**0.50**	**0.64**	**0.61**	0.11	0.21
F3	0.01	0.01	**0.80**	0.00	0.43	0.11	0.03	0.10	0.03	0.00	0.01	**0.82**	0.19	0.04	0.30	0.18	0.02	0.01

Figures in bold indicate values for which the squared cosine is largest at p=0.05

Table 5.6 shows that among the measured attributes, the warp and weft linear density (C1 and C2 respectively), and the flexural rigidity were the most significant. In relation to the human evaluated sensory attributes, the flexural rigidity, which is a hand attribute, may represent descriptors *soft* and *stiff*. Thus, hand attributes were significant by both human perception and objective measurements.

5.3.3 Clustering of fabrics by subjective and objective evaluation

5.3.3.1 Proximity measure (Euclidean distance)

Table 5.7 shows the Euclidean distance between pairs of fabrics by both subjective evaluation data and objective measurements.

Table 5.7 Euclidean distance between pairs of fabrics by objective and subjective evaluation

Fabric 1	SA	SK	SA	SK	SK	SE	SX	SA	SK	SA	SE	SX	SA	SX	SC
Fabric 2	SX	SX	SG	SE	SG	SG	SG	SE	SC	SC	SC	SC	SK	SE	SG
EDS	1.71	1.71	1.65	1.55	1.53	1.51	1.38	1.31	1.20	1.18	1.03	1.01	1.00	0.80	0.71
EDO	1.73	2.12	1.93	2.19	1.53	2.39	1.79	2.01	2.19	1.74	1.62	1.26	1.28	1.60	2.18

EDS- Euclidean distance from subjective evaluation, EDO- Euclidean distance from objective evaluation

Data on the Euclidean distance shows a general variation in values obtained from the two approaches. The maximum and minimum Euclidean distances were different, and between different pairs of fabrics, for each fabric evaluation method. For example, the maximum Euclidean distance recorded under objective evaluation was 2.39 (between SE and SG); compared to 1.71 (between SA and SX, and between SK and SX). Pearson correlation coefficient between EDS and EDO was 0.31.

The two distances, EDS and EDO were modeled by linear regression (Eq 5.4), with a resulting R^2 of 0.11 and p-value 0.23 (significance level 5%):

$$EDS = 0.712 + 0.312 * EDO \ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq\ 5.4$$

The test for significance and goodness of fit indicate that this linear regression model is weak. The PCA clustering by subjective data shows that fabrics are generally clustered by their fiber composition, except for modified fabrics SE and SX. Figure 5.1 shows the proximity and clustering of fabrics by objective and subjective data.

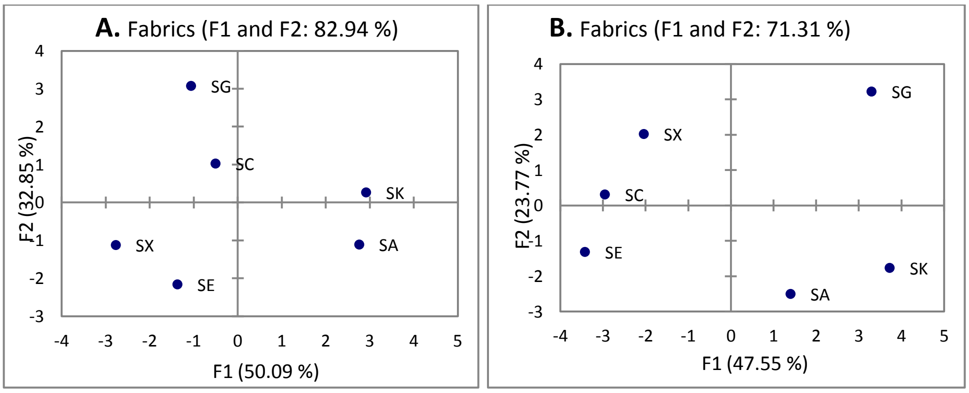


Figure 5.1 PCA clustering and proximity of fabrics: **A**- by subjective evaluation, **B**- by objective evaluation

5.3.3.2 Sensory profiles by subjective and objective evaluation

Figure 5.2 and Figure 5.3 show profile plots and dendrograms from AHC, for subjective and objective evaluation of the fabrics.

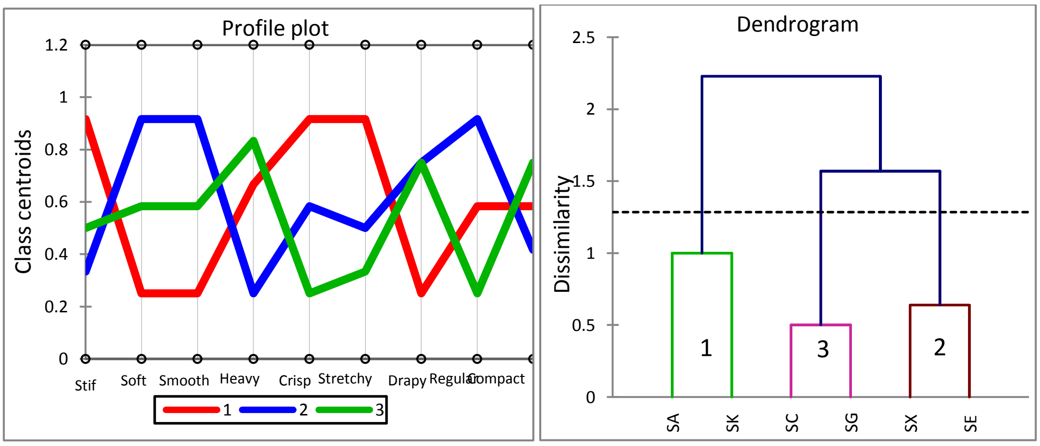


Figure 5.2 Sensory profiles and a dendrogram of cotton and PET fabrics by subjective evaluation

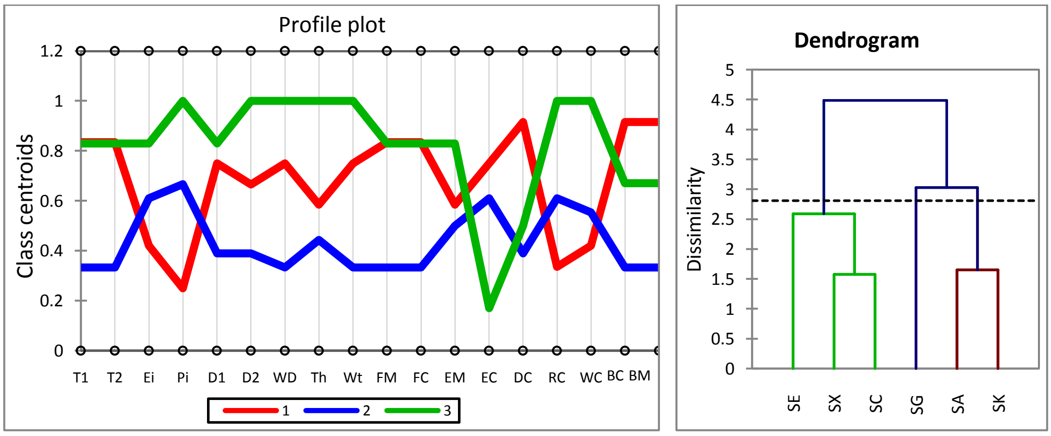


Figure 5.3 Profiles and a dendrogram of cotton and PET fabrics by objective measurements related to sensory behavior. C1- Warp count, C2- Weft count, Ei- Ends/inch, Pi- Picks/inch, D1-Warp density, D2-Weft density, WD- Weave density, Th- Thickness (mm), Wt- Weight (g/m2), FM- Flexural rigidity (mNcm) in the warp direction, FC- Flexural rigidity (mNcm) in the weft direction, EM- Elongation (%) in the warp direction, EC- Elongation (%) weft direction, DC- Drape coefficient, RC- Roughness coefficient, WC- Waviness coefficient, BC- Bending length (cm) in the weft direction, BM- Bending length (cm) in the warp direction

The human sensory profiling shows conventional PET fabrics classed independently, except for microfiber fabric SE. The visualization further indicates that cotton fabrics are classed closely in close classes. The distance between class centroids indicates that class 3 is closer to class 2 than it is to class 1; meaning that fabrics of similar fiber content share similar and close attributes. Hand and visual attributes; *stiff*, *soft*, *smooth*, *crisp*, *drapy* and *stretchy* most precisely define and distinguish between PET and cotton fabrics.

Compared to cotton fabrics, conventional PET fabrics are profiled with the largest values of bending length (BC and BM), drape coefficient, drape coefficient, flexural rigidity (FC and FM), and elongation in the warp direction (Figure 5.3). Again, compared to cotton fabrics, PET fabrics presented the lowest waviness and roughness coefficients. The waviness coefficients correspond to the ranks of fabrics in the subjective evaluation of *regular* (*even*), whereby PET fabrics presented stronger magnitudes. However, the roughness coefficients and the subjective evaluation of *smooth* presented contrasting implications. Cotton fabrics were perceived smoother than PET fabrics, by judges; however, objective measurements (of roughness coefficient) indicated that PET fabrics were smoother. The subjective evaluation of heavy equally corresponded to objective measurement of weight. Hence, subjective results for *heavy* were generally not influenced by fiber content.

Similar to the profiling with subjective data, fabrics in class 1 of objective measurement profiles are entirely of PET content. Fabric SE was profiled with the two cotton fabrics in class 2. According to the distance between class centroids, class 1 is closer to class 3 than it is to class 2; which finding was contrary to the profiling with subjective data. Hence, apart from the grouping of SA and SK, the grouping of other fabrics differed by the subjective and objective approaches. The inter-class distances generally suggest that classes of fabrics of similar fiber content are closer than they are to fabrics of dissimilar fiber content.
Mechanical properties- bending length, drape coefficient, flexural rigidity, and visual properties- roughness coefficient and waviness coefficient were the most defining attributes between PET and cotton fabrics. These can be related to the hand/tactile and visual properties under subjective evaluation. The clustering presented by PCA was similar to that by AHC for both subjective and objective data; conventional PET fabrics (SK and SA) are clustered together. Also, cotton fabrics are clustered in close proximity.

5.4 Conclusions

As evidenced by the correlation analysis, only a few sensory attributes were precisely expressed by instrumental measurements. Particularly, hand attributes were more expressed by fabric mechanical and surface attributes. Appearance attributes are more complex to express by objective measurements. Therefore, human evaluation and objective measurements present varying dimensions for sensory analysis. It is deduced that human perception cannot be directly represented by instrumental measurements. The profiling of fabrics indicates that conventional PET fabrics can be distinguished from conventional cotton fabrics using selected subjective and objective attributes.

