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Odor in textiles: A review of evaluation methods, fabric characteristics, and odor control technologies

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Abstract

During use, textile items can develop unpleasant odors that arise from many different sources, both internal and external to the human body. Laundering is not always effective at removing odors, with odor potentially building up over time due to incomplete removal of soils and odorous compounds and/or malodors transferred during the laundering process. Textile odor can lead to consumer dissatisfaction, particularly as there are high expectations that clothing and textile products meet multiple aesthetic and functional needs. The problem of odor in textiles is complex and multi-faceted, with odorous volatile compounds, microorganisms, and precursors to odor, such as sweat, being transferred to, and retained by, fabrics. This article reviews the literature that specifically relates to odor within textiles. Methods for evaluating odor in textiles, including methods for collecting odor on textile substrates, as well as sensory and instrumental methods of odor detection, were reviewed. Literature that examined differences among fabrics that varied by fabric properties were reviewed. As well, the effectiveness of specific odor controlling finishing technologies to control malodor within textiles was also examined.

Keywords

clothing, odor, wear trials, sensory measurement, fiber, odor control, antimicrobial, adsorption

Clothing and interior textiles are typically selected in order to fulfill specific functional or aesthetic needs. Sensory attributes that relate to appearance (e.g. color, luster, design) or fabric handle properties (e.g. texture, stiffness, resiliency) are important when consumers make purchasing decisions. But with use, the build-up and release of odor may become an undesirable feature of some textile items, resulting in consumer dissatisfaction. Odor which can become problematic due to its adherence and persistence within textiles can come from many different sources, both internal and external to the human body. Sources of odor that arise from the human body are secretions from the sweat glands, urine, feces, skin, and genitals. The main physiological contributors to body odor are from eccrine and apocrine sweat glands located in the axillary region, sternum, anogenital area, scalp, feet, and hands.[1] Secretions from sebaceous glands, found in many of these same areas, also contribute to odor. Ingesting foods such as garlic and onions, as well as alcohol and some therapeutic drugs, can strengthen the odor produced by the body.[1,2] Sources of malodor which are external to the body arise from many indoor and outdoor exposures, such as cigarettes, campfires, cooking, mildew and mold, and odorous products present in various workplaces (e.g. grease, pesticides, animals).[3] Laundering may remove malodors, often replacing them with fresh and fragrant odors present in detergent and laundry auxiliaries. However, the laundering process can become another source of textile malodor. Laundry malodor may result from the transfer of odorous compounds from the washing machine to textiles during washing,[4] transfer of microorganisms from the washing machine to the textile,[5,6] incomplete

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removal of soils resulting in a build-up over time,[4,7] or slow-drying.[8,9]

Although all these sources of odor can be unpleasant when transferred to and detected within textiles, sweat-related body odor has been reported to be the most common type of odor detected in clothing.[10] In fact, odor emanating from the axillary region has been described as the most "powerful and distinctive" of body odors,[11] which has led to much attention being placed on identifying microorganisms responsible for odor, their metabolic pathways, and odorous volatiles.[12–16] Reviews that address the chemical composition of key odorous volatiles released from the human axillary region,[11] volatiles released from human skin,[17,18] laundry-related malodor,[11] and malodors present in the domestic indoor environment[3] have been conducted. Yet a thorough review specifically relating to odor on textiles has not.

The unique problem of odor within textiles is highly complex and multifaceted. Odorants are volatile compounds perceived by the olfactory organ and therefore, by nature, are present in the ambient environment as gaseous compounds where they can be sorbed by fibers and subsequently released. Many problematic odors are caused by the biotransformation of non-odorous compounds (i.e. odor precursors) by specific microorganisms, as is the case with most odors arising from the human body[18] or due to prolonged dampness.[8,19] Odorants or precursors to odor can transfer to textiles through aqueous liquid media such as sweat or laundry water where the hydrophilic nature of the textile can influence odor sorption. Particulate matter in the air or from direct contact with another substrate could become another route for the transfer of odor as particles are trapped by the fibers within the textile structure. Furthermore, temperature, humidity, and airflow may all impact odor production, as well as retention and release of odorants.

The purpose of this review is to examine the literature on odor within textiles. This review is divided into three parts. First, it examines methods for collecting odor as well as methods for detecting odor. Second, it reviews the literature on differences among fabrics varying by inherent fabric properties but not specifically odor controlling finishes (e.g. fiber type, fabric structure). Finally, textile finishing technologies that have been used to control malodor within textiles will be identified. The review will be limited to reusable textiles that are designed to be used multiple times, such as clothing and household textiles, and not single-use, disposable items which may be used as an odor control substance for limited time periods (e.g. bandages to control wound odor). Not all odor sources are unpleasant, and imparting desirable odors to a textile may be beneficial. However, fragrances mask unpleasant odors rather than controlling them so they are also outside the scope of this review (fragrances and polymers for storing them have been reviewed elsewhere[20]). Nonetheless, methods for evaluating odor reduction of single-use textile items or fragranced textiles may still be included. Removal of odor from textiles via laundering or other refurbishment techniques, or addition of odor absorbing chemicals applied topically to textiles by the consumer, are also outside the scope of this review.

Evaluating odor on textiles

In evaluating odor on textiles, both the collection and detection of odor are important. That is, how different types of odors are trapped, generated, or collected on a textile substrate will influence the prediction of how effective an odor controlling textile will be under real use circumstances. A method that effectively collects odorants on a textile is as important as the method to detect the odorant.

Collection of odor on textiles

The most representative method for collecting body odors in fabrics is through human wear trials, as this is how odor would be transferred to a fabric in real life. Simple methods for collecting odor include sewing or pinning fabric swatches into T-shirts,[7,21,22] taping textile pads to the axillary vault,[23,24] wiping the axillary vault and/or other parts of the body with a textile swatch following excessive sweating.[7,25] Bisymmetrical T-shirts with a different fabric on each side of the body have been used when multiple wear and wash cycles were needed for odor to develop over time.[26,27] Sweat (predominantly eccrine) was obtained by sewing fabrics to gym mats during circuit training where multiple participants contributed to overall odor.[28] Collection of axillary and upper body sweat was obtained from sampling the whole T-shirt worn by participants after one hour of bicycling spinning exercise.[29] And in research related to laundry malodor, researchers collected used towels and clothing from a number of different households.[30]

Human wear trials can be limited by high inter- and intra-individual variability of odor emitted from human subjects.[31] This variability can result in it being difficult to compare the results obtained from an odor controlling textile in one session against another, unless suitable controls are set in place. Klepp et al.,[28] addressed some of these issues by rotating the position of multiple fabrics that were used by many different people during circuit training. McQueen et al.[32] grouped fabrics with axillary sweat and odor on them by fiber type and fabric structure, with each test sample consisting of fabrics worn by four to five different participants. However, the authors posited that a fabric worn by a participant who had strong odor may override the intensity of lower odor participants, thereby not addressing the problem of high inter-individual variation. Furthermore, it may often only be feasible to directly compare two fabrics at one time (one fabric swatch per axilla). Therefore, human wear trials, although realistic and representative of how odor is generated and transferred to fabrics, are time-consuming and can lack repeatability.

To counter many of these issues developing in vitro, or lab-based, methods may be done. However, in vitro trials for replicating how odor may develop on fabrics are lacking. Chung and Seok[33] inoculated cotton fabrics with triolein as the representative sebum-like soil and *Staphylococcus epidermidis* as the representative organism. They detected an increase in volatiles such as alcohols and one ketone (2-heptanone) after 168 h of incubation, which indicated some metabolism of the triolein soil by *S. epidermidis*. In an earlier study, Obendorf and colleagues[34] measured the presence of 5a-androst-2-en-17-one after inoculating antimicrobial-treated and control polyester fabrics with *Corynebacterium striatum* and androsterone sulfate. However, in both studies, no accompanying sensory detection was carried out to determine whether the presence of compounds corresponded to perceptible odor.

Instead of incubation of microorganisms on fabrics with precursors, the ISO test method 17299 evaluates the sorption of key odorants that are used to represent toilet odor (ammonia), sweat odor (ammonia, acetic acid, isovaleric acid), body odor (ammonia, acetic acid, isovaleric acid, nonenal) and excrement odor (ammonia, acetic acid, hydrogen sulfide, methyl mercaptan, and indole).[35] Odorants are presented separately in a gaseous form, with a textile substrate present as well as absent, and an odor reduction rate is calculated. The test method was developed in order to standardize the evaluation of odor controlling technologies on textiles using instruments rather than human assessors. To date, there are few published papers employing the ISO method.[36–39] Lee et al.[36,37] used the gas detector method to evaluate the deodorizing properties of natural dyes and mordants used on cotton, silk, and wool fabrics with ammonia and acetic acid as challenge odorants. No correlation of odor reduction rates with sensory panels was conducted. Whereas, Abdul-Bari et al.[38] used the gas chromatography method with 2-nonenal and isovaleric acid when evaluating differences in odor retention of nylon and polyester fabrics and found that, although nylon had a higher odor reduction rate than polyester, there were no significant differences among the fabrics in odor following wear next to the axillary region as assessed by a sensory panel. Therefore, there is still a need for an in vitro method which represents the mechanisms for odor development and transfer from an "artificial skin" to the textile substrate. Factors such as moisture, odorous compounds, odor precursors, bacteria, and mechanical action must all be considered. As well, hundreds of compounds may make up an odor that arises from a particular source. One or more volatiles may be characteristic of a particular odor source, but these volatiles alone may still not be as realistic as the overall mixture.[40] Therefore, selection of only one or two compounds to assess odor reduction of textiles treated with odor control technologies may be insufficient, due to the vast array of compounds that make up any specific odorous source (e.g. axilla, foot odor).

