Environmentally conscious fashion through responsible coloration techniques applied to sustainable fabrics: colouring outside the lines

A thesis submitted by

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Abstract

Colour for fashion and textiles is an immediately obvious aesthetic concern, both for designer and consumer. The environmental consequences in the creation and application of colour and the implications of the processes used in aiming to produce future sustainable fashion and textiles are less obvious and often overlooked. The purpose of the research described in this thesis was to explore reducing the environmental impact of coloured fashion and textiles through how they are designed and produced, questioning if coloured fashion and textiles can be sustainable? The research was conducted at the design/technology interface, carried out in collaboration with Lenzing, an Austrian fibre manufacturer. The newly developed interdisciplinary methodology provides a design driven framework from which to explore the relationship between fibre, colour and garment to identify the challenges and opportunities in producing coloured fashion & textiles. The creativity of design thinking is underpinned with the technical inquiry of coloration technology. The outcomes of the research provide innovative sustainability solutions for designing and producing coloured fashion and textiles.

The thesis establishes the current state of knowledge for the designing and producing of coloured fashion and textiles with reduced environmental impact, exploring both natural and synthetic sources of colour. A gap in knowledge relating to the sustainable coloration of cellulose fibres is highlighted resulting in the research direction being specifically focused on the regenerated cellulose fibre lyocell. The research outcomes provide two key approaches to colour for fashion and textiles, each based within the biological lifecycle, these being; sustainable and responsible coloration. For sustainable coloration where the biological life cycle is uninterrupted, a 'cyclical model' is developed, specifically focused on the utilization of a natural dye extracted from a by-product of lyocell fibre manufacture, this model provides a method for sustainable coloration that is of a commercial scale and technical standard. For responsible coloration, where the biological life cycle is interrupted through the introduction of additional chemical's for pre and post coloration stages as well as the use of petrochemical based synthetic dyes during coloration a carefully selected set of reactive dyes is used that provide minimal environmental impact, the preparation and finishing stages are explored and a method of best practice developed that minimises chemical, energy and water usage of pre-creative coloration stages. Within the

responsible coloration research the technical inquiry identifies the use of bi-functional dyes, the chemistry of these dyes inspires the creative inquiry and research outcome of ‘bi-surface fabrics’, screen print and digital print methods are merged with technical processes and auxiliary chemical’s minimized or removed to create a new approach to coloration that reduces environmental impact and provides an innovative bi-surface fabric. Through creating two surfaces within a single piece of fabric, the designer essentially can design a second life at the initial design stage for the garment the fabric is used to construct, ultimately extending the lifetime of the garments use phase within its lifetime to optimize the embedded energy from production stages and reduce waste from premature disposal.

The thesis presented involves traditional argument encompassing elements of both technology and design. As part of the design research process, a physical collection of samples and prototype garments was also produced, and these are referenced and documented photographically within the thesis.

Dedication

To the person without whom I wouldn’t have gotten this far,

Professor Robert Christie.

Thank you for your unwavering support and being my guiding star Bob.

Acknowledgement

I would like to thank my family for their love, support, encouragement and patience, especially my mum for turning my tears to laughter and believing in me when I couldn't believe in myself, this is our joint achievement, we did it together mum.

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Ellams, D., Christie, R. M., Robertson, S., 2014 'An Approach to Sustainable Coloration of Lyocell Fabrics by Screen Printing using Extracts of Leaves and Bark from Eucalyptus'. Coloration Technology, Vol.130, issue 1, pages 48-53, February 2014.

Conference Papers

Ellams, D., Christie, R. M., Robertson, S., 2013. 'Better than Beige: 'Sustainable Colour for Lyocell', Making Futures, Interfaces between Craft Knowledge and Design: New opportunities for social innovation and sustainable practice, Plymouth College of Art, 16th & 17th September 2013, in proceedings published April 2014.

Ellams, D., Christie, R. M., Robertson, S., 2012. 'Sustainable Colour for Lyocell through Design', Textile Institute 88th World Conference, Malaysia, 15th to 17th May 2012, in conference proceedings.

Exhibitions

Ellams, D., 2014. 'Denim-less Denim', Edinburgh Science Festival, Techno Threads - the future of fashion, Surgeons Hall, Edinburgh, 19th April 2014

Ellams, D., 2014. 'Cyclical Colour, Edinburgh Science Festival, Techno Threads - the future of fashion, Surgeons Hall, Edinburgh, 19th April 2014

CHAPTER 1. Introduction

1. Introduction

1.1 Background

The current fashion and textile industry has developed based on a linear model, in which a mass of waste is produced, driven by increased consumer demand for low cost fast fashion. Each stage of the production process contributes significantly towards environmental pollution; extensive amounts of chemicals, energy and water are consumed during both production and use. Waste is produced at two key stages, firstly from industrial manufacturing processes then secondly when garments are discarded by consumers and sent to landfill. The production of raw materials for textiles is heavily reliant on the use of diminishing, non-renewable natural resources. Increased awareness surrounding the use of these finite resources for production has created ongoing debate, particularly in the scientific community, as to how much longer chemicals based on fossil fuels will continue to be available for use. While opinions range from 50 to 500 years, it is broadly agreed that the reserves are limited and that research into new energy and material resources for fashion and textile production will be essential to satisfy future needs.

Developing solutions for sustainability within the fashion and textile industry has largely splintered into two independent research discipline approaches, either scientific or design based, with a focus on the key areas that highlighted where environmental impact occurs. These areas are mainly the fibre production, coloration and finishing stages, manufacturing processes, packaging and transportation, consumer use and end of life. Science and technology research has been fundamental in advancing towards a future sustainable fashion and textiles industry. However, the key for the commercial success of this industry is the aesthetic appeal of the product. The designer and the design process connect the product to the process within which it is produced. The amount of design research into the area of sustainable fashion and textiles has dramatically increased in the last decade. The focus has primarily been on addressing areas of fibre choice, garment design and production processes.

Though designers have made a significant contribution to industrial evolution through providing innovative design solutions for more responsible and efficient systems of production, this has generally been carried out alongside, rather than collaboratively with, science and technology disciplines. Developments in the area of textile coloration have been primarily left to and led by scientists and technologists with a focus on the chemistry involved, for example aiming to reduce the requirements for water, energy and raw materials used for dyeing and printing processes. Within sustainable design research, approaches to introducing colour have been largely overlooked, in spite of the fact that colour is often the most immediately visible feature in the design of fashion and textiles. Colour is usually the main aesthetic concern for both the designer and consumer; the main motivation for the use of colour within design is to create desirable aesthetics to ensure the commercial appeal and financial success of the product. It may be argued that designers commonly demonstrate only a limited understanding of, or regard for, the environmental impact caused by the production of colour and its application to textiles.

A gap in design research specifically focused on reducing the environmental impact of fashion and textile coloration therefore appeared to exist. The research described in this thesis recognizes that in aiming to reduce the environmental impact of coloured fashion and textiles, a technological understanding of the environmental consequences for design decisions made within the design process is fundamental. The research approach for this thesis therefore interwove the creative inquiry of design with an underpinning by the principles of textile coloration technology. The interdisciplinary research approach presented is focused on the relationships between fibre, colour and design; the methodology used takes into account the environmental credentials and performance of the materials selected within the design process to explore new opportunities to reduce the environmental impact of coloured fashion and textiles. The research uses the perspective of design to explore sustainability issues in producing coloured fashion and textiles. A principal aim of this research was to combine scholarly inquiry with design practice to create tangible design outcomes that inform and exemplify solutions for enhanced sustainability. Sustainability is defined in the research as 'learning to live in harmony with our planet and to take from it only what we are able to give back to it without causing detrimental damage'. The research explores, through practice underpinned by technical inquiry, how we produce, design with and use colour to create sustainable fashion and textiles, primarily questioning whether colour for fashion and textiles can be sustainable.

There are two broad sources of chemicals, which may be used to create colour: natural and synthetic. It is a common misconception to presume automatically that 'natural' inevitably means good and 'synthetic' bad in terms of the effect on the environment. Until the mid 19th century, when the development of synthetic dyes began, all textiles were coloured using dyes from natural sources. The lower cost, better reliability, reproducibility, and larger scale of operation that was achievable with synthetic dyes, together with the development of new technologies that have taken place over the years, have meant that the traditional processes used for natural dyeing and knowledge and experience of the methods have been largely eliminated. Modern industrial processes use natural dyes only in specific niche markets. The dyes currently used for the industrial coloration of textiles are almost exclusively synthetic products of the chemical industry, manufactured from finite, non-renewable petrochemical sources. Application of these synthetic dyes to textiles generally involves intense use of chemicals, water and energy, with inevitable environmental consequences.

Current opinion within the research community is increasingly concluding that all methods of coloration of textiles have environmental consequences. The thesis raises the question that the current systems for introducing colour must be considered as unsustainable over the longer term. This leads to the fundamental questions, which have motivated the research program described in the thesis, namely, how would we produce colour without the use of chemicals derived from fossil fuels?, and what happens when reserves run out?

While it may be argued that natural dyes offer some environmental benefit compared with synthetic dyes, for example in terms of cultivation from renewable natural sources, biodegradability and low toxicity, their use is not completely free of environmental impact. The cultivation of plants specifically for the production of natural dyes would require the use of a significant area of arable land, for which food production is a higher priority. In addition, natural dyeing of textiles commonly requires treatment with a mordanting agent, usually a metal salt, to fix the dye to fibres as many natural dyes have little direct affinity for fibres, and this mordanting process has inevitable environmental consequences. Commonly, natural dyes also show inferior fastness properties, limiting their suitability for use on textiles, especially fashion. In aesthetic terms, the range of colour and depth of shades that are capable of being produced from natural dyes is limited, and in no way comparable with the rainbow of possibilities achievable from the use of the modern range of synthetic dyes.

The primary motivation for this thesis therefore was to establish if colour for fashion and textiles can be sustainable? With Sustainable meaning 'learning to live in harmony with our planet and to take from it only what we are able to give back to it without causing detrimental damage', which is the author's modification of the original definition for Sustainable Development from the 1987 Brundtland report (Brundtland, 1987a).

1.2 Research Aims and Objectives

1.2.1 Aims

The research aimed to establish methods of reducing the environmental impact of coloured fashion clothing. To achieve this, the specific aims and objectives adopted are summarized below;

1. to establish the current state of knowledge regarding the range of approaches that are used in the coloration of cellulosic fibres for fashion and textiles;

2. to establish the current state of knowledge regarding approaches to environmentally responsible coloration of cellulosic fibres for fashion and textiles;

3. to explore the sustainability credentials of lyocell as a cellulosic fibre, especially in comparison to cotton;

4. to apply an interdisciplinary approach towards the development of novel methods for sustainable, or environmentally-responsible, coloration of fashion and textiles;

5. to explore printing on lyocell as a means to reduce the environmental impact of coloration techniques, especially in comparison with cotton;

6. to investigate the use of design methodology as a means to lower the environmental impact of coloration techniques applied to lyocell fibres for fashion and textiles.

1.2.2 Objectives

1. To establish the current state of knowledge regarding the range of approaches that are used in the coloration of cellulosic fibres for fashion and textiles the following objectives were applied:
    - identify relevant literature research on coloration methods for cellulose fibres;
    - explore through literature review current thinking, both from design and technology perspectives, on sources of colour and coloration techniques;
    - establish the current methods used for coloration processes relevant to the research approach adopted.

2. To establish the current state of knowledge regarding approaches to environmentally responsible coloration of cellulosic fibres for fashion and textiles the following objectives were applied:
    - identify relevant literature or research aiming at reducing the environmental impact of coloration methods, explored through literature review;
    - conduct discussions, site visits and training with key stakeholders.

3. To explore the sustainability credentials of lyocell as a cellulosic fibre, especially in comparison to cotton, the following objective was followed:
    - analyses of life cycle assessment data and other environmental assessment tools developed to support designers in making informed choices within the design process based on the environmental performance of fibres.

4. To apply an interdisciplinary approach towards the development of novel methods for sustainable, or environmentally-responsible, coloration of fashion and textiles, the following objectives were followed:
    - explore the development of a sustainable closed loop process for coloured fibre production.
    - explore each stage within the process of fabric preparation for coloration to identify areas where stages could be modified or combined to reduce environmental impact.

5. To explore printing on lyocell as a means to reduce the environmental impact of coloration techniques, especially in comparison with cotton, the following objectives will be followed:
    - explore through practice, screen and digital printing techniques applied to lyocell and cotton, to assess and compare and contrast advantages and disadvantages.

6. To investigate design methodology as a means to lower the environmental impact of coloration techniques of lyocell fibres for fashion and textiles the following objectives were applied:
    - explore current methodologies and design thinking for sustainable design.
    - incorporate 'design thinking' into the product life cycle from production through to end of life.
    - through practice, incorporate the methods of coloration developed and the design thinking to create prototypes that exemplify, demonstrate and test the research outcomes.

1.3 Thesis Contribution

The research outcomes offer a model for sustainable colour production that minimizes reliance on non-renewable materials, and also offer methods for designing and producing responsible coloured fashion and textiles that reduce the environmental impact of coloured lyocell for fashion clothing. An interdisciplinary method for research at the design/technology interface is also produced.

1.4 Thesis Outline

The stages followed to explore and achieve the aims of the research are presented in the chapters of this thesis as follows:

Chapter 2

The second chapter of this thesis describes the theoretical background to the research in a detailed literature review. The chapter opens with an overview of the fashion and textiles industry where the research is placed into context. The chapter presents the emerging vocabulary that is developing to categorize 'green fashion', a genre of fashion that aims to be more environmentally responsible throughout clothing life cycles and to tackle the 'fast' 'disposable' fashion culture of modern society. Terms such as bio, eco, natural, organic, slow, conscious and responsible are used to describe 'green fashion', resulting in a degree of confusion as to the meaning of what it is to be sustainable. The literature review continues by exploring sustainable fibres, regenerated cellulose and cotton fibres before progressing to the use of existing design methodologies within sustainable practice. Current research into colour for both design and technology and sources of colour close the chapter.

Chapter 3

The methodological framework for the research carried out is presented in Chapter 3. The chapter explains how the research framework was designed to interweave methods associated with the creativity of textile design and methods associated with technical enquiry, in particular involving coloration technology, thus providing an overarching methodology for the interdisciplinary study.

Chapter 4

Chapter 4 opens with the researcher's definition of 'sustainable'; an interpretation is presented, developed from literature proposals, for an appropriate definition of sustainability. The main body of research within Chapter 4 challenges the primary research question, can colour for textiles can be sustainable?

To achieve sustainable colour, the use of renewable resources for textile coloration must be re-considered, and in doing so incorporate the aim towards a future zero waste, zero emissions society. The development of agricultural production of plants used purely as a source of colour, and the use of the currently established methods both for extraction of natural colour and its application to textiles do not provide alternatives to dyeing with synthetic dyes that are necessarily sustainable or environmentally responsible. Chapter 4 provides an example of a new approach to sources of colour that incorporate the utilization of waste and by-products. Essentially the design process is linked to production incorporating life cycle design thinking in order to produce sustainable colour. Importantly, the outcome of this section of research provides a model from which opportunities and limitations for creating colour within a product life cycle are evaluated from both a technical and design perspective.

Chapter 5

The progression of the research into chapter 5 is driven from conclusions reached in chapter 4, where the research provides a potential long term solution in using natural dye obtained from production by-products and many avenues for further research, but does not address immediate concerns for the sustainability of colour use within fashion and textiles, which inevitably will continue to use synthetic dyes. Chapter 5 seeks to offer more immediate solutions for reducing environmental impact and focuses on responsible rather than sustainable coloration methods. An investigation into reactive dyes and their performance in screen printing on cellulosic fibres is explored including methods for preparation such as scouring and bleaching. In this respect, lyocell is directly compared with cotton and conclusions reached through assessment.

Chapter 6

Having addressed the technical avenues and conclusions reached on dye selection and methods for preparation and application of the dyes for screen printing, the final section of research presented in Chapter 6 uses design methodology applied to printing with synthetic dyes to explore through practice reducing environmental impact through design intervention. The design outcomes achieved, incorporated with the technical inquiry of chapter 5, are combined with the research methods developed to produce garment prototypes.

Chapter 7

Concludes the thesis by presenting a discussion of research results and possibilities for future work. The thesis is also accompanied by a collection of physical samples and garments that were produced using the methods presented within the research.

CHAPTER 2. Literature Review

2.1 Fashion & Textiles Industry,

2.1.1 Overview

The fashion and textile industry represents a significant part of the world's economy and is primarily a financially motivated sector of world trade. Fashion and textiles drive both micro-scale and macro-scale economies throughout the world, ranging from craft producers in the developing world to industrial scale fashion manufacturers and retailers (Farrer, 2011a). The sector is heavily reliant on non-renewable sources of energy and materials. The full environmental impact of the industry is yet to be measured, although it is being addressed by optimizing parts of the production process chain to improve the environmental and social impact of individual stages, from sourcing and supplying, production and finishing processes through to life cycle phases, as discussed by Fletcher (2009a).

The global textile industry faces significant challenges in addressing its responsibility towards a wide range of environmental issues. In aiming towards economic success, the industry has developed a dependency on non-renewable resources, consumes large quantities of chemicals, energy, and water, and generates large volumes of waste during production. Over 85.9 million tonnes of fibre were produced globally in 2012. 58.6 million tonnes of which were man-made fibres; 4.6 million tonnes of these man-made fibres were produced in Europe, 1 million tonnes were polyester and 562,000 tonnes were regenerated cellulosic fibres (CIRFS, 2014).

The attitude of sections of society towards fashion also has an impact on the environmental detriment caused by the sector. For example, in the desire to follow rapidly changing fashion trends, some brands now produce fashion garments for up to twelve ‘fashion seasons’ per year (Anson 2010), where low production costs and retail prices are key (Tham, 2013). Commonly these garments are only worn a handful of times before being discarded and replaced, this leads to premature disposal of garments, which inevitably end up in landfill, a situation that is unsustainable. Chapman (2005a) explains premature consumer waste as a symptom of failed relationships driven by the modern consumer’s continuous desire for fresh, new and novel goods. Allwood et al (2006a) identified four key areas associated with the environmental impact caused through production and over-consumption of fashion and textiles relating to energy use and the use of toxic chemicals within the sector, as c in Table 2.1.

Table 2.1: Four key environmental impacts in terms of energy and chemical use.

Environmental Issue	**Key Stage of Impact**
1. Energy use	Laundering and production of primary materials, especially man-made & natural fibres
2. Use of toxic chemicals	May be harmful to human health and the environment, particularly used within conventional processing of cotton.
3. Release of chemicals in water	Particularly in wet pre-treatment, dyeing, finishing and laundry.
4. Solid waste	Yarn manufacturing for natural fibres, construction stages of products and disposal of products at end of life stage.

Source: Allwood et al, 2006, p.14

The 2006 Allwood et al report, 'Well dressed?', provides a comprehensive, accessible account of research that aims to identify the major sources of environmental impact of the clothing and textile industry and examined the flow of materials through the United Kingdom. The study was undertaken in response to growing social awareness and concern for the decreasing cost and increasing demand and availability of fashion clothing, and increasing awareness of the environmental pollution caused by the industry. The report, Well dressed?, suggested that in the United Kingdom alone during 2004, consumer expenditure on clothing and textiles totalled £46.7 billion. 80% of this was spent on clothing, the remaining 20% on textiles (Allwood et. al., 2006b). The study found annually, 3.25 million tonnes of textiles flowed through the UK; of this 2.35 million tonnes of textile and clothing became waste. 13% went to material recovery, 13% to incineration and a huge 74% (1.8 million tonnes) was sent to landfill (Allwood et. al., 2006c). Textile waste buried in landfill sites is not 100% biodegradable, due largely to the chemicals used in production, especially at finishing stages. As textiles degrade there is potential for harmful toxins to be released into the earth. Slater (2003a) expresses the opinion that any substance derived from natural sources without the use of chemical treatment for its production will cause no physical harm to the earth following its disposal. In contrast, a substance derived from natural sources with a chemical treatment involved in its production will, in general, make the object harmful to the Earth upon its disposal.

Allwood et.al., (2006d) suggest that, in the UK, each person per year consumes 35kg of textiles and clothing, and of this 74% is discarded. This results, on average, in UK consumers sending 25.9kg of textiles to landfill each year. To visualise this amount of textile waste, if it is considered that the average generic cotton T-shirt in a size medium weighs around 0.18kg, this 25.9kg of textile waste is equivalent to 144 T-shirts.

Fletcher (2007a) proposes that consumers do not reconcile the increase in availability of cheap fashion clothing items with the environmental detriment caused through their production. Fletcher exemplifies this principle by presenting, as the example, that consumers are yet to associate the £5 cotton T-shirt that they bought, wore once then discarded, with the 4000 litres of water that were used to manufacture it, and that, to address this, we need to break the cycle of increased speed and decreasing prices through recognising the difference between symbolic fashion production, and material clothing production. Fletcher (2008a) explains the difference between fashion and material clothing as fashion clothing appealing to our emotions linking to a genre and period of time, whereas material clothing is concerned with meeting physical needs, such as shelter and protection.

2.1.2 Fast Fashion

Increased demand for low cost clothing has driven, and continues to drive, the cost of production lower. From 2001 to 2005 spending on women's clothing in the UK rose by 21%, and, by the end of 2005, prices for women's clothing had dropped by 14% in the same period (Allwood et.al. 2006e). Manufacturers are under pressure to supply products to fashion brands at as low a cost as possible to ensure that profit margins can be maintained. The fashion and textiles industry is operating within a dysfunctional system of supply and demand driven by financial gain to the detriment of the environment. Farrer (2011b) explains the economy of scale that British retailers have developed, allowing them to buy large volumes of clothing, continuously driving down the price and creating a cycle of affordable, well-designed clothing that the consumer buys as quickly as shelves are stocked, thus allowing the cycle to restart. Farrer simplifies this by stating: 'Cheaper goods mean more consumption, which in turn means cheaper goods, which means more consumption'.

The UK fashion industry initiated the strategy of producing clothing at low cost with high turnover when there was a realization that flexibility and rapid response to the market within the supply chain were vital for survival in the competitive market of high street fashion (Barnes and Lea-Greenwood, 2006). This resulted in a high street fashion industry that became transformed from product-driven to market-driven (Bhardwaj and Fairhurst, 2010a).

Fashion and textiles produced within this market driven system has resulted in a 21st century genre of fashion known as ‘fast fashion’. Fernie and Sparks (1998) explain fashion as clothing to be representative of an expression widely accepted by a group of people over time, and characterized by several marketing factors such as low predictability, high impulse purchase, shorter life cycle, and high volatility of market demand. Bhardwaj and Fairhurst (2010b) explain the term ‘fast fashion’ that has grown from a ‘throw away market’ as an outcome of the reduced time between designing and consumption on a seasonal basis. The term has been adopted in reference to the rise in demand for cheap, affordable clothing replicated from high-end fashion and produced with a ‘speed-to-market’ focus. ‘Fast fashion’ shortens product life cycles. Retailers aim to create shorter life cycles and higher profit margins from the sale of fast selling merchandise, avoiding the mark-down process altogether and keeping purchase price low all year round. Another tactic developed by retailers in recent years is to increase the number of fashion seasons per year with the introduction of micro trends within a trend hence creating micro collections, meaning that the shop floor is constantly ‘refreshed’, the idea being that there is always something ‘new’ to entice consumer purchases. This allows retailers to encourage consumers to visit stores more frequently with the idea of ‘here today gone tomorrow’ which satisfies consumer’s desire for new, novel and pleasurable experiences, Campbell (2006).

Behind 'fast fashion' is a marketing machine that offers consumers lifestyle ideals if they buy into brands. This type of clothing is designed only to satisfy immediate needs. Consumers only have a short-term interest with garments of 'fast fashion', before feeling the need to seek the next fashion fix, and aspire to a new image of lifestyle, a new fashion trend and one that has been un-noticeably filtered into the subconscious via media outlets. Fletcher describes the phenomenon that is 'fast fashion' as 'Fashion eating itself'. She explains the fashion industry as becoming detached from both reality and key issues such as climate change, consumption and poverty, issues that she points out barely register their presence on high streets or catwalks, (Fletcher, 2007b).

As a design product, this type of clothing is not designed or manufactured to provoke and maintain a long-term emotional relationship with the consumer. It is designed to provide and entice, manipulating consumer experience of the emotional 'high' on making a new purchase without experiencing financial guilt on having spent an excessive amount of money. Nor, as a product, is fast fashion designed to be disposable. Fibres used in construction are often mixed and so cannot be easily recycled and the synthetic fibres used do not biodegrade. Fast fashion appeals to human vanity, providing consumers with an ability that can be compared to chameleons, to exhibit an ever-changing outward appearance and worldly identity.

Most discarded clothing could, in principle, still fulfil a design purpose. Emotionally, however, the items are not designed for consumers to form any long-term attachment with. Consumers of fashion and textiles have become conditioned to living within a culture of 'Want, Need and Greed'. They want more, yet more is never enough, constantly seeking satisfaction and status through the material goods that they consume. When living in a world full of insecurities, the consumer seeks reassurance through what they buy and ultimately what they wear. Fletcher (2007c) believes unwanted textile products are representative of consumer boredom and broken relationships. She explains that the emotional needs of consumers are temporarily met through the coming together of the fashion sector and clothing industry in the production of fashion clothes. However, no matter how many are consumed, physical goods cannot meet the consumer's psychological needs. The fast fashion model, in Fletcher's view, promotes short-term thinking as the consumer is never satisfied long term through purchasing physical goods, but their purchasing behaviour fuels resource consumption and generates waste.

For the modern consumer, breaking bonds and replacing garments to which they once attached emotions of love, desire, mystery, and fascination, is carried out increasingly without thought or conscious awareness or without any concern for the environmental impact caused both through the initial production and disposal stages of the garment.

2.1.3 Slow Fashion

Slow Fashion is more than the literal opposite of fast fashion. It is a term associated with sustainable fashion solutions. The slow fashion movement aims to address the ethical and environmental detriments of the fashion clothing industry. This slow movement can be explained as involving the repositioning of strategies of design, production, consumption, and use (Clark, 2008a). The "Slow + Design Manifesto" presented at the "Slow + Design" symposium in Milan in 2006 describes the slow approach to design as offering time to produce, appreciate, and cultivate quality (Clark, 2008b). The slow fashion movement is often paralleled with a similar movement in the food industry, which saw the trend to move away from 'fast food' to 'slow food' (organic food). Fletcher and Grose (2012a) explain that the slow food movement started out as a reaction to globalised, homogenised, fast food culture. The slow food movement is, as with slow fashion, more than simply the opposite of fast. Rather, it aims to reconnect people to their communities and bio-regions.

