NON-DESTRUCTIVE FIBRE ANALYSIS OF BLENDED CLOTHING FOR FORENSIC APPLICATIONS

WONG TSUEY LYNN

UNIVERSITI TEKNOLOGI MALAYSIA

NON-DESTRUCTIVE FIBRE ANALYSIS OF BLENDED CLOTHING FOR FORENSIC APPLICATIONS

WONG TSUEY LYNN

A dissertation submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Science

Faculty of Science
Universiti Teknologi Malaysia

FEBRUARY 2016

To all who makes me who I am today

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Associate Professor Dr. Umi Kalthom binti Ahmad for her valuable guidance that had contributed to this project in a great amount. She had cleared my doubts and helped me to understand my project better. I also feel grateful for the advice given by my co-supervisor, SAC Selven a/l Tharmalingam. Despite of his busy schedule, he was willing to discuss with me.

Thanks are due to my family who had given me great support especially helping me to collect samples for this study. They also gave me words of encouragement when I felt unmotivated. A big thank you to all the people who gave the samples that I needed in this project. Without these samples, this study would not able to be carried out successfully.

The assistance from all the lecturers, science officers and laboratory assistants in Department of Chemistry of Universiti Teknologi Malaysia (UTM) is greatly treasured. I am thankful for their willingness to help and selfless sharing of knowledge.

Encouragement and help from my friends are also very much appreciated. Whenever I felt stressful, they cheered me up. They also gave me ideas whenever I felt lost during my project. Their help is definitely a huge relief.

Last but not least, thank you to those who had helped me either directly or indirectly. Your kindness will not be forgotten.

ABSTRACT

In recent years, global market demands for blended fibres are booming due to their cost-effectiveness and enhanced properties. Therefore, the usage of blended fibres is high and thus there are greater chances of encountering fibre blends at crime scene in forensic cases such as assault and hit-and-run. Fibre analysts have often relied on analytical techniques developed for single fibres to identify fibre blends. This study was therefore conducted to characterize binary-blended samples using light microscopy and infrared spectroscopy as well as to evaluate the effectiveness of these techniques on analyzing fibre mixture. In this study, 5 reference fibre samples and 25 clothing samples were subjected to physical examination, followed by examination with stereomicroscope, polarizing and fluorescence microscopes as well as attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR). Stereomicroscopy was found to provide preliminary screening by furnishing information regarding the weave or knit pattern and twist direction of yarns. Polarized light microscopy was found to be effective in detecting fibre blends and examining optical properties, delustrant levels and fibre diameters but it could not confirm the generic classes of man-made fibres. Fluorescence microscopy allowed fibre discrimination by comparing fluorescence activity. ATR-FTIR was superior in determining types of polymeric man-made fibres compared to polarizing microscope. However, it was found that the infrared spectra needed to be obtained from several areas of a fabric in order to discover the presence of fibre mixtures. In most of the blended samples, correlation of more than 80% was achieved by comparing the blended fibres with combined spectra of individual fibres. In conclusion, non-destructive techniques of microscopy using 3 types of microscope (stereo, polarizing and fluorescence) followed by infrared spectroscopy (ATR-FTIR) are recommended to be used for characterizing fibre blends effectively.