Detecting odor on textiles

As odor is detected through the sense of smell, the use of human assessors in sensory evaluation for detecting odors in textiles is appropriate. Sensory evaluation is a scientific discipline used to evoke, measure, analyze, and interpret reactions to those characteristics of products as they are perceived by the senses of sight, smell, taste, touch, and hearing.[41] In textile testing, sensory evaluation would more typically be applied to sensations of sight (e.g. color, wrinkling) or touch (e.g. fabric handle properties). However, sensory evaluation detecting the presence and quality and/or intensity of odorants is widely applied in food, beverages, and cosmetic industries (e.g. references 42–44). An alternative approach to detecting odors is through instrumental means of analysis such as chemical and/or electronic sensors to determine the types and concentrations of odorous volatiles in the air or textile substrate.

Sensory measurement. The human nose is a highly sensitive measuring tool. Essentially, it is because the human nose detects odor that the presence of odor within clothing becomes a problem. Many challenges arise from using humans in the detection of odor, such as natural human variation in sensitivity to odorants, ensuring reliability and repeatability of human assessors, and their ability to use scales to rate odor intensity and quality. Nevertheless, selecting assessors for a sensory panel who have been screened for odor acuity followed by training can result in consistent individual responses.[45] The ASTM E1207-09 test method specifies methods for how to screen and select assessors for a sensory panel for determining axillary deodorancy (as well as selection of odor-producing participants).[46] Assessors are first screened for odor sensitivity against isovaleric acid then, if they pass, for specific anosmia (odor blindness) to a number of compounds which may be present in human sweat (e.g. androstenone, androstenol, methyl ionone family and synthetic and natural musks). Key odorants which have been identified as the main contributors to typical axillary odor (i.e. 3-methyl-2-hexenoic acid, 3-hydroxy-3-methylhexanoic acid, 3-methyl-3-sulfanylhexan-1-ol) are not specifically mentioned but could also be included within the test procedure.

The main advantage of using human assessors as odor detectors is that odor thresholds of many compounds present in human sweat are extremely low and can be difficult to detect through instrumental techniques.[15,19,47] The other advantage is that many textile-related odors, such as axillary odor, are made up of a complex array of odorants and the human sensor can capture the whole "bouquet" rating odor intensity as a single rating.[32] Although, it may also be possible in highly trained sensory panels to describe odor quality and offer more descriptive analysis of odor notes.[12] Furthermore, the non-odorous volatiles which can complicate the volatile profile gathered by instrumental means are ignored in sensory analysis.

Sensory measurement can be affected by the context in which an odor source is assessed, making it difficult to view ratings as absolute or to compare ratings across different times, sessions, or settings.[48] The actual sensation itself may change due to adaptation where the perception of one odor is perceived weaker because of the immediately preceding odor. Selection of sensory test methods must be appropriate for the research objectives. Order of presentation, visual differences among test samples, and sample labeling should be prepared in such a way to avoid potential biases. Furthermore, limiting the number of samples and allowing sufficient time in between sniffing test samples should be done to reduce adaptation effects and/or sensory fatigue. The environment where sensory assessment is conducted should also be controlled, being odor-free as well as free of other distractions (e.g. fluctuating temperature, conversations, movement of others).[45]

There are several discrimination and scaling tests that are available to the sensory scientist, many of which have been applied directly to evaluating odor within textiles.[26,28,29,32] Discrimination test methods should be used when the objective is to determine whether there is a perceptible difference between two samples. Scaling test methods are used to show whether there are differences among samples, with the degree of these differences also indicated.[48] Based on discrimination testing, odor thresholds can be measured using a 3-alternative forced choice method utilizing olfactometers where sniffing occurs in three presentations. One will contain the odorant diluted with air, and the other two blanks of air.[49] Determining the odor threshold of an odor source can indicate its odor impact. Olfactometers have been used in determining the intensity of isovaleric acid applied to wool, cotton, and polyester fabrics with and without a cyclodextrin treatment[50] and in the comparison of wet and dry polyester/wool pants that differed in color.[49]

The paired comparison is one of the simplest discrimination tests that involves directly comparing two samples to one another and is useful when small differences between samples are required. Paired comparison tests have been applied in the evaluation of odor controlling technologies in non-woven fabric[51] as well as to odor absorbent technologies that may be used in sanitary products.[52,53] Although it has been used less widely in research on odor emitted from clothing. McQueen et al.,[32] used quad analysis which is a method based on a series of paired-comparisons resulting in a ranked order of samples. The quad analysis test procedure,[54] while more efficient than the traditional paired comparison approach, was still deemed to be more time-consuming than a line scaling procedure that was also conducted with the same type of worn fabric samples.[32] The advantages of a scaling procedure such as a line scale compared with paired comparison is that the magnitude of the difference among fabrics can be measured. McQueen et al.,[32] argued that an odor control technology should make a large enough difference from a control fabric that very small differences detectable through a discrimination test method do not provide additional benefit. Scaling methods, such as category scales or line scales, have been more commonly employed by researchers evaluating differences in odor attributes among fabrics that vary in fiber content[8,21,26,29] or evaluating the effectiveness of an odor controlling technology.[28,55,56]

Guidelines for recruiting, selecting, and training assessors for a sensory panel are outlined in ISO 8586.[57] The minimum number of assessors recommended for a sensory panel is 10, but depending on the sensory test, whether the results need to be interpreted statistically, and the level of sensitivity required, the number of assessors is typically larger. Larger panels increase the likelihood of detecting small differences among samples.[58,59] Considerations for the selection of assessors include ability to perform the sensory tasks required, availability to attend panels, willingness and interest to be involved on a sensory panel, and being in good health.[45] Assessors range in experience, acuity, and training.[45] Naive assessors are those who do not meet any particular criterion and initiated assessors are those who have already taken part in sensory tests.[45] Both naive and initiated assessors are common on consumer panels, particularly in food science, where the wide and varied perception of consumers is desired to better predict the performance of a product in the market.[60] Consumer panels have not been common in textile odor research; however, naive and/or initiated assessors have been used as a specific criterion in selecting assessors and subsequent training has not been carried out.[28,32,61] Selected assessors are those who have been specifically chosen and trained for a particular sensory test.[45] Selected assessors were used to detect axillary odor following multiple wear and wash cycles among cotton and polyester fabrics,[26] differences among worn polyester and nylon fabrics,[38] and worn antimicrobial-treated cotton and polyester fabrics.[56] To date, most of the research involving sensory analysis on odor released from textiles has screened or selected assessors based on some predetermined criteria, such as odor acuity to specific odorants [29] or showing good reliability and discrimination in earlier work,[21] but have provided no training prior to the sensory panels. Expert assessors are those who have been selected and trained for many sensory trials and exhibit high acuity and discrimination in sensory panels.[45] In determining the bacteria responsible for laundry malodor, three expert assessors were used.[30]

Instrumental analysis. Measurement of odorant structure and concentration is possible through chemical analytical techniques. The most common technique used for quantifying odorous volatiles retained within, or released from, textile substrates is gas chromatography (GC) coupled with different detectors (e.g. mass spectrometry [MS], flame ionization detection [FID]). For the separation and quantification of complex mixtures collected from human participants, GC-MS is more commonly employed as it facilitates the identification of the individual compounds in these mixtures.[62] Before chemical analysis can be conducted, it is necessary to extract volatile compounds first, which may involve either extracting the compounds retained within the textile substrate (e.g. reference 8) or collecting compounds from the headspace above the textile (e.g. reference 22). Extracting compounds from the textile substrate typically involves a multi-stage process of extraction and clean-up before compounds are analyzed, whereas headspace extraction does not.

Analysis of the headspace is more applicable to how the human nose detects odor, that is, as gaseous compounds in the environment. Yet, directly extracting compounds from the textile can be advantageous due to the extremely low odor thresholds of some key compounds (e.g. parts per trillion [14]) that results in them being difficult to detect in the headspace using available analytical tools. Direct extraction of compounds collected on textile fabrics (usually cotton) has been common in studies where skin volatiles were collected with the intent of examining differences in volatile profiles among people or groups of people or in the identification of key body odorants.[15,16,47,63] However, direct extraction could be inappropriate when evaluating different fiber types or odor controlling technologies, as odor sorption can be a key method for odor control (e.g. activated charcoal cloth). Far greater quantities of compounds could be extracted from a highly sorbent textile effective at controlling odor compared with a non-sorbent textile which is perceived to be odorous. On its own, directly extracting compounds from textiles may lead to erroneous results. Therefore, including sensory evaluation or additional headspace sampling may be necessary.

Methods for sampling volatiles in the headspace can vary and are classified as static headspace sampling (SHS), dynamic headspace sampling (DHS), and solid-phase microextraction (SPME)-headspace sampling.[64,65] For SHS, the simplest and cheapest approach is where an aliquot of air above a material is collected using a gas-tight syringe. But the most common SHS is a transfer line-based system where aliquots of headspace volatiles are directly transferred from a pressurized vial to the gas chromatograph via a capillary transfer line.[66] When conducted at ambient conditions, SHS extraction can best reflect the headspace volatiles.[67] Soiled and washed socks and T-shirts were analyzed using SHS to determine foot and axillary odors in laundry malodor.[4] In determining the odor reduction rate, SHS is used to sample volatiles from a vessel containing a specific odorant with and without a fabric specimen.[68] Yet, due to low odor yields of many important odorants, detection of compounds with SHS can be difficult,[64] so it is recommended that SHS be used when the concentration of compounds are in the high parts per billion.[65] Concentrating and trapping volatiles using dynamic headspace purge and trap methods may be desirable.[64] DHS purge and trap involves an inert gas being continuously passed over the headspace of the sample to then be trapped by a sorbent for later analysis, which achieves a more exhaustive extraction of volatiles.[66] SPME involves sampling headspace volatiles by a coated fused-silica fiber contained within a syringe needle, where the fiber is extended into a headspace vial for volatile extraction and again for desorption into a gas chromatograph.[66] Headspace sampling using SPME is useful compared with other sampling methods since SPME can be more sensitive and most volatiles present in the headspace are easily extracted.[67] Nevertheless, it is still important to consider the limitations of the SPME fiber, such as the selectivity of the SPME fiber which may result in a higher affinity for non-polar compounds; competition for adsorption to the SPME fiber when there are unequal concentrations of volatiles and one compound saturates the fiber; and since SPME is not exhaustive, it is not possible to quantify compounds in a complex mixture.[67] Carboxen-polydimethylsiloxane SPME fibers have been used in the extraction of volatiles from scoured and unscoured sheep wool.[69] Skin odors transferred to fabrics from the human axillae[26,70] and hands[71] have been extracted with divinylbenzene/carboxen/polydimethylsiloxane coated fibers.