Slow fashion has been adopted by the fashion industry to offer new marketing angles for products and brands that have a historic heritage, are durable or of classic design. Marketing clothing in this way and opposing the products to fast clothing, thus offering apparent legitimacy to existing business models and conferring upon them a sense of ethics by implying that the normal cycle of trend induced change and consumption does not apply to their brand, was not what the advocators of the slow design movement intended. Fletcher (2010) explains, "While fast is the opposite of slow in language, in the context of slow culture, fast and slow are not in opposition. They are different worldviews, with different economic logic and business models, values and processes." Sahinin (2010) defines Slow Design as referring to responsible design with a long term view, i.e., design that minimises ecological footprints of fashion products, explaining that Slow Design is formulated through elements of design that involve slow processes with the aim to slow human economic and resource use.

2.1.4. Sustainable Design for fashion and textiles

When designing future fashion and textiles that aim to be sustainable, designers and product developers must make informed choices based not only on the aesthetic and tactile qualities of the fabrics but also on the environmental credentials of the raw materials being used. (Hallet and Johnston, 2010a). The challenge for the future is to think beyond the immediate creative and technical process that bring a product to life, and to be aware of the wider context in which the product exists. (Hallet and Johnston, 2010b)

To aid the design process, guidelines have been suggested that, if applied at the design stage, would support the development of sustainable products. Anastas and Warner (2000) lay out twelve principles for consideration by anyone wishing to source or work with fabrics that are considered to have an environmental impact, in their book, Green Chemistry: Theory and Practice. For the design of textile and clothing, four main principles may be taken from this list: prevention of waste, maximising energy efficiency, using renewable resources, considering end of life.

Dieter Rams, a product and furniture developer, questioned his own work in the early 1980s, asking himself, 'is my design good design?'. This led him to propose ten principles for good design (Kemp and Ueki-Polet, 2010). The ten principles are shown in Table 2.2:

Table 2.2 Dieter Rams' Ten Principles of Good Design

1. Good design is innovative
2. Good design makes a product useful.
3. Good design is aesthetic.
4. Good design makes a product understandable.
5. Good design is unobtrusive.
6. Good design is honest.
7. Good design is long-lasting.
8. Good design is thorough down to the last detail.
9. Good design is environmentally friendly.
10. Good design is as little design as possible.

SOURCE Kemp & Ueki-Polet, (2010)

Although developed for use within furniture and product design, these ten principles of good design are widely relevant and can be applied across all design disciplines to produce well designed products. It can also be questioned whether sustainable design is just good design.

2.2 Fashion and Sustainability

In recent years the vocabulary used within the fashion sector to describe garments designed with a positive ecological story has expanded. Language such as 'green fashion', 'eco fashion', 'ethical fashion' and 'responsible fashion' are all used to convey an impression of 'sustainable fashion'. The vast array of approaches represented by these terminologies reflects the complexity involved in integrating sustainability into the fashion and textile industry.

Generally, these terminologies are used to categorise the same type of garments, that is garments with sustainability credentials or ‘sustainable fashion’. However, there are subtle differences in their meanings. ‘Green fashion’ is a term that represents garments designed and manufactured with a specific environmental agenda. ‘Green Designed Fashion’ (Bierhals, 2008) provides examples of ‘green fashion’ where the focus is often on a single ecological process. ‘Eco fashion’ represents garments that are designed with the minimum amount of waste and maximum resource efficiency (Black, 2008; Black, 2012). ‘Ethical fashion’ is largely associated with clothing that has been manufactured taking into account human and animal ethics, particularly in association with labour conditions and material selection. ‘Responsible fashion’ or ‘conscious fashion’ is an updated, consumer-friendly term for ‘green fashion’, commonly used by retailers within marketing campaigns as a way of associating garments that exhibit specific environmental credentials within their design, for example, incorporating sustainable fibres.

It is becoming acknowledged, perhaps due to consideration of the many terms associated with sustainability in fashion, that completely ‘sustainable fashion’ does not yet exist and is presently being questioned as an oxymoron (Black, 2012). It is not just the enormity of the fashion and textile sector that makes the development of ‘sustainable fashion’ so complex but also the very nature of fashion. As an industry, fashion is driven by globalised mass production and consumption. However, as textile garments chosen to cover parts of the body are involved, fashion is seen as a social signifier of status, identity, belonging and difference (Simmel, 1971), and has become representative of the consumerist, materialistic culture of today’s society. Cultural theorist Joanne Finkelstein describes fashion as being a hybrid phenomenon, with a social, economic and aesthetic force situated at the intersects of economics, art, psychology, commerce and creativity, (Finkelstein, 1991).

In attempting to understand the complexities of fashion with the additional complexities of sustainability, the question may be asked: what would 'sustainable fashion' encompass? In 'Design for Sustainability', Fletcher (2013a) explains fashion for sustainability as being designed and produced with awareness for the systemic influences and complex interconnections between material, social and cultural issues across the long term. Theory and strategies concerning how 'sustainable fashion' could be developed are provided at length in the literature, together with research recognising areas within the fashion and textile industry where issues of sustainability could be addressed. The focus in these respects is mainly on materials, processes, distribution, consumers, disposal and ethics (Walker et al, 2013; Black 2012; Fletcher and Grose 2012 b; Gwilt and Risannen, 2011; Fletcher, 2008b).

In general, concern for resource consumption and the sustainability agenda within the fashion and textiles sector was relatively dormant until after the United Nations Earth Summit in Rio de Janeiro in 1992, when environmental concerns for the planet such as climate change were highlighted. The fashion and textile sector, like others, had to be seen to be addressing approaches for 'sustainable fashion'. Rather than contributing to the growing interest in the sustainability agenda, the sector largely used the issue of environmental concerns as a design influence (Fletcher, 2013b). As an approach to tackling these emerging environmental concerns in the 1990s, nature was used to inspire design collections, resulting in the portrayal of an image concerning how sustainable garments should look. The garments were made up using natural fibres, mainly cotton and wool, colour palettes were neutral shades of beige with hints of brown and greens, while white was used to represent the ideal of purity. Ironically, it may be argued that the processes involved in both harvesting these natural fibres and the preparation of fabrics were detrimental to the environment meaning that these garments were far from 'eco'. The result was an aesthetic for 'eco fashion', (Textile View, 1993).

For a period of time, this garment style became a fashion trend used to differentiate between other standard products so as to increase sales, with the consumer believing it to be a type of fashion with environmental credentials incorporated into its production. This clichéd idea of what sustainable fashion is and what it looks like has had lasting repercussions within the industry. Natural fibres, neutral colour palettes and nature-based imagery are still often assumed to convey ecological credibility by some ill-informed consumers (Fletcher, 2013c). The exception to this response in the 90s was the brand ESPIRIT who responded to the Rio de Janeiro summit concerns by designing and producing a collection that focussed on reducing the environmental impact of the garments produced through material selection, manufacturing and the use of fastenings, for example zips or buttons (Grose, 1994).

Recent years have seen growth in attitudes towards social corporate responsibility (SCR). As consumers become more aware of environmental concerns, retailers need to be seen to show an awareness of the environmental and ethical issues that their industry faces. In January 2007, Marks and Spencers initiated their CSR strategy 'Plan A because there is no Plan B' (www.plana.marksandspencer.com/about). M&S were the first high street retailers to rebuild their brand around sustainability issues. 'Plan A' re-strategized all aspects of their business to incorporate ethical and environmental issues into the business model. The UK government have made some attempts to take charge of fast fashion by funding research for the industry, for example

The University of Cambridge Centre for manufacturing who in 2006 published the report '*Well Dressed*?' Academic institutions within the UK are also responding with initiatives such as the Centre for Sustainable Design at the London College of Fashion, and supportive design networks such as the online resource 'Textile Toolbox' from research group, Textile Environmental Design (TED) based at Chelsea College of Art within University of the Arts London.

2.2.1 Defining Sustainability within fashion and textiles

To establish a definition of sustainable fashion, we firstly need to define and understand what is meant by the term 'sustainable'. Then, it is required to define what it is we are trying to achieve in using this term in relation to fashion and textiles. Sustainability is a complex system of social, environmental and economical considerations that, when joined together, overlap, and it is the overlaps that create sustainability. Sustainability is often visually represented using a Venn diagram, based on a group of overlapping circles, as shown in Figure 2.1.

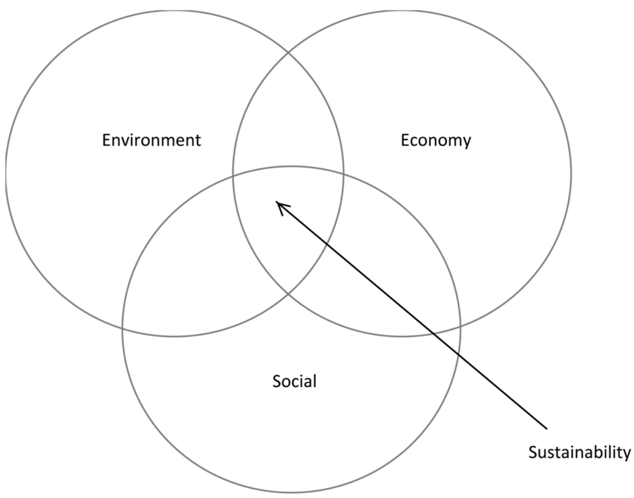


Figure 2.1. The Venn diagram representing sustainability

In defining sustainable fashion, an understanding of the term 'sustainable', and the context in which it is being used, need to be defined, so as to clearly communicate what it is we are trying to achieve in using this terminology in relation to fashion and textiles.

The literal definition for sustainable *(adjective)* is firstly something that is 'able to be sustained', and, secondly, (of industry, development or agriculture) avoiding using up of natural resources.' (Oxford English Dictionary, 2010a). The definition for fashion (*noun*) is firstly 'a popular style of clothes, way of behaving', and secondly, 'a way of doing something' (Oxford English Dictionary, 2010b). In using literal definitions, sustainable textiles and clothing could become a reality simply by turning it into a fashion, something that is popular, desired and essentially demanded by consumers. In aiming to achieve sustainable fashion, a mechanism for achieving it is required. Fashion and textiles have to be designed and so the design process can be used to incorporate sustainability. Design (*noun*) is defined as; "1. Plan or drawing produced before something is made. 2. The production of such plans or drawing. 3. Purpose or deliberate planning. 4. A decorative pattern." (Oxford English Dictionary, 2010c)

The literal definition for 'sustainable' has been presented in the opening discussion in this section, as the review of the literature is proving it to have become a word with many meanings. There are currently 70 definitions of sustainability (Farrer, 2011c; Holmberg and Sandbrook, 1992; Pearce et al, 1989). It is becoming a problematic term with increasing flexibility in the definition of its use, causing mounting confusion and misinterpretation away from a meaning which originates from sustainable development and stems from the 1987 World Commission on Environment and Development, Brundtland's Commission. The Commission defined sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al. 1987). Sustainable development is focused on human evolution within a social, economic and environmental paradigm. The social, economic and environmental resources are considered in relation to the impact of present and future generations. It is this same paradigm that sustainability fits within (Glavi & Lukman. 2007; Thompson, 2011; Farrer, 2011d).

Wood (2007a) expresses that 'the single term, sustainability, has mutated into a set of variations away from original environmental focus'. In his text, Wood continues to explain the original evolution of the term sustainability as having stemmed from the early 1970s 'alternative' agenda. This was an environmentally focussed movement fuelled by public alarm created during the oil crisis. A minority within society were, after this event in history, driven by environmental concerns to search for an 'alternative' approach, the alternative being life styles that moved away from the daily dependence and usage of the world's natural non-renewable resources. 'Alternative' was later replaced with 'sustainable development'. It was at this time in the mid 70s, that an individual engaged with environmental concerns was often immediately associated with sandals and lentils (Wood, 2007b). In terms of eco-design, this association has been hugely detrimental and difficult to shake off, as eco-design has failed to put aesthetic design at its forefront. Sustainable design has managed to not form such an association with the hippie stereotype, currently co-existing with mainstream industrial design, in a form of 'new design', that is 'more enabling, more approachable, more expressive and, consequently, more engaging' (Walker, 2006).

In addressing sustainability within design, designers are inspired to explore creative thinking in an attempt to improve the environmental impact of products from production through to life cycle and on to end of life. Thompson (2011) explains that in creating new systems for change, designers view this new form of design as an opportunity to re-think the way in which they design and produce. Hallet and Johnston (2010c) insist, when designing future textiles and clothing, that designers and product developers must make informed choices, not only based on the aesthetic and tactile qualities of fabrics but also on the environmental credentials of raw materials being used to create sustainable outcomes. They explain that future designers are challenged to think beyond the immediate creative and technical process of products and have an awareness for the wider context of the product's lifecycle.

There have been a number of specific initiatives to address the issues in the context of textile products, for example that they may be labeled as 'sustainable' if the raw materials originate from organic farming and if the manufacturing processes comply with ecologically and sociably acceptable production methods (Ganglberger, 2009). This statement, while well intentioned, is rather specific in that it may exclude other valid alternatives. In the context of the program of research presented in this thesis, the concept of sustainable fashion and textiles that has been adopted is that the essence of sustainability concerns 'learning to live in harmony with our planet and to take from it only what we are able to give back to it without causing detrimental damage', which is the author's modification of the original definition for Sustainable Development from the 1987 Brundtland report (Brundtland, 1987a). On the basis of this principle, textile and clothing designers are encouraged to incorporate environmental value into their design process, making informed choices based not only on aesthetic, tactile, and technical qualities, but equally on the environmental credentials of the materials and processes used (Hallet and Johnston, 2010c).

2.2.2 The Designer's role in sustainability

The fashion and textiles industry has been identified as a complex system, within which the designer has been identified as playing a crucial role in influencing the environmental impact of its products. Viktor Papanek first questioned the role of the designer in taking responsibility for products that they had designed and sent out into the world, debating whether designers should be held legally accountable for the environmental detriment caused through products that they had designed (Papanek, 1984). It has since been suggested that decisions made within the design process are responsible for 80 to 90% of a products environmental and economic costs (Graedel & Allenby, 1996). The estimate is regularly used to highlight the role of the designer and the design process, whether product design, design for manufacturing, design for environment/ecodesign or other design approaches in determining costs and impacts both financial and environmental throughout product life cycles. The idea that the design process can determine these costs was formalised in the Theory of Dispositions and is used by the European Union within the EcoDesign Directive (Directive/2009/125/EC).

The conclusion may be made that if designers make informed design decisions with regard to the environmental performance of chosen materials at the outset of the design process, then the environmental impact of final products may be greatly improved. This suggests a research focus on the need for designers to adapt the way in which clothing is designed, produced, used and disposed of, a life cycle approach, in order to significantly reduce the environmental impact of fashion clothing. Hence, academic research into fashion and sustainability in the last decade has involved an exploration of diverse design strategies, which have been widely discussed (Fletcher, 2008c; Fletcher and Grose, 2012b; Gwilt and Rissanen, 2011). Tools for designers have also been developed, Textiles Environmental Design (TED) based at the University of the Arts, London developed a 'toolbox' of ten design strategies (TEDS TEN) for designers, which explores both material process-based and conceptual approaches to sustainable design for fashion and textiles (Earley, 2007).

The TEDS TEN 'toolbox' identified the need for sustainability tools and strategies to cross the border from academic research into industry, to provide solutions and methods for designers working within industry. The toolbox presented in Figure 2.2, was aimed at both academic and corporate designers, demonstrating understanding of the profit focused constraints commercial designers work within. The objective of the ten cards that make up the toolbox was for them to be used by designers during the design process. Through engaging with any one chosen card and implementing the resulting knowledge within the product design process, designers were able to make small, low cost changes that when scaled up to commercial production volumes resulted in lowering the environmental impact of that product.

Figure 2.2. TEDS TEN by Textile Environmental Design research centre based at University of the Arts London, Source: http://blog.tedresearch.net/2013/04/23/new-the-ten-cards/

A research project lead by Jonathan Chapman based at the University of Brighton also aimed to engage and empower the corporate designer to reduce environmental impact of products at the design stage. Puma's '50 Ways of Thinking and Doing Sustainable Design' toolkit, a visual framework that enhances the social and ecological performance of products and processes was created from the research project, presented in Figure 2.3. The graphic for this toolkit was displayed on the studio walls of Puma's Global Design offices, to provide inspiration, support and guidance to designers and developers during the creative process (Chapman, 2013).

Figure 2.3. 50 Ways of Thinking & Doing Sustainable Design by University of Brighton researcher Jonathan Chapman, Source: arts.brighton.ac.uk http://arts.brighton.ac.uk/research/news/developing-sustainable-design-at-a-global-level

The method to provide designers with 'tools' to support sustainable design is an approach that can only be successful if industry supports and actively engages with such strategies. There is opportunity for Design management within industry to play a crucial role in developing future strategies and models that provide tools and methods to support managers, technicians and designers throughout the design process. If designers in industry were supported within a design management framework, fundamental change in how sustainability is addressed in the design and development process of new products could become part of all business strategies.

2.3 Fibre use within the fashion and textile industry

It is recognized that the environmental impact of the clothing and textile industry begins at the fibre production stages (Allwood et al., 2006a). Fibres fall into two main categories, natural and man-made. Natural fibres can be of either animal or plant origin; cotton, wool and silk fibres come from natural resources. Man-made fibres are either based on regenerated cellulose, such as lyocell made from sustainably farmed wood pulp, or synthetic fibres such as polyester, acrylic and nylon. Synthetic fibres such as polyester are produced using oil that is converted into polymers (Allwood et al., 2006f).

During much of the twentieth century, we have relied heavily on fibres that have a detrimental environmental impact, namely the natural cellulosic fibre, cotton, and the man-made synthetic polymer based fibre, polyester. Polyester production is heavily reliant on the naturally-occurring non-renewable resource, oil. (Hallet and Johnston, 2010c). Fibres provide the foundation for the fashion and textile industry. The majority of fashion garments are constructed using fabric that is made from yarns spun from fibres. Globally, the demand for textile fibres is increasing with two fibres dominating the market place - cotton and polyester, together accounting for 80% of the global textile market (Fletcher, 2008b). Demand for polyester has doubled in the last 15 years (Ferrigno, 2012a), thus overtaking cotton as the most popular textile material.

Traditionally fibres were categorized as natural staple fibres, man-made filament fibres from cellulose (regenerated) or synthetic from petrochemical sources, or natural staple fibres. Natural fibres are fibres that exist in their natural state as either plant-based cellulosic fibres, animal-based protein fibres, or mineral fibres (Wilson, 2011). Concerns over diminishing oil reserves, which impact on the availability and price of petrochemical-derived (synthetic) fibres, and growing awareness of the pollution caused by the need for chemicals, such as fertilizers and pesticides, and also the extensive use of both arable land and fresh water during the production of cellulosic and protein fibres (Ferrigno, 2012a), have driven research into the investigation of alternative sources and methods of production for fibres. Developments in this area and the launch of alternative fibre types within the commercial market have required an expansion in the way that fibre types are categorized, especially by designers. The category of man-made fibres includes not only the traditional synthetic polymers but also a section for natural polymers, of both animal and vegetable origin that involve an element of synthetic processing. This latter sub-category has been proposed as encompassing lyocell, although it differs from other regenerated cellulosic fibres, such as viscose, in that it does not involve any chemical conversion (Ferrigno, 2012),

The technical developments that have been achieved in the area of more resource efficient fibre production have resulted in one of the main areas for innovation within sustainable design for fashion and textiles being to focus on the wider choice of fibres available within the design process for garment production (Fletcher 2010; Fletcher & Grose 2012; Gwilt 2014; Gwilt and Rissanen, 2011). The innovation and availability of more sustainable fibres has driven this focus for designers in accordance with research opinion that environmental impact of fashion garments can be significantly reduced through the choices of materials made by the designer at initial stages of the design process (Olesen, 1992a).

Fletcher & Gross (2012c) acknowledge the many reasons why the factor that they refer to as materials choice in fashion design has experienced the lion's share of the focus in terms of sustainability. Among these reasons, they offer an anthropologic argument. They place emphasis on the role played by materials in communicating or representing the perceived ideals of what 'eco' fashion looks like. Consumers are confused over the nature of the environmental impact factors in producing textiles, in terms of what materials are deemed to be sustainable, with natural perceived to be ‘good’ and man-made ‘bad’.

2.3.1 Cotton

It has been established that fibre selection is of prime importance in the design of a textile product, in ensuring not only the desired qualities but also in determining the environmental impact. Currently cotton is by far the most important natural fibre, in terms of being the natural fibre most used and in highest demand within the clothing and textile industry (Ferrigno, 2012a). Cotton is produced in 80 countries, its cultivation occupying much of the earth’s land area and using significant amounts of fresh water resources. It was estimated that between 2012 and 2013 the area of arable land used to farm cotton was 33.3 million hectares, equivalent to 2.5% of globally-available arable land, i.e., land primarily suited for food crops (Ferrigno, 2012a). The cotton industry employs 100 million farmers providing employment for 250 million people in the fibre industry and sustains a $353 billion textile industry (Ferrigno, 2012b). Though important to the global economy, cotton production presents many challenges in terms of environmental sustainability. Most prominently, its cultivation has traditionally required the use of large areas of arable agricultural land, large quantities of water, and high levels of pesticides, insecticides, fungicides and herbicides. Although this needs to be balanced against a variety of initiatives that have significantly improved its environmental profile in recent years (Ferrigno, 2012c).

Methods for reducing the environmental impact of cotton production are being incorporated by the industry, thus opening up the market to materials derived from alternative methods of production, such as low-chemical cotton and organic cotton.

However, these more environmentally responsible approaches to cotton production need to be developed further and their use expanded within the industry, and to become part of 'best practice'.

Though cotton has been highlighted for its adverse environmental impact, it is also important to recognize that it is a huge economic driver. Both academic and industry opinion agree that cotton should not and cannot be replaced within the market, but that what is needed is for conventional cotton production to be developed into a more responsible industry with more resource-efficient fibres used both in cotton blends and as alternative fabrics (Fletcher, 2008c). A factor that must be considered is that cotton is currently regarded as at its maximum level of production in terms of arable land used for farming (Ferrigno, 2012d) and that, with a growing global population, demand for cotton will at some point in the future outweigh supply. Thus, there is a strong argument that alternative production methods for 'sustainable' fibres need to be explored in meeting the future demands of the industry.

2.3.2 Lyocell

Lyocell fibres are sourced and inspired by nature. Their production is based on botanical principles. Biological degradability is a feature of the nature of the fibres being produced ensuring a natural life cycle demonstrated in Figure 2.4.

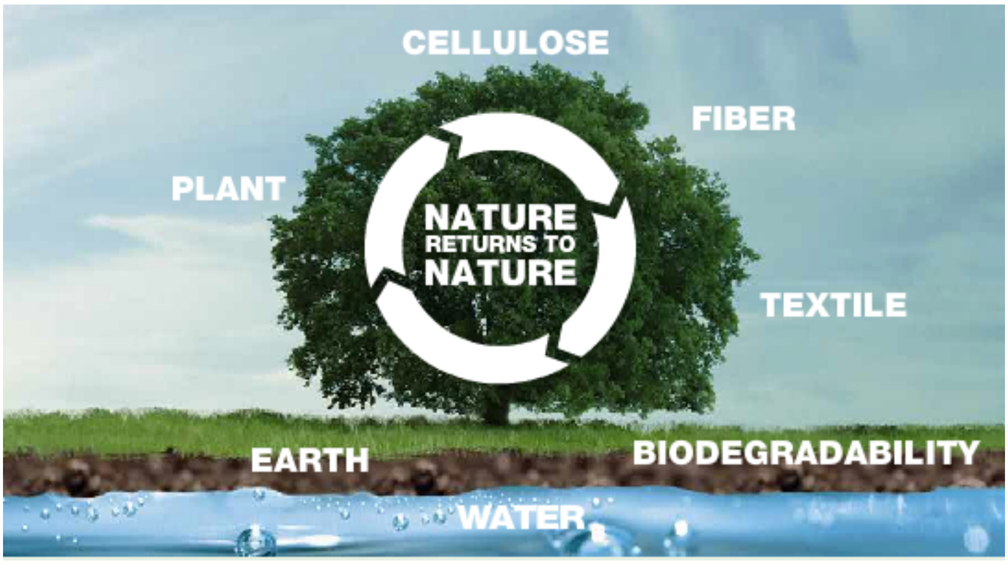


Figure 2.4 The Lenzing fibre life cycle: Source: Lenzing, 'Nature returns to Nature', (online), (accessed 20th January 2012)

Lyocell is a commercially available 'sustainable' alternative for cotton, marketed as **'**Tencel**'** by the manufacturers, Lenzing AG (Austria). Lyocell is a regenerated cellulosic fibre that has strong environmental credentials (Taylor, 1998; Mather & Wardman, 2011a). The manufacturing process uses, as its raw material, wood pulp derived from eucalyptus species, particularly *Eucalyptus Grandis, Urophylla, Nitens and Dunnii*, all of which are hybrids. These species are farmed on land described as **'**marginal**'**, i.e., unable to sustain agricultural crops. They are fast growing and have low requirements for water and pesticides.