ABSTRAK

Sejak kebelakangan ini, permintaan pasaran global bagi gentian campuran semakin berkembang pesat disebabkan oleh kos yang efektif dan ciri-ciri yang lebih baik. Maka, penggunaan gentian campuran adalah tinggi dan terdapat peluang yang lebih luas untuk menemui gentian campuran di tempat kejadian dalam kes-kes forensik seperti serangan dan langgar lari. Juruanalisis gentian kerap bergantung kepada teknik-teknik analisis yang dibangunkan untuk gentian tunggal bagi mengenalpasti identiti gentian campuran. Oleh itu, kajian ini dijalankan untuk mencirikan sampel yang mempunyai dua jenis gentian dengan menggunakan mikroskopi cahaya dan spektroskopi inframerah serta untuk menilai keberkesanan teknik-teknik tersebut pada gentian campuran. Dalam kajian ini, 5 sampel kawalan dan 25 sampel pakaian telah dianalisis dengan pemeriksaan fizikal, diikuti dengan analisis mikroskopi stereo, pengutuban dan pendarfluor dan juga spektroskopi ATR-FTIR. Mikroskopi stereo dapat menyediakan pemeriksaan awal dengan memberi maklumat mengenai corak tenunan atau kaitan dan arah pusingan benang. Mikroskopi pengutuban didapati berkesan dalam mengesan gentian campuran dan memerhati ciri-ciri optik, tahap agen penyahrelap dan diameter gentian tetapi mikroskopi tersebut tidak dapat mengesahkan kelas generik gentian sintetik. Mikroskopi pendarfluor membolehkan diskriminasi gentian dengan membandingkan aktiviti pendarfluor. Berbanding dengan mikroskopi pengutuban, ATR-FTIR lebih baik dalam menentukan kelas generik gentian sintetik yang jenis polimer. Akan tetapi, spektra inframerah didapati perlu diperolehkan daripada beberapa kawasan fabrik untuk mengesan kehadiran gentian campuran. Bagi kebanyakan sampel yang mempunyai gentian campuran, korelasi yang lebih daripada 80 peratus dapat dicapai dengan membandingkan gentian campuran dengan gabungan spektrum-spektrum gentian individu Kesimpulannya, teknik tanpa musnah 3 jenis mikroskopi, iaitu mikroskopi stereo, pengutuban dan pendarfluor diikuti dengan spektroskopi inframerah (ATR-FTIR) disyorkan untuk digunakan bagi mencirikan gentian campuran secara berkesan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

AATCC	- American Association of Textile Chemists and Colorists
ATR	- Attenuated Total Reflectance
ATR-FTIR	- Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy
DNA	- Deoxyribonucleic acid
DTGS	- Deuterated triglycine sulphate
IR	- Infrared
<	- Less than
MKMA	- Malaysian Knitting Manufacturers Association
MITI	- Malaysia International Trade and Industry
µm	- Micrometre
MSP	- Microspectrophotometry
mm	- Millimetre
nm	- Nanometre
N	- Newton
%	- Percent
PLM	- Polarized light microscope
PBT	- Polybutylene terephthalate
PET	- Polyethylene terephthalate
cm^{-1}	- Reciprocal centimetre
SEM	- Scanning electron microscope
SIMCA	- Soft Independent Modeling of Class Analogy

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

From the clothes you wear, the seat you sit to the carpet you step on, there are some tiny objects that follow you. These tiny objects called fibres can associate you to your surrounding. In the same way, a criminal, who had committed a crime such as hit-and-run, assault and break-in, would either leave or carry away fibres that can link him or her to the crime scene. High sheddability and ubiquitous nature of fibres cause them to be one of the most common trace evidence found at crime scene (Grieve, 2000; DeBattista *et al.*, 2014). Association can be made from the fibres at crime scene to the suspect's articles such as clothes, car seat and rope. In accordance with Locard's Exchange Principle, fibres from the suspect's belongings can shed and transfer to the victim or to the crime scene upon contact. The existence of the fibres is a proof of contact and thus it is possible to provide a link to the suspect (Hong *et al.*, 2014). It can help to disprove a suspect's alibi by supporting his or her presence at the crime scene. If the fibres are uncommon and match with the accused's belongings, it can lead to conviction (Deadman, 1984). For example, in a case reported by Deadman (1984), the rare yellowish green fibres on the victims matched the carpet fibres in the suspect's office, resulting in the fibres having strong forensic evidential value.

Fibres can originate from numerous types of objects; clothing being the most frequently encountered textile at crime scenes (Robertson & Grieve, 1999). In addition, the most common material for clothing is cotton/polyester blend (Davis *et* *al.*, 2011). Such situation concurs with Luniak's prediction that currently there is a greater chance to encounter fibre blends rather than a single fibre in an unknown specimen (Luniak, 1953). In fact, the demand for blended clothing in apparel industries is still growing.