Chapter 6

Radically photo-grafted PET woven fabric; Moisture, surface and dyeing properties

6.1 Overview

In this chapter, the hydrophilic potential and efficacy of two vinyl monomers radically photo-grafted on the surface of polyethylene terephthalate (PET) fabric was investigated. Poly-(ethylene glycol) diacrylate (PEGDA) and [2-(methacryloyloxy) ethyl]-trimethylammonium chloride (METAC), and a radical photo initiator 2-hydroxy-2-methyl-1-phenyl-1-propanone (HMPP) were utilized. The grafting of the monomers on PET was studied by X-ray photoelectron spectroscopy (XPS) and Energy Dispersive Spectroscopy (EDS). Water contact angle (WCA) measurements and dynamic moisture management tests (MMT) indicate that PEGDA and METAC induce complete wetting of PET at concentrations 0.1-5% (v:v). The grafted PET fabrics remain hydrophilic following ad hoc testing using washing and rubbing fastness tests. PEGDA grafted fabrics perform better, as static water contact angles of METAC grafted fabrics increase after washing. Colorimetric measurements (K/S and CIELAB/CH) and color fastness tests on dyed PET fabrics suggest that both monomers greatly improve the dyeing efficacy of PET. Grafted PET fabrics presented strong fastness properties, slightly better than the reference PET fabric. The hand and appearance of grafted PET fabrics remains largely unchanged, following drycleaning and laundering procedures. This study demonstrates the potential of PEGDA and METAC for a hydrophilic function in conventional textiles utilizing UV grafting. It is suggested that PEGDA and METAC generate hydrophilic radicals/groups on PET; the macroradicals are in a form of vinyl structures which form short chain grafts and demonstrate hydrophilic function at the tested concentrations.

6.2 Materials and methods

6.2.1 Materials

6.2.1.1 Fabrics and polymerization reagents

Mill-bleached polyester twill-5 fabric of weight 230 g/m^2 and 0.325 mm thickness was supplied by Atmosphere Tissus (59800 Lille- France). METAC (75 wt% in water, Mn 207.7) and PEGDA (Mn 700) were supplied by Sigma-Aldrich S.r.l. (Milano-Italy), in liquid and gel form respectively. The photo initiator 2-hydroxy-2-methyl-1-phenyl-1-propanone (HMPP) 99%, was supplied by BASF Kaisten AG (Hardmatt, Kaisten- Switzerland), in liquid form. Ethanol- CH_3CH_2OH (99.5%) (Sigma-Aldrich S.r.l., Milano-Italy) was used as solvent. The chemical structure of the monomers and the photo-initiator are reported in Figure 6.1.

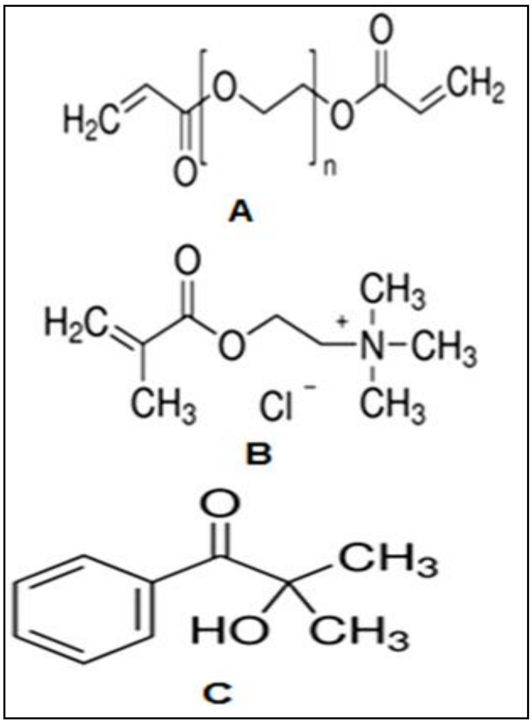


Figure 6.1 Structure of: A. PEGDA, Mn 700; B. METAC, 75% Wt in water; and C. HMPP

6.2.1.2 Light source for polymerization

Ultraviolet initiating light for all UV treatments was provided by a 400 W metal halide lamp (Dymax ECE 5000- Dymax Corporation, Torrington, USA) of optimum intensity of 225 $mWcm^{-2}$ at wavelength 365 nm (±5 nm), in the UVA domain. The UV intensity was measured using an irradiance meter- UV Power Puck II (EIT Inc, Sterling, VA, USA).

6.2.1.3 Dyeing materials for PET

The following materials were used in the dyeing process: a commercial acid-stable red disperse dye Anocron Rubine S-2GL (Shanghai Anoky Group Co., Ltd), acetic acid 99.5% and MW 60.05 (Guangzhou Congzhongxiao Chemical

Technolog Co., Ltd), high temperature leveling agent- styrene phenol polyoxyethylene ether ammonium sulfate (SPPEAS) 100% (Suzhou Eastion New Material & Technology Co., Ltd), and NNO ($C_{21}H_{14}Na_2O_6S_2$) of MW 472.44 (Guangzhou Congzhongxiao Chemical Technology Co., Ltd) as dispersant. Reducing agent sodium hydrosulfite ($Na_2S_2O_4$) and NaOH were used for washing.

6.2.1.4 Dyeing equipment

A precision electronic balance BL-500F (Tianjin Danaher Sensors & Controls Engineering Co., Ltd) with an accuracy of 0.001 g was used for weighting dyestuff and auxiliaries, a pH meter PHS-3E (Shanghai Leici Co., Ltd) was used to check the dyeing liquor pH and a Mathis Labomat (Wuxi Yangbo Textile Equipment Co., Ltd) for dyeing.

6.2.2 Methods

6.2.2.1 Fabric preparation

To eliminate any surface active agents and prior spinning and weaving oils, the polyester fabric was Soxhlet-extracted using a *Soxhlet-* apparatus (Carlo Erba-Milan, Italy) for 4 hours in petroleum ether, in the weight ratio of 1:5 (fabric:petroleum ether). After extraction, and drying, the fabric was then conditioned (according to *ISO 139:2005* Textiles— Standard atmospheres for conditioning and testing)[106] at 20°C (±2°C) and 65% RH (±4%) for 24 hours. Then, a preliminary wetting test was carried out on the fabric according to the test method *AATCC 79, 2007-* Absorbency of textiles[135]; which estimates the time taken for a water drop of 0.2 ml to be fully absorbed by a fabric. Sixteen PET woven fabric samples were then obtained and characterized for static water contact angles recorded over time[180,181] using a KRUSS drop shape analyzer–DSA100 (KRUSS, Hamburg- Germany). The fabric was also tested for dynamic liquid transport properties (*AATCC Test Method 195-2011-* Moisture management properties of textile fabrics)[135] using a moisture management test (MMT) device (SDL Atlas LLC, Charlotte, NC, USA).

6.2.2.2 UV-radical grafting

The working distance between the UV lamp and the fabric platform was set at 6 cm for all UV treatments, delivering irradiance (intensity) of 145 $mWcm^{-2}$ (UVA) and 135 $mWcm^{-2}$ (UVV). Firstly, the effect of UV irradiation (without any chemicals) on the untreated PET fabric was evaluated to assess any change of PET hydrophilicity after exposure to UV light. Five fabric samples of dimension 5 x 5 sqcm were exposed to the UV lamp for different durations (5, 10, 15, 20 and 25 minutes). After UV exposure, the static water contact angle for each specimen was measured.

The grafting treatment of PET with PEGDA or METAC in the presence of the photo-initiator and UV irradiation was then carried out according to the following procedure. In one experiment, PEGDA was dissolved in ethanol at concentrations between 0.1%-5% v/v. Then, the photo initiator at concentration of 0.1% with respect to ethanol was added. After thorough agitation, 5x5 sqcm PET fabric specimens were soaked in the bath for 10 minutes and then padded to squeeze out excess solution before air-drying under room conditions. The two sides of the monomer-soaked fabrics were then irradiated for one minute with intensity 280 $mWcm^{-2}$. Gaseous nitrogen was introduced in the irradiation chamber to create an inert atmosphere, avoid oxygen inhibition and prevent ozone formation. Fabrics were washed, ten minutes after removal from the irradiating chamber.

In a second set of experiments, the PET fabric specimens were treated with METAC following the same procedure as for PEGDA. The add-on, which can reflect the percentage of monomer grafted on the fabric, was obtained by Eq 6.1:

$$\%add - on = \frac{W_{Grafted} - W_{Pristine}}{W_{Pristine}} \times 100; \dots\dots\dots\dots\dots\dots\dots\dots. Eq\ 6.1$$

where $W_{Grafted}$ and $W_{Pristine}$ are the weights of the pristine and grafted PET fabrics respectively.

The weight of the PET samples and reagents was measured with an accuracy of 0.001 g on an analytical balance (ME104- Mettler Toledo, Milan-Italy)

6.2.2.3 Wetting and durability tests on grafted PET fabrics

Using the sessile drop technique,[182–184] static water contact angles (WCAs) of the grafted PET fabrics were measured after grafting. Moreover, the MMT device was used to study fabric dynamic moisture attributes based on the *AATCC Test Method (TM) 195-2011*– Liquid moisture management properties of textile fabrics.[135]

To ascertain the durability of the grafted monomers, the grafted PET fabrics were evaluated for appearance, hand and static WCAs after laboratory washing, drycleaning and rubbing (crocking).

Washing was carried out twice, for each sample, following standard home laundering conditions described in *ISO 6330- Domestic washing and drying procedures for textile testing* (similar to *AATCC Monograph (M) 6*[135]*- Standardization of home laundering conditions*), using 4 g/l distilled water solution of ECE non-phosphate detergent (A) without optical brighteners (SDL Atlas, UK), with a modification in the equipment; a high temperature laboratory machine (Labomat) was used, with stainless steel balls added in the washing beakers. The washing beakers rotated during washing. Washing was performed at a temperature of 40 ^{o}C (rising at a 1.5 ^{o}C per sec) with a fabric to liquor ratio of 1:20 for 30 minutes. The changes in hand and appearance after washing were evaluated using the rating scale described in *AATCC 86-2013*[135].

Drycleaning was carried out once on each fabric sample, following *AATCC 86-2013- Durability of Applied Designs and Finishes*[135], with a modification; petroleum ether was used as the solvent and in a *Soxhlet* apparatus (Carlo Erba, Milan-Italy). The changes in hand and appearance of drycleaned samples was evaluated using the rating scale described in *AATCC 86-2013*. Since major loss of finish material occurs in the first washing or dry cleaning, a single application of the test was assumed to furnish a good indication of the effect of repeated operations.

Rubbing/crocking test (wet and dry) was carried out using a crockmeter described in *AATCC Test Method 08, 2005*[135]. Ten strokes were applied on grafted fabric and tests for WCAs were carried out.