A major advantage of GC-MS techniques is that a complex array of compounds can be detected and identified, which makes them appropriate to use when analyzing odor samples collected during wear trials. However, as many volatiles may be odorless or have extremely low odor thresholds, they may not be important in odor. GC-MS has been used to compare the chemical profile of body odorants generated within cotton fabrics that had been treated with a plant extract that reportedly had antimicrobial properties compared to an untreated cotton control.[72] Differences were found among the treated and non-treated fabrics in mass spectra,[72] although no information was provided about the sampling procedure used to extract volatiles. Volatiles extracted from cotton and polyester fabrics using SPME were analyzed by comprehensive two-dimensional gas chromatography (GC $\times$ GC) with time-of-flight mass spectrometry (TOF-MS).[26,27] Two-dimensionality overcomes the problem of peak overlap that can occur in one-dimensional chromatograms of complex mixtures.[73] Between 1000 to 2000 individual compounds were detected, and through advanced chemometric analyses, fabric samples could be clustered by their chemical profile with differentiation between unwashed/washed fabrics, fiber type, and gender of participant.[27] Although, not all volatiles would have been odorous.

Coupling gas chromatographic techniques with olfactometry (GC-O) is an important technique enabling odor active compounds to be identified within a substrate as well as their relative importance to the overall odor profile.[74] When combined with mass spectrometry, the perceived odor compounds can be identified through their mass spectra. GC-O has been applied successfully for many years, particularly within food and beverages (e.g. references 75–77), but also in the identification of key body odorants, including those sorbed by fabrics,[7,8,16] and compounds responsible for laundry malodor.[7,19,78] As GC-O relies on detection by a human assessor, many of the same issues that apply among sensory panels apply to GC-O. For example, odor thresholds can vary significantly among individuals, with some people exhibiting specific anosmia to some odorants.[74]

Instruments which make use of chemical ionization allow for real-time analysis without the need for extensive preconditioning or complex extraction techniques.[79] Unlike electron impact ionization, fragmentation of organic molecules does not occur with chemical ionization. Proton transfer reaction mass spectrometry (PTR-MS),[80] selected ion flow tube mass spectrometry (SIFT-MS),[81] and ion mobility spectrometry (IMS)[82] are examples of chemical ionization. Chemical ionization techniques may be preferable when identification of specific volatiles within a mixture of gases is required. Carboxylic acids present in axillary odors were detected using PTR-MS through direct headspace analysis of the axilla and through analysis of worn fabric samples.[22,83] The release of selected volatiles from wool, cotton, and polyester fabrics was also measured with PTR-MS.[84,85]

Detector tubes and electronic noses are other instrumental techniques that have been used in the evaluation of deodorizing properties of textiles and comprise part of the ISO 17299 test method.[86,87] Electronic noses are made up of an array of gas-sensitive semi-conductors connected to an appropriate pattern-recognition system that has the capability to detect complex odors. More recently, the term electronic nose has been extended to other gas detecting systems such as IMS, particularly when it is portable.[88] Electronic noses can have up to 40 sensors, each calibrated for a different chemical specificity, which when combined provide a measurement pattern. The electronic nose relies on pattern recognition and therefore cannot identify unknown (or unexpected) compounds but is still considered an instrument that comes close to mimicking the human olfactory system.[89] Electronic noses have been employed in many areas such as the food industry, health and pharmaceutical areas, industrial waste management, and agricultural facilities (e.g. references 88 and 90–92). Although not as common, they have also been applied to detecting malodors and fragrances emitted from textiles.[61,93–96] Eza et al.[94] used a commercial electronic nose with metal oxide gas sensors to determine the reduction of onion odor by cotton and polyester fabrics printed with activated charcoal. A single metal oxide gas sensor was used to detect fragrances of jasmine and thyme essential essences applied to wool, cotton, and polyester fabrics.[61] Cigarette, milk, and sweat odors were distinguishable on wool, cotton, and polyester fabrics by a special gradient gas sensor microarray of metal oxide gas sensors.[95]

Gas detector tubes work as a chemical reaction between a vaporous compound and a detecting liquid or solid detecting reagent. The color within the detector tube changes proportionally to the concentration of the test compound.[86] Detector tubes are simple and have been historically used to detect hazardous gases in the environment.[97] Although they are useful in detecting some odorous compounds they are limited as they can only detect single compounds at a time and instead may only provide a useful screening method for assessing potential odor controlling technologies. Detector tubes have been applied to many textile and finishing applications, such as examining the deodorizing properties of mordant-acid dyed wool and cotton fabrics to ethyl mercaptan (ethanethiol);[98,99] silver and titanium dioxide treated polyester in the reduction of ammonia, acetic acid, and trimethylamine;[100] cotton, silk, and wool fabrics dyed with plant extracts to ammonia and acetic acid;[36,101] and dimethyloldihydroxyethyleneurea/acrylic acid cross-linked cotton fabrics post-treated with metallic salts to ammonia.[102]

Radiotracer analysis, in the liquid scintillation technique, relies on fluorescing of radioactive atoms which typically use ^{14}C or ^{3}H tracers to radiolabel compounds. In textile applications, liquid scintillation counting has been used to evaluate the efficacy of laundering to remove body oils,[103] industrial contaminants,[104] as well as in the analysis of oily soil aging processes on fabrics.[105] Liquid scintillation was used to quantify the sweat odorant isovaleric acid (^{14}C-radiolabled) that remained on untreated and β-cyclodextrin-treated wool, cotton, and polyester fabrics via an artificial skin model.[50] An advantage of this method is that the complex solvent extraction and clean-up processes often required in direct extraction methods are not needed as odor molecules are quantified in situ.

Odor retention and release in fabrics

The retention and release of odor in/from fabrics is complex and multifaceted. Microorganisms are responsible for many malodors, particularly those arising from the human body, with studies showing that fiber type can influence bacterial adherence and growth.[29,106,107] Control of microorganisms within textiles by way of antimicrobials can reduce secondary production of odor (i.e. odor produced within the textile). Yet textiles also sorb (adsorb and absorb) odorous compounds directly and release (desorb) them at varying rates. Adsorption is a surface phenomenon, whereas absorption occurs when molecules enter the bulk or volume of a substrate. In both phenomena, physical or chemical interactions can occur. In physical adsorption, or physisorption, electrostatic forces hold the adsorbed molecules onto the surface and the process does not involve the formation of chemical bonds. Adsorption of compounds using activated carbon and zeolites involves physisorption. Likewise, in physical absorption, non-reactive processes are involved where molecules enter the volume of the substrate but no chemical reaction occurs. In chemical adsorption, or chemisorption, chemical bonds are formed at the surface of the substrate, or within the substrate, as with chemical absorption.[108,109] It is not clear whether absorption or adsorption of odor is the primary process for how odor molecules adhere to textile fibers. Adherence of odor molecules to textiles must involve adsorption, as even when absorption occurs, molecules must first be adsorbed.[108] In many fiber/odorant interactions, absorption also occurs and will depend on fiber type, odor molecules, and the medium (liquid, vapor, particulate) in which odor molecules are transferred to the textile. Moisture has a plasticizing effect on hydrophilic fibers and swells the fibers.[110] Odor molecules may be transported into the fiber interior with water, where they become trapped when the fiber dries and/or subsequently desorb. The term sorption captures both adsorption and absorption phenomena and may be a more appropriate term when referring to adherence of odor molecules in textile fibers generally.

Effect of fiber type

Textile fibers inherently differ in chemistry and physical structure, thereby influencing their susceptibility to sorb moisture, soils, and other chemical compounds. Generic fiber type has been shown to impact odor intensity and quality following wearing of clothing next to the skin.[21,29] Clothing composed of natural fibers are generally perceived to be less odorous following wear than clothing made from synthetic fibers.[111] However, it was not until the beginning of the 21st century that research evaluating the effect of fiber on odor retention began to emerge.[8,21] The sorption and/or release of chemical volatiles related to human body odors for cotton, polyester, wool, and more recently, also viscose and nylon have been examined directly after contact with the human body[7,22,26,38] or with selected chemical compounds in vitro.[71,84,112]

Although laundering is used to remove soils and bad odors, malodor can still continue to emanate from laundered clothing, with both intensity and quality influenced by fiber type.[8] Over time, as clothing is repeatedly worn and washed, there is incomplete removal of soils via laundering, most notably in hydrophobic polyester fabrics, leading to perceptible odor still emanating from freshly laundered fabrics.[8,26,113] This is because the attraction of non-polar soils and odorous compounds to oleophilic polyester fibers plays a major role in the build-up and persistence of odor on polyester clothing. In a study examining the build-up of body odor in cotton and polyester jersey knit fabrics (both with 5% spandex), stronger odor intensity was perceived in polyester fabrics before as well as after laundering.[26] GC analysis of volatiles also revealed that C_4–C_8 carboxylic acids were more easily removed from cotton after laundering than from polyester. Although only carboxylic acids were identified by McQueen et al.,[26] poorer removal of other odorants from polyester, such as aldehydes, will also likely occur.[8,113] In fact, Munk et al.[7] stated that ketones, esters, and in particular, aldehydes are major contributors to the overall odor profile in washed fabrics. Whereas carboxylic acids, despite being a major contributor to axillary malodor, may only play a minor role in the odor profile of laundered clothing.[7]