Increasing number of fibre mixture in clothing requires well-researched characterization of fibre blends. The characterization methods of single fibre can be applied to fibre blend. In fact, the conventional tool for samples with mixture of fibres is microscope (Espinoza *et al.*, 2006), which is also a common technique for specimen with single fibre component. Infrared spectroscopy is another popular instrument that is employed in the analysis of fibre mixture (Espinoza *et al.*, 2006; Dozono *et al.*, 2011; Koyama *et al.*, 2013). Other instruments include X-ray diffraction (Abraham *et al.*, 2007), Raman spectroscopy (Lepot *et al.*, 2008) and microspectrophotometer (Palmer *et al.*, 2009). Dye composition is also frequently studied to discriminate the fibre samples (Houck, 2009). Besides, chemical method such as selective dissolution is often carried out to find out the composition of blended product (AATCC, 2011). However, non-destructive means are preferred for forensic evidence since most of the time they are of small quantities. Nayak *et al.* (2012) believed that light microscopy and infrared spectroscopy were sufficient to analyze single fibres. Therefore, this study used these approaches to characterize the fibres present in blended clothing.

1.2 Problem Statement

Despite of the increasing number of blended clothes, there are inadequate amount of researches on fibre blends, especially in forensic examination. Studies have been carried out on analysis of blended fibres but the existing investigations did not focus on fibre mixture or only employed one or two techniques. Current protocol also suggested separating blended fibres prior to analysis (ASTM International, 2012), which may damage forensic evidence. Although forensic examination of fibres is well established, there are some obstacles in characterization of fibre blends (Espinoza *et al.*, 2006). Examiners have to do thorough analysis in a proper manner so that they do not erroneously conclude fibre mixture as single fibre. Since fibre blends have different types of fibres, one of the fibre constituents may interfere with detection of other components in the mixture. Therefore, the effectiveness of the approaches for single fibre characterization has to be evaluated when the methods are performed on fibre blends. This study was conducted using four non-destructive techniques to analyze specifically fibre mixtures.

1.3 Objectives

The objectives of the study are as follows.

i. To characterize several binary fibre blends using three types of light microscopies (stereo, polarizing and fluorescence) in terms of fibre morphologies and optical properties as well as infrared spectroscopy.

ii. To evaluate the effectiveness of light microscopy and infrared spectroscopy for non-destructive analysis of fibre blends.

1.4 Scope

The scope of this research encompasses the analysis of binary-blended fibres using several non-destructive analytical techniques, *i.e.* stereomicroscope, polarizing microscope, fluorescence microscope and ATR-FTIR. Samples of blended clothes obtained through convenience sampling were analysed in this study after the clothes were examined physically for possible presence of fibre mixtures. Clothes with binary mixture were focused on in this study because fabrics with more than two fibre types are not common in practice (Sengupta & Debnath, 2012). Fibre blends containing cotton, polyester, rayon, silk and wool were chosen because these fibres are common in Malaysia (Sieh Lee, 2007) and thus there are high probability of encountering the fibre at crime scene.

1.5 Significance of Study

Through this study, characterization of fibre blends in forensic perspectives can be better understood. It can aid in identification of blended clothing for forensic purpose. Proper characterization of fibre blends is crucial in criminal investigation when blended textile products are encountered at crime scene. Misinterpretation as single fibres can be avoided if fibre mixture can be discovered when the same methods for single fibres are employed. It helps to differentiate the fibre samples and narrow down the suspect pool.

Besides, this study can also contribute to the assessment of manufactured clothes in apparel industries. The data obtained in this research may also be useful in a Malaysian fibre database in future.

REFERENCES

Abraham, J.T., Shukla, S.K. and Singh, A.K. (2007). Application of X-Ray Diffraction Techniques in Forensic Science. *Forensic Science Communications*. 9(2).

Ali, M., Mian, A.J., Islam, M.N., Awual, M.R., Fazal-E-Karim, S. and Chowdhury, A.M.S. (2001). Physio-mechanical Properties of Fabrics Prepared from Blends of Sulphonated Jute Fibre with Natural and Synthetic Fibres. *Indian Journal of Fibre & Textile Research*. 26: 414-417.

American Association of Textile Chemists and Colorists (AATCC). Fiber Analysis: Qualitative. North Carolina, AATCC Test Method 20. 2007.

American Association of Textile Chemists and Colorists (AATCC). *Fiber Analysis: Quantitative*. North Carolina, AATCC Test Method 20A. 2011.

Appalaneni, K. (2013). *Non-destructive Analysis of Trace Textile Fiber Evidence via Room-temperature Fluorescence Spectroscopy.* Ph.D. Thesis. University of Central Florida.