6.2.2.4 Surface characterization of fabrics by EDS-SEM and XPS

The surface elemental composition and morphology of treated and untreated samples were studied using a ZEISS Merlin field emission scanning electron microscope (ZEISS, Oberkochen- Germany) equipped with an energy dispersive X-ray spectroscope. The microscope was operated at a voltage of 5 kV, pressure of 200 Pa, and working distance of 5.8 mm. X-ray photoelectron spectroscopy (XPS) was used to complement results from EDS, following inconclusive findings on METAC-g-PET. XPS analysis was carried out by a PHI 5000 Versaprobe (Physical Electronics, Chanhassen, MN, USA) of monochromatic Al K-α X-ray source with a power of 25.2 W. A scan area of 100 μm^2 was used to collect the photoelectron signal while placed between the gold electrodes. A pass energy value of 187.85 eV was used for survey spectra, while 23.5 eV was used for high resolution peaks.

6.2.2.5 Dyeing of untreated and monomer grafted PET

A dyebath consisting 2% (w.o.f) of dye, fabric to liquor ratio of 1:20 w/v, 1g/l of leveling agent (SPPEAS) and 1 g/l of dispersant (NNO) was prepared. Using acetic acid, pH of the dyebath was adjusted to 5. A washing bath consisting 2 g/l of $Na_2S_2O_4$ and 2 g/l of NaOH was also prepared. Grafted and ungrafted PET fabric samples of 5 g each were then introduced into beakers containing the dye bath and later mounted onto the dyeing machine. With temperature rising at 2°C/min, dyeing was carried out at 130°C (temperature rise of 1.5°C per sec) for 60 minutes followed by cooling at 4°C /min. The dyed PET fabrics were then washed in the washing bath with a fabric to liquor ratio 1:30 w/v at 80°C for 15 minutes. The washed fabrics were then rinsed in distilled water before drying at room temperature.

6.2.2.6 Color measurements and fastness properties

The colorimetric parameters of the dyed PET fabrics were determined on an UltraScan PRO UV/VIS reflectance spectrophotometer D65 (HunterLab, Reston, VA, USA) with a 10^{o} standard observer. The K/S (color strength) was determined by applying the Kubelka-Munk equation[185,186] (Eq 6.2):

$$K/S = \left[\frac{(1-R)^2}{2R}\right] - \left[\frac{(1-R_O)^2}{2R_O}\right] \ldots\ldots\ldots\ldots\ldots Eq\ 6.2$$

where R is the reflectance of colored samples, while, K and S are the absorption and scattering coefficients respectively. R_o is a decimal fraction of the reflectance of the undyed fabric standard reference. The CIE color scale represented by codes- L* (Lightness), a*(+ a*=red, - a*=green), b*(+b*=yellow, - b*=blue), C* (chroma or saturation), and h (hue angle; 0°=red, 90°=yellow, 180°=green, 270°=blue)[187,188] were used to elaborate color differences between the dyed fabrics. Mean values from six measurements were recorded for each color parameter on each fabric sample.

Color fastness to washing was evaluated using test method- *BS EN ISO 105-C08:2002+A1:2008: Colour fastness to domestic and commercial laundering using a non-phosphate reference detergent incorporating a low temperature bleach activator* (similar to *AATCC 61-2013 2A accelerated machine laundering*)[42,135,189–191]. The test specimens were washed with a fabric to liquor ratio of 1:20, for 30 minutes in 4 g/l distilled water solution of ECE non-phosphate detergent (A) without optical brighteners (SDL Atlas, UK) at 40°C (rising at a 1.5°C per sec) in a Labomat laboratory machine with stainless steel balls added in the washing beakers. The washing beakers rotated during washing. Color fastness to rubbing (wet and dry crocking) was evaluated using test method *AATCC 8-2007*: *AATCC crockmeter method.* The colorfastness and ratings were read using the AATCC Gray Scale for Color Change and the AATCC Gray Scale Staining.

6.3 Results and discussion

6.3.1 Wetting of untreated fabrics

The liquid drop test (*AATCC Test Method 79-2007*)[135], showed that the untreated PET fabric was non-absorbent as the water drop took an average of 56 seconds (SD 9.6s and CV 17.2%) for total spreading. Figure 1 shows static WCAs measured on untreated PET fabric.

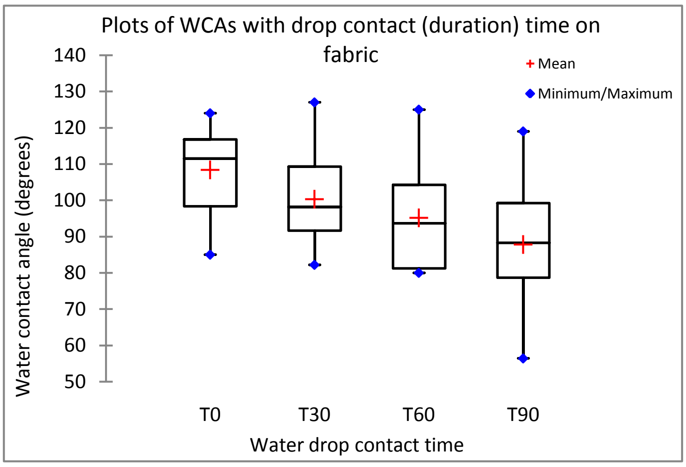


Figure 6.2. Univariate plots of static WCAs (degrees) measured against water drop contact time on 16 untreated PET fabrics. The water drop contact time denotes the time after the water drop is deposited on the fabric specimen.

Static WCAs measured between 0-5 seconds of water deposition ranged from 85° to 124° (T0 in Figure 6.2). The average static WCAs were 100° (CV 13%), 95° (CV 13%), and 88° (CV 19%) after 30, 60 and 90 seconds respectively (T30, T60 and T90 in Figure. 1). With the hydrophobic threshold being 90°, the untreated PET fabric can be deemed hydrophobic. The average WCA of polyester fabrics has been recorded between 72 and 140° depending on the fabric structure and surface properties.[192–195] The higher WCAs measured in this work on the untreated PET fabric can be partly attributed to the tight packing of the twill-5 configuration, which also increases fabric roughness.[196–198] Evidenced by the CV% of the WCAs, the untreated fabric exhibited a heterogeneous wetting profile. The wetting and adhesion behavior of a fabric surface is a function of both the chemical and topographical properties.[199]Young-Dupre's equation (Eq 6.3) is a common reference for defining equilibrium at the interfaces of solid-vapour, solid-liquid and liquid-vapor.[181] The Young's contact angle θ_Y is the result of interfacial tensions γ_{sv}, γ_{sl} and γ_{lv}.

$$Y_{sv} = Y_{sl} + Y_{lv} cos\theta_y \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . Eq\ 6.3$$

Young's equation is based on a chemically homogenous and topographically smooth surface. However, on a real surface, the actual contact angle is the angle between the tangent to the liquid-vapor interface and the actual, local surface of the solid. Hence, surface roughness is very important in wettability of fabrics. Particularly, twill weaves present series of successive grooves that are formed by the weft on the fabric surface- increasing surface roughness. Wenzel[200] noted that the hydrophobicity of hydrophobic materials increases with further surface roughness. Hence, the hydrophobic character of polyester is expected to increase when made into a twill-5 weave compared to basic weaves. This finding was also presented by other authors[196–198] who studied topography and structure of woven fabrics and their effect on wetting.

6.3.2 Effect of UV irradiation on the wettability of PET fabrics

PET fabric samples exposed to UV only, without any other chemicals, showed reduction in WCAs, more noticeable with increasing exposure time, as shown in Table 6.1.

Table 6.1 Static WCAs θ of PET fabrics for different UV exposure time

Water drop contact time (s)	UV irradiation time (min) and θ±standard deviation					
	0	5	10	15	20	25
5	106±5	100±3	100±9	98±4	90±8	86±6
30	102±8	97±7	95±7	89±9	82±9	84±5
60	99±4	90±5	89±4	87±8	71±6	73±9
90	99±5	89±6	87±7	86±8	70±8	70±7

In all cases, contact angles of UV-treated samples were lower than those of the untreated sample. Nevertheless, no considerable wetting was achieved as WCAs remained well above 70° for all UV exposure duration. The decrease of PET WCAs after UV irradiation exposure can be attributed to photo-degradation or photo-oxidation of PET, caused by photon absorption, which causes fracturing in molecular structures (photo-dissociation).

6.3.3 Effect of PEGDA and METAC grafting on the wettability of PET fabric

The add-on and wettability of PET fabrics grafted with PEGDA (PEGDA-g-PET) are shown in Table 6.2.

Table 6.2 Add-on and static WCAs θ of PEGDA-g-PET fabric

PEGDA conc. (% v/v)	HMPP conc. (% v/v)	Irradiation time (min)	Add-on (%)	θ in 0-5s
5	0.1	1	2.7	0
3	0.1	1	2.4	0
2	0.1	1	1.6	0
1	0.1	1	0.9	0
0.5	0.1	1	0.9	0
0.2	0.1	1	0.3	0
0.1	0.1	1	0.2	0

For all PEGDA concentrations, there was complete wetting on the PEGDA-g-PET fabrics. Hence, PEGDA was very effective in inducing hydrophilicity to the PET fabric, even at low concentrations. As expected, the monomer add-on increased with PEGDA concentration in ethanol.

The add-on and wettability of PET fabrics grafted with METAC (METAC-g-PET) are shown in Table 6.2. Similar to PEGDA, the monomer add-on increased with METAC concentration in ethanol. Complete wetting was achieved for all the five METAC concentrations, with the highest contact angle of 36° at concentration 0.5%. By comparing the results in Table 6.2 and Table 6.3, it can be observed that compared to METAC, PEGDA was more effective in making PET hydrophilic.

Grafting of PEGDA or METAC on PET creates moisture polar sites on the surface of PET. Therefore, grafting of PEGDA or METAC on PET is expected to increase the hydrophilic performance of the PET fabric since the grafted PET can form plenty of hydrogen bonds with water molecules. Additionally, the grafting reduces surface roughness by reducing surface troughs. The reduction in surface roughness and the enhanced surface moisture polarity reduce the surface tension at the liquid-fiber interface. These factors subsequently increase the wettability of the PET fabric. Further, with the penetration of the grafting monomer in the pore structure of PET fibers and yarns, wicking and porosity are improved. Static water contact angles are particularly lowered by increased porosity with time dependence.