Under some conditions, stronger malodor can be released from cotton fabrics. A comparison of polyester and cotton interlock knit fabrics contaminated with sebum and axillary sweat, washed and then stored wet, resulted in cotton fabrics being perceived as more odorous than polyester fabrics when no additional biocide was added to the wash.[8] The authors[8] described the stronger malodor emitted from cotton as likely to be associated with one compound, 3-methylindole (skatole), which was highly odorous and only present in the cotton samples. However, polyester retained more odor impactful volatiles than cotton, resulting in a more complex odor profile overall. With the inclusion of a biocide as part of the wash process, no difference in odor intensity between polyester and cotton was perceived.[8] These findings indicate that bacteria do play a major role in laundry-related malodors, which is supported elsewhere, particularly for fabrics composed of cellulosic fibers.[30]

Despite bacteria being responsible for the generation of most body odors, the role bacteria play in how odoriferous a textile becomes after contact with the human body is not completely clear. McQueen and colleagues[21] compared merino wool, cotton, and polyester knit fabrics in odor intensity and bacterial counts 1, 7, and 28 days after being worn next to the male axillae. Merino wool fabrics were significantly less odorous than cotton and polyester, and cotton was significantly less odorous than polyester (consistent across all time periods). Yet, surprisingly, bacteria persisted longer on merino wool fabrics than on cotton and polyester over the 28-day test period. Subsequent research indicated bacterial metabolism was apparent in textiles as compounds identified as short-chained carboxylic acids increased on polyester fabrics but not on wool or cotton despite polyester having lower bacterial populations after 7 days.[22] In another study involving 26 participants wearing cotton, polyester, or cotton/synthetic blend T-shirts, polyester garments were perceived as more intense, as well as more sweaty, musty, ammonia, and sour in terms of odor qualities.[29] *Micrococcus* species were prevalent on polyester and cotton/synthetic blended garments but not on 100% cotton. Whereas, staphylococci were present on all garments regardless of fiber type, but specific species such as *Staphylococcus hominis* were exclusively found on 100% cotton garments.[29] These findings were in agreement with earlier work by Teufel et al.[106] who found that following incubation with sweat samples staphylococci grew on all their test fabrics (i.e. lyocell, cotton, nylon, polyester, polypropylene) but with a higher percentage of clones found on the two cellulosic fabrics. *Micrococcus* species were present in only one sweat sample, but the authors noted that enrichment of *micrococci* occurred on polyester samples. Furthermore, two taxa otherwise low in the native sweat samples (*Bacillus* and *Pseudomonas* species) had a much higher proportion of growth on the synthetic fibers compared to the cellulosic fibers.[106] Bacterial species play a major role in odor production and there appears to be selective growth of certain species on materials differing by fiber type; however, the chemical–physical interactions of odorants and precursors to odor likely play a more significant role in odor retention and release following wear next to the skin.

The sorption and release of selected odorous compounds by different textile fabrics has been investigated.[84] Distinct profiles were evident by fiber type. Cotton exhibited the lowest levels of sorption followed by relatively faster rates of release of selected compounds; polyester sorbed the highest amounts of test compounds and had a high rate of desorption of sulfur compounds; wool also sorbed high amounts of compounds but had a slow relative release.[84] The authors discussed the findings in relation to the dipole moments of selected compounds and sorption by polyester, with benzaldehyde, which has a dipole moment of 1.11 D, being more completely sorbed by polyester and subsequently showing low release, whereas compounds with higher dipole moments (ranging from 1.53 D to 2.50 D) had lower amounts sorbed with higher rates of release.[84]

Generally a negative association between odor intensity and amount of isovaleric acid retained within the fiber/fabric structure was found by Hammer and colleagues.[50] Wool fabrics continued to hold onto greater amounts of isovaleric acid while being perceptibly less odorous than polyester fabrics that retained dramatically less isovaleric acid after 3 and 20 hours of contact.[50] The beneficial odor reduction properties of wool have been recognized as contributing to lower odor in polyester/wool blends, with 20% wool improving odor properties.[112] Wool has a number of potential binding sites within the fiber structure (e.g. polar, acidic, and basic), which could result in a variety of different odorous volatiles becoming sorbed and trapped within the wool fiber, so not detected by the human nose in the surrounding air. McQueen et al.,[22] found that odor intensity was inversely related to moisture regain, with hydrophobic polyester fabrics exhibiting more intense odor and absorbent merino wool fabrics exhibiting low odor. Hence, they postulated that the sorption capacity of the fiber may predict odor intensity. This finding led to a hypothesis that nylon, which has a moisture regain of around 4.5% at 20°C and 65% relative humidity would have lower odor intensity following wear than polyester which has a moisture regain of 0.4%. Despite nylon exhibiting a higher odor reduction rate for 2-nonenal and isovaleric acid and therefore being expected to have lower overall odor, no differences in odor intensity were apparent between the nylon and polyester fabrics following wear.[38] Clearly more work needs to be done to better understand the mechanisms of odor retention and release from fabrics differing in fiber type.

Effect of other fabric properties on odor

Although fiber type has a major impact on odor intensity following wear, small differences relater to fabric structure have also been found.[21] In the study by McQueen et al.[21] the thicker, heavier interlock and 1×1 rib fabrics were perceived to be more odorous than the thinner, lightweight single jersey polyester fabrics.[21] As both cotton and wool fabrics had low-odor properties following wear, no difference was perceivable among fabric structural differences. However, it is possible that increasing the thickness and surface area of a fabric made from fibers with high odor sorption characteristics may further lower odor, whereas a fabric from odor "emitting" fibers may intensify odor.[21]

Odor emitted from textiles can be influenced by color. Following customer complaints about a pair of beige polyester/wool pants that were deemed unpleasantly odorous when wet, pairs of wet and dry beige, navy, and charcoal pants were assessed by a panel of expert assessors.[49] No differences were found among the pants when dry; however, when wet, the beige polyester/wool pants had far higher odor threshold values (500 compared to 30 for navy and 150 for charcoal pants) and were perceived to be more "animal and wet dog or fur like," whereas the wet charcoal colored pants had a higher proportion of fruity and floral descriptors.[49] Although, the reason for the high odor of the beige pants was not explained, it may be possible that the dyes used in the darker colors had deodorizing effects which reduced the unpleasant odor commonly emitted from wool when wet.[69] In other studies, researchers have found that mordants in dyeing can have a deodorizing effect on fabrics, particularly wool.[98,99] This was the case for copper II sulfate ions, where the Cu ions complex with the dissociated carboxyl groups in wool, as well as Congo Red dyes.[98] Two deodorization effects on ethanethiol associated with the copper ions were likely: first, that there was an oxidative decomposition of the thiol, and second, adsorption of the thiol to the copper ions.[98] More work on the effect of color on odor is needed.

Odor controlling technologies

Antimicrobials

As many problematic odors within textiles are a result of the biotransformation of odor precursors by microorganisms, then incorporating an antimicrobial in a textile is viewed as one method for controlling and/or preventing the development of odor. Common antimicrobial agents used in textiles are silver, tricoslan, polyhexamethylene biguanides (PHMB), and quaternary ammonium compounds (QAC), which have been extensively reviewed elsewhere.[114,115] Antimicrobials should inhibit the growth of, or kill microorganisms within, the textile rather than influence the resident skin microflora of the person wearing/using it. Hence, the durability of the treatment is important as most textiles where an antimicrobial for odor control may be desired (e.g. underwear, sports clothing) would require frequent laundering. Neither the leaching of the antimicrobial onto the skin of the wearer nor into the wash liquor to be subsequently released into the environment is wanted. Therefore, complete control of axillary odors will not be possible as the treated textile may only control odor developing within the textile and not at its source. Despite odor control being one purported benefit of an antimicrobial,[116] there are surprisingly few studies that have examined odor control of antimicrobial treated textiles.[34,37,56,117–120]

Many standard test methods for evaluating the antimicrobial activity of textile products against selected bacterial strains exist and have been reviewed elsewhere.[114,121] Claims of odor control based solely on the basis of such in vitro tests are not appropriate as antimicrobial activity does not always indicate odor reduction.[56] Furthermore, antimicrobial activity in vitro does not necessarily predict antimicrobial activity during use.[122,123] Antimicrobial efficacy tests should, therefore, be coupled with odor assessment, and preferably under realistic use scenarios. In one such study, Mao and Murphy[118] examined the odor controlling properties of Tinosan AM 100, a triclosan based antimicrobial. Twenty participants wore an untreated and treated fabric (fiber content not reported) under each axilla and assessed the odor emanating from the fabrics after periods of wear and storage. Participants reported to "prefer" the treated fabrics compared to untreated fabrics in 90% of the total evaluations, and reportedly the treated fabrics were perceived to be "fresher." A 2–3 log reduction in *S. aureus* and *Klebsiella pneumoniae* was found for the Tinosan AM 100 treated fabrics in vitro,[118] although an examination of bacterial counts from the wear trial was not also carried out. In another wear trial, eight male participants wore polyester fabrics that had been treated with varying levels (1.25 and 2.50%) of a silver chloride antimicrobial finish against the axillae.[123] All treated fabrics were matched with an untreated polyester fabric worn in the opposite axilla as the control. Sensory assessment revealed that there were no perceptible differences in odor intensity between any of the antimicrobial treated fabrics compared to the untreated fabrics. Furthermore, the bacterial counts obtained from the worn fabrics did not significantly differ, yet in vitro tests confirmed that the treated fabrics did have antimicrobial activity against *S. aureus*, *K. pneumoniae*, and *Corynebacterium* species with >99% reduction.[123] These findings highlight the problem with relying on in vitro antimicrobial efficacy tests to predict odor control in textiles.