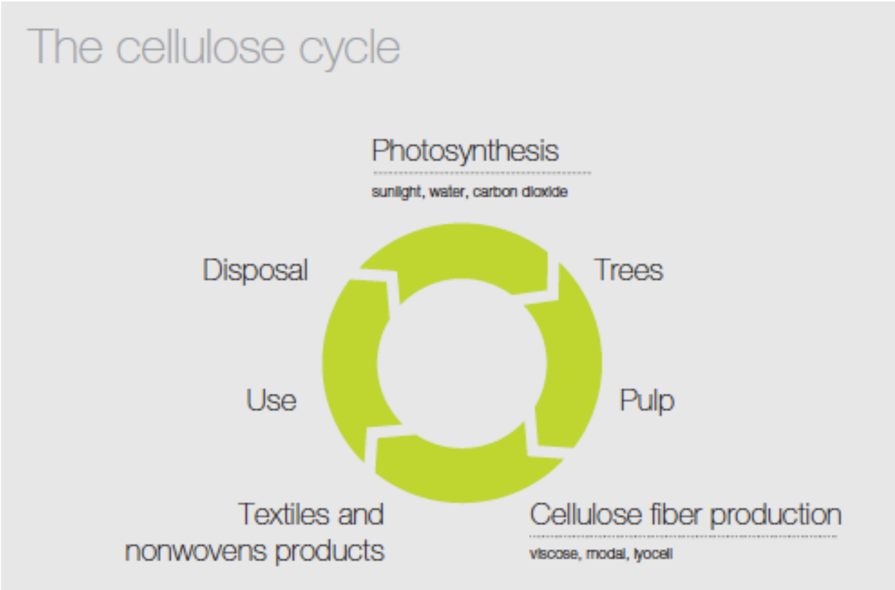


Figure 2.5. The regenerated cellulose life cycle: Source: Lenzing, Focus Sustainability Report, Sustainability in the Lenzing Group, 2008, page 41

The manufacture of lyocell involves dissolving the pulp in N-methylmorpholine-N-oxide (NMMO) containing a small amount of water. The fibres are formed by a dry-jet wet spinning process in which the viscous, concentrated solution of cellulose is extruded through a spinneret into a water bath. The solvent, which is claimed to be essentially non-toxic and biodegradable, is recovered at a rate of 99.5% (Mather and Wardman, 2011b). Unlike other regenerated cellulosic fibres, such as viscose, there is no chemical conversion involved, and the cellulose content of the pulp used to feed the lyocell process remains chemically unchanged in the final product.

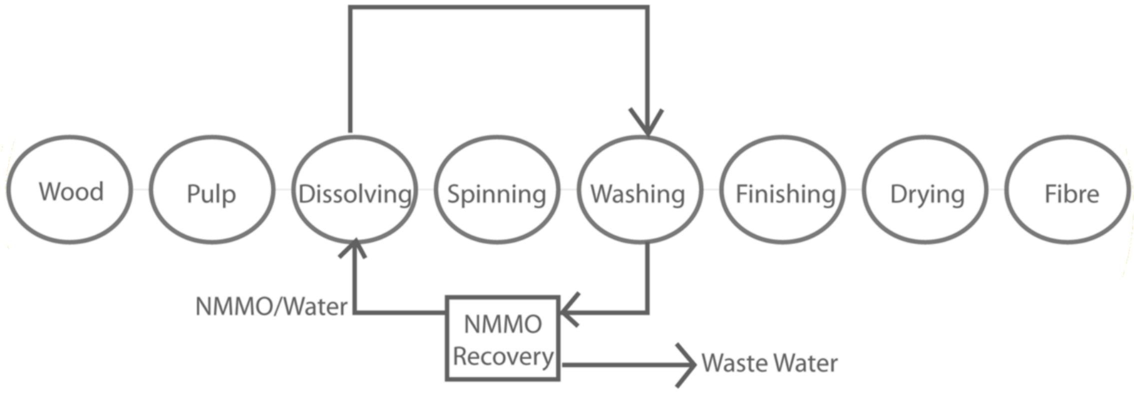


Figure 2.6 The Lenzing closed loop Lyocell Process developed from source: Taylor, J.M. (2010) Reducing the Textile Environmental footprint with Tencel.

Lenzing explain a major advantage in the use of the eucalyptus plants, in comparison to cotton farming, as their ability to be planted and grown on marginal land that is unsuitable or unable to be used for the production of plants used for food production. Also, no pesticides or water that requires an irrigation system are used in the cultivation of Eucalyptus, contrasting with the situation with cotton. Another important comparison between Tencel and cotton is the fibre yield. According to figures provided by Lenzing, the fibre yield for Tencel is 10 times higher than that of cotton; this effectively means that one T-shirt made from cotton can be produced from approximately $6m^2$ of soil, as compared with ten t-shirts from Tencel. To farm eucalyptus for Tencel production requires significantly less land than that needed for cotton farming, it is suggested that up to 70% less acreage per 1 tonne of fibre is required (Shen & Patel, 2010).

The lyocell fibre used in the study described in this thesis is produced by Lenzing AG. Two types of fibre are produced: standard Tencel and Tencel A100. Tencel A100 differs from standard Tencel in that it is prepared using a treatment with the crosslinking agent, trisacryloylhexahydrotriazine (TAHT). The open fibre structure of Tencel A100 has been found to have a positive influence on its dyeing performance making it of particular interest and relevance for the aims of this research.

2.4 Colour for fashion and textiles

2.4.1 Colour use within fashion and textiles

Fletcher and Grose (2012) suggest textile coloration is one of the most important elements in the commercial appeal of fashion products. They explain this is due to colour providing designers and manufacturers with the ability to rapidly change the appearance of products and garments to the consumer, which, leads to additional purchases. Colouring textiles is a complex, technical and resource intensive process requiring extensive use of water, energy and chemicals.

Colour can be applied at fibre, yarn or fabric stage. Each fibre type has an affinity for a particular type of dye, and various colours and shades are achieved using differing dye sub-classes within the category of dye that is recommended for use with the particular type of fibre. However, auxiliary chemicals are also required to increase this affinity, in order to maximize the uptake of dyestuff by fibres.

The global textile industry uses more than 700,000 tonnes of synthetic dyestuff each year (Hardin, 2007). Depending on the particular dye class used, the percentage of dye that remains unfixed to the fibre during the dyeing process and subsequently finds its way into the dyehouse effluent, ranges from 5-50% (Hardin, 2007). Colour is the most immediately visible feature in the design of fashion and textiles. It is often the main aesthetic concern for both the designer and consumer and can be the reason for financial success or failure of products within the market place. The main motivation for the use of colour within design is to create desirable aesthetics, to ensure the commercial appeal and financial success of the product. Designers commonly demonstrate only a limited understanding of, or regard for, the environmental impact caused by the production of colour and its application to textiles.

There are two broad sources of chemicals, which may be used to create colour for textiles: natural and synthetic. It is a common misconception to presume that natural inevitably means good and synthetic bad in terms of its effect on the environment. Natural dyes were the only source of colour up until the mid 19th century, when the development of synthetic dyes began (Cardon, 2007a). The lower cost, better reliability, reproducibility, and larger scale of operation that was achievable with synthetic dyes, together with the development of new technologies that have taken place over the years, have meant that the traditional processes used for natural dyeing and knowledge and experience of the methods have been largely eliminated.

2.4.2 Natural Colour

Imagine a world where cloth has no colour. Throughout history, cultures from the world's civilizations have developed methods for colouring textiles using natural dyes extracted from locally available resources provided by the environment in which these cultures existed. For example, plants, insects and shellfish have all been exploited for their colour-providing qualities. (Cardon, 2007b). This method of coloration has been termed 'natural dyeing'.

Up until the development of synthetic dyes in the late nineteenth century, natural dyes were the only source of colorant used for everyday textiles, leather, fur, hair and feather, and they were also components of the pigments used for painting. Natural colorants were also important in the colouring of food, cosmetics and medicine. (Cardon 2007c).

Cardon, (2007) explains that it was the fascination with colour production and the need for understanding of what was happening during dyeing processes that drove the research of 18th and 19th century chemists such as Claude-Louis Berthollet (1748-1822), Michel Eugene Chevreul (1786-1889), August Wilhelm von Hofmann (1818-1892) and William Henry Perkin (1838-1907). It was this research that eventually led to the invention of synthetic dyes. Synthetic dyes dominated over the use of natural dyes within a short period of time after their invention in the early nineteenth century, largely for economic and technical reasons.

The opinions of designers and technologists are split on the environmental sustainability of natural dyes. It is argued in some literature that natural dyes offer environmental benefit compared with synthetic dyes, in terms of cultivation from renewable natural sources, biodegradability and low toxicity, but it is noted that their use is not completely free of environmental impact (Glover, 1998).

One of the main issues with natural sources of colour is cultivating the quantity demanded by the modern fashion and textile industry. The cultivation of plants specifically for the production of natural dyes would require the use of a significant area of arable land, for which food production is a higher priority. In addition, natural dyeing of textiles commonly requires treatment with a mordanting agent, usually a metal salt, to fix the dye to fibres as many natural dyes have little direct affinity for fibres, and this mordanting process has inevitable environmental consequences (Bechtold & Mussak, 2009a). Commonly, natural dyes also show inferior fastness properties, limiting their suitability for use on textiles, especially for fashion. In aesthetic terms, the range of colours and depth of shades that are capable of being produced from natural dyes is limited, and in no way comparable with the rainbow of possibilities achievable from the use of the modern range of synthetic dyes.

Re-investigations of natural dyeing processes aiming to address some of these negative issues (Bechtold et el, 2003) propose that, in striving to achieve sustainable colour, we must re-consider the use of renewable resources for textile coloration, and in doing so incorporate the aim towards a future zero waste, zero emissions society. The development of agricultural production of plants used purely as a source of colour, and the use of the currently established methods both for extraction of natural colour and its application to textiles do not provide alternatives to dyeing with synthetic dyes that are necessarily sustainable or environmentally responsible.

It has been suggested previously that 'the perfect t-shirt', in terms of sustainability, would be constructed from unbleached, undyed organic cotton (Black, 2012). While there is technical and social justification for the conclusion from this study (Gwilt & Rissanen, 2011a), the removal of colour from the process of design for textiles is arguably unsustainable from a design perspective, based on the very nature of design. After all, how desirable can beige be? It is questionable as to whether the plain light beige 'eco-fashion' look would appeal widely to both designers and consumers who have higher expectations in terms of colour. This approach to colour prioritizes environmental concerns over aesthetic value.

Within modern industrial processes for the coloration of textiles, natural dyes are used only in specific niche markets. In October 2008, San Francisco based designer Casey Larkin launched the 'eco-fashion' label Mr. Larkin, with the ambition of creating sustainable fashion that stood apart from the previous stereotypical look for this fashion genre. Larkins spring collection from 2010 incorporated an array of alternative fibres such as soy, organic bamboo, milk fibre and cupro sateen (made from cotton by-products) and sourced recycled or vintage pieces for embellishment. The feature that is of most interest to the research aims in this thesis is the source chosen for coloration. Larkin collaborated with Berkeley textile artist and founder and co-director of Permacouture Institute, Sasha Duerr to create a muted colour palette of pastel hues that were locally-made from plants and vegetables. From its original launch, Mr. Larkin has moved away from natural dyes, now stating that they are a source of inspiration rather than the method used for coloration. The brand has become a hub for ethical designers selling their garments and accessories online, rather than as previously portrayed.

The fundamental difference between synthetic and natural colorants is found in the chemical make up. Synthetic dyes typically, though not always, consist of a single colouring molecule, whilst natural dyes result from a synergy involving different colorants that can belong to different chemical groups existing in the same plant, mollusc or insect. It is this chemical make up that gives natural dyes an unequalled richness and subtlety in the shades of colour produced, making them instantly recognizable against synthetic dyed textiles (Cardon, 2007c). The main concern when using a natural colorant to dye textiles is the problematic nature of the colorants being made up of groups of molecules which often have a weak affinity with textile fibres, thus creating very poor fixation levels. To overcome this deficiency, the additional use of another substance is required, a 'mordant', to help 'fix' the colorants to the fibre. (Cardon, 2007).

In her book 'Natural Dyes Sources, Tradition, Technology and Science', Dominique Cardon expresses the importance of good practice in the use of natural dyes to prevent ecological damage through practical experimentation with colorants derived from species that are today rare. "As a general rule, it is better to begin experimentation with dye-plants that are either cultivated or, if wild, very common or destined to be destroyed". (Cardon, 2007) Increased awareness surrounding the world's diminishing natural non-renewable resources has created debate amongst scientists as to how much longer fossil fuels will be available for use with opinions ranging from fifty to five hundred years. However, it is agreed that the reserve is limited and essential research into new energy and material sources is required. (Bechtold & Mussak, 2009b).

2.4.3 Synthetic colour

The dyes currently used for the industrial coloration of textiles are almost exclusively synthetic products of the chemical industry, manufactured from finite, non-renewable petrochemical sources (Christie, 2001a). Application of these synthetic dyes to textiles generally involves intense use of chemicals, water and energy, with inevitable environmental consequences (Bide, 2007). Natural fibres such as cotton have good permeability, while synthetic fibres such as polyesters are much harder to penetrate due to a higher crystallinity (Cegarra *et al.,* 1992). For this reason, dyes are categorized into specific groups for coloration of specific fibres. To support uptake of dye to fibre chemical auxiliaries are often used and the rate of fixation varies between fibre and dye categories; any unfxed dye to fibre will be lost in the effluent (Perkins, 1996).

2.4.4 Reactive Dyes

Commercial reactive dyes vary in complexity and molecular size. Hunter and Renfrew (1999a) explain they can contain one, two and (rarely) three chromophoric units with up to three different reactive groups. It is the range of chromophores (colour-forming entities) used in the molecular structure of reactive dyes that give this group its significant advantage in the scope of colours that are achievable on cellulosic fibres with the use of only one type of dye (Gutjahr and Koch, 2003a).

For both dyeing and screen printing of fabrics, the same mechanisms of dye fixation apply, meaning that, in principle, a dye used to produce a plain coloured fabric can also be used to print on to this same fabric (Gutjahr and Koch, 2003b). Printing, however, is problematic in that not all the fabric is covered, and unprinted white ground can be left exposed as part of the desired design. It is important, therefore, in textile printing that the fixation and hydrolysis processes involved in reactive dyeing proceed to completion so that no dye in reactive form is left to stain the white ground (Gutjahr and Koch, 2003c).

Reactive dyes fix to the fabric by forming a covalent bond between the fibre and dye (Gutjahr and Koch, 2003d). The stability of this bond for the type of reactive dye being used must be considered in the finishing process. Too long a time under the hot alkaline conditions, which are required for fixation, will lead to a reduction in colour yield. Levels of fixation are important both economically and environmentally; unfixed hydrolysed dye must be removed thoroughly through washing off stages.

Gutjahr and Koch (2003), explain that one successful approach to obtaining significantly higher fixation levels has been to build two reactive centres into each dye molecule, aiming to increase the probability of reaction with fibre, and leading to fixation levels of about 90%, rather than the levels of around 70% that are normally achieved. This, in consequence, reduces by about two-thirds the amount of hydrolysed dye that is required to be removed by a wash off process (Gutjahr and Koch, 2003c).

2.4.5 Colour and the Environment

Current opinion within the research community is increasingly concluding that all methods of coloration of textiles have environmental consequences (Better thinking, 2006). The current systems for introducing colour must be considered as unsustainable over the longer term. This leads to the fundamental questions; how would we produce colour without the use of chemicals derived from fossil fuels? - what happens when reserves run out?

The use of renewable resources for textile coloration requires the development of agricultural production of plants used purely as a source of colour, and the use of the currently established methods both for extraction of natural colour and its application to textiles do not provide alternatives to dyeing with synthetic dyes that are necessarily sustainable or environmentally responsible. The use of land to farm colour for textiles would require water and chemical resources as well as agrile farming land to farm colour rather than food for a growing population. Current commercial methods of extraction of colour from the plant sources use synthetic chemicals within extraction methods and required vast amounts of energy. Application of natural dyes to substrates require an additional mordanting process; the mordants used, though often natural, present additional environmental impacts as with the dye sources themselves through extracting from the natural source. The typically poor technical performance of natural dyes when applied to textiles, these being, poor light, wash and rub fastness suggests fashion and textile products produced from natural dyes have a shortened 'use' stage within the life cycle, as opposed to those produced with synthetic dyes which have superior light, wash and rub technical performance.

CHAPTER 3. Methodological Research Framework

3.1 Introduction

This chapter presents an overview of the way that the methodological approach to the research has been designed and implemented. The various methods used to explore reducing the environmental impact of coloured fashion and textiles are discussed, the interdisciplinary relationship is presented and methods for integrating technical information to inform the design process explained. Further details of methods used for specific aspects of the investigations are described as appropriate in the individual chapters that follow.

The principal aim of this research was to address reducing the environmental impact of coloured fashion and textiles. The research could, in principle, focus either on the technical performance of materials as a scientific study or on the design process and practice leading to products through a creative practical study. However, in undertaking research to reduce environmental impact, it has been recognized that there is a need for an interdisciplinary approach to the research (Repko, 2008). Through integrating scientific approaches with research from other disciplines, it is suggested that the potential for identification and implementation of initiatives that would reduce environmental impact is enhanced. With this in mind, and to reinforce the observation that there has been little interconnected research activity focusing on sustainable coloured fashion and textiles, the methodological research framework developed for this study takes an interdisciplinary approach to unite two separate disciplines in developing research solutions for enhanced sustainability of coloured fashion and textiles.

The technical inquiry involving relevant aspects of coloration technology was thus interwoven within the creativity of the design process, aiming to minimize, ideally to prevent, environmental impact of coloured fashion and textiles through how they are designed and produced. The research outcomes provided through the implementation of this research approach have resulted from investigations of an exploratory, inquisitive and creative nature, underpinned with technical understanding. It is the collaboration of the two disciplines that has led to the practical, physical outcomes of this study, in parallel with an assessment of the technical performance, in terms of reducing the environmental impact involved in producing the creative samples. This approach provides the design outcomes from the research with firm technical foundations from which conclusions can be drawn.

3.2 The Research Framework

3.2.1 Interdisciplinary Research

Interdisciplinarity emerged as a methodological approach to research in the 1960s and 1970s (Thompson & Klein, 1990a). Interdisciplinary research involves the crossing of boundaries between two separate disciplines to discover new knowledge that is not restricted within the limits of any one discipline. Thompson, Klein and Newell (1997) define it as a process of answering a question, or solving a problem that is too complex to be addressed by one single discipline, through the practice of integrating several disciplinary perspectives and contributions. Darbellay et al (2014) summarizes it as uniting specific disciplines in relation to a common objective. Berger (1972) defines interdisciplinary as an interaction among two or more different disciplines that incorporates the communication of ideas, the integration of concepts, methodology, procedures, epistemology, terminology, data and the organization of research. An interdisciplinary research group is described by Berger (1972a) as consisting of individuals trained in different disciplines of knowledge working together with continuous intercommunication to address a common problem from the different disciplines.

An overview of recent publications on interdisciplinarity demonstrates evidence of the theoretical and practical advances made in this field and the value placed on interdisciplinarity as a methodological approach for research as, for example, in the 'Oxford Handbook of Interdisciplinarity' (Frodeman, et al.,, 2010), 'The Handbook of Transdisciplinary Research' (Hirsch, Hadorn et al., 2008) and 'Interdisciplinary Research Process and Theory' (Repko, 2008). Within the literature, a dialogue of terminology has developed to categorize the degrees of interaction and integration between disciplines, for example, *interdisciplinary, multidisciplinary*, *and transdisciplinary* (Huutoniemi et al, 2010; Thompson & Klein, 1990). *Multidisciplinarity* addresses a theoretical or practical problem incorporating two or more unconnected discipline viewpoints in succession, without any interaction occurring between disciplines. *Interdisciplinarity* unites two or more disciplines, whereby the disciplines interact to analyze and understand the complexity of a practical or theoretical research problem (Darbellay et al, 2014a) *Transdisciplinarity* is a knowledge process transcending and crossing disciplinary boundaries requiring the reconfiguration of disciplinary divisions. Clark (2002), presents transdisciplinarity as a research procedure that takes on board political, social, and economic factors in problem-solving research. Robinson (2008), explains it as issue-driven research.

The strength of interdisciplinary research and the reasoning for its use within this research framework is the diversity of knowledge and expertise that can be explored in addressing complex research problems that are beyond the realms of individual disciplines.

3.2.2 The Interdisciplinary Research Process

Methods of mapping the interdisciplinary research process have been developed to help identify disciplinary competencies so as to establish a research dialogue between separate disciplines. Graphical representations of varying degrees of complexity have been developed to demonstrate visually the process of collaboration between disciplines. Repko's (2006) summarizing statement which draws mainly on the work of Thompson Klein (1990), Szostak (2002), and Newell (2007) was used within this research.

Table 3.1. Repko's Integrated Model of the Interdisciplinary Research Process

A. Drawing on disciplinary insights

1. Define the problem or state the focus question
2. Justify using an interdisciplinary approach
3. Identify relevant disciplines
4. Conduct a literature search
5. Develop adequacy in each relevant discipline
6. Analyze the problem and evaluate each insight into it

B. Integrating insights and producing an interdisciplinary understanding

7. Identify conflicts between insights and their sources
8. Create or discover common ground
9. Integrate insights
10. Produce an interdisciplinary understanding of the problem and test it.

Developed From Source: Repko, 2006a; Repko, 2008a

Repko provides a formulation of the different stages for the interdisciplinary research process describing each stage as given in Table 3.1; it is the logic of this formulation that is the reason why this approach was used initially to inform the framework developed within this study. Repko (2006, 2008) identifies ten complementary stages for the interdisciplinary research process, divided into two phases A and B. Phases A and B are organized around the definition of the problem and disciplinary insights, leading to the integration of these insights within the separate disciplines and a general understanding of the problem.

The interdisciplinary research process presented by Repko, illustrated in Figure 3.1, is a logical linear progression in linking stages 1 to 10 (as identified in Table 3.1) with the overall aim being to establish an interdisciplinary understanding of the complex question or problem being addressed through the research.

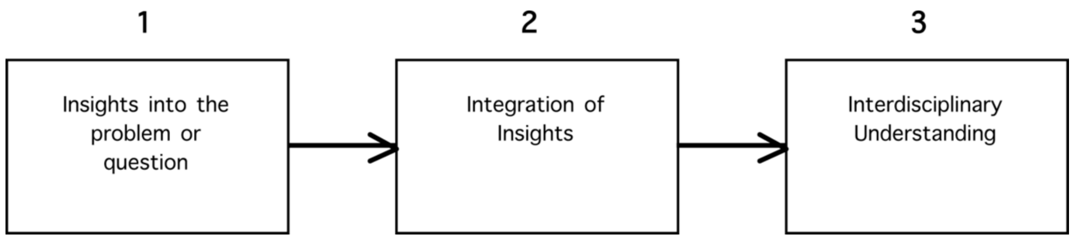


Figure 3.1. Repko's Interdisciplinary Research Process. Source: Repko, 2008b

Although the interdisciplinary research process is presented as a linear model, it contains the potential for feedback, interactivity, and negotiation mechanisms to introduce flexibility into the process. A standard research process can then be established and followed that involves formulation of the problem, development of research questions and hypotheses, methodological choices, and analysis and interpretation of results. The interdisciplinary research process is then divided into stages that are firmly established aiming towards the solving of a problem through explanation and understanding. Following Repko's linear structure in this way aims to achieve 'interdisciplinary understanding' within the researcher(s) involved, but does not recognize or aim to provide the researcher(s) with 'interdisciplinary knowledge' that can be acquired during the process.

The researcher observed that it is through the interaction within the 'space between' disciplines that new methods of working and innovative solutions for sustainability could potentially be developed, through the researcher developing technological understanding of the environmental consequences for design decisions made. It is the 'interdisciplinary knowledge' acquired by the researcher from working within this inter-discipline space during the research process that is required to inform the development of new methods of working and innovative solutions for sustainability to be developed. The interdisciplinary research framework developed for this thesis therefore was required to support the researcher in developing interdisciplinary knowledge through working within the space between the disciplines on which the research is focused.

3.2.3 Interdisciplinary Research Model; a Methodological research approach formulated based on Design and Science

Interdisciplinarity within the research presented is based on a cross discipline relationship formulated to explore the common problem, namely reducing the environmental impact of coloured fashion and textiles on the basis of individual disciplines. However, as explained, this common issue cannot be addressed in a completely satisfactory way from a single discipline, but rather requires the uniting of separate disciplines to allow a coherent research language and structure to develop, aiming to solve the common problem between the separate disciplines from a new interdisciplinary perspective.

In developing a logical interdisciplinary framework for the research methodology appropriate to this study, the creative and intuitive nature of the design process and creative experimentation was required to be interwoven within the factual nature of the science, established by technical experimentation to create an iterative loop in which one stage informs another. This framework was essential to establish interdisciplinary knowledge for both the researcher and research outcomes. The process developed is presented in figure 3.2. mapped onto Repko's Interdisciplinary process presented in figure 3.1. A 'mixed methods' framework was therefore developed incorporating quantitative and qualitative research, supported by tacit knowledge. The study followed the traditional foundation for research design to fit in with the process of interdisciplinary research, and the requirements of Repko's Integrated Model of the Interdisciplinary Research Process. The research was initiated by a literature review, presented in Chapter 2, before progressing on to conducting quantitative data collection through experimentation as described in Chapter 4 and qualitative research presented in Chapter 5. These stages of research were used to draw technical conclusions that through critical reflection and technical analyses informed the designer and the design process, as collated and presented in chapter 6; tacit knowledge was also used to inform the design of garments that were constructed to test the research processes and methods developed throughout the study.

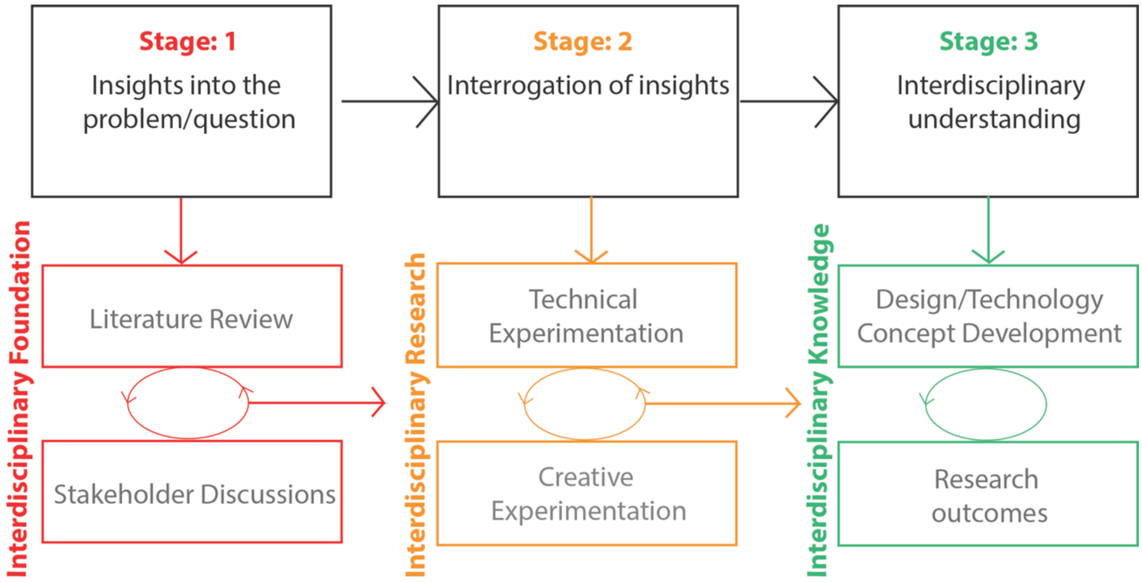


Figure 3.2. Interdisciplinary Research Process developed for this study. Mapped against Repko's model presented in figure 3.2.