ASTM International. *Standard Guide for Forensic Analysis of Fibers by Infrared Spectroscopy*. Pennsylvania, E 2224. 2002.

ASTM International. *Standard Test Methods for Identification of Fibres in Textiles.* Pennsylvania, D276. 2012.

Banerjee, P.K. (2015). *Principles of Fabric Formation*. Boca Raton: CRC Press. p. 84.

Barker, R.H. (1975). Additives in Fibers and Fabrics. *Environmental Health Perspectives*. 11: 41-45.

Basch, A. and Tepper, E. (1973). The Analysis of Polyester-Wool Mixtures by Attenuated Total Reflectance Infrared Spectroscopy. *Applied Spectroscopy*. 27(4): 268-270.

Bell, S. (2006). *Forensic Chemistry*. New Jersey: Pearson Prentice Hall.

Bennett, S., Roux, C.P. and Robertson, J. (2010). The Significance of Fibre Transfer and Persistence – A Case Study. *Australian Journal of Forensic Science.* 42(3): 221-228.

Beton, A., Dias, D., Farrant, L., Gibon, T., Le Guern, Y., Desaxce, M. and Boufateh, I. (2014). *Environmental Improvement Potential of Textiles (IMPRO-Textiles).* Seville: Publications Office of the European Union.

Brinsko, K.M. (2010). Optical Characterization of Some Modern “Eco-friendly” Fibers. *Journal of Forensic Sciences*. 55(4): 915-923.

Brooks, M.M. (2012). *Identifying Fibres and Fabrics*. [online] Available at: http://www.dressandtextilespecialists.org.uk/FINAL_Identifying%20Fibres%20%20Fabrics%20DATS%20Workshop%20handbook%20mmb.pdf [Accessed 29 January 2015].

Burch, J. (2008). *The Tranfer and Persistence of Fibres on Bare Skin*. Master Thesis. University of Strathclyde.

Cantrell, S., Roux, C., Maynard, P. and Robertson, J. (2001). A Textile Fibre Survey As An Aid to the Interpretation on Fibre Evidence in the Sydney Region. *Forensic Science International*. 123: 48-53.

China National Cotton Reserves Corporation (2014). Pure Cotton Yarn Loses Ground to Blended Yarn. Available at: http://www.cncrc.com.cn/522-1222-13819.aspx [Accessed 15 February 2015].

Christie, R.M. (2015). *Colour Chemistry*. 2nd edition. Cambridge, U.K.: The Royal Society of Chemistry. p. 37.

Collier, B.J., Bide, M. and Tortora, P.G. (2009). *Understanding Textiles*. New Jersey: Pearson Education, Inc.

Crinis, V. (2012). Global Commodity Chains in Crisis: The Garment Industry in Malaysia. *Institutions and Economies*. 4(3): 61-82.

Cunningham, G. (2014). *Camping Equipment Which Is Lightweight and How to Make It.* Sea Salt.

Cyniak, D., Czekalski, J. and Jackowski, T. (2006). Influence of Selected Parameters of the Spinning Process on the State of Mixing of Fibres of a Cotton/Polyester-Fibre Blend Yarn. *Fibres and Textiles in Eastern Europe*. 14(4): 36-40.

Czekalski, J. and Patejuk-Duda, A. (2004). Methods of Determining the Fibre Content and Evaluating the Fibre Blending in Bicomponent Cellulose Blends. *Journal of Natural Fibers*. 1(2): 25-35.

Davis, R., El-Shafei, A. and Hauser, P. (2011). Use of Atmospheric Pressure Plasma to Confer Durable Water Repellent Functionality and Antimicrobial Functionality on Cotton/Polyester Blend. *Surface & Coatings Technology*. 205: 4791-4797.

De Muth, J. E. (2014). *Basic Statistics and Pharmaceutical Statiscal Applications*. 3rd edition. Boca Raton: CRC Press.

Deadman, H.A. (1984). Fiber Evidence and the Wayne Williams Trial (Conclusion). *FBI Law Enforcement Buletin*. 53(5): 10-19.

DeBattista, R., Tidy, H., Thompson, T.J.U. and Robertson, P. (2014). An Investigation Into the Persistence of Textile Fibres on Buried Carcasses. *Science and Justice*. 54: 288-291.