Combining an antimicrobial, to limit further growth of microorganisms within a fabric, with another way to control odor (e.g. an adsorbent) may be necessary for effective odor control.[124] Yet, some antimicrobials may exhibit this dual-action function inherently. For example, a silver ion–polymer complex antimicrobial that was applied to various cotton, polyester, and nylon fabrics was shown to have this effect.[117] Treated fabrics exhibited a >99% reduction of *Escherichia coli* and continued to do so even after 10 washes. Furthermore, no isovaleric acid was detected on treated textiles after inoculation with *S. aureus* and leucine, and low odor scores were obtained from treated fabrics incubated with milk. The silver ion–polymer complex also exhibited lower odor scores following incubation with milk than zinc pyrithione (ZP) and QAC treated fabrics. The authors suggested that this may be due to the lack of a dual-action odor adsorption property in the ZP and QAC fabrics that was present in their silver complex treatment.[117] Deodorizing effects of metal oxides have also been shown and are likely to be associated with the dual-action of the antimicrobial and adsorption properties of the metal oxide.[120,125]

This dual-action property was also noted in finishes from plant extracts that have been used to reduce odor within fabrics made from natural fibers.[36,37,119] Lee and colleagues investigated the antimicrobial properties of fabrics dyed with immature pine cones[37] and myrrh.[36] In both studies, there was evidence that the dyes did impart antimicrobial properties on the fabrics, but in these studies, the reduction in odor was unrelated to antimicrobial performance as the ISO test method was used to measure deodorant properties which is based on the fabrics' ability to sorb odorants in the ambient air.[35]

Despite some evidence that odor intensity can be controlled through antimicrobials, the total elimination of body odors, at least, may be more difficult to achieve, and inherent fiber type likely plays a greater role. In a study examining commercially available sportswear clothing, a reduction in odor on polyester fabrics incorporating odor control technologies (most of them based on silver based antimicrobial properties) was perceived by a sensory panel compared with non-odor control polyester fabrics. Yet, the odor control polyester fabrics were still perceptibly more odorous than cotton and wool fabrics that did not have special finishing treatments to control odor.[28]

Odor control through adsorption

Adsorption refers to the process where molecules of two materials (the adsorbent and adsorbed) are attached at the surface level without any penetration occurring and may involve physisorption or chemisorption. This process includes the adhesion of liquid or gas molecules on the surface of a liquid or solid substrate. By using the principle of adsorption to select suitable substrates, components that are hazardous, undesired, or obnoxious can be removed from a material. The adsorptive capacity of a substrate can be determined by using its surface area-to-weight ratio (known as the specific surface area). The contaminants that remain on the surface of an adsorbent can be removed by heating to regenerate the adsorptive capacity of a substrate.[126] Based on their adsorptive property, some materials can be used to remove unpleasant and malodorous components from clothing. The most common adsorbents that are used for odor removal and have applications in textiles are activated carbon, zeolites, and cyclodextrins.

Activated carbon, made from the combustion or thermal decomposition of carbon-containing substances, is highly porous and, due to its large surface area, has the capacity to adsorb many gases and liquids. The most common commercially available activated carbon is in the powdered and granular forms used in many industrial applications such as filtration and purification of water and air, decolorization in food and beverages, control of toxins and contamination in pharmaceuticals.[127] Through the carbonization and activation of textile fibers and fabrics, activated carbon fibers and cloth can be produced directly. Activated carbon fibers have a much higher surface area and a larger pore volume than powdered or granular forms.[127] As well, due to the flexibility of the textile structure, activated carbon fibers and cloth can be molded into a variety of shapes. Several fabric structures can be made using activated carbon fibers, such as woven, felt, and knitted fabrics. These structures have been widely used in the fields of medicine, healthcare, and manufacturing of protective wearable products.[128] In the medical industry, activated carbon cloth is used to control odors from wounds.[129,130] The black color of activated carbon makes it difficult to color, which may be one reason it is not commonly used in everyday apparel items.[131] However, Flexzorb™, which utilizes activated carbon, have claimed that their technology not only is able to control odor in healthcare but also provides sufficient odor control apparel items for consumers, such as underwear, denim, and pajamas.[132] Granular or powdered forms of activated carbon can be applied to textiles through impregnating, coating, or printing onto fabrics and fibers.[94,133,134] For example, a mixture of powdered activated carbon, obtained from coconut and palm shells, in a printing paste at 5–15% levels of activated carbon was both printed and coated onto polyester and cotton fabrics. The intensity of onion smell was reduced as the proportion of activated carbon was increased for both printed and coated fabrics. The coated fabrics exhibited higher reduction than the printed fabrics due to the higher content of activated carbon.[94,135] However, the ability of the fabrics to retain their odor controlling performance following washing was not investigated, nor was its potential impact on fabric handle and color limitations.

Zeolites are microporous crystalline materials consisting of aluminosilicate components that have a three-dimensional structure. This three-dimensional framework provides pores of uniform sizes (0.3–2.0 nm in diameter) which allow the molecules to be adsorbed and trapped. Zeolites have been studied with respect to their application as ion-exchange materials.[136,137] In odor control, they have been widely used in applications such as agricultural and municipal wastes, as well as in pet litter,[138,139] applied as topical agents to control body odor,[140] and combined in cellulosic films for food packaging.[141] Zeolites have been incorporated into cotton and polyester fabrics with the potential to provide protection against radiation.[142–144] Odor control using zeolite technology by Sciessent Lava™ has multiple textile applications, including apparel, sporting equipment, linens, and pet products,[145] with laundering regenerating the zeolite adsorption capacity. However, no scholarly articles were found providing evidence of the odor-reducing capabilities of zeolites incorporated into clothing and other reusable textiles.

A common application of adsorbents such as activated carbon and zeolites in odor control within apparel has been the incorporation of them into hunting apparel to reduce the risk of detection by wild animals during hunting.[134,146,147] For instance, Vickers[134] introduced a hunting clothing model that included an outer, inner lining, and one odor-adsorbing non-woven flexible sheet. The odor-adsorbing layer was made of synthetic activated carbon fibers placed between the two other layers. Reactivation of the activated carbon can reportedly occur through washing and drying[146] or after 40 minutes on high heat in a tumble dryer.[148]

Cyclodextrins (CD) are natural cyclic oligosaccharides with six to eight D-glucose units derived from starch molecules.[149,150] The internal free space in CDs' chemical structure provides the possibility of trapping different molecules with non-covalent bonds, referred to as host–guest interactions.[151] In the textile industry, applications of CDs for odor can occur in two ways: first, to control odor by removing malodors through sorption into their internal structure, and second, to mask unpleasant odors by incorporating fragrances as the inclusion molecules.[149] The potential for CD to be effective as an odor adsorbent was evident in the work by Alzate-Sanchez and colleagues.[152] High amounts of adsorption of selected volatile compounds (i.e. styrene, benzaldehyde, and aniline) by cotton treated with β-CD cross-linked with tetrafluoroterephthalonitril occurred against untreated cotton, as well as three commercially available fabrics reported as having odor adsorbing properties (one of which was an activated carbon treated cotton fabric).[152] Polyester fabrics treated with β-CD and citric acid showed a complete reduction in ammonia following 1 h exposure to the gas in an enclosed chamber.[153] Isovaleric acid was retained in β-CD treated polyester and cotton fabrics 1, 3, and 20 h following contamination via an artificial skin model, resulting in a detectable decrease in odor intensity.[50]

Conclusion

The build-up and release of unpleasant odors from textile items during use can lead to consumer dissatisfaction, particularly as there are high expectations that clothing and textile products meet multiple aesthetic and functional needs. The problem of odor within textiles is complex and multifaceted with odors arising from many different sources, both internal and external to the human body. Selection of appropriate methods for collection and detection of odor on textiles is paramount. Human wear trials represent how odor can be transferred and retained within textiles during use; however, controlling odor intensity and quality can be difficult so that comparisons across several test sessions may not be possible. In vitro methods that have been used include inoculation of textiles with odor precursors and microorganisms and exposure of fabrics to odorants in a gaseous or liquid medium. However, these in vitro methods for collecting odor can also suffer from limitations given the complex array of compounds that can make up an odor source and the multiple methods for how odor can be developed within, or transferred to, fabrics. Therefore, an in vitro method that better represents the mechanisms for odor development and transfer from an ''artificial skin'' to a textile substrate is still required. Such in vitro methods are important to allow for comparison across different test fabrics and laboratories. But it is important to note that due to the variety and complexity of human sweat and diversity of microflora, any such in vitro method would still be an approximation.

Methods for detecting odor emitted from textiles encompass sensory and instrumental means of measurement. Sensory measurement, which uses human assessors to detect odor, is a highly applicable measurement tool. The selection and training of the sensory panel, control of the test environment, and selection of appropriate test methods for the research objectives are all vital considerations in order to avoid potential biases that can occur with sensory measurement. Many different instrumental methods exist which analyze the concentration and types of odorants present in the headspace above a textile or directly within the textile using either chemical and/or electronic sensors. The most common of these have been a gas chromatograph coupled with different detectors such as a mass spectrometer, which is useful when the identification of individual compounds in complex mixtures is required, or a flame ionization detector, when known compounds are being measured. Real-time analysis, without the need for extensive preconditioning or complex extraction methods, can be done with a chemical ionization technique, and radiotracer analysis can detect odors in situ. Electronic noses and detector tubes also offer simpler analyses of single or only a few known compounds. However, without accompanying sensory analysis, the impact of the odorant detected through instrumental means alone may be unknown, hence more work needs to be conducted determining what are acceptable levels of key odorants released from textiles.