3.3 Formulating the Interdisciplinary Relationship

Life cycle thinking was used to create the foundations of this research. The 'Eco Design' element of the design process incorporated Life Cycle Assessment data to map the areas of highest environmental impact caused in producing coloured fashion and textiles. The information gathered and presented in the following section 3.4 at this stage highlighted the optimum discipline collaboration; integrating textile coloration and technology with fashion and textile design also representing the three key areas of focus for the research: Fibre, Coloration, Design.

3.4 Research Methods

3.4.1 Ecological Design/Eco-Design

Designing products with the specific goal of reducing the environmental impact caused through their production requires the designer to be responsible for the environmental consequences of materials and processes used for manufacture as they relate to specific decisions made during the design process (Lewis et al., 2001). To design with environmental performance as a chief goal for the designer is a method categorized as ecological design, also referred to as eco-design.

Ecodesign identifies areas within the product lifecycle of high environmental impact, also known as 'hotspots'. It is suggested that implementing eco-design at the initial design stage of products and processes can reduce environmental impact by up to 80% (Graedel and Allenby, 1998). The primary objective of the research described in this thesis is to reduce the environmental impact in producing coloured fashion and textiles, and so the research presented adopted an eco-design method. Eco-design is a sustainable design approach for processes and products that incorporate lifecycle thinking into the design process, whereby the designer is consciously aware of the ecological impact of products that they are designing for production throughout their whole lifecycle from manufacture to consumption (Chick & Micklethwaite, 2011). A consideration of the whole lifecycle was an important feature within this study, which meant that the design process started from the fibre and incorporated the end-use and end-of-life stages, including re-use or recycling considerations. Designing within the whole lifecycle allowed the identification of key stages of environmental impact caused by the production and consumption arising from the design outcomes, and highlighted areas for interception aiming to reduce the environmental impact of final products. Environmental considerations were integrated into design decisions, including material and process choices that aim to balance aesthetic and environmental value without sacrificing one for the other.

The research used reported lifecycle assessment data (Shen & Patel, 2010) which measure the use of chemicals, water and energy, to identify key areas within the lifecycle of coloured fashion and textiles that cause environmental impact. Once identified, the 'hotspots' within the production stages of coloured fashion clothing became the focus for this research. The 'hotspots' where mapped onto the production process of coloured fashion and textiles by the researcher, presented in figure 3.3. then incorporated within the research process and also used to inform the interdisciplinary relationship, illustrated in figure 3.4. At the creative stages within the design processes technical experimentation investigated reducing the environmental impact within these 'hotspots', this information then informed the design decisions made, to provide points of interdisciplinary intersection within the lifecycle and providing innovative outcomes. Traditional materials and process choices were replaced as judged necessary, and alternative options explored whereby design decisions were linked to environmental performance based on selection of the fibre and coloration processes, forming an iterative loop.

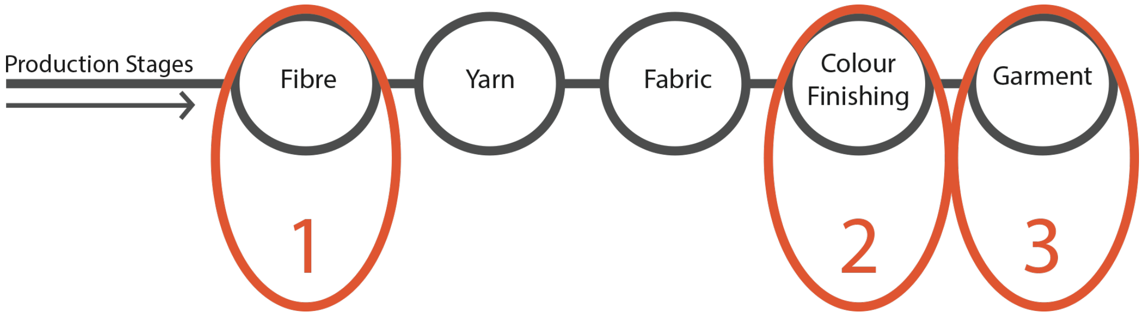


Figure 3.3. Life Cycle Production Stages Hotspots

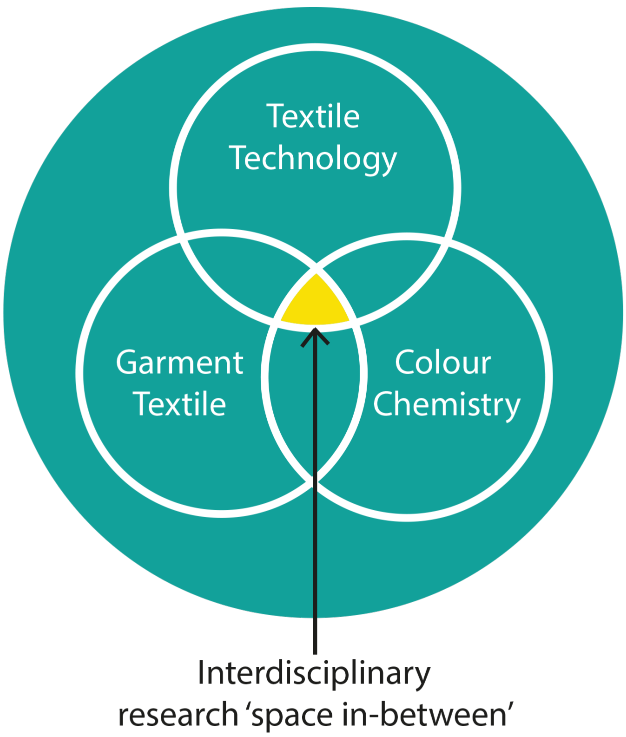


Figure 3.4. The interdisciplinary relationship 'Space in-between'

3.4.2 Sustainable Design

The design stage has been identified as decisive in determining the environmental impact of a product over its lifecycle (Baumann et el, 2002). The design process offers an intervention point for identifying areas, within a product lifecycle, which cause the greatest impact on the environment, and this then leads to the implementation of changes that will allow environmental goals to be achieved (Graedel and Allenby, 1998; Pongracz, 2009).

The design agenda within the research incorporated sustainable design primarily because the field of sustainable design has both informed and contributed to the development of research for the fashion and textiles sustainability agenda (Chapman, 2005; Walker, 2006; Chapman and Gant, 2007; Manzinin, 2008; Thorpe, 2007). Design for sustainability may be regarded as the antithesis of 'design for design's sake' to produce something 'new'. This is an evolving interdisciplinary field that, in each case that has been explored, is attuned to place and context (Cowan & Van der Ryan, 2007). Though sustainable design may be considered as a relatively young discipline, Fletcher and Goggin (2001) explain that William Morris was among the first to incorporate environmental and social concerns into his work, whilst Walker and Giard (2013) acknowledge the work of Packard (1960), Carson (1962), Fuller (1968), Papanek (1971) and Schumacher (1973) who, in questioning the conventions and assumptions of their time, laid the foundations for today's understanding and importance of incorporating sustainability within design. Victor Papanek discusses in his book 'The Green Imperative', the responsibility of the designer in creating tools, objects, appliance, and buildings that cause environmental detriment (Papanek, 2003) .

Papanek's questioning is useful in encouraging designers to step out of the design space and reflect on a bigger picture. In understanding the problem, a start can be made to seeking solutions, which was a principal aim of this research. Broadly explained, sustainable design is a creative method applied to solving the problems in meeting the daily life needs of a growing global population in terms of clothing, food, shelter, care and education. Thakara (2005) explains that Sustainable Design is not about telling people how to live but enabling through design the reduction and or sharing of resources, such as energy. Conventional sustainable design and the aim of sustainable design used within this research is explained by Chapman and Gants (2007a) as a collection of strategies broadly including products designed for ease of disassembly and recycling, involving design that incorporates low environmentally impacting materials, design that optimizes energy consumption and incorporates alternative methods of power, and design that extends product life cycles in terms of physical and emotional endurance. This comprehensive yet simple explanation for sustainable design provides a framework from which designers can begin to gain an understanding of the constraints within which they need to work in order to design and produce more environmentally responsible tools, objects, appliances and buildings.

3.4.3 Research-led Practice

In establishing methods for use in the practice phase of the research, methods associated with research in the field of art and design were considered and evaluated for their appropriateness as methods of enquiry (Gray & Malins, 2004). As the design process of this study followed the principles of eco-design, a logical foundation of stages was cemented within the design process. Consequently, the practical, creative design element of the research required to be informed by the environmental performance of the materials selected for use in producing final designs. Thus, the practical element of the study that followed involved a method of research-led practice. The technical research and creative practice inform each other within an iterative cycle web (Smith & Dean, 2009).

The specific design discipline of focus was print design for fashion and textiles. Appropriate methods of research inquiry undertaken by practitioners suitable for this research were deemed to be:

- documenting information and generating data/evidence
- reflecting on and evaluating information
- analyzing and interpreting information
- synthesis and communication of research findings to formulate new research

Methods of practice that were used included:

- sketchbook
- experimentation with materials and processes
- brainstorming
- critical writing
- reflective practice
- publications

3.4.4 Technical experimentation

The specific technical methodological approaches as appropriate methods for research inquiry required for this research were deemed to be:

- experimentation
- data collection
- data evaluation
- technical testing
- technical evaluation

3.4.5 The Literature Review

The process of contextualizing research was used to compile a literature review (chapter 2) that established and defined the scope of inquiry and provided an understanding of the current knowledge regarding sustainable coloration for fashion and textiles. The literature review explored:

- environmental impact of the fashion and textiles industry
- design for sustainability within fashion and textiles
- previous research on environmentally conscious coloration methods for fashion and textiles
- sustainable fibres used within the fashion and textiles industry

On the basis of the extensive search of literature conducted, the deficiency in both design-focused and interdisciplinary research for sustainable coloured fashion and textiles became evident.

3.4.6 Triangulation as a Method of Integration

The use of a range of mixed methods derived both from creative practice and technical research inquiry paradigms means that the research used two or more methods of gathering information, as defined for the method of 'triangulation'. Denzin and Lincoln, (2005) explain that the Triangulation model of research was developed and originated within architectural research. The triangulation method enables investigations involving science and art, through quantitative and qualitative research processes, to be undertaken within one study with each process informing the other. It has been explained that the model creates an iterative loop in which one stage is informed by another, and that for the research to be at its most effective, and thus for knowledge to develop, it has to feed this loop (Till, 2005). Though the approach was originally referring to architecture, this paradigm can also be applied to the interdisciplinary research study described in this thesis. Triangulation was used as a method to integrate sustainable design and eco design with technical inquiry.

The triangulation model splits into three stages within interdisciplinary research studies, with triangulation used to explain the depth, breadth, and integration required. Triangulation within an interdisciplinary study is the achieving of balance between disciplinary depth, breadth and interdisciplinary integration, as illustrated in Figure 3.5.

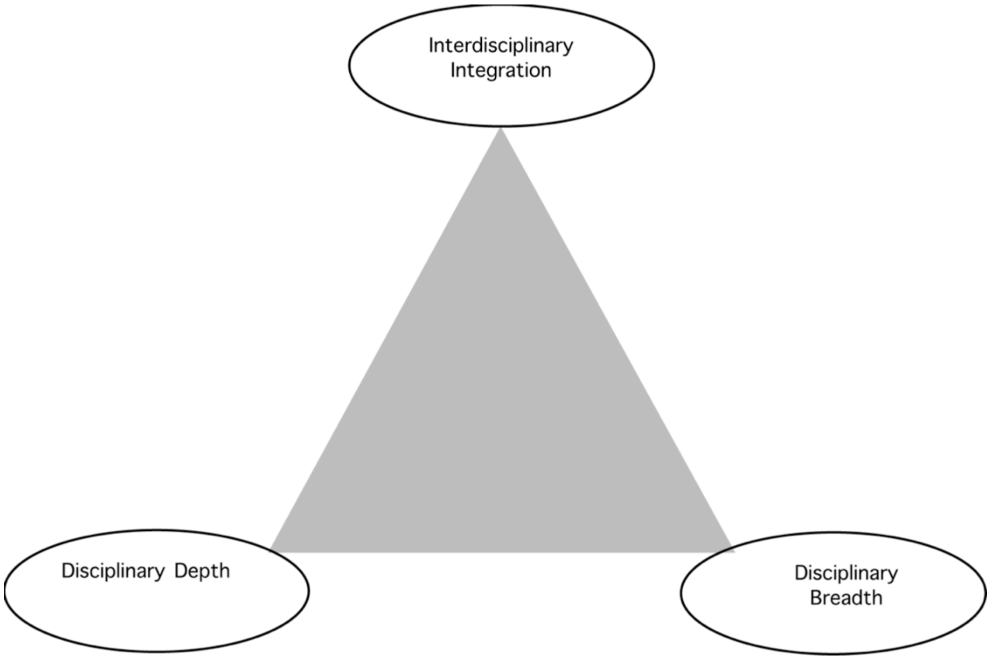


Figure 3.5. Triangulation of Disciplinary Depth and Breath and Interdisciplinary Integration. Source: Repko, 2008, p.124

3.5 Primary research question

Drawing from conclusions based on the literature review and on careful consideration of the aims and objectives of the study, the primary research question that emerged to provide the starting point for the research was: *can colour for fashion and textiles be sustainable*?

This question was explored and answers established through various methods, which relate to the different stages of the design process, also informed by various methods of technical inquiry. As the study progressed, secondary research questions developed throughout the course of the research, formulated from conclusions drawn at each stage of the research and these were used to inform the next stages of research.

3.6 Cyclical Design; The Developed Interdisciplinary Framework

In developing a logical interdisciplinary framework for the research, the creative and intuitive nature of the design process and creative experimentation was required to be interwoven within the factual nature of the science established by technical experimentation to create an iterative loop in which one stage informs another. This framework was essential in aiming to establish 'interdisciplinary knowledge' for both the researcher and research outcomes; ultimately it is the knowledge gained through undertaking the process that can be fed back into the research cycle. The framework was structured into three sections: stage 1 interdisciplinary foundation, stage 2 interdisciplinary research, stage 3 interdisciplinary knowledge. The interdisciplinary framework developed for 'interdisciplinary knowledge is presented in figure 3.6 and the stages of research followed within this thesis expanded upon in figure 3.7.

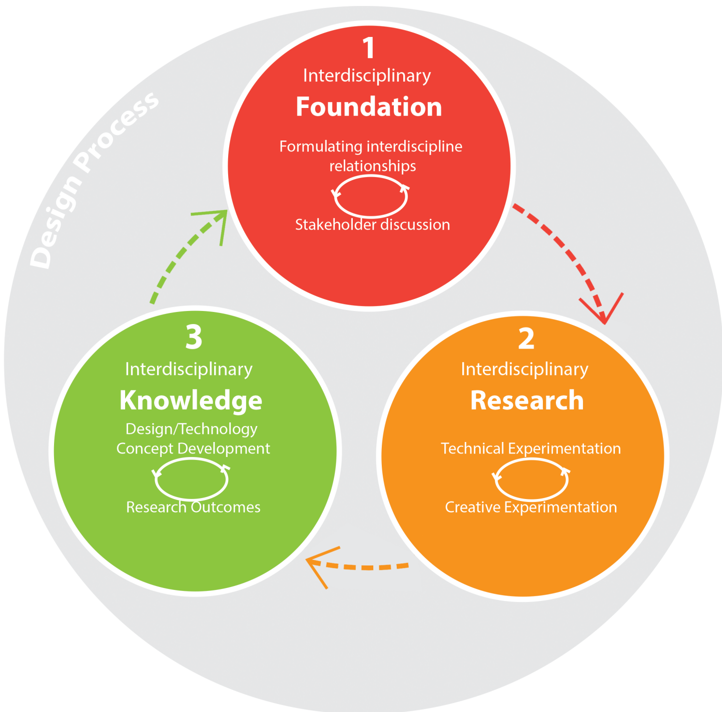


Figure 3.6. Developed Interdisciplinary Research Framework working in the 'space in-between' for 'interdisciplinary knowledge'

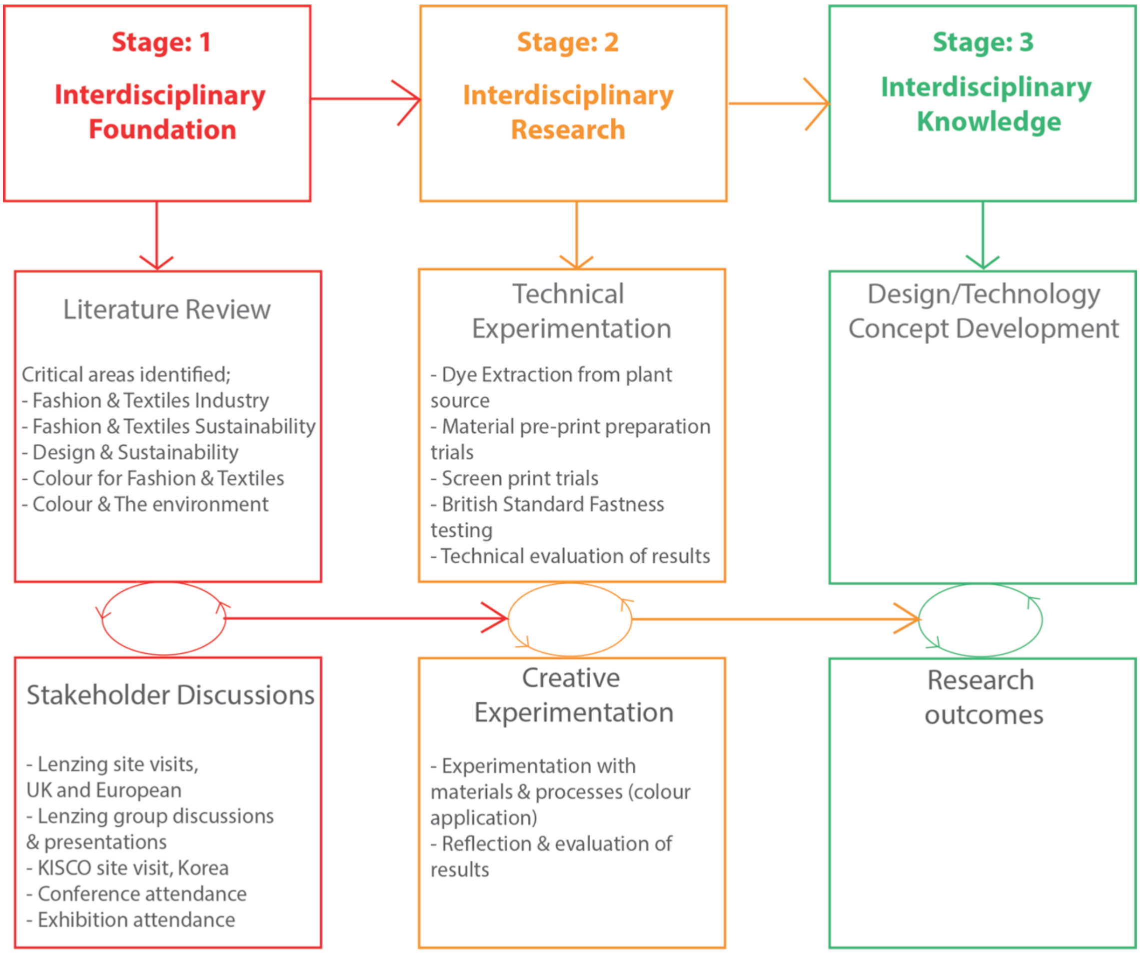


Figure 3.7. Interdisciplinary Research Stages

CHAPTER 4: Sustainable Coloration

4.1 Introduction

It was concluded on the basis of the literature review that all forms of coloration, either with natural or synthetic dyes and pigments, have some detrimental environmental impact within the current systems of production and so cannot be classified as sustainable, based on the concept (discussed and developed in section 2.2.1) of what the researcher believes to be the essence of sustainability, namely 'learning to live in harmony with our planet and to take from it only what we are able to give back to it without causing detrimental damage'.

Section 2.4.2 of the literature review presented the findings of research that suggest that the most sustainable method for producing garments is to use unbleached, un-dyed, organic cellulosic (cotton) fabric. As human beings, we are programmed to react to colour on psychological and physiological levels. Adopting this proposal and thus removing the aesthetic variety provided by colour on the grounds of sustainability would effectively require that a world of fashion and textiles consisting only of shades of naturally occurring beige would be acceptable. This would mean that removing all creativity from design in terms of colour use would be an appropriate sacrifice for the production of sustainable fashion and textiles. Although the un-dyed, unbleached organic fabrics may have been produced using the method of least environmental detriment, it may also be argued, in terms of longevity and emotional durability, that it is doubtful whether the consumer would be prepared to wear such garments repeatedly as they would be likely to stain easily in use, thus requiring extensive laundering, which would increase their environmental impact throughout their lifetime (Choudhury, 2014; Fletcher & Grose, 2012d). Inevitably, the garments would be discarded by the consumer and, although they should be biodegradable, the embedded energy from their production would be wasted. It may be hypothesized that if the lifetime of the unbleached, un-dyed garment is the same as, or even reduced, in comparison to, for example, an organic cellulosic, bleached and dyed fashion textile, then this coloured garment, with its possible extended wearability and reduced washing requirements, might have similar, if not lower, environmental impact. Without conducting rigorous lifecycle assessments for both of these garments, no definitive conclusion can be drawn. However, neither approach provides a completely sustainable outcome for coloured fashion and textiles.

The research described in this chapter explores, both from design and environmental impact perspectives, two key conclusions from the literature review that, in terms of cellulosic fibres, the use of organic, un-bleached, un-dyed materials is proposed as the most sustainable means for producing fashion and textiles, and that all colour for fashion and textiles has a negative environmental impact and must therefore be classed as unsustainable. The purpose of the research reported within this chapter is to establish through interdisciplinary life cycle inquiry, whether colour for fashion and textiles can be sustainable.

In providing an interdisciplinary response to this fundamental research question, the outcomes from this chapter are able to provide a definitive research opinion on sustainable coloured fashion and textiles. The broad aims of this section of the research are essentially to design processes which link production with design through incorporating lifecycle thinking in order to produce sustainable colour, and to establish a model from which opportunities and limitations for creating colour within a product lifecycle may be evaluated. An example of a new cyclical approach to sources of colour that incorporate the utilization of waste and by-products is presented. The evaluation of this work and the conclusions drawn underpin the subsequent phases of research are presented in chapters 5 and 6.

The opinion that 'beige is best' is challenged by the researcher through using interdisciplinary lifecycle thinking to develop an alternative method for sourcing and producing colour for textiles with the aim of achieving an innovative method for sustainable coloration. The design process that is used is underpinned by research in textile and coloration technology, by developing an interdisciplinary methodological approach that links creativity of design with technical inquiry, leading to a practical design outcome that is concluded to be a definitive sustainable option for coloration. The research is presented in two sections. The first part of the chapter focuses on the technical development and testing stage of the research. Following successful completion of the technical underpinning, a method based on coloration within the lifecycle was used to create a sustainable coloured garment. The second part of the chapter presents the design research process for the garments that incorporate the principles of sustainable design, for example providing longevity by evolving within its lifetime, and also the likelihood of complete biodegradability as the colour applied is of natural origin. The research highlights that for sustainable design to be successful, it must incorporate aesthetic value balanced with environmental value, rather than sacrificing one for the other.

4.2 Coloration within the Lifecycle

All coloured fashion and textiles begin life at the fibre selection stage and so, in developing sustainable coloured fashion and textiles, the two standard primary materials are fibre and dyestuff. Fibre selection is a critical part of the overall sustainability classification. Thus, in aiming to produce a sustainable coloured garment, the design process must begin with, and evolve from, the lifecycle within which the fibre is produced. In producing sustainable coloured fashion and textiles, the fibre used will determine the lifecycle which constrains the coloration and end of life criteria. Two categories of lifecycle have been proposed, the technological lifecycle and the biological lifecycle. It is explained (Braungart & McDonough, 2009) that these lifecycle considerations result in design frameworks that may be considered as product metabolisms whereby designers create systems that mimic nature's cradle to cradle system of nutrient flow and metabolism, in which waste is not an issue. Within this cradle to cradle design framework, materials represent nutrients circulating in a healthy continuous biological or technical metabolism, where waste materials are productively re-incorporated into new production and use phases.

4.2 1 Technical Lifecycle.

The technical cycle involves a cycle of materials or products designed to be continuously returned into the cycle so as to create new materials or products, as illustrated in Figure 4.1.

4.2.2 Biological Lifecycle

The biological cycle is the cycle of materials or products designed to be returned to nature through safely biodegrading after use, as illustrated in Figure 4.2.