Deedrick, D.W. (2000). Hairs, Fibers, Crime, and Evidence Part 2: Fiber Evidence. *Forensic Science Communications*. 2(3).

Deopura, B.L. and Padaki, N.V. (2015). Chapter 5: Synthetic Textile Fibres: Polyamide, Polyester and Aramid Fibres. In: Sinclair, R. (Ed.) *Textiles and Fashion: Materials, Design and Technology*. Cambridge, U.K.: Woodhead Publishing.

Department of Statistics Malaysia (2014). *Monthly Manufacturing Statistics*. [online] Available at: http://www.statistics.gov.my/portal/download_Manufacturing/files/MANUFACTURING/2014/MMS_OGO2014.pdf [Accessed 8 October 2014].

De Wael, K., Baes, C., Lepot, L. and Gason, F. (2011). On the Frequency of Occurrence of A Peculiar Polyester Fibre Type Found in Blue Denim Textiles. *Science and Justice*. 51: 154-162.

De Wael, K. and Driessche, T.V. (2011a). Dichroism Measurements in Forensic Fibre Examination Part 1 – Dyed Polyester Fibres. *Science and Justice*. 51: 57-67.

De Wael, K. and Driessche, T.V. (2011b). Dichroism Measurements in Forensic Fibre Examination Part 2 – Dyed Polyamide, Wool and Silk Fibres. *Science and Justice*. 51: 163-172.

Dozono, T., Ishizawa, H., Tokutake, S., Takei, Y. and Miki, T. (2011). Basis Examination for Nondestructive Qualitative Analysis of Textile by Infrared Absorption Features. *SICE Annual Conference 2011*.

Encyclopaedia Britannica (2014). Natural Fibre. [online] Available at: http://global.britannica.com/EBchecked/topic/406148/natural-fibre [Accessed 18 November 2014].

Espinoza, E., Przybyla, J. and Cox, R. (2006). Analysis of Fiber Blends Using Horizontal Attenuated Reflection Fourier Transform Infrared and Discriminant Analysis. *Applied Spectroscopy*. 60(4): 386-391.

Fan, Q. (Ed.). (2005). Chemical Testing of Textiles. Cambridge, England: Woodhead Publishing Limited.

Farah, S., Tsach, T., Bentolila, A. and Domb, A.J. (2014). Morphological, Spectral and Chromatography Analysis and Forensic Comparison of PET Fibers. *Talanta*. 123: 54-62.

Farah, S., Kunduru, K.R., Tsach, T., Bentolila, A. and Domb, A.J. (2015). Forensic Comparison of Synthetic Fibers. *Polymers for Advanced Technologies*. 26: 785-796.

Fei, J., Lu, W., Duan, J., Yang, J., Zhou, Z. and Yu, J. (2013). Study on Precision of a DNA Analysis Method for Quantifying Cashmere/Wool Mixture. *Advanced Materials Research*. 821-822: 243-247.

Fourné, F. (1999). *Synthetic Fibers: Machines and Equipment Manufacture, Properties*. Munich: Carl Hanser Verlag.

Flynn, K., O'Leary, R., Roux, C. and Reedy, B.J. (2006). Forensic Analysis of Bicomponent Fibers Using Infrared Chemical Imaging. *Journal of Forensic Science*. 51(3): 586-596.

Fredericks, P.M. (2012). Forensic Analysis of Fibres by Vibrational Spectroscopy. In: Chalmers, J.M., Edwards, H.G.M. and Hargreaves, M.D. (Eds.) *Infrared and Raman Spectroscopy*. New Jersey: John Wiley & Sons, Ltd. pp. 153–169.

Greaves, P.H. (1990). Fibre Identification and the Quantitative Analysis of Fibre Blends. *Review of Progress in Coloration and Related Topics*. 20: 32-39.

Grieve, M.C. (1990). Fibres and Their Examination in Forensic Science. In: Maehly, A. & Williams, R.L. (Eds.) *Forensic Science Progress* (Vol. 4). Berlin: Springer Berlin Heidelberg. pp. 41-125.

Grieve, M.C. (2000). Back to the Future – 40 Years of Fibre Examinations in Forensic Science. *Science & Justice*. 40(2): 93-99.