Textile fibers which inherently differ in their chemistry and physical structure influence odor intensity and quality following exposure to various odorous sources. Natural fibers such as wool and cotton have been perceived to be less odorous following wear next to the body than synthetic fibers such as polyester and nylon. A build-up of odor over time due to multiple uses can occur, particularly to oleophilic polyester fibers, where laundering may not completely remove odors. Under wet conditions, cellulosic fibers can exhibit unpleasant odors resulting from bacterial action. However, the role bacteria play in how odoriferous a textile becomes after contact with the human body is not clear. Selective growth of some microorganisms on different textiles is apparent, yet odor is first generated on the body and transfer of sweat and odorants to fabrics also occurs. For example, in low odor wool, bacteria have been shown to persist for longer than on high odor polyester. There is also evidence that other fabric properties such as fabric physical properties and color can influence the intensity of odor released. More research is needed to better understand the mechanisms involved in how fiber type influences odor retention and release, as well as the impact of other common fabric properties.

The main two approaches to controlling odor in textiles are applying antimicrobials to the textile and incorporating odor adsorbents within the textile. As antimicrobials within textiles should remain in the textile substrate rather than leach to the skin or during laundering, then complete control of malodors generated from sources internal to the human body is unlikely. Therefore, combining the action of the antimicrobial with an adsorbent is likely to be most successful as a holistic approach to odor control and appears to be an inherent characteristic of some antimicrobials (e.g. metal oxides). Three of the most common odor control technologies that rely on adsorbing odorants are activated carbon, zeolites, and cyclodextrins.

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References

1. Henkin RI. Body odor. *JAMA J Am Med Assoc* 1995; 273: 1171–1172.
2. Labows JN and Preti G. Human semiochemicals. In: Van Toller SD (ed.) *Fragrance: The Psychology and Biology of Perfume*. London: Elsevier Applied Sciences, 1992, pp. 69–90.
3. Hammond CJ. Chemical composition of household malodours – an overview. *Flavour Fragr J* 2013; 28: 251–261.
4. Denawaka CJ, Fowlis IA and Dean JR. Source, impact and removal of malodour from soiled clothing. *J Chromatogr A* 2016; 1438: 216–225.
5. Callewaert C, Van Nevel S, Kerckhof FM, et al. Bacterial exchange in household washing machines. *Front Microbiol* 2015; 6: 1381.
6. Gattlen J, Amberg C, Zinn M, et al. Biofilms isolated from washing machines from three continents and their tolerance to a standard detergent. *Biofouling* 2010; 26: 873–882.
7. Munk S, Münch P, Stahnke L, et al. Primary odorants of laundry soiled with sweat/sebum: Influence of lipase on the odor profile. *J Surfactants Deterg* 2000; 3: 505–515.

8. Munk S, Johansen C, Stahnke LH, et al. Microbial survival and odor in laundry. *J Surfactants Deterg* 2001; 4: 385–394.
9. Nagoh Y, Tobe S, Watanabe T, et al. Analysis of odorants produced from indoor drying laundries and effects of enzyme for preventing malodor generation. *Tenside Surfactants Deterg* 2005; 42: 7–12.
10. McQueen RH, Moran LJ, Cunningham C, et al. The impact of odour on laundering behaviour: An exploratory study. *Int J Fash Des Technol Educ*. Epub Ahead of print.
11. Takeuchi K, Yabuki M and Hasegawa Y. Review of odorants in human axillary odour and laundry malodour: The importance of branched C7 chain analogues in malodours perceived by humans. *Flavour Fragr J* 2013; 28: 223–230.
12. Troccaz M, Starkenmann C, Niclass Y, et al. 3-Methyl-3-sulfanylhexan-1-ol as a major descriptor for the human axilla-sweat odour profile. *Chem Biodivers* 2004; 1: 1022–1035.
13. Starkenmann C, Niclass Y, Troccaz M, et al. Identification of the precursor of (S)-3-methyl-3-sulfanylhexan-1-ol, the sulfury malodour of human axilla sweat. *Chem Biodivers* 2005; 2: 705–716.
14. Natsch A, Schmid J and Flachsmann F. Identification of odoriferous sulfanylalkanols in human axilla secretions and their formation through cleavage of cysteine precursors by a C-S lyase isolated from axilla bacteria. *Chem Biodivers* 2004; 1: 1058–1072.
15. Hasegawa Y, Yabuki M and Matsukane M. Identification of new odoriferous compounds in human axillary sweat. *Chem Biodivers* 2004; 1: 2042–2050.
16. Zeng X-N, Leyden JJ, Lawley HJ, et al. Analysis of characteristic odors from human male axillae. *J Chem Ecol* 1991; 17: 1469–1492.
17. de Lacy Costello B, Amann A, Al-Kateb H, et al. A review of the volatiles from the healthy human body. *J Breath Res* 2014; 8: 014001.
18. Dormont L, Bessière J-M and Cohuet A. Human skin volatiles: A review. *J Chem Ecol* 2013; 39: 569–578.
19. Stapleton K, Hill K, Day K, et al. The potential impact of washing machines on laundry malodour generation. *Lett Appl Microbiol* 2013; 56: 299–306.
20. Kaur R, Kukkar D, Bhardwaj SK, et al. Potential use of polymers and their complexes as media for storage and delivery of fragrances. *J Control Release* 2018; 285: 81–95.
21. McQueen RH, Laing RM, Brooks HJL, et al. Odor intensity in apparel fabrics and the link with bacterial populations. *Text Res J* 2007; 77: 449–456.
22. McQueen RH, Laing RM, Delahunty CM, et al. Retention of axillary odour on apparel fabrics. *J Text Inst* 2008; 99: 515–523.
23. Ferdenzi C, Schaal B and Roberts SC. Human axillary odor: Are there side-related perceptual differences? *Chem Senses* 2009; 34: 565–571.
24. Roberts SC, Kralevich A, Ferdenzi C, et al. Body odor quality predicts behavioral attractiveness in humans. *Arch Sex Behav* 2011; 40: 1111–1117.
25. Curran AM, Rabin SI, Prada PA, et al. Comparison of the volatile organic compounds present in human odor using SPME-GC/MS. *J Chem Ecol* 2005; 31: 1607–1619.
26. McQueen RH, Harynuk JJ, Wismer WV, et al. Axillary odour build-up in knit fabrics following multiple use cycles. *Int J Cloth Sci Technol* 2014; 26: 274–290.
27. de la Mata AP, McQueen RH, Nam SL, et al. Comprehensive two-dimensional gas chromatographic profiling and chemometric interpretation of the volatile profiles of sweat in knit fabrics. *Anal Bioanal Chem* 2017; 409: 1905–1913.
28. Klepp IG, Buck M, Laitala K, et al. What's the problem? Odor-control and the smell of sweat in sportswear. *Fash Pract* 2016; 8: 296–317.
29. Callewaert C, De Maeseneire E, Kerckhof F-M, et al. Microbial odor profile of polyester and cotton clothes after a fitness session. *Appl Environ Microbiol* 2014; 80: 6611–6619.
30. Kubota H, Mitani A, Niwano Y, et al. Moraxella species are primarily responsible for generating malodor in laundry. *Appl Environ Microbiol* 2012; 78: 3317–3324.
31. Leyden JJ, Kenneth MD, McGinley J, et al. The microbiology of the human axilla and its relationship to axillary odor. *J Invest Dermatol* 1981; 77: 413–416.
32. McQueen RH, Laing RM, Wilson CA, et al. Odor retention on apparel fabrics: Development of test methods for sensory detection. *Text Res J* 2007; 77: 645–652.
33. Chung H and Seok HJ. Populations of malodor-forming bacteria and identification of volatile components in triolein-soiled cotton fabric. *Fibers Polym* 2012; 13: 740–747.
34. Obendorf SK, Kim J and Koniz RF. Measurement of odor development due to bacterial action on antimicrobial polyester fabrics. *AATCC Rev* 2007; 7: 35–40.
35. International Organization for Standardization. *ISO 17299-1: 2014 Textiles – Determination of deodorant property: Part 1 General principle*. Geneva, Switzerland: ISO, 2014.
36. Lee Y-H, Lee S-G, Hwang E-K, et al. Dyeing properties and deodorizing/antibacterial performance of cotton/silk/wool fabrics dyed with myrrh (*Commiphora myrrha*) extract. *Text Res J* 2017; 87: 973–983.
37. Lee Y-H, Kim A-L, Park Y-G, et al. Colorimetric assay and deodorizing/antibacterial performance of natural fabrics dyed with immature pine cone extract. *Text Res J* 2018; 88: 731–743.
38. Abdul-Bari MM, McQueen RH, Nguyen H, et al. Synthetic clothing and the problem with odor: Comparison of nylon and polyester fabrics. *Cloth Text Res J* 2018; 36: 251–266.
39. Zhu L, Liu Y, Ding X, et al. A novel method for textile odor removal using engineered water nanostructures. *RSC Adv* 2019; 9: 17726–17736.
40. Huggins GR and Preti G. Vaginal odors and secretions. *Clin Obstet Gynecol* 1981; 24: 355–377.
41. Stone H and Sidel JL. *Sensory Evaluation Practices*. 3rd ed. San Diego, CA: Elsevier Academic Press, 2004.
42. Cortez-Pereira CS, Baby AR, Kaneko TM, et al. Sensory approach to measure fragrance intensity on the skin. *J Sens Stud* 2009; 24: 871–901.