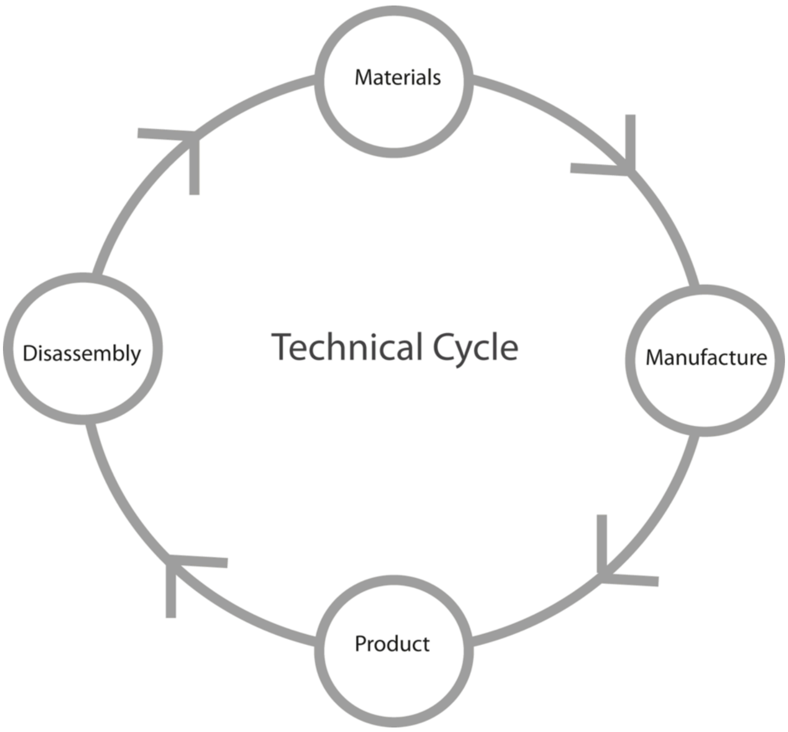


Figure 4.1. The Technical Cycle

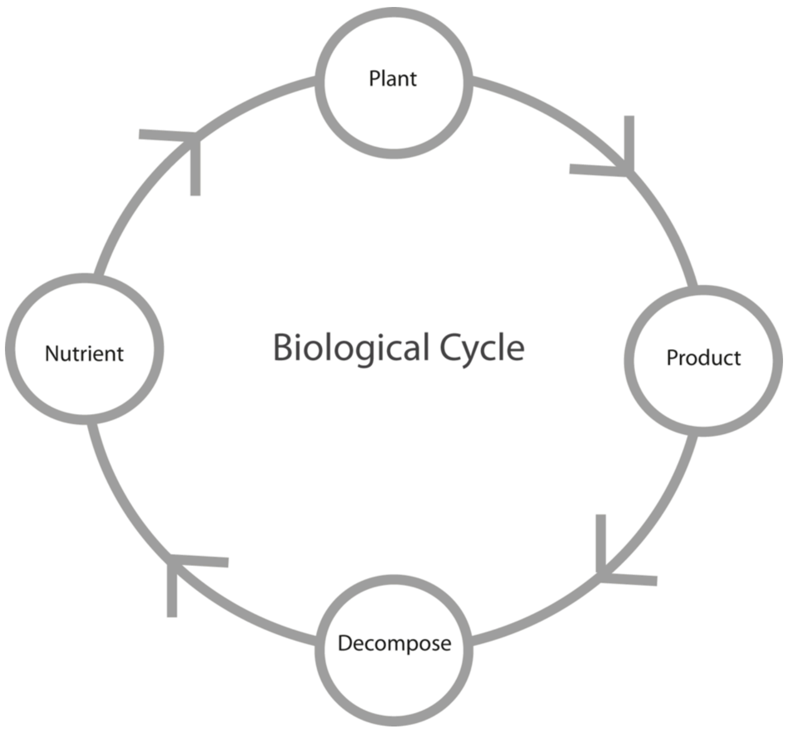


Figure 4.2. The Biological Cycle

4.3 Lifecycle Design Thinking

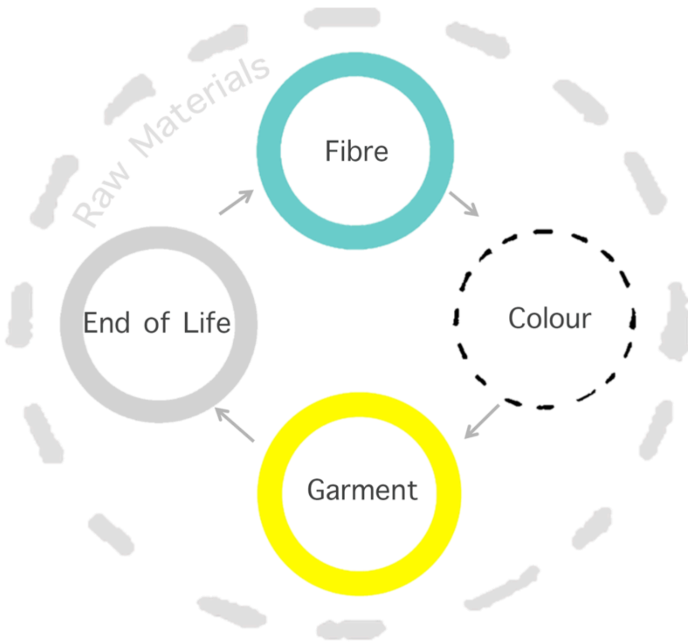


Figure 4.3. Cyclical Coloration

The incorporation of lifecycle design thinking at this early stage of the investigation incorporates a consideration of the environmental implications of the product throughout its entire lifecycle, in this case from fibre through to end of life. Figure 4.3 illustrates the research concept developed for the requirements envisaged in producing a sustainable coloured fashion garment, working within the constraints of a biological cycle. These constraints require that the fibre and colour should be produced within the same lifecycle and that at end of life stages the textile garment can biodegrade without releasing harmful chemicals into the earth, thus acting as fertiliser for the next generation of raw materials.

To incorporate a cyclical design approach into cellulosic fibres and their coloration, a suitable fibre was identified upon which to base the research. The regenerated cellulose fibre, lyocell, was selected based on its closed loop production process, which is inspired by the natural biological lifecycle discussed in section 2.3.2 of the literature review, and interpreted in Figures 4.4 and 4.5.

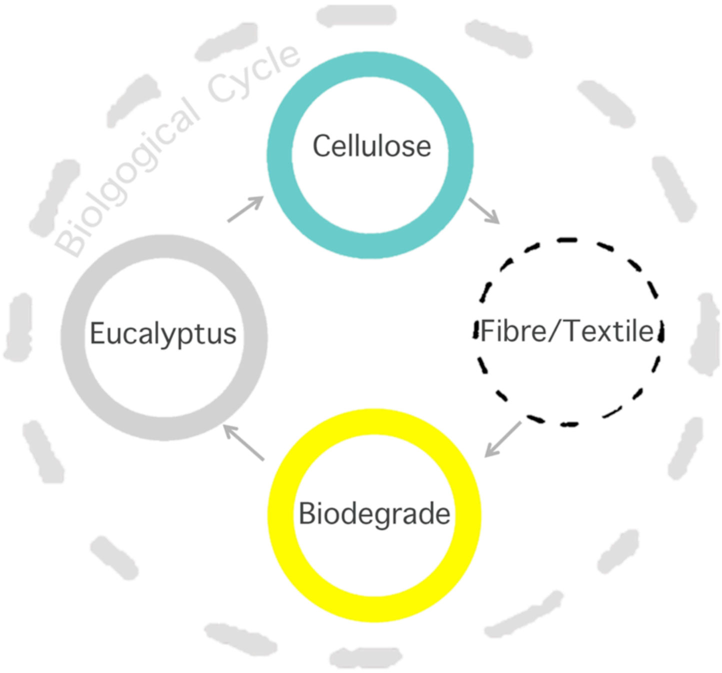


Figure 4.4. Lyocell Biological Lifecycle

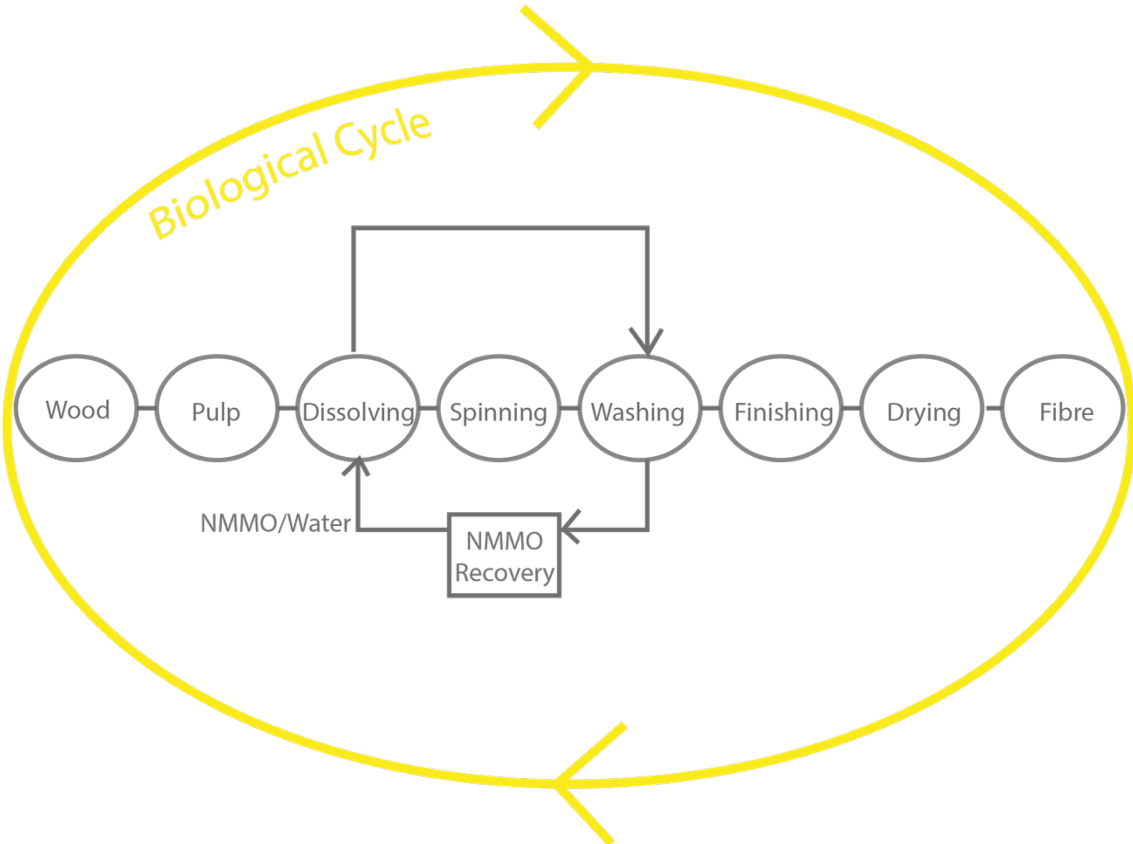


Figure 4.5. The Lyocell Process within the Biological Cycle

4.3.1 Technical Inquiry

Designing coloured fashion and textiles from the fibre stage within the lyocell lifecycle identified opportunities for closed loop, inherited coloration by utilizing by-products from the lyocell fibre production to create colour, namely the bark and leaves of the eucalyptus plants that are used for fibre production. The research exploited the closed loop 'lyocell process', as discussed in section 3.3.2 and demonstrated in Figure 4.5, to explore the utilization of by-products that have the potential to provide natural colorant for the coloration of fabrics constructed from lyocell fibres, in particular the grades referred to as Standard Tencel and Tencel A100. This design concept is demonstrated in Figure 4.6. To address the aims, natural colour was extracted from the leaves and bark, which are by-products of the sustainably forested eucalyptus from which the fibres are derived. No harmful chemicals were used at any stage and only water was used in the extraction process. Colour was applied to fabrics by screen-printing using gum tragacanth as a natural thickening agent for the print paste. The printing process was evaluated, both with and without the use of mordants.

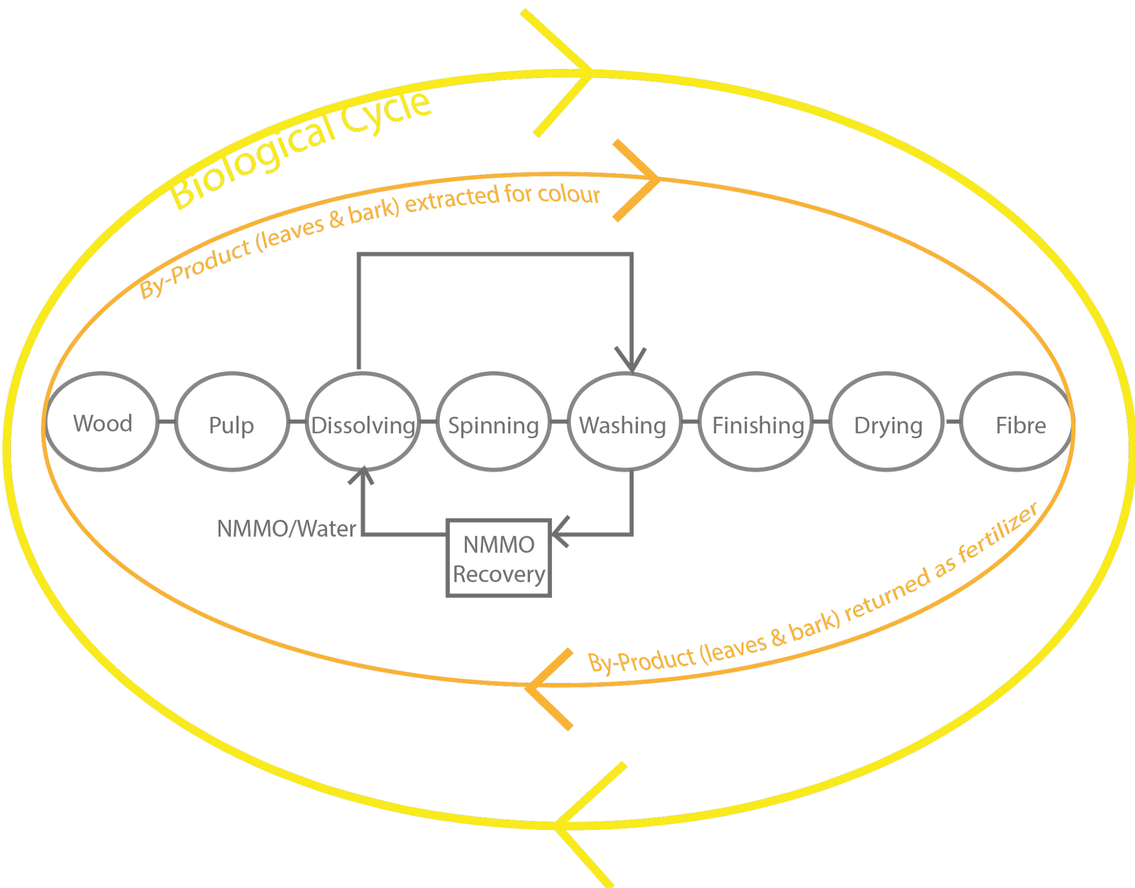


Figure 4.6 Cyclical Coloration within the Lyocell Biological Lifecycle

Positive and negative aspects of this inherited colour model, 'coloration within the lifecycle' are reviewed within this chapter, which closes with the conclusions from the research, leading to the proposal that this new lifecycle approach may provide a long term solution for sustainable coloration. The conclusions are also used to inform the subsequent stage of research, as presented in chapter 5, which tackles the possibilities of more immediate short term solutions.

4.4 Experimental Work

The fabrics used in the research described throughout this thesis are specified in Table 4.1. The same knit structure was used throughout technical testing for all fibres, Lenzing constructed each fabric to ensure any difference during experimentation was due to the fibre. Woven fabric was introduced later in the study for aesthetic reasons. This section presents and discusses the technical experimental research described in this chapter.

Table 4.1 Fabric Specification Table

Fabric	Yarn Count, Tex		Fabric Weight, g/m^2	Structure
Standard Tencel	12		125	Weft-knitted from 1/30s ring spun yarns in interlock structure.
Tencel A100 	12		168	Weft-knitted from 1/30s ring spun yarns in interlock structure.
Cotton	12		137	Weft-knitted from 1/30s ring spun yarns in interlock structure.
Modal 	12		129	Weft-knitted from 1/30s ring spun yarns in interlock structure.
Tencel A100 	Warp	28	194	Woven plain weave structure
	Weft	23		

4.4.1 Materials & Processes

(a) Fabric

The fabric used in this section was 100% Tencel A100 un-scoured, unbleached, supplied by Lenzing AG, Austria, knitted to the following fabric specification: 1.4dtex, staple length 38mm, 168 g m^{-2}, weft-knitted from 1/30s ring spun yarns in interlock structure.

(b) Dyes

Fresh eucalyptus leaves and bark were provided by Sappi, PO Box 62, Umkomaas 4170, South Africa, the supplier of wood pulp to Lenzing.

4.2.2 Dye extraction

The leaves and bark were separately left to air dry for two weeks at room temperature in a laboratory. Drying in this manner removed excess moisture with a view to optimizing dye extraction. The materials were then separately slurried in water (*ca*. 10g leaves and 20g bark per litre of water). The mixtures were raised to the boil, and boiling was continued for one hour. The slurry was then filtered and the water removed from the filtrate by rotary evaporation to provide a brownish-orange crystalline powder. A further quantity of dye was obtainable from a second extraction by returning the mixture to the boil, and allowing to boil for a further hour. Dye was thus extracted from the materials after a total boiling time of one hour for the first extraction and two hours for the second extraction. Visual evaluation of preliminary results from screen-print experimentation showed no variation in the colour produced in screen prints obtained from different extractions of dye.

4.4.3 Fabric Pre-treatment

It is important, before the application of colour to fabric, to ensure that the fibres are clean and free of any impurities. The lyocell fabrics were scoured using a solution of 0.1% solution of Exenol XB in water at 40°C for 30 minutes, rinsed with cold water and then air-dried at room temperature. Exenol XB, described as an anionic/nonionic alcohol ethoxylate surfactant, a simple soaping composition considered to have minimal environmental impact, was supplied by J. & W. Whewell Ltd, Manchester, UK.

4.4.4 Mordanting

The mordanting stage of fabrics is only required when the application of colour uses natural dyes. Mordants are used to reinforce the bond between dye and fabric, and thus increase fixation. Arguably, the use of a mordant at this stage of the research would increase environmental impact and thus mean that the coloration process was not completely contained within a closed loop. However, it was judged to be important for the validity of the technical inquiry to ensure that the technical performance of the dye extracted was assessed for both unmordanted and mordanted fabrics. Thus, a selection of commonly used mordants for natural dyeing was investigated. Gum tragacanth was supplied by Makebake, Preston, UK. Potassium aluminum sulphate (alum), calcium carbonate and tannic acid were obtained from Sigma-Aldrich, UK. Alpro unsweetened soya long life milk was purchased at a local supermarket.

The scoured fabric was treated separately with the mordants - alum, calcium carbonate, soya milk and tannic acid. An aqueous solution of the mordant was applied to the fabric at a concentration of 20% of the mass of fabric (o.m.f.) using a liquor ratio of 15:1. Two methods of mordanting were trialed. Method one used a Pyrotech S infrared dyeing machine. Method two used a Roaches engineering 2 Bowl BVHP Padder with the mordant solution poured over the fabric (12g) as it was passed through the machine.

Preliminary results for screen-printing were subjected to visual evaluation in a light box under the daylight setting. The first method of mordanting, involving the use of an infrared dyeing machine to soak the fabric in the mordant solution under conditions commonly used for dyeing, resulted in an uneven covering of colour across the fabric surface, creating a blotchy appearance on the finished sample as illustrated in Sample EA and EB of Figure 4.7. The second method of mordanting, using a padding machine was more successful, creating an even appearance of colour across the fabric surface as demonstrated in sample EB of Figure 4.7. This is likely to be due to the more even coverage of mordant solution across the fabric surface as it passes through the padding machine. In doing so, a consistent coverage was achieved across the surface to which the dye is applied by screen printing.

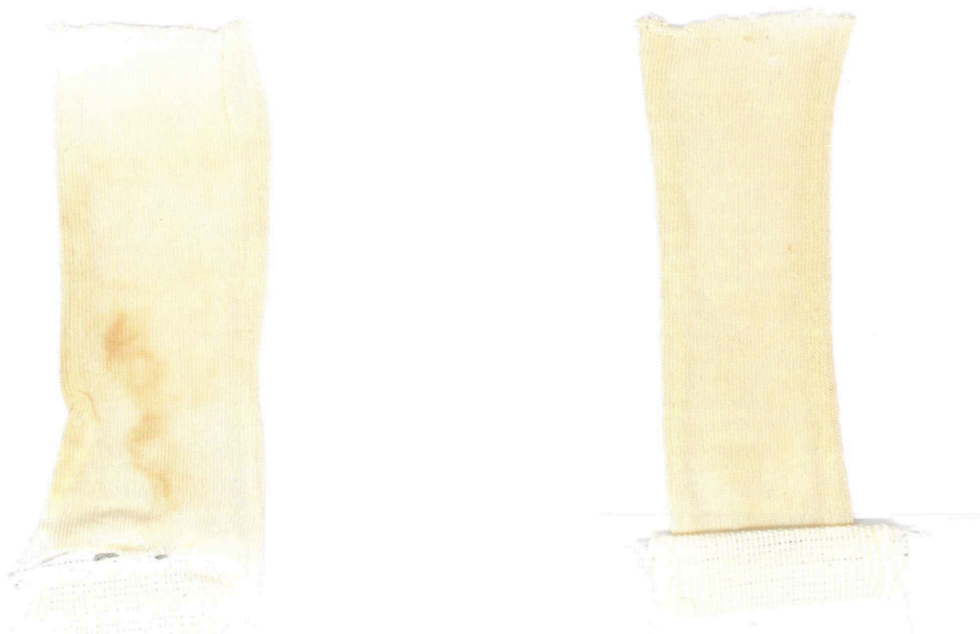


Figure 4.7. Samples of Tencel A100, mordanted with calcium carbonate, sample A using infrared dyeing machine, sample B using padding machine before being screen-printed with eucalyptus extract.

4.4.5 Screen-printing

The print pastes were obtained by dissolving the extracted dye in a solution of gum tragacanth in water (40g l^{-1}) at concentrations of 2, 4, 8 and 16 %. These concentrations refer to the total amount of extracted solids in solution, which are likely to be complex mixtures of naturally occurring components, rather than pure dye. Fabric samples for technical testing were screen printed on a Zimmer magnetic print table with a single pass of the print paste across the fabric using a metal rod. The samples were then steamed at 100°C for 20 minutes, washed with a 0.1% aqueous solution of Exenol XB, initially cold and then at 40°C, then with water and finally they were air-dried. For design trials to explore colour depth and shade effects, the magnetic table was also used but with more passes of print paste across the fabric.

4.4.6 Assessment

Colour on the fabric is commonly assessed by visual inspection with the naked eye, especially by designers. However, for the development of an application process that is to be used successfully in a commercial environment as a method of providing sustainable colour, it is vital to assess technically certain features of the fixation of dyestuff to fibre. Natural dyes are reported generally to have poor affinity for textiles and hence often perform poorly when compared to synthetic dyes in terms of fastness properties. For this reason, and since the aim of the research involves application for fashion garments, it was considered important to establish the fastness properties of the dyes to light, washing and rubbing.

Samples were evaluated for wash fastness in accordance with ISO:105, part C10, colour fastness to rubbing with ISO:105-C10:2007 part X12, and colour fastness to light with ISO:105, part BO1. Colour measurement was carried out using a Datacolour Spectraflash SF600 reflectance spectrophotometer, processed using Datamatch 3.1 software, using the small aperture, for the 10° observer with specular reflectance included and the UV component excluded, under D65 illumination. The instrument was calibrated using a black trap, white tile and green tile respectively according to the manufacturer's recommendations. Samples were folded four times and measurements were made on the back of the fabric. An average of three measurements from different parts of the fabric was obtained in each case. Reflectance measurements in the UV region were obtained using a Perkin Elmer Lambda 35 UV/visible spectrometer equipped with a labsphere RSA-PE-20 reflectance spectroscopy accessory.

4.5 Technical Results and Discussion

4.5.1 Technical Evaluation

Lyocell was selected as the textile substrate for this study, as an example of a fibre that has sound environmental credentials and also because certain fabrics constructed from the fibre offer attractive and interesting aesthetic and tactile qualities from a textile designer's perspective. Lyocell also offers environmental advantages in terms of coloration, especially in reactive dyeing (Taylor, 1999). Tencel A100 is of particular interest in this respect (Farrington & Oldham, 1999). The open fibre structure of Tencel

A100 has been shown to have a positive influence on its dyeing performance. High colour yields are obtained from reactive dyes, the most commonly used class of dyes applied to cellulosic fibres, attributed to the high affinity of the dyes for the fibre, a high rate of exhaustion and a high degree of fixation. This means that the amount of dye that needs to be applied initially, and the level of certain chemical auxiliaries required for the dyeing process, may be minimized (Taylor et al, 2001a; Taylor et al, 2001b)

In aiming towards a future 'zero-emissions, zero-waste society', consideration of the use of renewable resources for textile coloration has been proposed, especially by making use of by-products from agricultural processes and ensuring that all parts of the plant are utilized in some way (Geissler, 2009). A potentially sustainable source of natural colour for application to lyocell was identified as the leaves and bark of the particular species of eucalyptus used in its production. Currently, the trees are debarked in the field and the leaves and bark are left there as natural compost. There are several previous reports of the use of colour extracted from species of eucalyptus in natural dyeing (Ali et al, 2007; Mongkholrattanasit et al, 2009; Mongkholrattanasi et al, 2010; Mongkholrattanasit et al, 2011). This is used to a certain extent in craft-based natural dyeing processes.

For this research, It was found that a simple extraction of the dried leaves and bark using boiling water, with no additives, in both cases provided a reasonable quantity of an orange-brown crystalline material after evaporation of the water that provided a yellow colour when applied to textiles. In principle, the solid residue from the leaves and bark after the extraction process could continue to fulfill their purpose as a composting material.

Screen-printing was selected as the method of colour application to the Tencel A100 fabric, in view of its simplicity and the fact that localized coloration and creative pattern selection might be used to produce attractive colour effects, while minimizing the use of dyes and auxiliary chemicals. The traditional screen preparation procedure involves an initial application of a coating of a photosensitive emulsion on the screen. An acetate film containing the image is then placed over the screen and the system is subjected to a photochemical curing process after which uncured material is washed off to reveal the image. To avoid the environmental consequences of this chemical process, in this research, the print imagery was derived from stencils formed using lyocell fabric, which were then placed on the fabric to be printed beneath an open screen. It is envisaged that the lyocell fabric used for this stenciling purpose might, in principle, be re-used, for example in stencil production, as a structured piece of fabric by sewing or bonding, or recycled in some other way.

Print pastes were prepared simply using gum tragacanth as a natural thickening agent dissolved in water, in which the dye extract was found to dissolve readily. Other auxiliary chemicals that are commonly used in print paste formulation, the most obvious of which is urea used as a fibre-swelling agent to promote dye uptake, were avoided to minimize environmental impact. Initial print trials using this print paste on untreated Tencel A100 gave prints that showed a degree of non-uniformity. To address this issue, a light scouring of the fabric at 40^{o}C was carried out using a dilute aqueous solution of a particular surfactant, Exenol XB, recommended by a local specialist textile finishing company on the basis of its low environmental impact. The process used contrasts with the rather vigorous scouring procedure, often supplemented by bleaching, that is commonly required as a print pre-treatment for cotton fabric. Screen prints of the scoured Tencel A100 with the pastes derived from the eucalyptus extracts were finished by a traditional steaming process to promote fixation. Attractive golden-yellow prints on a clean white fabric background were produced, as illustrated in Figure 4.8. The colours of the prints derived from extracts of the eucalyptus leaves and bark were virtually identical, presumably because the compositions of the coloured materials from the two sources are similar. Previous studies of eucalyptus extracts have identified the principal coloured components as flavonoid species, found in association with tannins and polyphenols (Mongkholrattanasit et al, 2010).