Grieve, M.C., Biermann, T.W. and Schaub, K. (2005). The Individuality of Fibres Used to Provide Forensic Evidence – Not All Blue Polyesters Are the Same. *Science & Justice*. 45(1): 13-28.

Grieve, M.C. and Deck, S. (2002). Black Cellulosic Fibres – A "Bête Noire"?. *Science & Justice*. 42(2): 81-88.

Grieve, M.C. and Kotowski, T.M. (1986). An Improved Method of Preparing Fiber Cross Sections. *Forensice Science Society*. 29-34.

Guruprasad, R., Chattopadhyay, S.K., Jadhav, R.K. and More, C.M. (2014). Cotton Blended Yarns – A Review of Present Status. [online] Available at: http://www.fibre2fashion.com/industry-article/printarticle.asp?article_id=5199&page=1 [Accessed 19 November 2014].

Hong, S., Han, A., Kim, S., Son, D. and Min, H. (2014). Transfer of Fibres on the Hands of Living Subjects and Their Persistence During Hand Washing. *Science and Justice*. 54(6): 451-458.

Houck, M.M. (2001). *Mute Witnesses: Trace Evidence Analysis*. London, United Kingdom: Academic Press.

Houck, M.M. (2004). *Trace Evidence Analysis: More Cases in Mute Witnesses*. Burlington: Elsevier.

Houck, M.M. (2009). *Identification of Textile Fibers*. Cambridge, U.K.: Woodhead Publishing Limited.

Houck, M.M. and Siegel, J.A. (2010). *Fundamentals of Forensic Science*. 2nd edition. Burlington: Academic Press. pp. 371-383.

Keating, S.M. (1988). The Laboratory's Approach to Sexual Assault Cases. Part 2: Demonstration of the Possible Offender. *Journal of the Forensic Science Society*. 28: 99-110.

Kirkbride, K.P. and Tridico, S.R. (2010). The Application of Laser Scanning Confocal Microscopy to the Examination of Hairs and Textile Fibers: An Initial Investigation. *Forensic Science International*. 195: 28-35.

Koyama, S., Morishima, M., Miyauchi, Y. and Ishizawa, H. (2013). Non-destructive Identification and Mixture Ratio Analysis of Cotton-Polyester Blended Textile Products by IR Spectroscopy. *Textiles and Light Industrial Science and Technology*. 2(4): 153-160.

Kubic, T. and Petraco, N. (2009). *Forensic Science Laboratory Manual and Workbook*. 3rd edition. Boca Raton: CRC Press. pp. 101-105.

Lang, P.L., Katon, E.J., O'Keefe, J.F. and Schiering, D.W. (1986). The Identification of Fibres by Infrared and Raman Microspectroscopy. *Microchemical Journal*. 34: 319-331.

Lepot, L., De Wael, K., Gason, F. and Gilbert, B. (2010). Application of Raman Spectroscopy to Forensic Cases. *Science and Justice*. 48: 109-117.

Luniak, B. (1953). *The Identification of Textile Fibres: Qualitative and Quantitative Analysis of Fibre Blends*. London, U.K.: Sir Isaac Pitman & Sons, Ltd.

Lyle, D.P. (2004). Forensics for Dummies. New Jersey: Wiley Publishing, Inc. pp. 267, 273-275.

Maitra, K.K. (2007). *Encyclopaedic Dictionary of Clothing and Textiles*. New Delhi: Mittal Publications. pp. 487, 493.

Malaysian Knitting Manufacturers Association (MKMA). (2013). Major Sourcing Countries of Textiles. Available at: http://www.mkma.org/statistic/2013/2013SeptMajorOriginTextiles.htm [Accessed 15 February 2015].

Malaysia International Trade and Industry (MITI). (2008). *Textiles and Apparel Industry*. Malaysia International Trade and Industry Report 2008.

Martin, J. and Lehu, P.A. (2009). *Fashion for Dummies*. New Jersey: Wiley Publishing, Inc. pp. 69-71.

Mather, R.R. and Wardman, R.H. (2011). *The Chemistry of Textile Fibres*. Cambridge, U.K.: The Royal Society of Chemistry.