Table 6.3 Add-on and static WCAs θ of METAC-g-PET fabric

METAC conc. (% v/v)	HMPP conc. (% v/v)	Irradiation time (min)	Add-on (%)	θ in 0-5s	θ in 30s
5	0.1	1	2.1	0	0
3	0.1	1	0.89	5	0
2	0.1	1	0.62	7	0
1	0.1	1	0.45	10	5
0.5	0.1	1	0.15	36	0
0.2	0.1	1	0.08	34	10
0.1	0.1	1	0.05	45	15

The grafting of PEGDA and METAC did not alter the stiffness of the PET fabrics, which remained as pliable as the pristine ones, upon manual handling. However, PEDGA performed better with the hydrophilic function on PET. The different effects of the monomers on wettability can be discussed in terms of the add-on, which is considerably lower for METAC than PEGDA. The differences in grafting yield may result from different reaction kinetics with the photo-initiator, and UV light. For instance, higher concentrations of the photo-initiator and longer UV irradiation time may be required to enhance radical activity and lifetime and monomer reaction. Differences in polymerization rates have also been found to contribute to disparities in grafting yields in UV-grafting. Monomer homopolymerization[201] instead of grafting polymerization has also been noted to impact on grafting efficiency of some monomers.[202,201] Earlier, it was found that acrylic acid photografting of PET resulted in a more hydrophilic effect compared to acrylonitrile for equivalent amount of grafts.[203] Hence, the number of imparted polar groups may also vary with each monomer.

The moisture management test (MMT) method[135] attempts to provide objective measurements and an evaluation of liquid moisture management properties of textile fabrics. The MMT takes into account the water resistance, water repellency and water absorption characteristics as influenced by the fabric structure and the wicking characteristics. Moreover, MMT measurements provide an overall evaluation of in-plane and off-plane wettability, giving the information of the time for water to penetrate through the fabric thickness and reach the bottom surface. A predetermined amount of conductive solution that facilitates the measurement of electrical conductivity is automatically dropped onto the surface of the fabric specimen held flat between upper and lower arrays of concentric electric sensing pins. The liquid drop behavior is evaluated for 120 seconds. The test device is used to monitor the top and bottom radial spreading of the conductive liquid drop, as well as the moisture absorption from the top surface to the bottom surface of the specimen. During the test, changes in electrical resistance of the specimen are used to calculate changes in the fabric liquid moisture content that quantify dynamic liquid moisture transport characteristics in the three directions of the specimen. Predetermined indices are used to grade the fabric moisture management behavior basing on the measurements as in Table 6.4.

Table 6.4 Dynamic moisture management properties of pristine and selected grafted PET fabric

Fabric	TW (s)	BW (s)	TA (%/s)	BA (%/s)	TM (mm)	BM (mm)	TS (mm/s)	BS (mm/s)	AOT
SK	3.5	120	29.2	0.0	5.0	0.0	1.4	0.0	-834
SKU5	2.5	120	40.9	0.0	5.0	0.0	1.8	0.0	-893
SKU10	2.9	120	41.3	0.0	5.0	0.0	1.6	0.0	-828
SKP	3.0	5.8	39.5	25.0	13.8	22.5	3.0	3.6	-43.9
SKP1	2.6	2.3	46.5	37.3	17.5	27.5	4.5	6.5	214
SKM	3.5	5.6	32.2	19.7	10.0	15.0	1.9	2.0	-242
SKM5	3.0	4.5	36.7	23.8	15.0	17.0	2.3	2.1	-136

TW- Top wetting time, BW- Bottom wetting time, TA- Top absorption rate, BA- Bottom absorption rate, TM- Top maximum wetted radius, BM- Bottom maximum wetted radius, TS- Top spreading speed, BS-Bottom spreading speed, AOT- Accumulative one-way transport index; SK- Pristine PET, SKU5- UV-treated 5 min, SKU10- UV-treated 10 min, SKP- 0.2% PEGDA-g-PET, SKP1- 1% PEGDA-g-PET, SKM- 1% METAC-g-PET, SKM5- 5% METAC-g-PET.

Results of BW, BA, BM, and BS (Table 6.4) suggest that the test liquid was not absorbed through the bottom side of untreated PET fabric as well as PET fabrics exposed to UV only. These tests are consistent with the WCA and the drop test results which indicate that the PET fabric is hydrophobic. UV treatment alone had only a notable effect on top wetting properties. The grafting of PEGDA and METAC enhanced the moisture absorption and spreading rates of PET fabric. Particularly, PEGDA had the most significant impact on bottom wetting properties with higher monomer concentration imparting a pronounced hydrophilic effect. The transfer of moisture from the top to the bottom of fabric represents how fast a fabric would transfer sweat from the wearer to the outer part of clothing. This has an effect on the wearing comfort. Based on standard MMT scaling, the 1% PEGDA-g-PET fabrics posted a very good grading (4/5), and the best for one-way transport ability. Figure 6.3 is a visual presentation of the MMT result. The light blue areas indicate the wetted areas on the top and bottom surfaces of the fabric at the end of the test. The standard test duration is usually120 seconds after dosing the 2 ml water drop on the fabric top surface. PEGDA imparted complete wetting of both sides while METAC imparted partial wetting of the top and bottom sides of PET fabric. The effect of UV irradiation only can be visualized by comparing discs in Figure 6.3 **A** and **B** for the bottom wetting; slight bottom absorption was achieved for UV treated (**B**) unlike for the untreated fabric (**A**). The effect of monomer concentration is also reflected by the depth and area of the absorbed liquid; higher monomer concentration showed deeper and wider absorption. The most impacted were the bottom moisture properties, given that the untreated fabric showed no bottom wetting at all. This wetting behavior is consistent with the earlier result from the WCA and water drop tests. With only-UV treatment, bottom dynamic properties remained largely unchanged.

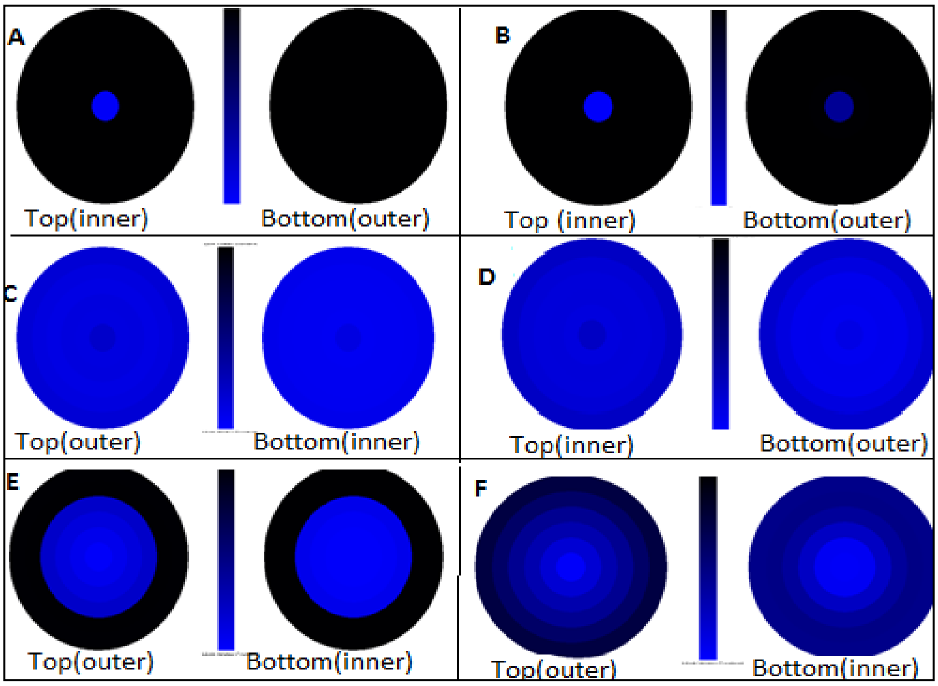


Figure 6.3 Schemes of top and bottom wetted radius for the tested fabrics: A-Pristine PET; B- UV-treated 5 min; C-1% PEGDA-g-PET; D- 0.2% PEGDA-g-PET; E-5% METAC-g-PET; F-1% METAC-g-PET

The observed effect of UV treatment alone on top wetting properties indicates degradation from photo activity of UV energy. MMT results, showing good off-plane liquid transport from the top to the bottom surface, demonstrated that UV grafting was able to partly penetrate the inner structure of the fabric, modifying PET substrate to allow water to go through the fabric thickness. The multidirectional nature of MMT evaluation can depict moisture movement in clothing such as ease of drying, during sweating and perspiration on the human skin. The spreading speed also depicts the wicking properties of a fabric. Moisture management balance is not often achieved and highly absorbing fabrics tend to post low wicking due to moisture retention. Wicking provides the most needed route to achieve a feeling of comfort by the wearer. Through wicking, moisture from the skin is spread through the fabric while evaporating off to give the wearer a cool and dry feel.

6.4.4 Durability of grafted monomers

Table 5 shows WCAs of PEGDA-g-PET after washing with a standard acqueous detergent solution and *Soxhlet* extraction in petroleum ether. To notice the changes in WCAs of PEGDA-g-PET, reference should be made to Table 6.2 which shows WCAs of PEGDA-g-PET.

Table 6.5 Static WCAs θ of PEGDA-g-PET after washing and *Soxhlet* extraction

PEGDA conc. (% v/v)	after two washing cycles		after *Soxhlet* extraction		
	θ in 0-5s	θ in 30s	θ in 0-5s	θ in 30s	θ in 60s
5	0	0	31	0	0
3	0	0	12	0	0
2	0	0	19	0	0
1	0	0	32	0	0
0.5	5	0	28	0	0
0.2	33	5	25	5	0
0.1	43	0	64	21	0

Washing with detergent solution affected fabrics grafted with the lowest PEGDA concentrations of 0.1% and 0.2%; however, the grafted fabric remained hydrophilic. On the other hand, WCAs for PEGDA-g-PET increased after *Soxhlet* extraction, for all concentrations of PEGDA, albeit maintaining wetting thresholds. Table 6.6 shows WCAs of METAC-g-PET after washing with detergent solution and Soxhlet extraction. To notice the changes in WCAs of METAC-g-PET, reference should be made to Table 6.3 which shows WCAs of METAC-g-PET.

Table 6.6 Static WCAs θ of METAC-g-PET after washing and extraction

METAC conc. (%v/v)	After two washing cycles			after *Soxhlet* extraction		
	θ in 0-5s	θ in 30s	θ in 60s	θ in 0-5s	θ in 30	θ in 60s
5	103	42	0	27	15	0
3	103	61	0	18	0	0
2	100	55	0	22	5	0
1	83	30	0	55	37	0
0.5	101	20	0	85	35	30
0.2	98	51	22	89	56	27
0.1	88	50	28	80	30	25

WCAs of METAC-g-PET increased after washing in aqueous detergent (Table 6.6). However, wetting was attained within 30 seconds for all monomer concentrations. Relatively lower increase of WCAs was noted for METAC-g-PET after *Soxhlet* extraction. It is reasonable to suspect an interruption on the grafted monomer matrix due to washing and extracion. Table 6.7 shows results of the rubbing fastness test (wet and dry) on PEGDA-g-PET. Rubbing had negligible effect for all monomer concentrations as PEGDA-g-PET remained completely wettable.