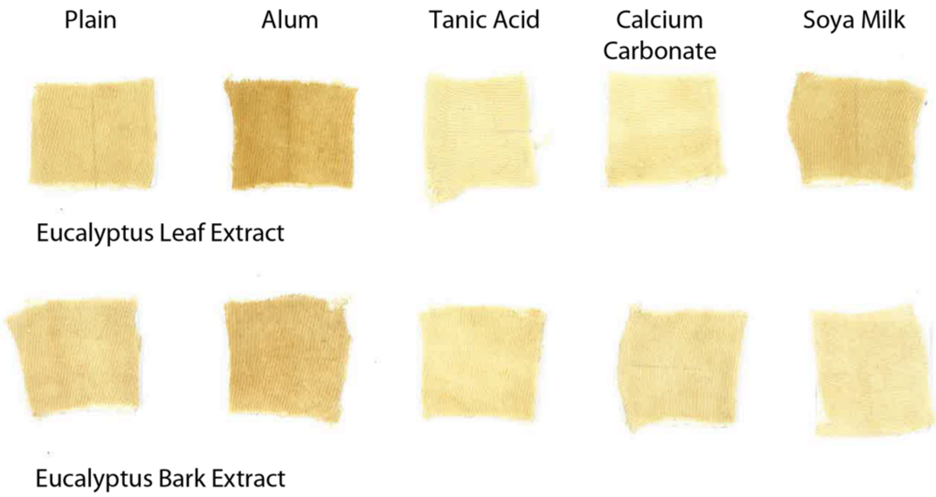


Figure 4.8. Screen-printed Eucalyptus leaf and bark extract

Reflectance spectrophotometry was used to provide a quantitative measurement of the colour of the fabrics. This well-established instrumental analytical technique operates by shining light of wavelengths covering the entire visible range on to a fabric surface, and measuring the amount of this incident light that is reflected, as a function of the wavelength of the light. The instrument provides as its output a range of numerical data that describe various features of the colour of the fabric. In the context of this investigation, K/S values (the Kubelka-Munk function) are useful in providing information on how the coloured fabric absorbs light throughout the visible light region, the region of the spectrum to which our eyes are sensitive. The higher the K/S value at a particular wavelength, the higher the absorption of light and the stronger the colour that is observed visually on the fabric. A graph illustrating the variation in K/S values with the wavelength in the visible light region (400-700nm) for scoured Tencel A100 printed with leaf and bark extracts at a concentration of 4% in the print paste is given in Figure 4.9. The yellow colour that is observed visually is due to the absorption of light in the low wavelength region. This feature is demonstrated by the higher K/S values towards the left side of the graph, corresponding to wavelengths of around 400-450nm.

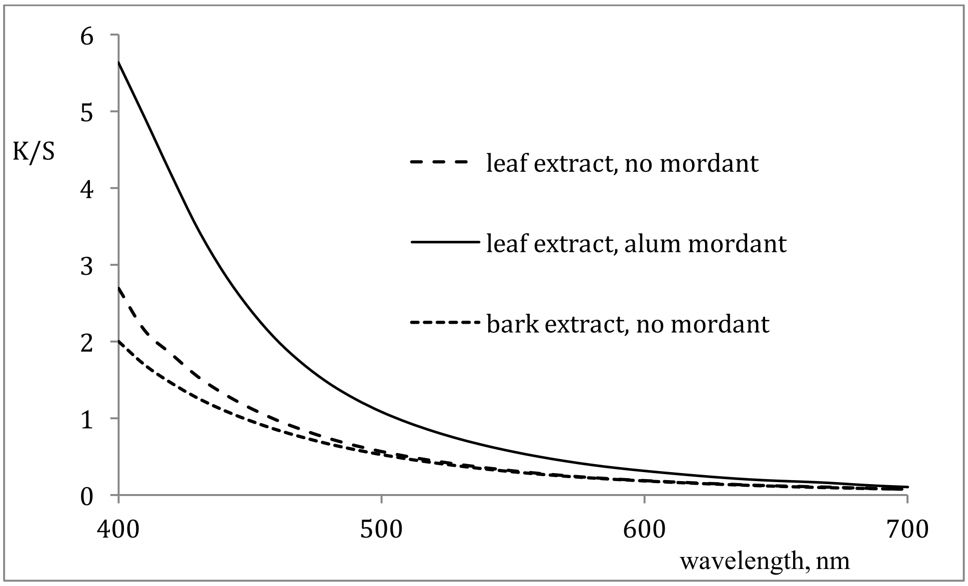


Figure 4.9. K/S curve for Tencel A100 printed with eucalyptus leaf extract, at 4% dye concentration in the print paste.

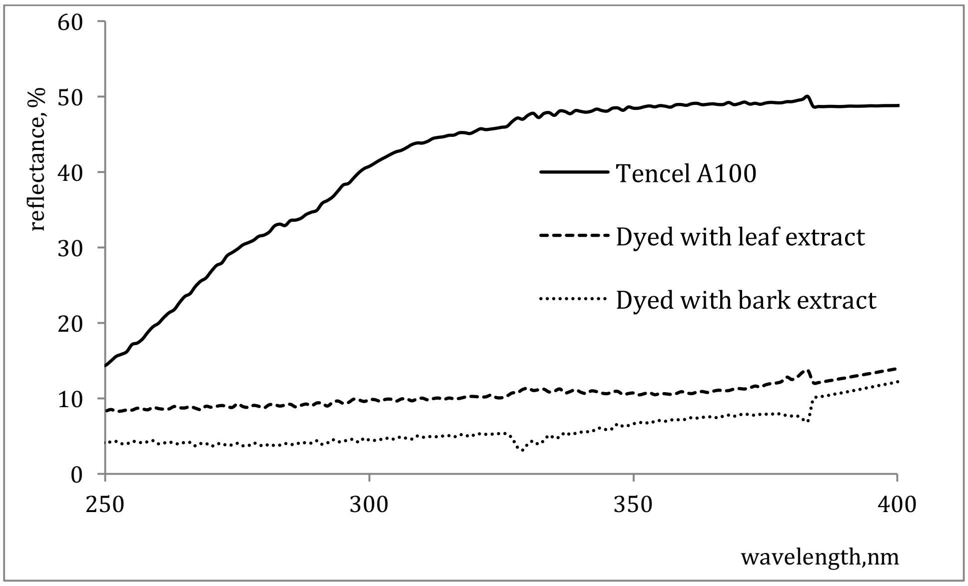


Figure 4.10. Reflectance (%) of *Tencel A100*, unscoured and printed with leaf and bark extracts.

Reflectance spectrophotometry was also used to investigate the ability of the fabrics to absorb ultra-violet (UV) light. It was confirmed that the visible light absorption, shown in Figure 4.9, is an extension of absorption in the UV region, which is at wavelengths lower than the visible region, i.e., below 400nm. This conclusion is based on the reflectance curves (graphs of % reflectance against wavelength) for the UV region, shown in Figure 4.10. It can be seen from these curves that un-dyed Tencel A100 shows around 40-50% reflectance in the UV region (300-400nm), while the corresponding reflectance is less than 10% in the printed samples. This observation confirms that the extracts obtained from the leaves and bark strongly absorb UV light. The UV absorption properties of fabrics treated with extracts of eucalyptus have been reported previously (Mongkholrattanasi et al, 2011). This finding is potencially beneficial for summer wear clothing, or climates with high levels of UV.

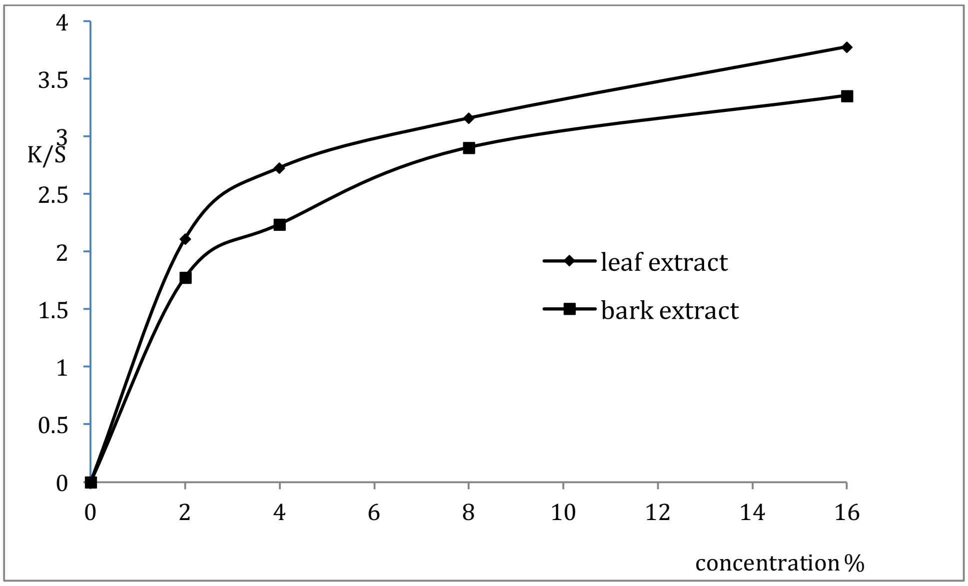


Figure 4.11. Relationship between the concentration of dye in the print paste and colour developed, assessed as the K/S value at 400nm.

The effect of dye concentration in the print paste derived from eucalyptus leaves and bark on the colour strength of printed Tencel A100 is illustrated in Figure 4.11. The colour strength is assessed as the K/S value at the wavelength which gives the highest value, in this case 400nm. The graph shows the expected increase in colour strength (i.e., increasing K/S value) with concentration, a feature that was also evident from visual observation of the fabric samples. A dye concentration of 4% in the print paste was considered to be the most reasonable practically, as experimentation showed that higher dye concentrations (8% and 16%) did not lead to proportionately higher colour strength on the printed fabric, and also because it was observed that there was significant colour loss into the wash liquors from excess dye at these higher concentrations during the wash-off procedures employed after steaming. Thus, all subsequent experimental investigations were carried out using a dye concentration of 4%.

Table 4.2. K/S values at 400nm for Tencel A100 samples printed with eucalyptus leaf and bark extracts, at 4% concentration in the print paste.

	Unmordanted	Alum	Tannic acid	Calcium carbonate	Soya milk
Leaf extract	2.7	5.6	1.8	2.2	3.1
Bark extract	2.0	3.5	1.8	1.8	1.7

In view of the fact that natural dyes commonly require a mordant treatment for adequate fixation on textiles, printing was also carried out on a range of fabric samples pre-treated with a selected group of mordants. The mordants selected included alum, which is traditionally the most commonly used and most effective mordant, although its use introduces some environmental consequences as it is a metal-containing agent (Mongkholrattanasit, 2011). The other mordants used were tannic acid, proposed recently as a natural botanical alternative to metal-containing mordants (Cardon, 2007a), calcium carbonate and soya milk, which are commonly used in natural craft dyeing, in particular for eucalyptus (Burkinshaw & Kumar, 2009). K/S values at a wavelength of 400nm (where the fabrics show their maximum light absorption) for each of the Tencel A100 samples printed with eucalyptus leaf and bark extracts, at a concentration of 4% in the print paste, are given in Table 4.2. These values are a measure of the colour strength. Mordanting with alum provides a stronger, although visually less attractive brownish-yellow colour in the printed samples. The broader K/S curve given by mordanted fabric is characteristic of a duller colour, as illustrated in Figure 4.8. In contrast, none of the other mordants were observed to modify the colour significantly.

Table 4.3. Washfastness assessment of Tencel A100 fabrics printed with eucalyptus leaf and bark extracts, at a concentration of 4% in the print paste.

			Staining											
	Colour change		cellulose acetate		cotton		nylon		polyester		acrylic		wool	
Mordant	leaf	bark	leaf	bark	leaf	bark	leaf	bark	leaf	bark	leaf	bark	leaf	bark
none	4-5	4-5	5	5	4-5	5	5	5	5	5	5	5	5	5
alum	5	5	5	5	4-5	5	5	5	5	5	5	5	5	5
tannic acid	4-5	4-5	5	5	4-5	4-5	4-5	4-5	5	4-5	5	5	5	5
calcium carbonate	5	4-5	5	5	4-5	4-5	5	5	5	5	5	5	5	5
soya milk	4-5	4-5	5	5	4-5	4-5	5	5	5	5	5	5	5	5

Washfastness results obtained based on laundering tests, carried out on the printed fabrics under a set of standard laundering conditions where the washing temperature is 40^{o}C, are given in Table 4.3. Washfastness is investigated in technical practice in terms of both the colour change of the fabric after washing, and also the staining of a multifibre strip (a strip of fabric consisting of the range of commonly used fabrics), which is kept in contact with the coloured fabric during washing. The fastness is then assessed by comparison with a standard set of grey scales, with 1 as the lowest and 5 the highest rating. In the case of these printed samples, the washfastness was assessed as excellent, rated at 4-5 or 5 throughout. The most interesting result is the excellent washfastness provided by printing on fabric that has received no mordanting treatment. An explanation for this observation may be proposed based on previous observations of protein fibres being dyed with eucalyptus extracts, the eucalyptus extracts were found to contain natural tannins, which are capable of acting as dye fixing agents (Mongkholrattanasit et al, 2010$_a$). Thus, it is likely that the extracts from the eucalyptus leaves and bark in this case contain both the colouring materials and also tannins, and are thus 'self-mordanting'. This result is technically highly significant for printed garment applications.

Table 4.4. Rubfastness assessment of Tencel A100 fabrics printed with eucalyptus leaf and bark extracts, at a concentration of 4% in the print paste.

Mordant	Dry rubfastness (leaf)	Wet rubfastness (leaf)	Dry rubfastness (bark)	Wet rubfastness (bark)
None	5	4-5	5	4-5
Alum	5	4	5	3-4
tannic acid	5	4-5	5	4-5
calcium carbonate	5	4-5	5	4
soya milk	5	4	5	4

Rubfastness refers to the resistance of a fabric towards changing colour due to mechanical abrasion. Rubfastness results, assessed by tests on the printed fabrics using a James Heal manual wet/dry crocking instrument for both dry and wet fabrics, are given in Table 4.4. The dry rubfastness was found to be excellent, rated at 5 against the grey scales, for all samples. There was, in some cases, slightly inferior wet rubfastness, although still at a level that would be acceptable for most applications. Interestingly, the unmordanted fabric proved to be superior compared with the alum treated fabric in this respect.

Table 4.5. Lightfastness of Tencel A100 fabrics printed with eucalyptus leaf and bark extracts, at a concentration of 4% in the print paste.

Mordant	Lightfastness (leaf)	Lightfastness (bark)
None	5-6	5-6
Alum	5	5
tannic acid	4	4-5
calcium carbonate	5	5
soya milk	5	5

The ability to withstand the effect of exposure to light during their lifetime is a key attribute of coloured textiles. Lightfastness is frequently reported as a deficiency in naturally dyed fabrics. It has been suggested that lightfastness ratings of naturally dyed textiles rarely exceeds a grading of 4 when assessed against the blue wool scale standards, which is the most commonly-used scale, providing ratings of 1 to 8, used for this purpose (Glover, 1995). The lightfastness data for the printed samples obtained by a standard exposure procedure using a Xenotest fadeometer, are given in Table 4.5. It is of considerable interest, therefore, that lightfastness ratings up to 5-6 were provided by the printed fabric, a level that exceeds the normal average performance of natural dyes and is comparable with that provided by many traditional synthetic dyes in common use. It is especially interesting that the optimum lightfastness was provided by the printed fabric with no mordant pre-treatment. In view of this exciting and rather unexpected outcome, this particular assessment was repeated several times to provide verification, and the results were demonstrated to be consistent and reproducible. A technical explanation for the observation may be proposed based on the UV-absorbing properties of the printed fabrics that have been demonstrated by the UV reflectance data illustrated in Figure 4.10. A potential explanation for the good light resistance of the printed fabrics is that the UV absorption by components of the eucalyptus extracts, as demonstrated from Figure 4.10, may provide the coloured species of Eucalyptus with a degree of protection from the damaging effect of UV radiation (Mongkholrattanasit et al , 2011a).

The selection of Tencel A100 as the fabric for this investigation was based on its particular suitability for coloration. However, there is a potential environmental issue associated with this version of lyocell fibre in that it is manufactured using a chemical treatment to provide crosslinking, although used in only small quantities. It was thus decided to investigate the performance of standard Tencel, a grade of the fibre which has not been subjected to a comparable chemical treatment, under the same screen printing conditions. A comparison of the results of this investigation, given in Table 4.6, with those presented in Table 4.2 for printed Tencel A100, demonstrates that the dye extracts performed similarly in terms of the strength of colour developed, as represented by the K/S values, on the two versions of lyocell. The range of fastness properties of the printed standard Tencel fabrics was acceptable, as illustrated in Table 4.6, although marginally inferior in some cases compared with the results given by Tencel A100 (see Tables 4.3-4.5). A tentative explanation is proposed that the location of the coloured species within the open cross-linked structure of Tencel A100 may be a factor that provides a marginal enhancement in fastness performance.

Table 4.6. Properties of unmordanted standard Tencel fabrics printed with eucalyptus leaf and bark extracts, at a dye concentration of 4% in the print paste.

		leaf	bark
K/S at 400nm		2.3	2.7
Washfastness			
Colour change		4	4
Staining	cellulose acetate	5	5
	cotton	5	5
	nylon	5	5
	polyester	5	5
	acrylic	5	5
	wool	5	5
Rubfastness	dry	4-5	4
	wet	4-5	4
Lightfastness		5	5

4.6 Design Inquiry

The technical research described in the previous section has provided a natural dye obtained from a sustainable source with remarkable fastness properties, which are well-suited for use within the production of a sustainably coloured 100% lyocell fashion textiles. The current literature conclusion that unbleached, un-dyed organic fabrics provide the most sustainable method for producing fashion textiles is thus questioned on the basis of this technical exploration. However, it was considered important to investigate the visualization of the outcome of this alternative process in practice.

Initially, this involved the production of a T-shirt that was coloured using the technique developed for sustainable colour.

A significant limitation of the research conducted up to this point is that only one colour has so far been produced. However, it was found during print trials that the depth of shade could be modified, not using dye concentration as might normally be used with synthetic dyes, but through the number of passes made over the fabric of the dye during the screen printing process. The two depths produced are illustrated in Figure 4.12.

Figure 4.12. A basic sleeveless T-shirt produced using the technique of increasing the number of passes of dye over the fabric during screen-printing.

On the basis that the T-shirt is constructed from lyocell and is coloured using a natural dye, it is reasonable to assume that it would be biodegradable. Thus, the garment has been designed from fibre to product and also incorporating this end of life biodegrading stage to ensure that the energy and resources used in its production are optimized.

Further, it was considered important to explore how the design of the garment could be utilized to incorporate extending the lifetime of the garment, on the basis both of its wearability and its desirability to the consumer, before it is discarded. The problem with coloured fashion garments originates from the feature that is highly desirable, namely permanence. In aiming to extend the use phase of garments within the lifecycle, a common approach for designing a 'change' in the way that they can be worn is to design the garments to be reversible. The typical method used is to sew two pattern pieces of fabrics together when constructing the garment, attaching reverse face to reverse face of the fabrics. This results in the production of a garment that has two front faces of fabric, allowing them also to be worn 'inside out'.

This standard method for creating reversible garments was thus selected for incorporation into the design process, aiming to further explore how a garment could evolve and change through the way it is worn. Thus, two separate garments, a top and a skirt were developed. The garments were developed to be worn either separately or together to form a dress, and the skirt was also designed to be worn at different lengths. The garment design specification is illustrated in Figure 4.13.

Toiles, mock-up garments, were developed to check that the pattern was correct. This stage also allowed testing of the concept for the garments, with two colours of fabric used to represent the two sides of the garment, grey and beige. The toile was used to simulate how the final garment could be worn to change its appearance and how the printed pattern of each side of the garment would need to relate to one another. Figure 4.14 illustrates this process and the various styles in which the two garments can be worn together.

4.6.1 Print Design

Floral and stripes were chosen as the print themes in view of their common recurrence in fashion trends.

Figure 4.13. Evolving cyclical coloured garment design

Figure 4.14 Evolving garment toile development

4.7 Summary and conclusions.

Natural colouring materials may be extracted, using a simple water-based process, from leaves and bark, which are by-products from the responsible farming of the eucalyptus species used to produce the wood pulp from which lyocell fibres are manufactured. Thus, they represent a potentially renewable resource of colour, inherited from the plant source used to produce the fibre. Screen prints were produced successfully on fabrics constructed from two commercial grades of lyocell, which required only a mild scouring pre-treatment, using print pastes containing only the extracted colour, a natural thickener and water. The prints provided an attractive golden-yellow colour on a clean white background. The performance of the prints, in terms of fastness to washing, rubbing and light, was good to excellent, rather unexpectedly, and was marginally superior to the performance of the prints on fabric which had received an alum mordant treatment. The alum pre-treatment gave rise to enhanced colour strength but a less attractive brownish-yellow colour. Explanations have been proposed for the excellent set of technical properties on unmordanted fabrics, based on the probable presence in eucalyptus extracts, supported by previous literature reports, of ingredients that provide both self-mordanting properties and a degree of UV protection. On the basis that the colours are natural, it is anticipated that they would be biodegradable.

The attractive colour and the level of technical performance of the process described in the first part of this chapter offer distinct possibilities for the design of fashion fabrics, with the process offering significant advantages in terms of sustainability. This may well be the most sustainable approach to coloured textiles that has been reported to date. The second part of research presented gave life to the technical findings by using the concept of 'cyclical colour' within design to produce sustainably coloured fashion garments. This research finding is illustrated in Figure 4.15.

There is a significant limitation at this stage in only providing one colour. It is concluded that, although the research provides a model for sustainable coloration of fashion and textiles, it is a long-term solution. Additionally, industrial development towards a large scale operation would be required. More immediate solutions are thus also required, and so the research direction for the following chapter aims to explore alternative shorter terms solutions for sustainability of coloured cellulosic fashion and textiles.

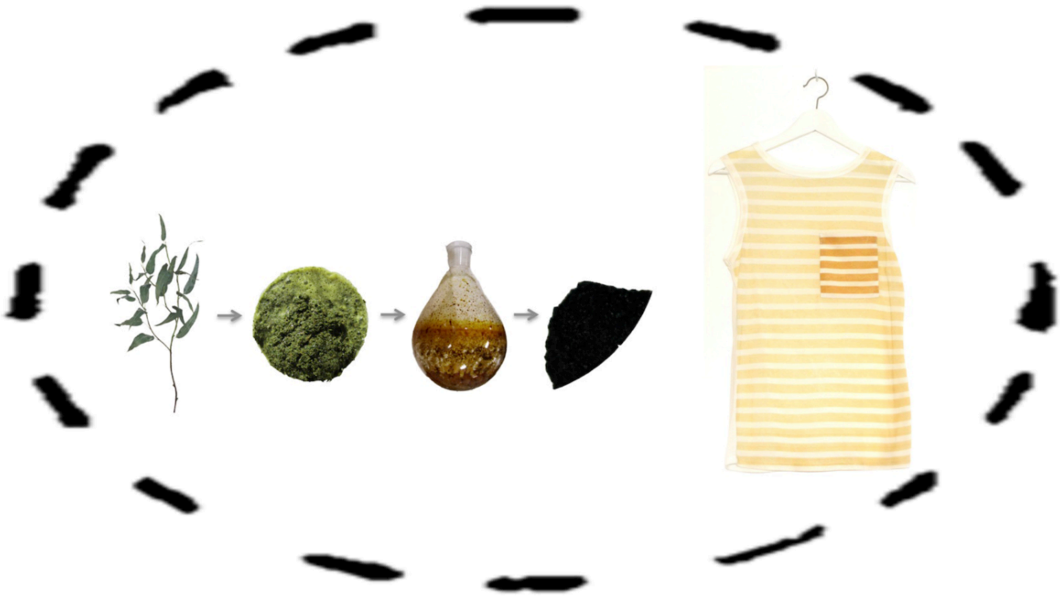


Figure 4.15. Cyclical coloration

CHAPTER 5: Responsible Colour

5.1 Introduction

A consideration of the results from the initial technical and design experimentation presented in Chapter 4 informed the next stages of the research. It was concluded from the limitations observed in achieving sustainable colour based on natural dyes extracted from eucalyptus bark and leaves, primarily that only one colour, yellow, was achievable at this stage, that other more immediate solutions considered as environmentally responsible whilst offering a range of colours are required for colouring lyocell fabrics. The research described in this chapter therefore explores the use of a carefully selected set of synthetic dyes aimed at minimizing the environmental impact of colour for fashion textiles.

In Section 2.2.1, a definition was devised and adopted by the researcher for the term 'sustainable' in the context of this research project. The phrase 'learning to live in harmony with our planet and to take from it only what we are able to give back to it without causing detrimental damage' was adopted with the intention to provide a benchmark for the research outcomes. Synthetic dyes are oil-based, meaning that their creation and production is reliant on a non-renewable, finite resource. In using synthetic dyes as the source of colour for the progression of the research from this point forward, it is conceded that truly sustainable coloured fashion textiles, such as those described in Chapter 4, are not achievable. In expanding the colour palette to create desirable and diverse aesthetics with appropriate commercial fastness properties, it was recognized that the use of synthetic reactive dyes would be required, so that the research direction moved towards exploring environmentally responsible, rather than sustainable, coloured fashion textiles.

The aim of the research described in this chapter was to establish the most environmentally responsible method for screen-printing lyocell fabrics. The approach to responsible colour was achieved through two phases of research. The first phase, presented in this chapter, focused on the technical aspects of reactive dyes and fabric preparation for screen-printing, based on identifying that the relationship between fibre and colour was the key feature. The second phase, informed by the technical outcomes and presented in the following chapter, Chapter 6, focused on exploring the use of design methods to minimize the inevitable environment impact that is incurred thorugh the use of chemical, water and energy during coloration stages. This was achieved through extending wearability within the life cycle stages of garments, and extending the key relationship identified in this chapter between fibre and colour to incorporate the relationship between fibre, colour and garment.