43. Schieberle P and Hofmann T. Evaluation of the character impact odorants in fresh strawberry juice by quantitative measurements and sensory studies on model mixtures. *J Agric Food Chem* 1997; 45: 227–232.
44. Ylimaki G, Hawrysh ZJ, Hardin RT, et al. Response surface methodology in the development flour yeast breads: Sensory evaluation of rice. *J Food Sci* 1991; 56: 751–755.
45. International Organization for Standardization. *ISO 6658:2017 Sensory analysis – Methodology – General guidance*. Geneva, Switzerland: ISO, 2017.
46. American Society for Testing and Materials. *ASTM E1207 – Standard Guide for Sensory Evaluation of Axillary Deodorancy*. West Conshohocken, PA: ASTM International, 2009.
47. Natsch A, Derrer S, Flachsmann F, et al. A broad diversity of volatile carboxylic acids, released by a bacterial aminoacylase from axilla secretions, as candidate molecules for the determination of human-body odor type. *Chem Biodivers* 2006; 3: 1–20.
48. Lawless HT and Heymann H. *Sensory evaluation of food: Principles and practices*. 2nd ed. New York, NY: Springer, 2010.
49. McGinley MA and McGinley CM. Methods for odor evaluation of textiles and other materials. In: *AATCC International Conference Proceedings*. Research Triangle, NC: AATCC, Wilmington, NC, 28–30 March 2017, pp. 250–264.
50. Hammer TR, Berner-Dannenmann N and Hoefer D. Quantitative and sensory evaluation of malodour retention of fibre types by use of artificial skin, sweat and radiolabelled isovaleric acid. *Flavour Fragr J* 2013; 28: 238–244.
51. Wood WE and Beaverson NJ. *Malodor absorbent polymer and fiber*. Patent US 8,241,747 B2, USA, 2009.
52. La Fortune JM. *Odor control absorbent article and method*. Patent US 6,867,343 B2, USA, 2005.
53. McGee T, Purzycki KL and Sgaramella RP. *Process for maintaining fragrance perception in the presence of an absorbent material*. Patent US 6,803,033 B2, USA, 2002.
54. Miller RW. Subjective property characterization by 'quad' analysis: An efficient method for conducting paired comparisons. *Text Res J* 2002; 72: 1041–1051.
55. Rathinamoorthy R and Thilagavathi G. Axillary odour studies on alkali-treated knitted polyester fabric. *Int J Cloth Sci Technol* 2017; 29: 251–261.
56. Xu Y, McQueen R and Wismer W. A preliminary study on the collection and detection of axillary odor within textiles. *J Text Apparel, Technol Manag* 2013; 8: 1–13.
57. International Organization for Standardization. *ISO 8586:2012 Sensory analysis - General guidelines for the selection, training and monitoring of selected assessors and expert sensory assessors*. Geneva, Switzerland: ISO, 2012.
58. International Organization for Standardization. *ISO 5495:2005 Sensory analysis – Methodology – Paired comparison test*. Geneva, Switzerland: ISO, 2005.
59. International Organization for Standardization. *ISO 4120:2004 Sensory analysis – Methodology – Triangle test*. Geneva, Switzerland: ISO, 2004.
60. Worch T, Lê S and Punter P. How reliable are the consumers? Comparison of sensory profiles from consumers and experts. *Food Qual Prefer* 2010; 21: 309–318.
61. Shakoorjavan S, Akbari S, Kish MH, et al. Correlation of sensory analysis with a virtual sensor array data for odour diagnosis of fragrant fabrics. *Measurement* 2016; 90: 396–403.
62. Li S. Recent developments in human odor detection technologies. *J Forensic Sci Criminol* 2014; 1: 1–12.
63. Prokop-Prigge KA, Greene K, Varallo L, et al. The effect of ethnicity on human axillary odorant production. *J Chem Ecol* 2015; 42: 33–39.
64. Steinhart H, Stephan A and Bucking M. Advances in flavor research. *J High Resolut Chromatogr* 2000; 23: 489–496.
65. Snow NH and Slack GC. Head-space analysis in modern gas chromatography. *TrAC Trends Anal Chem* 2002; 21: 608–617.
66. Sithersingh MJ and Snow NH. Headspace-gas chromatography. In: Poole CF (ed.) *Gas Chromatography*. Amsterdam: Elsevier, 2012, pp. 221–233.
67. Bazemore R. Sample preparation. In: Goodner K and Rousseff R (eds) *Practical analysis of flavor and fragrance materials*. Hoboken, NJ: Wiley, 2011, pp. 23–44.
68. International Organization for Standardization. *ISO 17299-3: Textiles – Determination of deodorant property: Part 3 Gas chromatography method*. Geneva, Switzerland: ISO, 2014.
69. Lisovac A and Shooter D. Volatiles from sheep wool and the modification of wool odour. *Small Rumin Res* 2003; 49: 115–124.
70. Hara T, Kyuka A and Shimizu H. Butane-2,3-dione: The key contributor to axillary and foot odor associated with an acidic note. *Chem Biodivers* 2015; 12: 248–258.
71. Prada PA, Curran AM and Furton KG. The evaluation of human hand odor volatiles on various textiles: A comparison between contact and noncontact sampling methods. *J Forensic Sci* 2011; 56: 866–881.
72. Rathinamoorthy R and Thilagavathi G. GC-MS analysis of worn textile for odour formation. *Fibers Polym* 2016; 17: 917–924.
73. Dewulf J, Langenhove HV and Wittmann G. Analysis of volatile organic compounds using gas chromatography. *TrAC Trends Anal Chem* 2002; 21: 637–646.
74. Delahunty CM, Eyres G and Dufour J-P. Gas chromatography-olfactometry. *J Sep Sci* 2006; 29: 2107–2125.
75. Chin S-T, Eyres GT and Marriott PJ. Identification of potent odourants in wine and brewed coffee using gas chromatography-olfactometry and comprehensive two-dimensional gas chromatography. *J Chromatogr A* 2011; 1218: 7487–7498.
76. Du X, Plotto A, Baldwin E, et al. Evaluation of volatiles from two subtropical strawberry cultivars using GC–olfactometry, GC-MS odor activity values, and sensory analysis. *J Agric Food Chem* 2011; 59: 12569–12577.
77. Peres F, Jelen HH, Majacher MM, et al. Characterization of aroma compounds in Portuguese extra virgin olive oils from Galega Vulgar and Cobrançosa cultivars using GC–O and GC × GC–ToFMS. *Food Res Int* 2013; 54: 1979–1986.

78. Takeuchi K, Hasegawa Y, Ishida H, et al. Identification of novel malodour compounds in laundry. *Flavour Fragr J* 2012; 27: 89–94.
79. Ruzsanyi V, Mochalski P, Schmid A, et al. Ion mobility spectrometry for detection of skin volatiles. *J Chromatogr B* 2012; 911: 84–92.
80. Lindinger W, Hansel A and Jordan A. On-line monitoring of volatile organic compounds at pptv levels by means of proton-transfer-reaction mass spectrometry (PTR-MS) medical applications, food control and environmental research. *Int J Mass Spectrom Ion Process* 1998; 173: 191–241.
81. Smith D and Španěl P. Selected ion flow tube mass spectrometry (SIFT-MS) for on-line trace gas analysis. *Mass Spectrom Rev* 2005; 24: 661–700.
82. Denawaka CJ, Fowlis IA and Dean JR. Evaluation and application of static headspace–multicapillary column-gas chromatography–ion mobility spectrometry for complex sample analysis. *J Chromatogr A* 2014; 1338: 136–148.
83. Von Hartungen E, Wisthaler A, Mikoviny T, et al. Proton-transfer-reaction mass spectrometry (PTR-MS) of carboxylic acids. *Int J Mass Spectrom* 2004; 239: 243–248.
84. Richter TM, Bremer PJ, Silcock P, et al. Textile binding and release of body odor compounds measured by proton transfer reaction–mass spectrometry. *Text Res J* 2018; 88: 2559–2567.
85. Yao L, Laing RM, Bremer PJ, et al. Measuring textile adsorption of body odor compounds using proton-transfer-reaction mass spectrometry. *Text Res J* 2015; 85: 1817–1826.
86. International Organization for Standardization. *ISO 17299-2:2014 Textiles – Determination of deodorant property: Part 2 Detector tube method*. Geneva, Switzerland: ISO, 2014.
87. International Organization for Standardization. *ISO 17299-5: Textiles – Determination of deodorant property: Part 5 Metal-oxide semiconductor sensor method*. Geneva, Switzerland: ISO, 2014.
88. Loutfi A, Coradeschi S, Mani GK, et al. Electronic noses for food quality: A review. *J Food Eng* 2015; 144: 103–111.
89. Arshak K, Moore E, Lyons GM, et al. A review of gas sensors employed in electronic nose applications. *Sens Rev* 2004; 24: 181–198.
90. Ameer Q and Adeloju SB. Polypyrrole-based electronic noses for environmental and industrial analysis. *Sensors Actuators B Chem* 2005; 106: 541–552.
91. Baldwin EA, Bai J, Plotto A, et al. Electronic noses and tongues: Applications for the food and pharmaceutical industries. *Sensors* 2011; 11: 4744–4766.
92. Nimmermark S. Use of electronic noses for detection of odour from animal production facilities: A review. *Water Sci Technol* 2001; 44: 33–41.
93. Asadi Fard P, Shakoorjavan S and Akbari S. The relationship between odour intensity and antibacterial durability of encapsulated thyme essential oil by PPI dendrimer on cotton fabrics. *J Text Inst* 2018; 109: 832–841.
94. Eza TSM, Ahmad WYW and Ahmad MN. The activated carbon as anti-odour coated and pigment printed fabric. *2012 IEEE Business, Eng Ind Appl Colloq* 2012; 210–215.
95. Haeringer D and Goschnick J. Characterization of smelling contaminations on textiles using a gradient microarray as an electronic nose. *Sensors Actuators B Chem* 2008; 132: 644–649.
96. York RK. *Studies on textile stabilization of environmental malodors for sensory and electronic nose analyses*. PhD Thesis, University of Manitoba, Canada, 2005.
97. Rae Systems. *Gas Detection Tubes and Sampling Handbook*. 2nd ed. San Jose, CA: Rae Systems Inc, 2013.
98. Amemiya T and Nakanishi T. Deodorization for ethanethiol by cotton and wool fabrics mordant dyed with congo red and copper (II) sulfate. *Text Res J* 2018; 88: 1056–1064.
99. Kobayashi Y, Nakanishi T and Komiyama J. Deodorant properties of wool fabrics dyed with acid mordant dyes and a copper salt. *Text Res J* 2002; 72: 125–131.
100. Chen C-C, Wang C-C and Yeh J-T. Improvement of odor elimination and anti-bacterial activity of polyester fabrics finished with composite emulsions of nanometer titanium dioxide-silver particles-water-borne polyurethane. *Text Res J* 2010; 80: 291–300.
101. Hwang E-K, Lee Y-H and Kim H-D. Dyeing, fastness, and deodorizing properties of cotton, silk, and wool fabrics dyed with gardenia, coffee sludge, *Cassia tora. L.*, and pomegranate extracts. *Fibers Polym* 2008; 9: 334–340.
102. Yen M-S, Chen J-C and Chen C-C. Degree of crosslinking and physical properties of dimethyloldihydroxyethyleneurea/acrylic acid crosslinked cotton fabrics after treatment with various metallic salts. *J Appl Polym Sci* 2005; 97: 584–594.
103. Huisman MA and Morris MA. A study of the removal of synthetic sebum from durable-press fabrics using a liquid-scintillation technique. *Text Res J* 1971; 41: 657–661.
104. Mettananda CVR and Crown EM. Quantity and distribution of oily contaminants present in flame-resistant thermal-protective textiles. *Text Res J* 2010; 80: 803–813.
105. Chi YS and Obendorf SK. Aging of oily soils on textiles. Chemical changes upon oxidation and interaction with textile fibers. *J Surfactants Deterg* 1998; 1: 371–380.
106. Teufel L, Pipal A, Schuster KC, et al. Material-dependent growth of human skin bacteria on textiles investigated using challenge tests and DNA genotyping. *J Appl Microbiol* 2010; 108: 450–461.
107. Takashima M, Shirai F, Sageshima M, et al. Distinctive bacteria-binding property of cloth materials. *Am J Infect Control* 2004; 32: 27–30.
108. Ballantine DS, Martin SJ, Ricco AJ, et al. Materials characterization. In: Ballantine DS, Martin SJ, Ricco AJ, et al. (eds) *Applications of Modern Acoustics, Acoustic Wave Sensors*. San Diego: Academic Press, 1997, pp. 150–221.