Table 6.7 Static WCAs θ of PEGDA-g-PET after the rubbing test

PEGDA conc. (% v/v)	after dry rubbing		after wet rubbing	
	θ in 0-5s	θ in 30s	θ in 0-5s	θ in 30s
5	0	0	0	0
3	0	0	0	0
2	0	0	5	0
1	7	0	0	0
0.5	0	0	0	0
0.2	10	0	15	5
0.1	0	0	10	0

Table 6.8 shows static WCAs of METAC-g-PET after both rubbing tests.

Table 6.8 Static WCAs θ of METAC-g-PET after the rubbing test

METAC conc. (% v/v)	after dry rubbing			after wet rubbing		
	θ in 0-5s	θ in 30s	θ in 60s	θ in 0-5s	θ in 30	θ in 60s
5	0	0	0	5	0	0
3	5	5	0	5	0	0
2	7	0	0	11	0	0
1	16	0	0	13	0	0
0.5	41	20	0	31	5	0
0.2	26	11	0	39	15	0
0.1	30	15	0	45	25	10

METAC-g-PET fabrics (Table 6.8) showed less resistance to rubbing for both wet and dry. The changes in hydrophlicity however are rather small and PET remained hydrophilic.

6.3.5 Surface analysis of untreated PET and grafted fabrics

Surface characterisaztion was carried out to study the surface morphological and elemental changes of the fabrics through grafting, and fastness tests.This helped to explain the relative moisture behavior for different specimens. Fabric prepared with 3% were chosen for both PEGDA and METAC. Figure 3 shows SEM images of pristine PET and grafted fabrics.

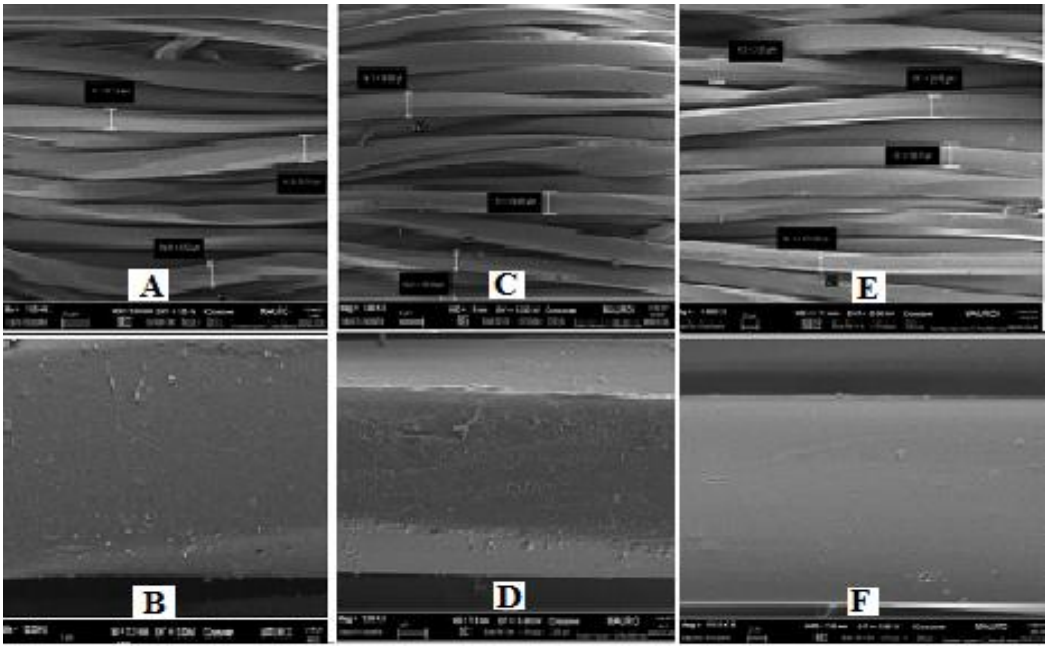


Figure 6.4 SEM images of fabric yarns/fibers: A and B (Mg 1000X and 10000 respectively)- reference PET; C and D (Mg 1000X and 10000 respectively)- METAC-g-PET; E and F (Mg 1000X and 10000 respectively)- PEGDA-g-PET

It can be observed that the PET fibers have a regular geometrical section whose size ranged between 17 µm and 23 µm, with an average of 19 µm. The fiber surface of pristine PET fabric appeared rough with a pentagonal cross-section (Figure 6.4: A and B). The average yarn/fiber size for METAC-g-PET ranged between 15 µm and 19 µm with an average of 18 µm. With PEDGA-g-PET, the fiber size ranged between 14 µm and 20 µm, with an average of 18 µm. Hence, grafting of METAC and PEGDA did not significantly alter the fiber size, cross-sectional and longitudinal features of the fibers/yarns. Although grafting of METAC on PET did increase surface irregularity,the grafting of PEGDA did enhance surface regularity, giving the fibers a much smoother appearance compared to both the reference and METAC-g-PET. The differences in texture may be partly attributed to differences in polymerization, adhension and formulation properties. For instance, rapid polymerization and early chain termination may apply in the case of METAC-g-PET. Grafting of PEGDA led to an added nano layer of about 734 nm onto the fabric surface, while grafting of METAC yielded about 670 nm of added thickness. This result is closely consistent with the add-on reported in Table 6.2 and Table 6.3, as PEDGA yielded higher add-on compared to METAC, for the same monomer concentrations.

Figure 6.5 presents the EDS results of pristine PET, PEGDA-g-PET and METAC-g-PET.

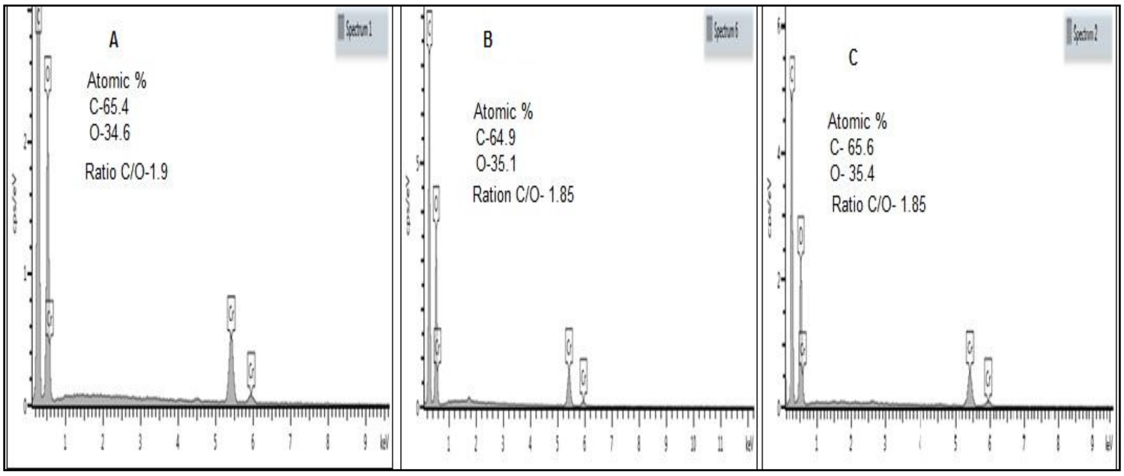


Figure 6.5 The EDS spectrum of fabrics: A- Pristine PET; B- PEGDA-g-PET; C- METAC-g-PET

The surface of pristine PET recorded 65.4% and 34.6% atomic composition for carbon and oxygen respectively (Figure 6.5A). Following grafting with PEGDA on PET, the C/O ratio remained largely unchanged, with a 1% gain in favour of oxygens (atomic %) (Figure 6.5B); this slight gain in oxygen could stem from the acrylate end group function in the PEG linear chain. As the grafting process and layer deposition may not be uniform for the bulk of the fabric, there might be eminent differences in surface elemental composition and morphology at different points of a specimen. The EDS spectrum of METAC-g-PET (Figure 6.5C) could not confirm nor explain the grafting of METAC on PET. There is hardly a difference between the EDS spectrum of METAC-g-PET and that of PEGDA-g-PET. The expected representative nitrogen (N) and chlorine (Cl) atoms were absent in the spectra of METAC-g-PET. To complement results from EDS, XPS analysis was carried out on METAC-g-PET fabrics. Given that PET has similar characteristic carbons and oxygens, XPS would not be effective in distinguishing between pristine PET and PEGDA-g-PET fabrics,similarly as observed with EDS results in Figure 6.5.

Figure 6.6 presents the XPS chemical shifts of pristine PET fabric. The characteristic C1s peaks at binding energy 288.66 eV, 284.6 eV and 284.7 eV represent the carboxyl (COOH), hydroxyl (OH) and aromatic (C=C) groups of PET respectively. The O1s detected between binding energy levels 531 eV and 533.22 relate to hydroxyl and carbonyl carbons. The experimental ratio of carbon atoms to oxygen atoms on pristine PET is 2.8, which is very close to the theoretical value of 2.5, for PET. The traces of fluorine (0.7%) may be considered a contamination.

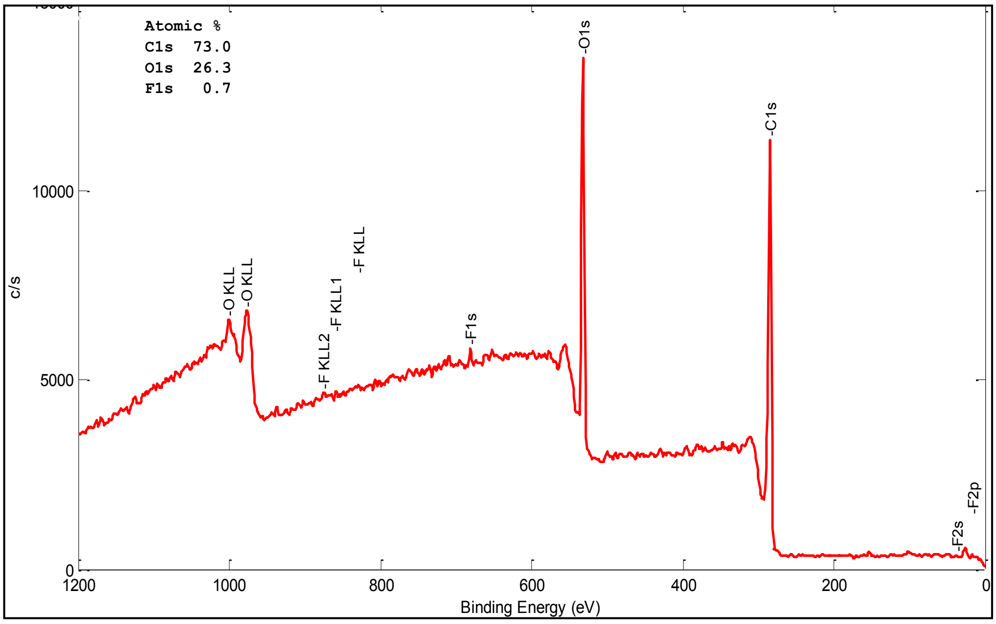


Figure 6.6 XPS spectrum of pristine PET fabric.