Matsuyama, Y., Nagatani, Y., Goto, T. and Suzuki, S. (2013). Discrimination of Cultivated Silk and Wild Silk by Conventional Instrumental Analyses. *Forensic Science International*. 231: e37-e42.

McBurney, D.H. & White, T.L. (2010). *Research Methods*. 8th edition. Belmont: Wadsworth. p. 412.

McCrone Associates, Inc. (2005). McCrone Atlas of Microscopic Particles. [online] Available at: http://www.mccroneatlas.com/ [Accessed 7 November 2015].

O'Connor, R.T. (1972). *Instrumental Analysis of Cotton Cellulose and Modified Cotton Cellulose*. New York: Marcel Dekker, Inc. p.126.

Nayak, R.K., Padhye, R. and Fergusson, S. (2012). Chapter 11: Identification of Natural Textile Fibres. In: Ryszard, M. K. (Ed.). *Handbook of Natural Fibres – Volume 1: Types, Properties and Factors Affecting Breeding and Cultivation*. Cambridge, U.K.: Woodhead Publishing Limited.

Palmer, R. and Burch, H.J. (2009). The Population, Transfer and Persistence of Fibres on the Skin of Living Subjects. *Science and Justice*. 49(4): 259-264.

Palmer, R., Hutchinson, W. and Fryer, V. (2009). The Discrimination of (Non-denim) Blue Cotton. *Science and Justice*. **49**: 12-18.

Patterson, A. (2015). *Towards Recycling of Textile Fibers: Separation and Characterization of Textile Fibers and Blends*. Master Thesis. Chalmers University of Technology.

Perkin-Elmer. (2004). ATR Accessories – An Overview. [online] Available at: http://shop.perkinelmer.de/Content/TechnicalInfo/TCH_ATRAccessories.pdf.

Petraco, N. and Kubic, T. (2004). *Color Atlas and Manual of Microscopy and Criminalists, Chemists, and Conservators*. Boca Raton: CRC Press.

R. v. Simon John Hall. (2011). Available at: http://www.homepage-link.to/Justice/Hall/index.html [Accessed 26 January 2016].

Ravandi, S.A.H. and Valizadeh, M. (2011). Properties of Fibers and Fabrics That Contribute to Human Comfort. In: Song, G. (Ed.) Improving Comfort in Clothing. Cambridge, U.K.: Woodhead Publishing Limited. pp. 63-67.

Robertson, J. and Grieve, M. (Eds.). (1999). Forensic Examination of Fibres. 2nd edition. Boca Raton: CRC Press.

Rodgers, J. and Beck, K. (2009). NIR Chracterization and Measurement of the Cotton Content of Dyed Blend Fabrics. *Textile Research Journal*. 79(8): 675-686.

Ruckebusch, C., Orhan, F., Durand, A., Boubellouta, T. and Huvenne, J.P. (2006). Quantitative Analysis of Cotton-Polyester Textile Blends from Near-Infrared Spectra. *Applied Spectroscopy*. 60(5): 540-544.

Saferstein, R. (2007). *Criminalistics: An Introduction to Forensic Science*. 9th edition. New Jersey: Pearson Prentice Hall. pp.219-232.

Salter, M.T., Cook, R. and Jackson, A.R. (1987). Differential Shedding from Blended Fabrics. *Forensic Science International*. 33: 155-164.

Sengupta, S. and Debnath, S. (2012). Studies on Jute Based Blended Yarns. *Indian Journal of Fibres & Textile Research*. 37: 217-223.

Shaikh, T.N. and Agarwal, S.A. (2014). Qualitative and Quantitative Characterization of Textile Material by Fourier Transform Infra-Red: A Brief Review. *International Journal of Innovative Research in Science, Engineering and Technology*. 3(1): 8496-8502.

Shui, S. and Plastina, A. (2013). FAO/ICAC World Apparel Fiber Consumption Survey. Washington: International Cotton Advisory Committee.

Siegel, J.A. (2007). *Forensic Science: The Basics.* Boca Raton: CRC Press. pp. 436-445.

Sieh Lee, M.L. (2007). *Menangani Cabaran Dunia: Strategi Globalisasi di Malaysia.* Shah Alam: McGraw Hill. p. 249.