109. Do DD. *Adsorption analysis: Equilibria and kinetics*. London: Imperial College Press, 1998.
110. Bishop DP. Physical and chemical effects of domestic laundering processes. In: Carr CM (ed.) *Chemistry of the Textiles Industry*. Dordrecht: Springer, 1995, pp. 125–172.
111. Murtagh J. Body odour. *Aust Fam Physician* 1994; 23: 1591.
112. Wang J, Lu X, Wang J, et al. Quantitative and sensory evaluation of odor retention on polyester/wool blends. *Text Res J* 2019; 89: 2729–2738.
113. Abdul-Bari MM. *Retention of odorous compounds by textile materials*. Masters Thesis, University of Alberta, Canada, 2018.
114. Gao Y and Cranston R. Recent advances in antimicrobial treatments of textiles. *Text Res J* 2008; 78: 60–72.
115. Windler L, Height M and Nowack B. Comparative evaluation of antimicrobials for textile applications. *Environ Int* 2013; 53: 62–73.
116. Lacasse K and Baumann W. Finishing. In: *Textile Chemicals: Environmental Data and Facts*. Berlin: Springer, 2004, pp. 373–483.
117. Frattarelli D, Powers L, Doshi D, et al. Holistic management of textile odor using novel silver-polymeric complexes. *AATCC J Res* 2018; 5: 7–16.
118. Mao BJ and Murphy L. Durable freshness for textiles. *AATCC Rev* 2001; 1: 28–31.
119. Rathinamoorthy R, Thilagavathi G, Brindha S, et al. Odour control studies on apparel fabrics finished with methanol extract of *Terminalia chebula*. *Fibers Polym* 2014; 15: 1669–1676.
120. Saito M. Absorbing materials obtained with zinc oxide (ZnO) coated fabrics. *J Coat Fabr* 1993; 23: 150–164.
121. McQueen RH and Ehnes B. Antimicrobial textiles and infection prevention: Clothing and the inanimate environment. In: Bearman G, Munoz-Price S, Morgan DJ, et al. (eds) *Infection Prevention*. Cham, Switzerland: Springer, 2018, pp. 117–126.
122. Walter N, McQueen RH and Keelan M. In vivo assessment of antimicrobial-treated textiles on skin microflora. *Int J Cloth Sci Technol* 2014; 26: 330–342.
123. McQueen RH, Keelan M, Xu Y, et al. In vivo assessment of odour retention in an antimicrobial silver chloride-treated polyester textile. *J Text Inst* 2013; 104: 108–117.
124. Trogolo JA. Odor control textiles: Is "antimicrobial" enough? In: *AATCC Book of Papers, AATCC International Conference & Exhibition*. Charleston, SC: AATCC, 2011.
125. West H, Elston C and DeJong D. *Reducing odor in absorbent products*. Patent US 7,175,741 B2, USA, 2007.
126. Brunner CR. Odor emissions. *Hazardous Air Emissions from Incineration*. New York: Chapman and Hall, 1985, pp. 66–76.
127. Chen JY. Activated carbon. In: Chen JY (ed.) *Activated Carbon Fiber and Textiles*. Duxford, UK: Woodhead Publishing, 2017, pp. 3–20.
128. Giraudet S and Le Cloirec P. Activated carbon filters for filtration-adsorption. In: Chen JY (ed.) *Activated Carbon Fiber and Textiles*. Duxford, UK: Woodhead Publishing, 2017, pp. 211–243.
129. Akhmetova A, Saliev T, Allan IU, et al. A comprehensive review of topical odor-controlling treatment options for chronic wounds. *J Wound, Ostomy Cont Nurs* 2016; 43: 598–609.
130. McQueen RH. Odour control of medical textiles. In: Bartels VT (ed.) *Handbook of Medical Textiles*. Oxford: Woodhead Publishing, 2011, pp. 387–416.
131. Hu S-H, Edens RL, Lindsay JD, et al. *Coated activated carbon*. Patent US 6,740,406 B2, USA, 2004.
132. Calgon Carbon Corporation. *Apparel*. www.calgoncarbon.com/apparel/ (2019, accessed 22 June 2019).
133. Bailly RL. *Odor absorbing wrap*. Patent US 4,539,982, USA, 1985.
134. Vickers TW. *Odor-absorbing clothing article*. Patent US 5,678,247, USA, 1997.
135. Eza TSM, Wan Ahmad WY, Ahmad MR, et al. Effectiveness of activated carbon produced from coconut and oil palm shells as anti-odour on textile fabrics. *Indian J Fibre Text Res* 2014; 39: 190–195.
136. Maesen T and Marcus B. The zeolite scene: An overview. In: Van Bekkum H, Flanigen EM, Jacobs PA, et al. (eds) *Studies in Surface Science and Catalysis*. Amsterdam: Elsevier, 2001, pp. 1–9.
137. Flanigen EM. Zeolites and molecular sieves: An historical perspective. In: Van Bekkum H, Flanigen EM, Jacobs PA, et al. (eds) *Studies in Surface Science and Catalysis*. Amsterdam: Elsevier, 2001, pp. 11–35.
138. Eroglu N, Emekci M and Athanassiou CG. Applications of natural zeolites on agriculture and food production. *J Sci Food Agric* 2017; 97: 3487–3499.
139. Luo J and Lindsey S. The use of pine bark and natural zeolite as biofilter media to remove animal rendering process odours. *Bioresour Technol* 2006; 97: 1461–1469.
140. Nakane T, Gomyo H, Sasaki I, et al. New antiaxillary odour deodorant made with antimicrobial Ag-zeolite (silver-exchanged zeolite). *Int J Cosmet Sci* 2006; 28: 299–309.
141. Keshavarzi N, Mashayekhy Rad F, Mace A, et al. Nanocellulose-zeolite composite films for odor elimination. *ACS Appl Mater Interfaces* 2015; 7: 14254–14262.
142. Grancaric AM, Prlic I, Tarbuk A, et al. Activated natural zeolites on textiles: Protection from radioactive contamination. In: Kiekens P and Jayaraman S (eds) *Intelligent Textiles and Clothing for Ballistic and NBC Protection. NATO Science for Peace and Security Series B: Physics and Biophysics*. Dordrecht: Springer, 2012, pp. 157–176.
143. Grancaric AM, Tarbuk A and Kovacek I. Nanoparticles of activated natural zeolite on textiles for protection and therapy. *Chem Ind Chem Eng Q* 2009; 15: 203–210.
144. Ojstršek A, Hribernik S and Fakin D. Thermal, mechanical and optical features of aluminosilicate-coated cotton textiles via the crosslinking method. *Polymers (Basel)* 2018; 10: 1–14.
145. Sciessent. *Sciessent Lava*. www.sciessent.com/sciessent-lava-technology (2019, accessed 22 June 2019).

146. Sesselmann GJ. *Odor absorbing article of clothing*. Patent US 8,069,492 B2, USA, 2011.
147. White M. *Hunting mask*. Patent US 5,697,105, USA, 1997.
148. Scentlok Technologies. *Care*. www.scentlok.com/care (2019, accessed 22 June 2019).
149. Buschmann H, Knittel D and Schollmeyer E. New textile applications of cyclodextrins. *J Incl Phenom Macrocycl Chem* 2001; 40: 169–172.
150. Ammayappan L and Moses JJ. An overview on application of cyclodextrins in textile product enhancement. *J Text Assoc* 2009; 70: 9–18.
151. Martel B, Morcellet M, Ruffin D, et al. Capture and controlled release of fragrances by CD finished textiles. *J Incl Phenom Macrocycl Chem* 2002; 44: 439–442.
152. Alzate-Sanchez, Diego M, Smith BJ, et al. Cotton fabric functionalized with a βcyclodextrin polymer captures organic pollutants from contaminated air and water. *Chem Mater* 2016; 28: 8340–8346.
153. Voncina B and Vivod V. Cyclodextrins in textile finishing. In: Günay M (ed.) *Eco-friendly Textile Dyeing and Finishing*. Rijeka, Croatia: Intech Open, 2013, pp. 53–75.