Figure 6.7 shows the spectrum of METAC-g-PET.

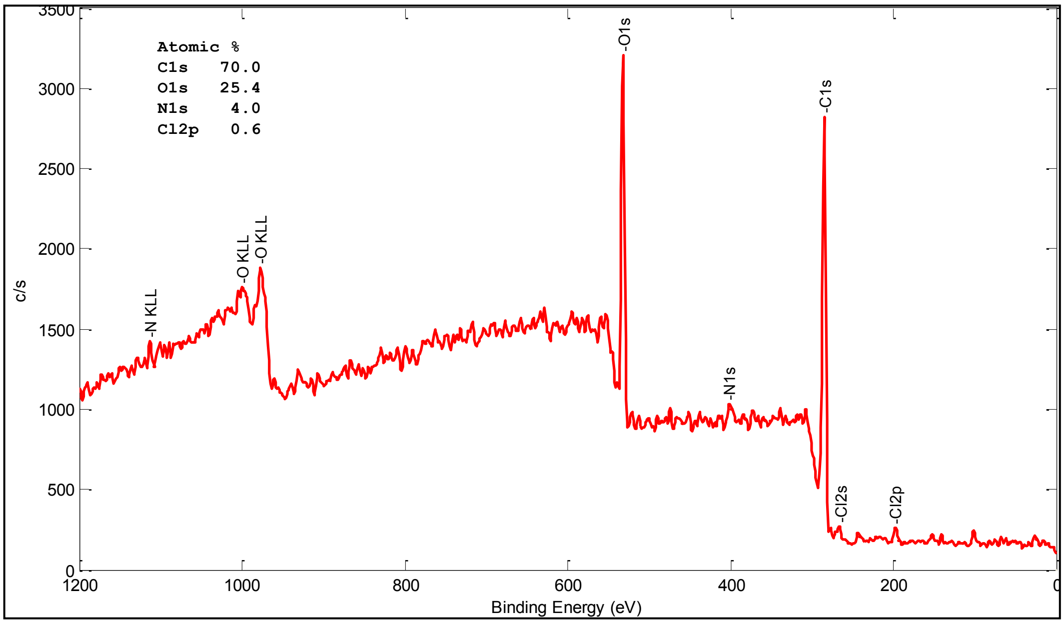


Figure 6.7 XPS spectrum of METAC-g-PET fabric

The grafting of METAC is confirmed by the presence of N1s (nitrogen) and Cl2p (chlorine) signals with atomic composition of 4% and 0.7% respectively. The peak N1s chemical shift at binding energy 401.8 eV represents an ammonium salt, usually falling between binding energy range 400.4 eV-403.2 eV. The detected CI2p signals at 198.7 eV are the attribute of an alkali chloride; in this case, the most relevant is the ammonium chloride. Inaccuracies have been noted during quantitative analysis of certain samples by the EDS technique due to their complex composition and that only chemical elements with atomic number $Y \geq 11$ are considered for computation of atomic concentrations.[204,205] The atomic numbers of fluorine, chlorine, and nitrogen are 9, 17, and 7 respectively. It is also suggested that by EDS, only elements with concentrations above 1% can be included in mapping by EDS.[206] Hence, even with a high atomic number, chlorine atoms had very low concentration to be detected by EDS. The mass-sensitivity of EDS analysis can thus be said to significantly rely on the ratio of peak signal to emission background.

On account of EDS and XPS results, it is fair to confirm the grafting of METAC and PEGDA on the PET fabric; the grafted monomers were responsible for the relative changes in PET wettability already discussed.

6.3.6 Surface analysis of fabrics after washing and wet rubbing

Figure 6.8 shows SEM images of grafted fabrics before and after the washing and wet rubbing tests. As observed, wet rubbing did not have a significant impact on the surface of grafted fabrics (Figure 6.8: F and J). However, washing did alter the grafted fabric surface significantly (Figure 6.8: G and K); more so, for METAC-g-PET. This surface alteration could explain the reversed hydrophilicty of grafted PET after washing particularly for METAC-g-PET fabric, presented earlier in Table 6.6.

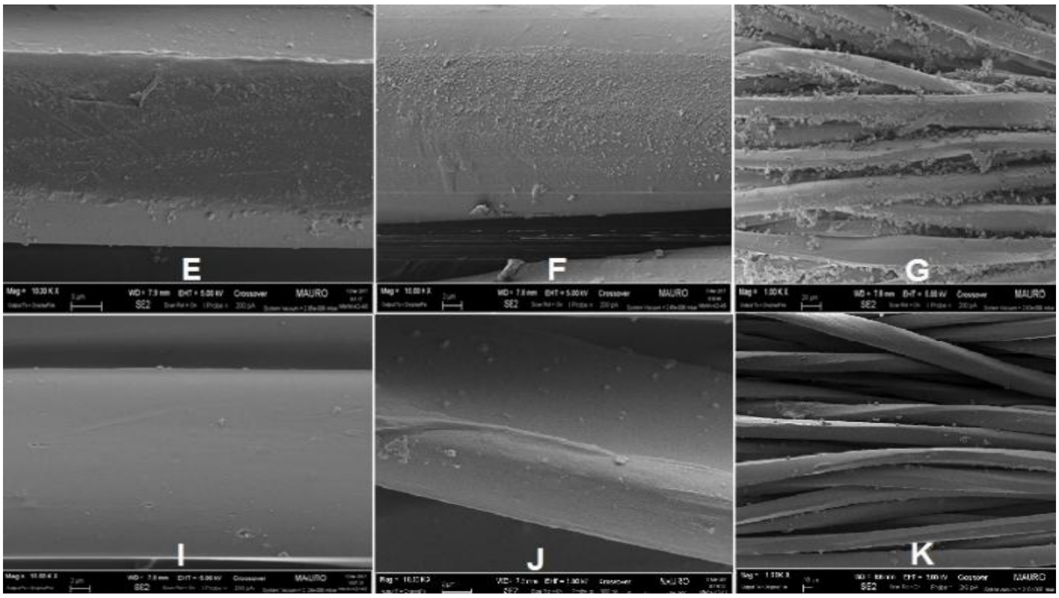


Figure 6.8 SEM images of: E- METAC-g-PET; F and G- METAC-g-PET after wet rubbing and washing respectively; I- PEGDA-g-PET; J and K- PEGDA-g-PET after wet rubbing and washing respectively

Figure 6.9 shows the XPS spectrum of METAC-g-PET after the washing test.

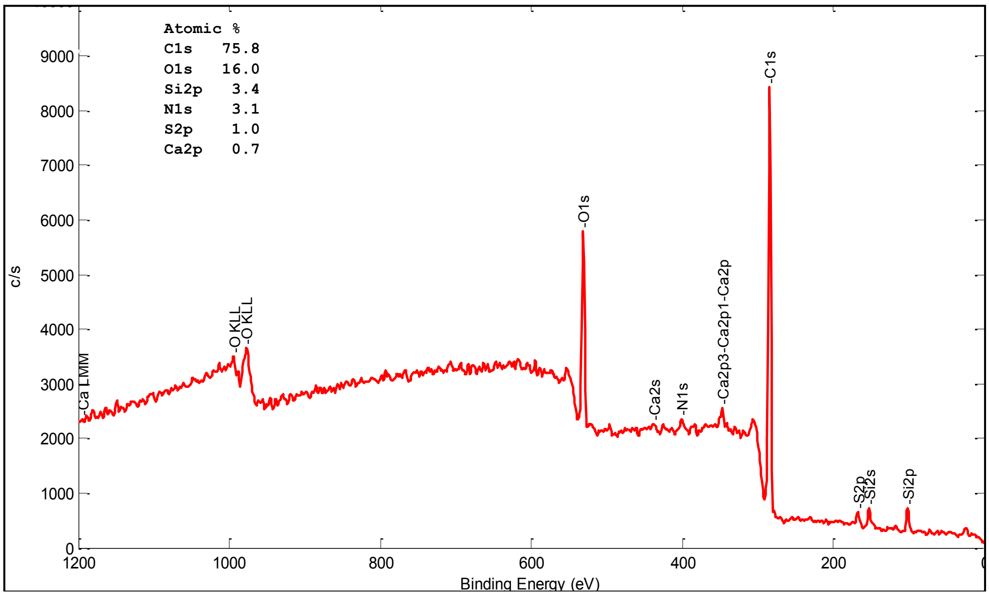


Figure 6.9 XPS pectrum of METAC-g-PET fabric after washing

Washing introduced impurities (calcium, sulfur, and silicon derivatives) on METAC-g-PET. However, there were still signals of N1s with an atomic composition of 3.1% and a characteristic N1s peak at binding energy 401.8 Ev attributed to METAC grafting. The materials safety data sheet for ECE detergent indicates that ECE contains, among others- sodium silicate, sodium aluminum silicate zeolite, sodium carbonate, and sodium sulfate.[207] These compounds are linked to the traces of calcium, sulfur, and silicon detected in washed METAC-g-PET. Some elements are also potential reducing agents, and thus contributed to the reduction of oxygen atoms leading to reduced wettability of METAC-g-PET after washing. Hence, drycleaning may be a better care approach. Figure 6.10 shows the XPS spectrum of METAC-g-PET after wet rubbing.

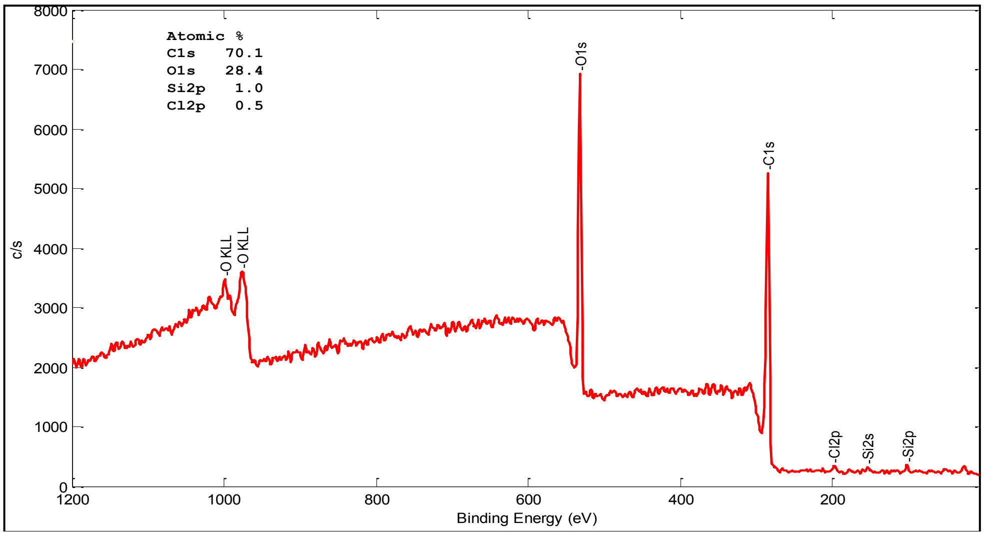


Figure 9 XPS spectrum of METAC-g-PET after wet rubbing

Chlorine (Cl2p) and nitrogen (N1s) signals were conspicuously absent despite retaining better wetting compared to the washed METAC-g-PET. The presence of

1% silicon in rubbed METAC-g-PET is attributed to contamination since the pristine PET and METAC-g-PET did not present this element. Thus, the changes in the hydrophilic behavior of both METAC-g-PET and PEGDA-g-PET can be explained by the surface changes occuring due to removal of unreacted monomer or alteration due to the physical activity on the surface of fabrics. With several washes or continuous rubbing, this effect could be pronounced especially with METAC-g-PET.