Široká, B., Široký, J and Bechtold, T. (2011). Application of ATR-FT-IR Single-Fiber Analysis for the Identification of a Foreign Polymer in Textile Matrix. *International Journal of Polymer Analysis and Characterization*. 16(4): 259-268.

Smith, B. (1999). *Infrared Spectral Interpretation: A Systematic Approach*. Boca Raton: CRC Press.

Srivastava, S. (2012). *Natural and Man-Made Fibres*. Allahabad: Pushpa Publishing House.

Stuart, B.H. (2013). *Forensic Analytical Techniques*. West Sussex: John Wiley & Sons, Ltd.

Suzuki, S., Higashikawa, Y., Sugita, R. and Suzuki, Y. (2009). Guilty by His Fibers: Suspect Confession Versus Textile Fibers Reconstructed Simulation. *Forensic Science International*. 189: e27-e32.

Taupin, J.M. and Cwiklik, C. (2011). *Scientific Protocols for Forensic Examination of Clothing*. Boca Raton: CRC Press.

Thomas Reuters (2015). 2015 Journal Citation Reports®. Available at: http://apps.webofknowledge.com [Accessed 14 August 2015].

Thomas, S., Paul, S.A., Pothan, L.A. and Deepa, B. (2011). Natural Fibres: Structure, Properties and Applications. In Kalia, S., Kaith, B.S. and Kaur, I. (Eds.) *Cellulose Fibers: Bio- and Nano-Polymer Composites*. Berlin: Springer Berlin Heidelberg. pp. 3-42.

Tilstone, W.J., Savage, K.A. and Clark, L.A. (2006). *Encyclopedia of Forensic Science: An Encyclopedia of History, Methods, and Techniques*. California: ABC-CLIO. pp. 142-145.

Tungol, M.W., Bartick, E.G. and Montaser, A. (1990). The Development of a Spectral Data Base for the Identification of Fibers by Infrared Microscopy. *Applied Spectroscopy*. 44(4): 543-549.

Uğur, Ș.S. and Sariișik, A.M. (2015). Deposition of Nanoparticle Multilayers to Improve Mechanical Properties of Denim Fabrics. *The Journal of The Textile Institute*. 106(7): 718-724.

United States International Trade Commission. (2008). Viscose Rayon Staple Fiber: Probable Effect of Modification of U.S.-Australia FTA Rules of Origin. [online] Available at: http://www.usitc.gov/publications/332/pub4041.pdf [Accessed 13 February 2015].

Wakelyn, P.J., Bertonier, N.R., French, A.D., Thibodeaux, D.P., Triplett, B.A., Rouselle, M.A., Goynes, W.R., Jr., Edwards, J.V., Hunter, L., McAlister, D.D. and Gamble, G.R. (2007). *Cotton Fiber Chemistry and Technology*. Boca Raton: CRC Press. p. 16.

Wampler, T. P. (2007). Chapter 1: Analytical Pyrolysis: An Overview. In: Wampler, T.P. (Ed.) *Applied Pyrolysis Handbook*. 2nd edition. Boca Raton: CRC Press. pp. 11-13

Wiggins, K. and Drummond, P. (2007). Identifying A Suitable Mounting Medium for Use in Forensic Fibre Examination. *Science & Justice*. 47: 2-8.

Wiggins, K. and Holness, J.-A. (2005). A Further Study of Dye Batch Variation in Textile and Carpet Fibres. *Science and Justice*. 45(2): 93-96.

Wilson, J. (2001). *Handbook of Textile Design: Principles, Processed and Practice.* Cambridge, U.K.: Woodhead Publishing Limited. p. 3.

Wortmann, F.–J. and Wortmann, G. (1992). Quantitative Fiber Mixture Analysis by Scanning Electron Microscopy – Part IV: Assessment of Light Microscopy as an Alternative for Analyzing Wool/Specialty Fiber Blends. *Textile Research Journal*. 62(7): 423-431.

You, F., Hu, Y. and Hu, S. (2011). Composition Identification of Typical Decorative Textiles in Tibetan Historical Buildings by Burning test and Projection Microscope Test. *Advanced Materials Research*. 143-144: 515-519.

Zięba-Palus, J. and Trzcińska, B.M. (2012). Comparing the Color of Forensic Traces. *Analytical Letters*. 45: 1333-1346.