The research reported within this chapter set out to identify the fibre, process and dyestuff combinations that would provide minimized environmental impact. A method of best practice for the screen-printing of lyocell fabrics was developed, on the basis of the outcomes of experimentation and on conclusions derived from visual assessment of screen-printed samples. The technical understanding that emerged from the investigations, and the methods that were developed for both fabric preparation and coloration provided a 'responsible colour' outcome. The technical underpinning was then used as a tool to inform the design inquiry phase of the research, as presented in the following chapter, Chapter 6, which made practical use of the environmentally responsible methods developed in the production of the coloured garments.

5.2 Pre-creative Stages of Coloration

Before fibres can be subjected to coloration processes, they must firstly be prepared appropriately. Several stages from fibre development up to the coloration stage are required, all of which use water, energy and chemicals, to prepare fabrics for finishing processes, and these give rise to a combined environmental impact (Slater, 2003b). Of prime importance among these preparatory processes, especially for cellulosic fibres, such as cotton and lyocell, are scouring and bleaching. Scouring is an aggressive washing procedure to remove impurities that may hinder efficient dye uptake by the fabric, while bleaching is a chemical process used to remove background colour and create a white fabric. It was considered of particular importance in the context of this study to minimize the environmental impact of the pre-creative stages involved prior to colour being incorporated, reducing as far as possible the use of chemicals, water and energy, taking into account the nature of the fibre and dyes selected, and the subsequent processing.

For reasons discussed in Chapter 4, lyocell remained the fabric of choice for the research based on its environmental credentials, and screen-printing the method selected for coloration, rather than dyeing. For the coloration, dyestuff selection becomes a vital consideration with a view to minimizing environmental impact. This feature is considered in detail in Section 5.3 of this chapter. Once the fabric is prepared for coloration, the particular dyestuff is selected, the print paste is formulated, the ingredients mixed and the fabric is made ready for printing. These pre-creative stages were the focus for this phase of research as described in this chapter; each stage was analyzed technically in order to establish a method of best practice for the screen-printing of lyocell fabric. In addition, a comparison was carried out of the outcomes on cotton fabrics and the regenerated cellulose fabrics, Tencel A100, standard Tencel and Modal, at specifications stated in the fabric specification table (Table 4.1, chapter 4).

5.3 Technical inquiry for the pre-creative sages

5.3.1 Synthetic dye selection

Typically for the coloration of cellulose fibres, including cotton and the regenerated fibres, lyocell and Modal, the group of synthetic dyes selected for colour application is reactive dyes. Thus, reactive dyes were the appropriate application class for the purpose of this research.

The reactive dye group is a class of synthetic dyes that can be used for the coloration of cellulosic, protein and synthetic fibres such as cotton, silk and nylon respectively (Lewis, 2014a). The name given to this group of dyes derives from the fact that they react chemically with (i.e., are *reactive* towards) the fibres. The performance of this group of dyes is due to their unique ability in forming covalent bonds not only with cellulosic fibre substrates, but also with protein and polyamide fibres (Christie, 2001b; Carr, 1995a). It is their flexibility in application, good fastness properties and the variety in the range of achievable shades of colour that the reactive dyes offer that has led to their commercial success and their current dominant use in the coloration of modern textiles (Lewis, 2014b; Bride, 2007; Hunter & Renfrewb, 1999; Carr, 1995b).

There is a particular environmental issue with reactive dyes, in that they are not capable of fixing 100% on the fibre. The main reason for this is that some of the dye undergoes a chemical reaction with water (*hydrolysis*) under the alkaline conditions (commonly using sodium bicarbonate) that are required for fixation. This results in the formation of *hydrolysed dye*, which is no longer able to react with the fibre and has to be thoroughly washed off after dyeing or printing, so that it inevitably appears in the effluent from the dyeing process. Within the range of reactive dyes, three broad levels of fixation can be achieved, high fixation (90%), moderate fixation (75%), low fixation (60%) (Miles, 2003). The higher the level of fixation achieved, the lower the environmental impact caused through loss of dyestuff in the effluent at washing stages. However, for screen-printing purposes, low fixation dyes are commonly recommended, the group that cause the highest environmental impact. There are technical reasons why this is the case. These dyes are relatively inert towards alkali at low temperatures, so that reasonably stable screen print pastes may be formulated that incorporate together both the dye and the alkali (sodium bicarbonate) required for fixation. These dyes also have the technical advantage that the hydrolysed dye remaining at the end of the process is easily washed off and ensures that there is no back staining in white areas of the fabric. It is apparent that most manufacturers and suppliers of reactive dyes continue to recommend the same types of dyes for screen-printing that have been offered for decades. This opinion was reinforced by the researcher's attendance at ITMA, the major international trade show and conference for manufacturers and suppliers of textile raw materials and chemicals, machinery and equipment, in Barcelona, Spain (September 2011), and informal discussions carried out at the event with delegates from the leading global suppliers of reactive dyes.

The South Korean dyestuff manufacturer KISCO was identified as a potential supplier, on the basis that they have recently developed a range of reactive dyes, marketed as Synocron RD, specifically aimed at the screen-printing of textiles. This range of dyes are claimed to reduce both financial and environmental cost, mainly on the basis of increased dye fixation compared with the range of dyes that are traditionally used. This concept underlying the dyes fits with the current research trend in developing more environmentally responsible reactive dyes. However, most companies have been focusing their dye research on textile dyeing, while KISCO appear to be unique in developing products specifically for screen-printing applications. Increasing fixation rates compared with those of traditional reactive dyes results in less dye being removed during the washing off stage and ending up in the effluent. As well as minimizing waste, the need for less processing also reduces chemicals, water and energy consumption.

Increased fixation of the dyes is created through altering the chemical structure of the dye molecules. Traditional reactive dyes, especially those used in screen-printing, have one functional group that reacts in contact with the substrate of a fibre to create a covalent bond. This bond is permanent and is the feature that secures the dye molecule to the fibre to create fixation.

The range of Synocron RD dyes developed by KISCO have modified chemical structures, in which more than one functional group is present. This type of molecule is known as bi-functional, if it has two functional groups, and tri-functional if it has three. Increasing the number of functional groups in the dye molecule increases the opportunity for reaction during coloration stages with the fibre substrate. Essentially, they can be visualized as having more than one arm with which to cling onto the fibre. For example, if the first functional group does not manage to bond, the second or third most likely will.

The KISCO dyes were chosen as appropriate for the research study, due to their unique position as a group of dyes specifically developed for reduced environmental impact during screen-printing. However, it is a feature of this group of dyes that the range of colours achievable with their use is limited to medium to dark shades. The dyes are less well suited for achieving lighter, brighter shades. This colour limitation with this range of dyes is consistent with a general trend that can be observed across the market for new generation reactive dyes that use more than one functional group.

Initial investigation of the KISCO Synocron RD dyes was conducted through experimentation at the KISCO laboratory in South Korea, carried out by the researcher following an approach and invitation by the company based on their interest in the project concept. Fabric samples of Tencel A100, Standard Tencel, Modal and cotton were screen printed for assessment using the eight available colours within the full Synocron RD range, following their technical procedures and advice. The initial results obtained in this investigation provided the important observation that deeper colours were achievable with screen printing on Tencel A100 compared with cotton when applied at the same concentration. This demonstrates that less dyestuff is required for screen-printing on Tencel A100 than on cotton in order to achieve the same depth of colour, a feature that is positive both economically and environmentally. The full report on this investigation can be found in Appendix 2. The experience working in the Korean laboratory was used in subsequent print experimentation, which was carried out in the laboratories in the School of Textiles & Design, Heriot-Watt University.

5.3.2 Preparation of lyocell fabric for screen-printing

Regenerated cellulose fabrics, such as lyocell as used for this study, are generally treated in a similar way as other cellulosic fabrics, such as cotton, for fabric preparation before coloration stages. In the case of cotton, an intensive scouring stage is carried out to ensure that fibres are clean when exposed to the dye molecules so as to increase dye uptake. Cotton is also bleached prior to being printed, as in its natural state it is an off-white, beige colour. Bleaching cotton white allows the development of optimum colour brightness when printed. The chlorine-containing bleach that is traditionally used to prepare cotton fibres for coloration is known to be toxic to both the environment and the consumer (Kant, 2012). Alternative methods for bleaching are used by some mills, including ozone treatment, a relatively new technology that uses cool water in contrast with traditional bleaching processes, which require maintaining the fabric in hot water for many hours. Ozone breaks down during the process into innocuous materials, water and oxygen, thus minimizing contamination of wastewater .

Unlike cotton, lyocell is produced within a solvent-based, closed loop process, as described in section 2.3.2, and consequently it is a much cleaner fibre than cotton that has been grown in the open and harvested. Lyocell has experienced no exposure to external factors that would create 'dirt', up until the point where it is spun into yarn and either woven or knitted. So the primary purpose of the scouring process in the case of lyocell is to remove any build up of wax that has been used to provide smooth yarns during their construction into fabrics. In comparison, the cotton scouring process needs to remove natural oils, fats, waxes and the build up of grime from farming and harvesting, all of which interfere with the dyeing process. It was therefore hypothesized that lyocell fabrics could incorporate a reduced, gentler scouring process than cotton.

5.4 Experimental

5.4.1. Materials

The following reactive dyes were provided by KISCO, 112-31 Yeomchang-Dong Kangseo-Gu, Seoul, 157-040, Korea.

Synocron Yellow RD
Synocron Deep Red RD
Synocron Navy Blue RD
Synocron Orange RD
Synocron Rubine RD
Synocron Black RD
Synocron Red RD
Synocron Brilliant Blue RD

Knitted Tencel A100, standard Tencel, Modal and cotton were supplied by Lenzing AG, Austria. Exenol XB, described as an anionic/nonionic alcohol ethoxylate surfactant, a simple soaping composition considered to have minimal environmental impact, was supplied by J. & W. Whewell Ltd, Manchester, UK. Manutex F 700, urea, Matexil-Pal, and sodium bicarbonate were all available as routinely used chemicals within the Heriot-Watt University dyeing laboratory.

5.4.2. Fabric pre-treatment

Fabric samples were scoured in a 0.1% solution of Exenol XB in water at 40°C for 30 minutes, rinsed with cold water and then air-dried at room temperature. .

5.4.3 Screen-printing

Fabric samples for technical testing were screen printed on a Zimmer magnetic print table with a single pass of the print paste across the fabric using a metal rod. The print paste was mixed following a standard recipe and method for reactive dyes, exemplified in Table 5.1 for a quantity of 500g.

Table 5.1. Typical print paste recipe

Ingredients	Quantities
Water	225ml
Manutex F 700	23g
Warm Water	150ml
Urea	50g
Matexil-Pal	5g
Cold Water	25ml
Dye	Variable quantity
Sodium Bicarbonate	12.5g

5.4.4 Finishing

After printing, the samples were then steamed at 100°C for 10 minutes, given a first hot rinse for 1 minute at 98°C, a second hot rinse for 1 minute at 98°C, a third rinse with a 0.1% aqueous solution of Exenol XB, a fourth rinse with a 0.1% aqueous solution of Exenol XB, and a final rinse with cold water at 40°C for 1 minute. Finally they were air-dried.

5.4.5. Assessment

Samples were visually evaluated for coverage and uniformity across fabric surface.

5.5 Developing 'Best Practice' For Printing

As a first step to establish a best practice method for colouring lyocell, printing trials were conducted initially on unscoured, unbleached fabric samples. Tencel A100, Standard Tencel, Modal and cotton were used for comparison. Initially to ascertain whether printing on to unscoured, unbleached fabrics was a viable process, the Synocron Navy Blue RD dye was screen printed on to the fabric samples, to give the results as shown in the samples in Figure 5.1. Initial visual inspection demonstrated positive results in that the dye is clearly present across the fabric surface leading to the initial conclusion that the process provides a viable option. It was observed at this stage that the quality of colour printed across the fabric surface of the cotton sample appears much poorer; an uneven quality is demonstrated compared to the other fabric samples for Tencel A100, Standard Tencel and Modal shown in Figure 5.1.

Test R1. Knitted Cotton fabric sample RA was not scoured or bleached before being screen-printed with a navy blue block print, steamed, washed, air dried, and then assessed. Test R2. Knitted Tencel A100 fabric sample RB was not scoured or bleached before being screen-printed with a navy blue block print, steamed, washed, air dried, and then assessed. Test R3. Knitted Modal fabric sample RC was not scoured or bleached before being screen-printed with a navy blue block print, steamed, washed, air dried, and then assessed. Test R4. Knitted Tencel Standard fabric sample RD was not scoured or bleached before being screen-printed with a navy blue block print, steamed, washed, air dried, and then assessed.

Table 5.2 shows the methods and swatch samples (RA to RD) for print test's conducted. The samples produced are presented in Figure 5.1.

Table 5.2. Methods and swatches for samples RA to RD

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RA 	Cotton Knitted	None	Synocron Navy Blue RD, 10g/1kg	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RB 	Tencel A100 Knitted	None	Synocron Navy Blue RD ,10g/1kg	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RC 	Modal Knitted	None	Synocron Navy Blue RD ,10g/1kg	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RD 	Tencel Standard	None	Synocron Navy Blue RD ,10g/1kg	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

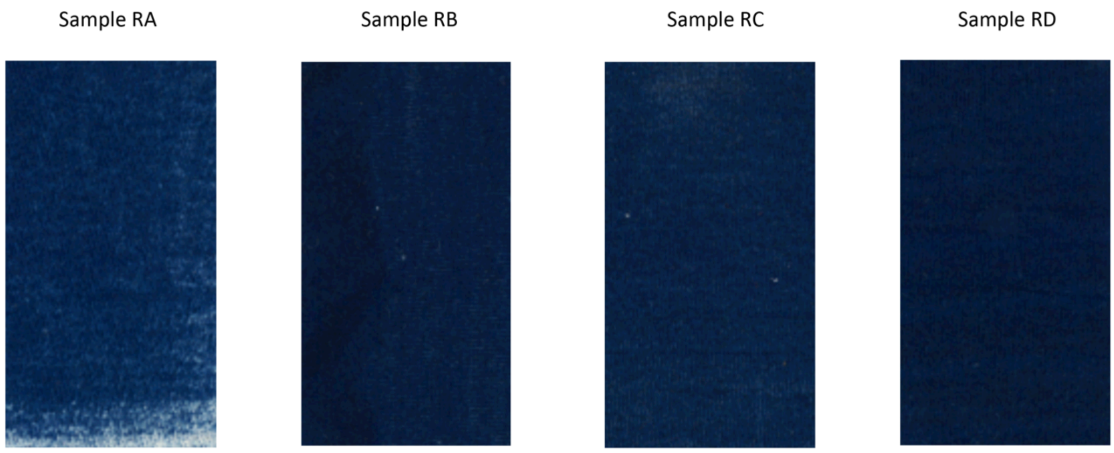


Figure 5.1. Samples RA to RD

To establish more definitive results and observe the quality of colour printed across the surface of the samples, three other colours, Synocron Brilliant Blue RD, Synocron Red RD, and Synocron Yellow RD were screen printed on to the unscoured and unbleached four test fabrics at light, medium and dark shades.

Test R5. Knitted Cotton fabric sample RE.1 was not scoured or bleached before being screen-printed with brilliant blue block print in 'light' shade, steamed, washed, air dried, and then assessed.

Test R6. Knitted Cotton fabric sample RE.2 was not scoured or bleached before being screen-printed with brilliant blue block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R7. Knitted Cotton fabric sample RE.3 was not scoured or bleached before being screen-printed with brilliant blue block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R8. Knitted Tencel A100 fabric sample RF.1 was not scoured or bleached before being screen-printed with brilliant blue block print in 'Light' shade, steamed, washed, air dried, and then assessed.

Test R9. Knitted Tencel A100 fabric sample RF.1 was not scoured or bleached before being screen-printed with brilliant blue block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R10. Knitted Tencel A100 fabric sample RF.2 was not scoured or bleached before being screen-printed with brilliant blue block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R11. Knitted Tencel A100 fabric sample RF.3 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Test R12. Knitted Modal fabric sample RG.1 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘light’ shade, steamed, washed, air dried, and then assessed.

Test R13. Knitted Modal fabric sample RG.2 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Test R14. Knitted Modal fabric sample RG.3 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Test R15. Knitted Tencel Standarad fabric sample RH.1 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘light’ shade, steamed, washed, air dried, and then assessed.

Test R16. Knitted Tencel Standarad fabric sample RH.2 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Test R16. Knitted Tencel Standarad fabric sample RH.3 was not scoured or bleached before being screen-printed with brilliant blue block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Table 5.3 shows the methods and swatch samples (RE.1 to RH.3) for print test’s conducted using Synocron Brilliant Blue RD. The samples produced are presented in Figure 5.2.

Table 5.3. Methods and swatches for samples RE.1 to RH.3

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RE.1 	Cotton Knitted	None	Synocron Brilliant Blue RD, 20g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RE.2 	Cotton Knitted	None	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RE.3 	Cotton Knitted	None	Synocron Brilliant Blue RD, 80g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RF.1 	Tencel A100 Knitted	None	Synocron Brilliant Blue RD, 20g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RF.2 	Tencel A100 Knitted	None	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RF.3 	Tencel A100 Knitted	None	Synocron Brilliant Blue RD, 80g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RG.1 	Modal Knitted	None	Synocron Brilliant Blue RD, 20g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RG.2 	Modal Knitted	None	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RG.3 	Modal Knitted	None	Synocron Brilliant Blue RD, 80g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RH.1 	Tencel Standard Knitted	None	Synocron Brilliant Blue RD, 20g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RH.2 	Tencel Standard Knitted	None	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RH.3 	Tencel Standard Knitted	None	Synocron Brilliant Blue RD, 80g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

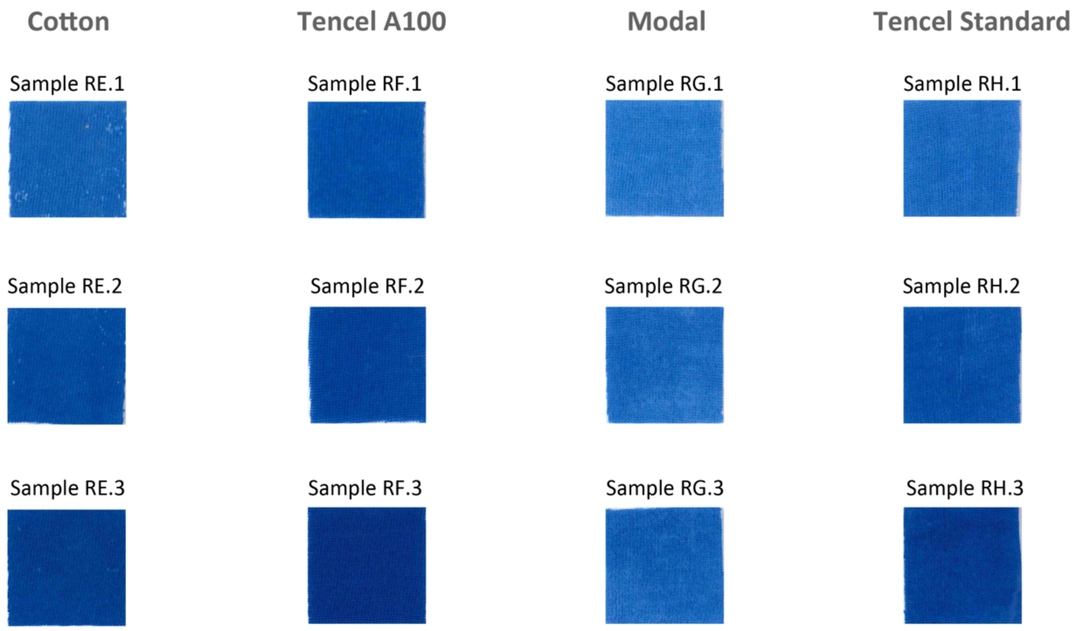


Figure 5.2. Samples RE.1 to RH.3.

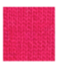
Table 5.4 shows the methods and swatch samples (RE.1 to RH.3) for print tests conducted using Synocron Red RD. The samples produced are presented in Figure 5.3.

Test R17. Knitted Cotton fabric sample RI.1 was not scoured or bleached before being screen-printed with red block print in 'light' shade, steamed, washed, air dried, assessed.
Test R18. Knitted Cotton fabric sample RI.2 was not scoured or bleached before being screen-printed with red block print in 'medium' shade, steamed, washed, air dried, assessed.
Test R19. Knitted Cotton fabric sample RI.3 was not scoured or bleached before being screen-printed with red block print in 'dark' shade, steamed, washed, air dried, assessed.
Test R20. Knitted Tencel A100 fabric sample RJ.1 was not scoured or bleached before being screen-printed with red block print in 'light' shade, steamed, washed, air dried, assessed.
Test R21. Knitted Tencel A100 fabric sample RJ.2 was not scoured or bleached before being screen-printed with red block print in 'medium' shade, steamed, washed, air dried, assessed.
Test R22. Knitted Tencel A100 fabric sample RJ.3 was not scoured or bleached before being screen-printed with red block print in 'dark' shade, steamed, washed, air dried, and then assessed.

Test R23. Knitted Modal fabric sample RK.1 was not scoured or bleached before being screen-printed with red block print in ‘light’ shade, steamed, washed, air dried, and then assessed.
Test R24. Knitted Modal fabric sample RK.2 was not scoured or bleached before being screen-printed with red block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.
Test R25. Knitted Modal fabric sample RK.3 was not scoured or bleached before being screen-printed with red block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.
Test R26. Knitted Tencel Standard fabric sample RL.1 was not scoured or bleached before being screen-printed with red block print in ‘light’ shade, steamed, washed, air dried, and then assessed.
Test R27. Knitted Tencel Standard fabric sample RL.2 was not scoured or bleached before being screen-printed with red block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.
Test R28. Knitted Tencel Standard fabric sample RL.3 was not scoured or bleached before being screen-printed with red block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Visual outcomes of the large samples obtained from these initial print trials are presented for Synocron Red RD tests R17 to R28 in figure 5.3. The methods and swatch samples (RI.1 to RL.3) for each print test conducted (R17 to R28) are shown in table 5.4.

Table 5.4 methods and swatch samples for RI.1 to RL.3.

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RI.1 	Cotton Knitted	None	Synocron Red RD, 12.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RI.2 	Cotton Knitted	None	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RI.3 	Cotton Knitted	None	Synocron Red RD, 50g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RJ.1 	Tencel A100 Knitted	None	Synocron Red RD, 12.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RJ.2 	Tencel A100 Knitted	None	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RJ.3 	Tencel A100 Knitted	None	Synocron Red RD, 50g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RK.1 	Modal Knitted	None	Synocron Red RD, 12.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RK.2 	Modal Knitted	None	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RK.3 	Modal Knitted	None	Synocron Red RD, 50g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RL.1 	Tencel Standard Knitted	None	Synocron Red RD, 12.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RL.2 	Tencel Standard Knitted	None	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RL.3 	Tencel Standard Knitted	None	Synocron Red RD, 50g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

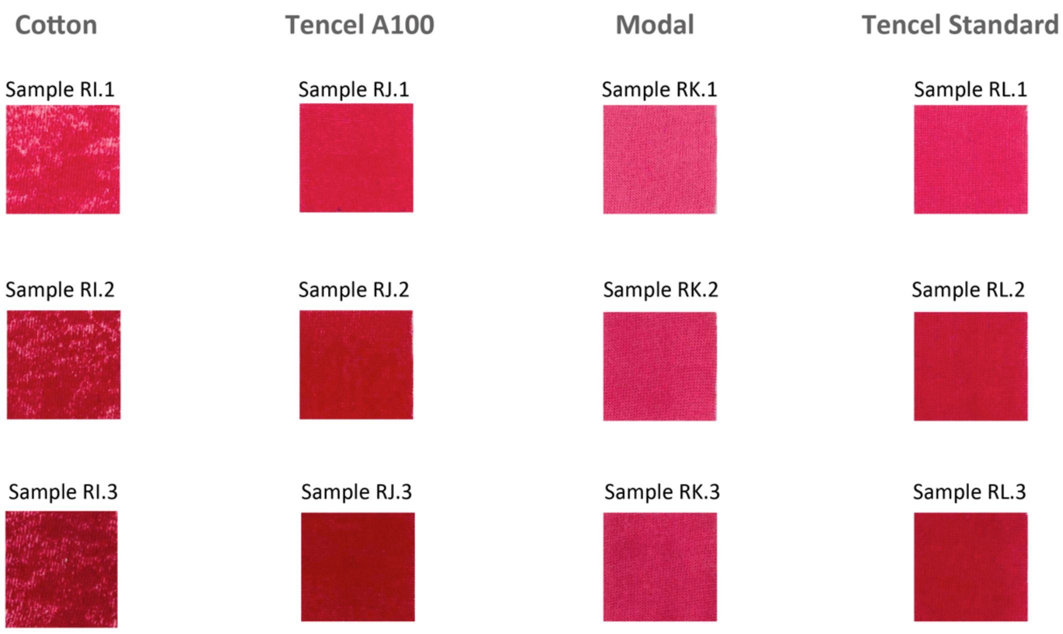


Figure 5.3. Samples RI.1 to RL.3.

Table 5.5 shows the methods and swatch samples (RM.1 to RP.3) for print test's conducted using Synocron Yellow RD. The samples produced are presented in Figure 5.4.

Test R29. Knitted Cotton fabric sample RM.1 was not scoured or bleached before being screen-printed with yellow block print in 'light' shade, steamed, washed, air dried, and then assessed.

Test R30. Knitted Cotton fabric sample RM.2 was not scoured or bleached before being screen-printed with yellow block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R31. Knitted Cotton fabric sample RM.3 was not scoured or bleached before being screen-printed with yellow block print in 'dark' shade, steamed, washed, air dried, and then assessed.

Test R32. Knitted Tencel A100 fabric sample RN.1 was not scoured or bleached before being screen-printed with yellow block print in 'light' shade, steamed, washed, air dried, and then assessed.