6.3.7 Color strength parameters of dyed PET fabrics

Figure 10 shows color strength (K/S) values of dyed PET fabrics measured over the UV-VIS spectral range 350 nm- 700 nm.

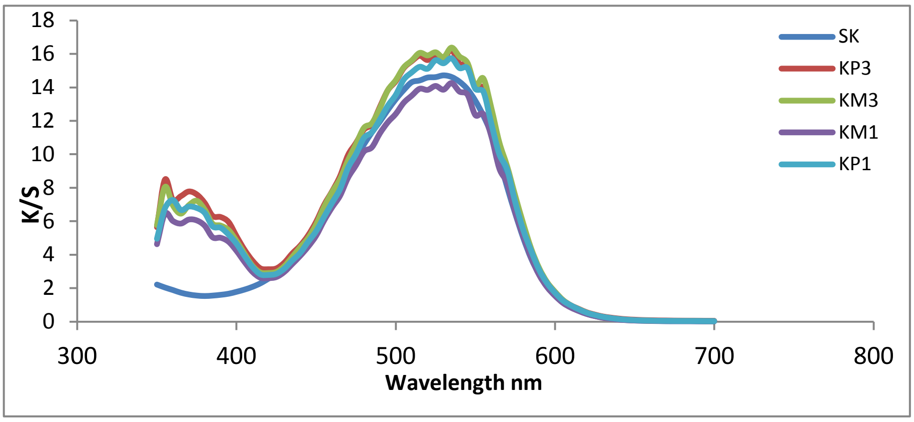


Figure 6.11 K/S for dyed PET fabrics at different wavelengths: SK is pristine PET, KP1 and KP3 are PEGDA-g-PET at 1% and 3% monomer concentration respectively, KM1 and KM3 are METAC-g-PET at 1% and 3% monomer concentration respectively.

Pristine PET fabric exhibited the lowest K/S values for wavelengths 350 nm- 425 nm, and had the lowest, next to METAC-g-PET of monomer concentration 1%, for wavelengths 425 nm- 650 nm. Hence, grafted fabrics generally presented higher color intensity compared to the ungrafted fabric. The color strength especially increased with monomer concentration and was highest for PEGDA grafted PET. The significance of the grafted monomers on the dyeing efficiency of PET can also be elaborated from the CIE color measurements[185]: L*, a*, b*, c, and h. Table 6.9 shows the means of six measurements for CIE color parameters.[185]

Table 6.9 Colorimetric measurements of disperse dye red Anocron Rubine on PET fabrics

Fabric	L*	a*	b*	C*	h
SK	40.52	51.53	8.53	53.22	9.22
KM1	38.46	51.97	8.27	53.66	8.79
KM3	37.64	52.21	7.77	53.79	8.46
KP1	38.61	52.60	7.71	53.47	8.34
KP3	37.77	52.32	6.64	54.76	7.35

SK is pristine PET fabric, KP1 and KP3 are PEGDA grafted PET at 1% and 3% concentration respectively, KM1 and KM3 are METAC grafted PET at 1% and 3% concentration respectively.

The grafting of PEGDA and METAC on PET fabrics reduced the lightness, increased the redness, enhanced the chroma, and reduced the hue angle. Especially, there were significant differences ($P< 0.05$) for K/S, L*, a*, b*, C*, and hue angle, suggesting enhanced color depth due to monomer grafting. The differences in L* between SK and the monomer grafted fabrics ranged between 5%-7%, towards darkness. The yellowness reduced by 3%-22%; higher values were recorded for PEGDA-g-PET. The chroma, which represents the color saturation, increased more for KP3 by about 3%. Figure 6.12 shows a visualization of the colorimetric differences among the dyed PET fabrics.

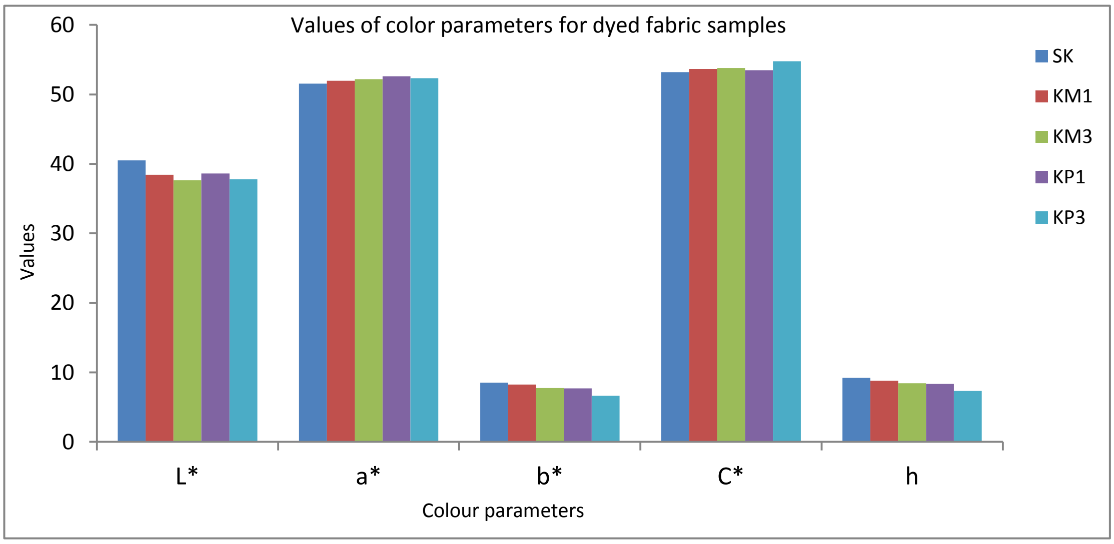


Figure 6.12 Color parameters of disperse dye red Anocron Rubine on PET fabrics: SK is pristine fabric, KP1 and KP3 are PEGDA grafted PET at 1% and 3% concentration respectively, KM1 and KM3 are METAC grafted PET at 1% and 3% concentration respectively

The wettability of fabrics is a very significant function in dictating the state of the molecular polymer chains. When the polarity is increased by monomer grafting, the speed of the segment polymer chains and moisture during dyeing is increased; the dyeing transition temperature is subsequently decreased. Hence, the rate of diffusion, and spreading of disperse dye molecules into the PET fabric is enhanced with potential increase in color strength. It is deduced that the rate of dye uptake and the total dye uptake, increase increasing hydrophilicity.

6.3.8 Appearance and hand of grafted fabrics after laundering and drycleaning

Table 6.10 Appearance and hand grades of grafted fabrics

Fabric	Laundering Hand	Appearance	Dry cleaning Hand	Appearance
KM1	B5	A5	B4	B4
KM3	B5	A5	B5	B5
KP1	B5	A5	B5	B5
KP3	B5	A5	B5	B5

The observed results in Table 6.10 indicate that all tested grafted fabrics were not affected by laundering, according to the subjective handle and appearance result. Except for KM1, the changes in hand and appearance were negiligible for the dry cleaning test. According to the evaluation protocol, B5 is the highest grade for hand, while, A5 is the highest grade for appearance, indicating a no change in the perceived change.

6.3.9 Colourfastness of dyed fabrics

Table 6.11 presents colour fastness results on grafted PET fabrics.

Table 6.11 Color fastness grades of dyed fabrics

Fabric	Dry rubbing	Wet rubbing	Washing-Colour change	Washing- Staining
SK	4	3.5	4	4
KM1	4	3.5	4.5	4.5
KM3	4.5	4	4.5	4.5
KP1	4.5	4	4.5	4
KP3	5	4.5	5	4.5

Colorfastness results indicate that PEGDA grafted PET fabrics had better colorfastness, generally. Additionally, grafted fabrics had better colorfastness compared to the reference fabric SK. Particularly, fabrics obtained from grafting with higher monomer concentration showed stronger colorfastness. These results are related to color strength properties, indicating that higher concentrations of monomer during grafting, lead to grafting of more hydrophilic groups on the surface of PET.

6.4 Conclusions

This study explored the surface grafting of two vinyl monomers to PET using photochemistry. The add-on, which represents the grafting yield, increased with monomer concentration in the solvent, more remarkably for PEGDA than for METAC. Surface quantification by EDS and XPS confirmed the grafting of PEGDA and METAC respectively. With either of the two monomers complete wetting was achieved. However, PEGDA offers a more sustainable hydrophilic functionality, both in terms of durability and economy as low monomer concentrations were required. Washing and solvent extraction reduced the wetting effect of METAC-g-PET. The grafting of PEGDA and METAC enhanced the color strength of PET fabric dyed with a disperse dye. Grafted PET fabrics presented strong fastness properties, slightly better than the reference PET fabric. The hand and appearance of grafted PET fabrics remains largely unchanged, following drycleaning and laundering procedures. This study demonstrates the potential of PEGDA and METAC for a hydrophilic function in conventional textiles utilizing UV grafting. It is suggested that PEGDA and METAC generate hydrophilic radicals/groups on PET; the macroradicals are in a form of vinyl structures which form short chain grafts and demonstrate hydrophilic function at the tested concentrations.

Chapter 7

General conclusions and future work

7.1 General conclusions

The potential of polyester as a possible substitute to cotton fiber was motivated by the available literature already surveyed. The global fiber market survey indicates that the future of cotton fiber supply, against the growing demand is unpredictable. Meanwhile, consumer surveys indicate a large preference towards cotton, in many countries. Global cotton fiber demand for 2017/2018 was projected to increase by 5% to 120.4 million bales, compared to 2016/2017 figures. Through available literature, it was also noted that polyester currently dominates the global fiber market share at about 60%, against cotton's share of about 30%, which was about 80% in the 1980's. A further projection is that polyester will peak to about 70% in 2025, against cotton's global share of about 21%. Meanwhile, polyester trades the largest in global synthetic fiber market, which peaked at 82% in 2015 and currently at about 80%. These statistics portray abundance of polyester fiber on a global scale. However, available literature also suggests that polyester has inadequate preference and usage in conventional apparel. Polyester and cotton have been compared for ecological sustainability. Researchers have argued against conventional cotton production, processing and handling; which poses strong bearing on ecological footprints. Moreover, polyester is also well priced compared to cotton. Through experimental studies and consumer surveys, inferior sensory properties, mass and heat transfer properties (moisture and thermal behavior) have largely been argued for the low exclusive use of polyester in apparel.

Therefore, this research explored the sensory and moisture properties of polyester and cotton fabrics. Sensory analysis of cotton and polyester woven fabrics was used to quantitatively determine and reduce the gap between the two fiber generics.

Using a sensory panel data, the largest dissimilarity was found between fabrics of dissimilar generic. The descriptor *crisp* was found to account for the highest variability between PET and cotton fabrics ($p \leq 0.05$). *Crisp*, was strongly associated with descriptor *stiff*. Hence, towards cotton replacement via this sensory approach, the modification of stiffness of polyester woven fabrics has been judiciously suggested. For the fabrics studied, sensory perception can be expressed via vision and touch, and that PET and cotton fabrics can be distinguished by appearance via vision. Important to note is also the superiority of intelligent computing in rank aggregation methods.

The use of NaOH and an amino-functional polysiloxane softener, with atmospheric air plasma pre-oxidation, to modify the stiffness of polyester was attempted. NaOH and softening treatment of polyester bridged between cotton and polyester woven fabrics studied. NaOH and softening treatment on PET fabrics yield fabrics perceived *soft, smooth, less crisp*, and *less stiff* compared to untreated polyester fabrics. However, cotton fabrics are perceived *natural* compared to any treated polyester fabrics. NaOH-treatment on polyester fabrics enhance air permeability and hydrophilicity, although it induces loss in weight—accompanied with loss in abrasion resistance and bursting strength. NaOH-treated polyester fabrics become hydrophobic and less air-permeable when treated with a silicon based softener. It is deduced that characterization by human perception can play a vital role in human centered production and processing of fabrics. A better understanding of fabric sensory perceptions was realized by integrating sensory analysis data with objective measurements data.

The sensory study of knitted fabrics indicates that fiber content, the knitted fabric structure and physical properties influence the sensory perception of knitted fabrics. Perceived sensory attributes of knitted fabrics were found to mostly correlate with the stitch density and thickness. The sensory perception of knitted fabrics was noted to be distinct from that of woven fabrics. However, similar to woven fabrics, the visual and hand attributes were found to dominate in differentiating between polyester and cotton knitted fabrics. Towards the replacement of cotton fiber with polyester, the modification (increase) in the stiffness or drape of PET knitted fabrics has been suggested.

Comparing instrunmental measurement and subjectiveevaluation of sensory attributes, this study noted that only a few sensory attributes were precisely expressed by instrumental measurements. Particularly, hand attributes were more expressed by fabric mechanical and surface measurements. It is deduced that human perception cannot be directly represented by instrumental measurements. The profiling of fabrics indicates that conventional PET fabrics can be distinguished from conventional cotton fabrics using selected subjective and objective attributes.

The hydrophilic activity of two vinyl monomers Poly-(ethylene glycol) diacrylate (PEGDA) and [2-(methacryloyloxy) ethyl]-trimethylammonium chloride (METAC), on PET was studied. Grafting polymerization was carried out with UV, using a radical photo initiator 2-hydroxy-2-methyl-1-phenyl-1-propanone (HMPP). Water contact angle (WCA) measurements and dynamic moisture management tests (MMT) indicate that PEGDA and METAC induce complete wetting of PET at concentrations 0.1-5% (v:v). The grafted PET fabrics remain hydrophilic following testing using washing and rubbing fastness tests. PEGDA grafted fabrics perform better, as static water contact angles of METAC grafted fabrics increase after washing. Colorimetric measurements (K/S and CIELAB/CH) and color fastness tests on dyed PET fabrics suggest that both monomers significantly improve the dyeing efficacy of PET. The grafting of PEGDA and METAC enhanced the color strength of PET fabric dyed with a disperse dye. Grafted PET fabrics presented stronger fastness properties, compared to the reference PET fabric. The hand and appearance of grafted PET fabrics remained largely unchanged, following drycleaning and laundering tests. The potential of PEGDA and METAC for a hydrophilic function in conventional textiles utilizing UV grafting has therefore been demonstrated. It is suggested that PEGDA and METAC generate hydrophilic radicals/groups on PET; the macroradicals are in a form of vinyl structures which form short chain grafts and demonstrate hydrophilic function at the tested concentrations.

These studies demonstrate the potential to functionalize PET woven fabrics using the studied methods. Physiochemical and performance studies indicate that, with controlled processing parameters, optimal products with enhanced moisture management and improved sensory perception can be obtained.

7.3 Recommendations for future work

As the study ensued, some presented elements were identified for further improvement.

The sample selection wasn’t based on a uniform structure and pattern of fabrics. A future study could consider a set of plain weave fabrics, twill fabrics, or still uniform weave density, fabric weight and yarn linear density. In this case, the main varying parameter would be fiber content. In the same vein, more blended fabrics could be considered, unlike in this study, where one blended woven fabric was considered. This would give a view on effect of cotton/polyester blend ratios on sensory perception.

In this study, all sensory evaluation panelists had at least some background knowledge of textiles and clothing attributes. This could pose potential emergence of bias as professionals and novices could easily recognize and profile some fabrics. Although training was carried out, in a future study, panelists could be pooled from a general population without such prior knowledge of products being evaluated.

The sensory evaluation utilized only one session. However, it is recommended that a future study does consider two sessions, and average values obtained. Also, through the available literature, the use of rank-based evaluation has some limitations; it is not possible to precisely estimate magnitudes and differences in perception for sensory attributes, between different samples. The use of score based scales would offer such estimates. Further, the sensory evaluation of woven fabrics and knitted fabrics in the same experiment could give an interesting dimension, instead of different sets of sensory panels for the two different fabric structures.

To arrive at some findings and conclusions, this study involved longer computations such that errors are likely. Some soft computing approaches such as fuzzy computing might lend credence in reducing these stages.

This study mainly considered fabric modification through chemical treatments and surface photo-grafting. The sensory functionalization of PET fabrics could also be considered on the point of view of polymerization, fiber spinning stages, yarn modification (e.g during staple spinning, blending and texturizing) and fabric structures.

Due to limitations in the scope of study, the sensory functionalization of knitted fabrics was not undertaken. A future study could consider this gap so as to compare approaches for knitted and woven fabrics.

The hydrophilic enhancement of PET fabrics through surface grafting could consider further studies on:

- Effect of different photo-initiators
- Efficacy of other grafting approaches e.g evaporative
- Effect of other hydrophilic monomers
- Performance properties of grafted PET fabrics e.g physical, mechanical, comfort and aesthetics; and sensory evaluation of grafted fabrics
- Cationic or ionic dyeing of grafted PET fabric as the fabric surface is modified
- Antimicrobial activity of METAC

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Appendix

Sensory evaluation tools

Individual identified fabric characteristics (descriptors of perceptions)

	Descriptor and meaning

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	

Bridged listing of sensory descriptors

	Descriptor and meaning
1 2 3 4 5 6 7 8 9 10 11	

Ranking of fabrics for descriptors: knitted fabrics

	Fabric ranks/rank lists				
Perception Descriptor	1	2	3	4	5
Stiff					
Soft					
Smooth					
Heavy					
Noisy					
Crispy					
Stretchy					
Drapy					
Regular					
Natural					
Compact					

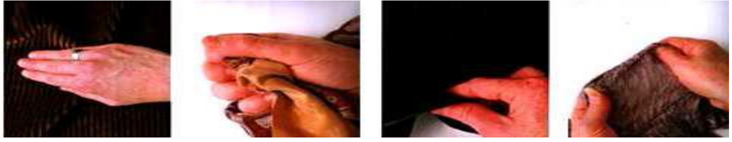
Ranking of fabrics for descriptors: woven fabrics

	Fabric ranks/rank lists					
Perception Descriptor	1	2	3	4	5	6
Stiff						
Soft						
Smooth						
Heavy						
Noisy						
Crispy						
Stretchy						
Drapy						
Regular						
Natural						
Compact						

Protocol for sensory evaluation

1. *Smooth*: We examine how smooth the fabric feels. The opposite of rough/lumpy
Assessment: Feel the fabric placed flat on a table by gently running your fingertips across the fabric surface once in all directions and assess the amount of smoothness

2. *Soft*: We examine how soft a fabric feels. The fabric slips easily between the fingers and thumb when rubbed; there is no resistance/drag. The opposite is hard
Assessment: Pick up the fabric and gently rub the fabric between fingers and thumb of your hand and assess the amount of softness.



3. *Stiff*: The amount of stiffness the fabric sample has. How rigid/inflexible the sample feels. The opposite is limpm or flexible
Assessment: Gather the fabric in hand applying some pressure to bend or compress in your hand. Assess how stiff the fabric feels during manipulation.

4. *Heavy*: The perceived weight of the fabric. The opposite is light
Assessment: Look and hold the fabric and assess its weight by comparing.

5. *Crisp*: Fresh, firm; brittle; also related to how rigid the sample feels
Assessment: Observe the firmness, freshness of fabric and also how stiff and brittle it feels upon bending

6. *Drapy*: How well the fabric drapes or hangs freely
Assessment: Using a pen or point finger let the fabric hang freely and observe how gracefully it shapes or deforms

7. *Noisy*: The amount and quality of noisy when fabric is rubbed against another surface
Assessment: Rub fabric to its other surface, also rub your fingers against the fabric and note the kind and intensity of noise

8. *Stretchy*, resilient, elastic: Ease of stretching, and recovering back. The opposite is nonstretchy
Assessment: Stretch with a small force, and see how much, and how easily the fabric stretches and returns back. Again, press/wrinkle the fabric in your hands and observe how easily it gets back to original shape

9. *Regular/even*: How even a fabric appears. The opposite is irregular
Assessment: Observe/touch the surface of the fabric for textural variations, lumps, slabs, soiling, pills, and fluff. Less of these, means more regular. Not related to variation in color shade or patterns

10. *Compact/dense*: The intensity of packing or closeness. The opposite is loose

Assessment: Observe the density of packing or tightness in the fabrics

11. Natural: Not synthetic; feeling of nature
Assessment: Observe, touch fabric to relate to natural or synthetic fiber. A more natural appeal means it ranks higher

10. Dry: A feeling of dryness, no moisture. The opposite is damp. Feel the fabric while fully gathered in your palms/hand

11. Bulky: Feeling of liveliness, springy, fullness and voluminous