Test R33. Knitted Tencel A100 fabric sample RN.2 was not scoured or bleached before being screen-printed with yellow block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R34. Knitted Tencel A100 fabric sample RN.3 was not scoured or bleached before being screen-printed with yellow block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Test R35. Knitted Modal fabric sample RO.1 was not scoured or bleached before being screen-printed with yellow block print in ‘light’ shade, steamed, washed, air dried, and then assessed.

Test R36. Knitted Modal fabric sample RO.2 was not scoured or bleached before being screen-printed with yellow block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

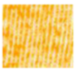
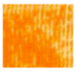
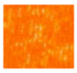
Test R37. Knitted Modal fabric sample RO.3 was not scoured or bleached before being screen-printed with yellow block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Test R38. Knitted Tencel Standard fabric sample RP.1 was not scoured or bleached before being screen-printed with yellow block print in ‘light’ shade, steamed, washed, air dried, and then assessed.

Test R39. Knitted Tencel Standard fabric sample RP.2 was not scoured or bleached before being screen-printed with yellow block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Test R40. Knitted Tencel Standard fabric sample RP.3 was not scoured or bleached before being screen-printed with yellow block print in ‘dark’ shade, steamed, washed, air dried, and then assessed.

Table 5.5. Methods and swatches for samples RM1 to RP.3

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RM.1 	Cotton Knitted	None	Synocron Yellow RD, 10g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RM.2 	Cotton Knitted	None	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RM.3 	Cotton Knitted	None	Synocron Yellow RD, 40g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RN.1 	Tencel A100 Knitted	None	Synocron Yellow RD, 10g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RN.2 	Tencel A100 Knitted	None	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RN.3 	Tencel A100 Knitted	None	Synocron Yellow RD, 40g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RO.1 	Modal Knitted	None	Synocron Yellow RD, 10g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RO.2 	Modal Knitted	None	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RO.3 	Modal Knitted	None	Synocron Yellow RD, 40g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RP.1 	Tencel Standard Knitted	None	Synocron Yellow RD, 10g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RP.2 	Tencel Standard Knitted	None	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RP.3 	Tencel Standard Knitted	None	Synocron Yellow RD, 40g/1kg (DARK)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

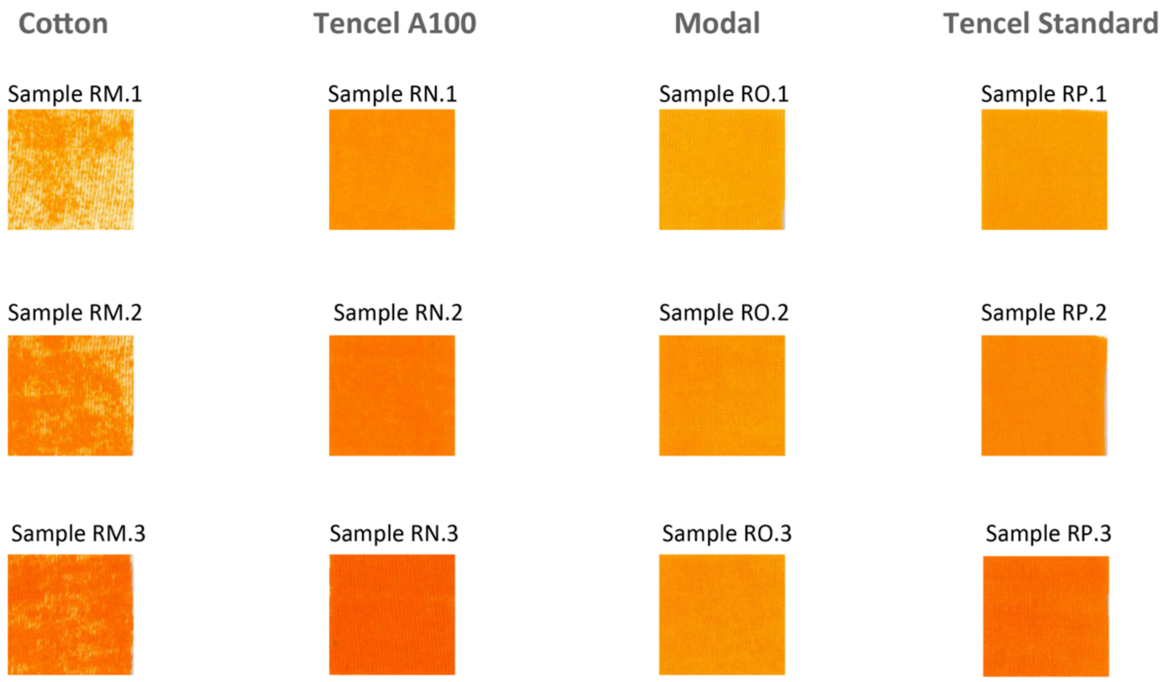


Figure 5.4. Samples RM.1 to RP.3.

The printed samples were visually assessed. As Figures 5.1 – 5.4 demonstrate, on visual inspection, Tencel A100 was observed to have acquired a more uniform coverage of colour than cotton, which was exceptionally patchy in coverage as first observed in samples presented in figure 5.1. This feature is most noticeable visually in Figure 5.4, in the cotton sample printed with Synocron Orange RD at a light shade. This contrasts with only an occasional and intermittent line hardly noticeable but identified as causing a stripy effect across the pattern surface of the Tencel A100. This suggested that, although a reasonable coverage is achievable with unscoured Tencel A100, there is a stripy effect of uneven colour after screen-printing, demonstrated in the sample from the first set of print tests for sample RB, presented again in Table 5.6, and sample RB shown in close-up in Figure 5.5. This effect was probably due to the difference between the spin finish of yarns used at different feeds of the multi-feed knitting machine.

Table 5.6. Method and swatch for sample RB

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RB 	Tencel A100 Knitted	None	Synocron Navy Blue RD, 10g/1kg	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

Tencel A100
Enlarged 'Stripey' Effect
Sample RB

Figure 5.5. Enlarged sample RB demonstrating 'stripy' coverage of print paste across the fabric surface of unscoured Tencel A100.

On the basis of these initial trials, further print tests were conducted that incorporated a gentle scouring process before screen printing. The purpose of introducing the scouring process was to assess if the observed ‘stripey’ effect from previous unscoured samples, presumably caused by wax left on fibres from construction would be still be present. Samples of Tencel A100, Standard Tencel, Modal and Cotton were subjected to a light scouring under mild conditions using a solution of 0.1% of Exenol XB a gentle biodegradable washing agent in water at 40°C for 30 minutes, rinsed with cold water and then air-dried at room temperature. The samples were then printed using the same colours at the previous medium shade depth from the initial trials using unscoured fabrics (R5 to R40) and the results were again visually assessed.

Test R41. Knitted Cotton fabric sample RQ was gently scoured before being screen-printed with brilliant blue block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.
Test R42. Knitted Tencel A100 fabric sample RR was gently scoured before being screen-printed with brilliant blue block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.
Test R43. Knitted Modal fabric sample RS was gently scoured before being screen-printed with brilliant blue block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.
Test R44. Knitted Tencel Standard fabric sample RT was gently scoured before being screen-printed with brilliant blue block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Table 5.7 shows the methods and swatch samples (RQ to RT) for each print test conducted (R41 to R44). The larger samples produced are presented in Figure 5.6.

Table 5.7. Methods and swatches for samples RQ to RT, print trials R41 to R44

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RQ 	Cotton Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RR 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RS 	Modal Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RT 	Tencel Standard Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

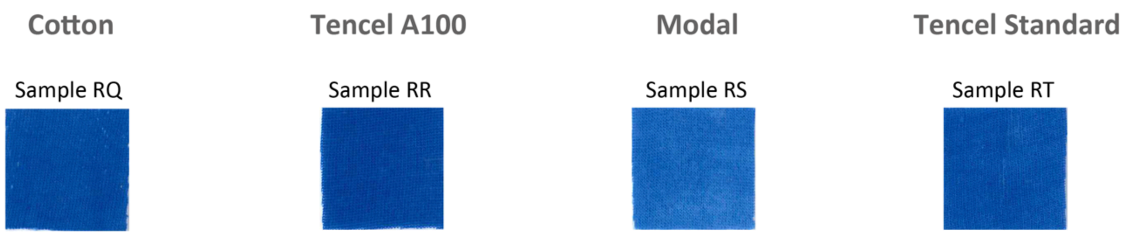


Figure 5.6. Samples (RQ to RT) from tests R41 to R44.

Test R45. Knitted Cotton fabric sample RU was gently scoured before being screen-printed with red block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Test R46. Knitted Tencel A100 fabric sample RV was gently scoured before being screen-printed with red block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Test R47. Knitted Modal fabric sample RW was gently scoured before being screen-printed with red block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Test R48. Knitted Tencel Standard fabric sample RX was gently scoured before being screen-printed with red block print in ‘medium’ shade, steamed, washed, air dried, and then assessed.

Table 5.8 shows the methods and swatch samples (RU to RX) for each print test conducted (R45 to R48). The larger samples produced are presented in Figure 5.7.

Table 5.8. Methods and swatches for samples RU to RX, print trials R45 to R48

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RU 	Cotton Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RV 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RW 	Modal Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RX 	Tencel Standard Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Red RD, 25g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

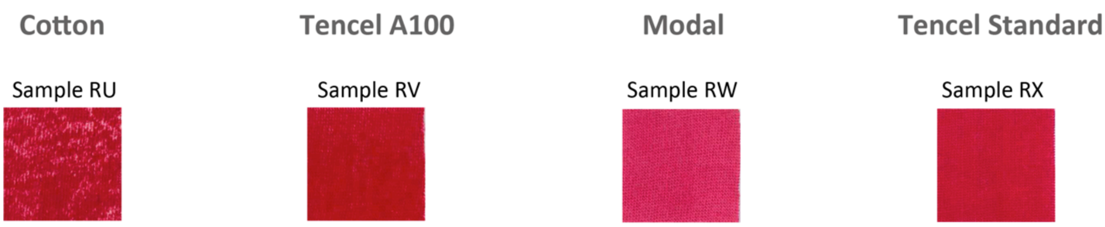


Figure 5.7. Samples (RU to RX) from tests R45 to R48.

Test R49. Knitted Cotton fabric sample RY was gently scoured before being screen-printed with yellow block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R50. Knitted Tencel A100 fabric sample RZ was gently scoured before being screen-printed with yellow block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R51. Knitted Modal fabric sample RA2 was gently scoured before being screen-printed with yellow block print in 'medium' shade, steamed, washed, air dried, and then assessed.

Test R52. Knitted Tencel Standard fabric sample RB2 was gently scoured before being screen-printed with yellow block print in 'medium' shade, steamed, washed, air dried, and then assessed.

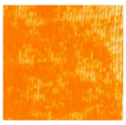
Table 5.9. shows the methods and swatch samples (RY to RB2) for each print test conducted (R49 to R52). The larger samples produced are presented in Figure 5.8.

Table 5.9. Methods and swatches for samples RY to RB2, print trials R49 to R52

Sample	Substrate	Preparation Method	Dye	Print Method	Finished	Washed
RY 	Cotton Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RZ 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RA2 	Modal Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
RB2 	Tencel Standard Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Synocron Yellow RD, 20g/1kg (MEDIUM)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C

Cotton

Sample RY



Tencel A100

Sample RZ

Modal

Sample RA2

Tencel Standard

Sample RB2

Figure 5.8. Samples (RY to RB2) from tests R49 to R52.

Samples shown in Figures 5.6 - 5.8 demonstrate that with the Tencel A100, Tencel Standard and Modal, the regenerated cellulose fibres, there is an even, consistent coverage of colour for each shade and depth. The cotton, however, remains uneven and blotchy, which clearly needs a more significant scouring tretment. This leads to the conclusion that there is a significant environmental advantage in terms of the nature of the scouring preparation that is required for screen-printing Tencel and Modal compared with that needed for cotton.

5.5.1 Bleaching

Lyocell is inherently significantly whiter than cotton. The results from printing trials to establish the best practice method for scouring Tencel A100 led to the conclusion that the bleaching stage in pre-treatment for printing fabrics was not required for Tencel, on the basis that the whiteness of the fabric was judged to be acceptable. Instrumental whiteness measurement could, in principle, be conducted to establish the exact shade of white and comparative differences for each of the four fabrics tested. However, for this study, visual assessment as shown in Figure 5.9 clearly demonstrated the differences in whiteness for each fabric. This leads to the conclusion that the man made cellulosic fabrics do not need to be bleached for printing, but cotton does, thus offering an important environmental advantage for Tencel and Modal.

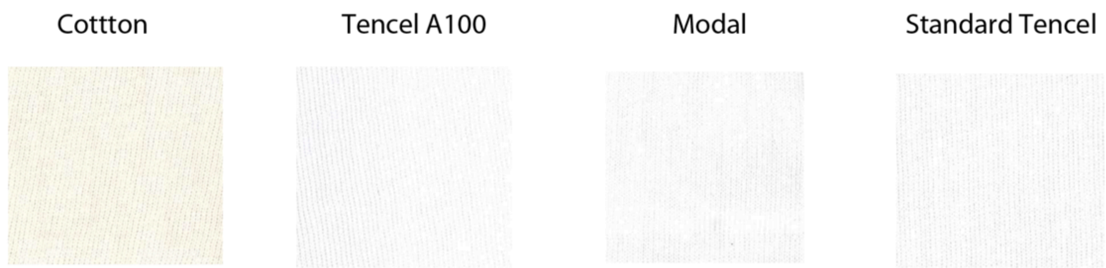


Figure 5.9. Unscoured, unbleached fabric samples to demonstrate natural whiteness.

5.5.2 Experimentation Conclusions

As a result of testing four fabrics, cotton, Tencel A100, Tencel standard and Modal, some clear environmental advantages were identified. Screen printing onto Tencel fabrics is shown to be a more environmentally responsible process, compared to screen printing on cotton fabrics on the basis of a need for a reduced temperature gentle scouring process, and no requirement for the stage of bleaching for Tencel and Modal. Tencel A100 and standard Tencel samples also demonstrate a deeper depth of colour in appearance compared to the Modal samples. This suggests Modal fabrics require either an increased concentration of dye in the print paste recipe to create the same depth of colour achieved and demonstrated in the Tencel A100 and Tencel Standard samples, or, that the reduced colour depth is a result of the fabric samples not being scoured and/or bleached. Although Modal performs well when compared to Cotton in the appearance of colour across the fabric surface of unscoured, unbleached samples, the reduced colour depth is a major disadvantage and undesirable quality for the purpose of this study.

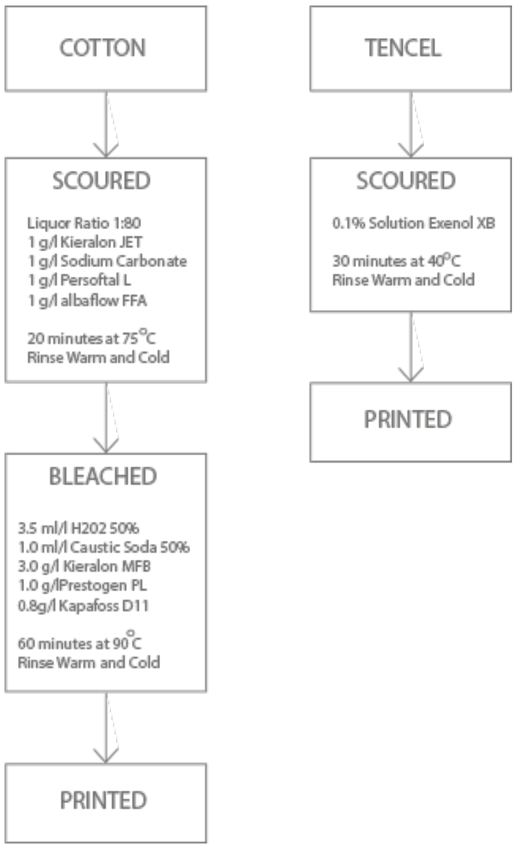


Figure 5.10. Comparison of the stages of preparation for cotton and Tencel to the point of screen printing: cotton stages based on industry methods, Tencel stages as the process developed within the research.

The environmental credentials for selecting lyocell fibres were presented earlier in the thesis, section 2.3.2. This initial decision was based on field to factory gate life cycle analysis data reported for lyocell, as well as a series of fabric assessments to be used as design tools. The practical experimentation and observations as described in this chapter allowed an independent conclusion, based on the research outcomes, that coloured Tencel fabric is a more environmentally responsible choice for use within the design outcomes than coloured cotton, including the observation that less dye is required to achieve a comparable shade.

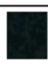
This technically focussed stage of research established the dyestuff selection for use within the next phase of research, based on the KISCO Synocron RD range and an environmentally conscious method for preparing Tencel fabric, involving light scouring at 40°C and eliminating the bleaching process was also established. These two technical elements would be used to within the design process of the next phase of research, allowing technically informed creative samples to be produced.

5.5 Colour Palettes

In terms of design and aesthetics, a significant limitation was observed at this stage in the colour range achievable of the Synocron RD dyes. The range of dyes selected for use comprises the eight colours available from the KISCO Synocron RD range. Table 5.10 illustrates the complete range of colours printed at light, medium and dark shades. This led the researcher to explore and develop a selected colour palette for use within the design process that provided shades of blue, red, green and yellow and included Black.

Table 5.10. Shows the methods and swatch samples used. Each sample of knitted Tencel A100 fabric was gently scoured using the method developed in Section *5.4.2* before being screen-printed with each colour of dye available within the KISCO RD range in a block print in 'light', 'medium' and 'dark' shade, steamed, washed, air dried, and then assessed. The larger samples produced are presented in Figure 5.11.

Table 5.10. Methods and swatches for samples TA to TH, print trials R49 to R52

Sample	Substrate	Preparation Method	Dye			Print Method	Finished	Washed
TA	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TA1		Synocron Yellow RD, 10g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TA2		Synocron Yellow RD, 20g/1kg (MEDIUM)			
			TA3		Synocron Yellow RD, 40g/1kg (DARK)			
TB	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TB1		Synocron Orange RD, 7.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TB2		Synocron Orange RD, 15g/1kg (MEDIUM)			
			TB3		Synocron Orange RD, 30g/1kg (DARK)			
TC	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TC1		Synocron Red RD, 12.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TC2		Synocron Red RD, 25g/1kg (MEDIUM)			
			TC3		Synocron Red RD, 50g/1kg (DARK)			
TD	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TD1		Synocron Deep Red RD, 10g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TD2		Synocron Deep Red RD, 20g/1kg (MEDIUM)			
			TD3		Synocron Deep Red RD, 40g/1kg (DARK)			
TE	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TE1		Synocron Rubine RD, 7.5g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TE2		Synocron Rubine RD, 15g/1kg (MEDIUM)			
			TE3		Synocron Rubine RD, 30g/1kg (DARK)			
TF	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TF1		Synocron Brilliant Blue RD, 20g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TF2		Synocron Brilliant Blue RD, 40g/1kg (MEDIUM)			
			TF3		Synocron Brilliant Blue RD, 80g/1kg (DARK)			
TG	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TG1		Synocron Navy Blue RD, 20g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TG2		Synocron Navy Blue RD, 40g/1kg (MEDIUM)			
			TG3		Synocron Navy Blue RD, 80g/1kg (DARK)			
TH	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	TH1		Synocron Black RD, 40g/1kg (LIGHT)	Screen, solid	Steamed at 100°C, 10 minutes	Hot wash @ 95°C
			TH2		Synocron Black RD, 60g/1kg (MEDIUM)			
			TH3		Synocron Black RD, 80g/1kg (DARK)			

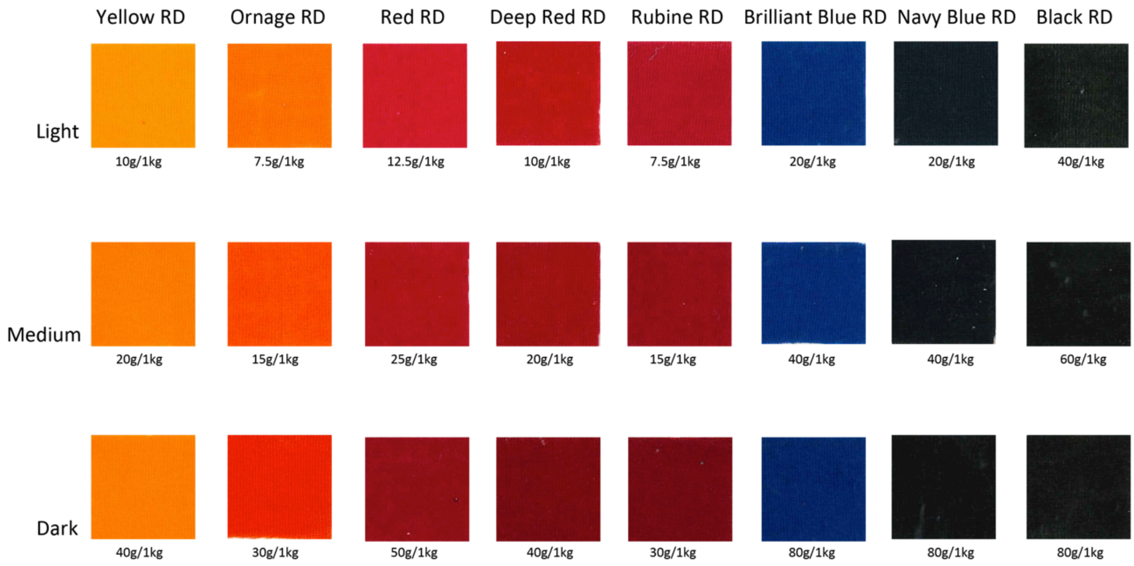


Figure 5.11. Samples (TA to TH) KISCO RD range in 'light', 'medium', 'dark' shades.

The dyes presented in Figure 5.12 were then used to create a colour palette that was developed from the KISCO Synocron RD range and subsequently used in developing design imagery. This colour palette provided a series of strong dark colours, in combination with some bright colours that are capable of providing a range of cross-seasonal shades. For example, the deeper blues and reds could be used to design Autumn/Winter fashion garments and the brighter yellows and greens could be included in Spring/Summer garment designs. The colour palette did not so readily offer lighter shades for design purposes, a limitation stemming from the bi-functional chemistry of the reactive dyestuffs being suited to creating dark rather than lighter colour shades..

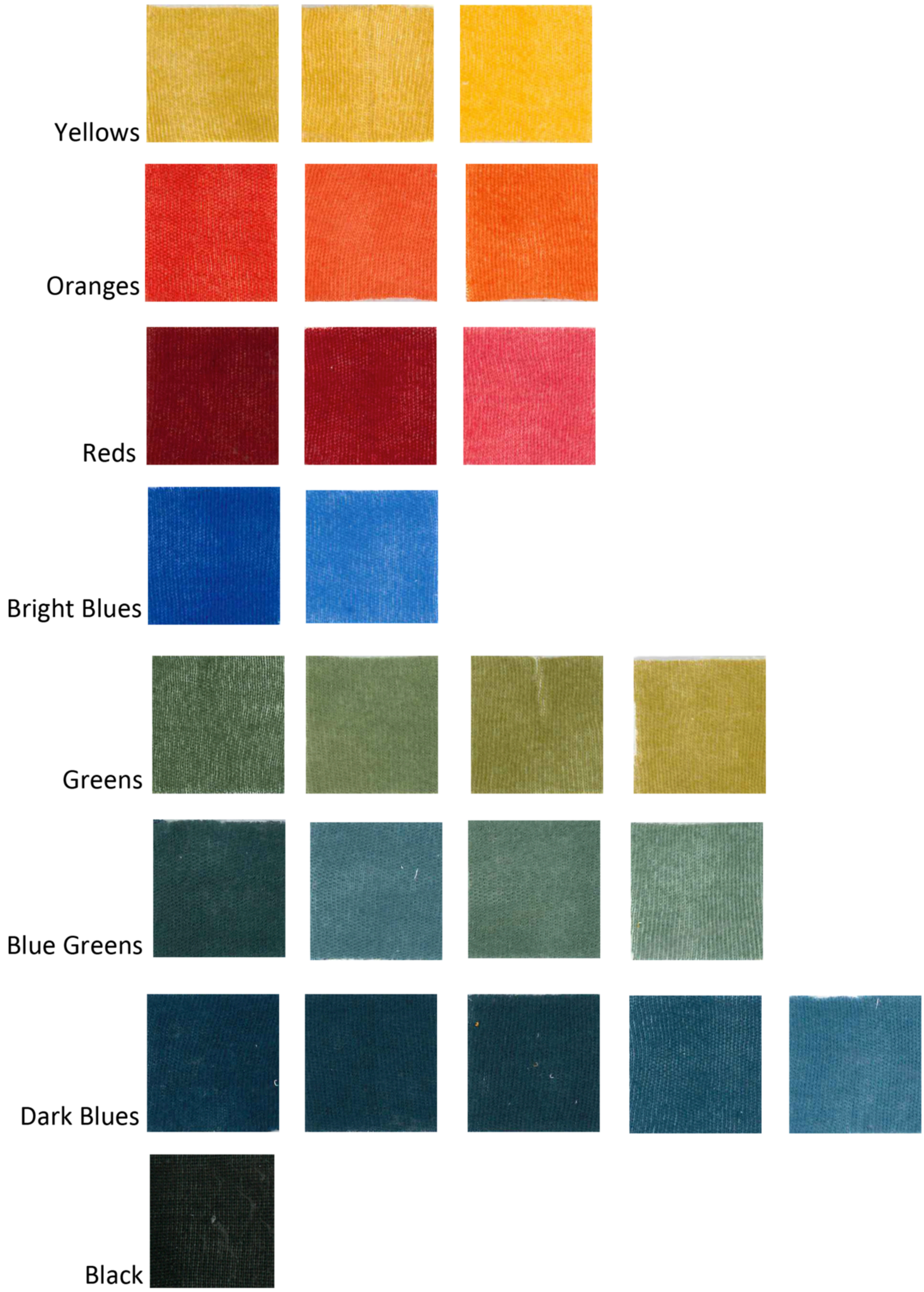


Figure 5.12. Final 'responsible colour' palette developed using the KISCO Synocron RD range.

5.6 Surface Design Development

During screen-printing of the knitted Tencel A100 fabrics, an interesting aesthetic quality within the printed fabrics was observed, involving the creation of a colour on the reverse sides of the fabric, which gave an illusory impression. This was first noted in the printed black fabric sample, Sample TH1 from table 5.10. shown in Figure 5.13 for both the front and reverse surface of the fabric, the reverse, unprinted side of the fabric appeared grey.

Figure 5.13 Large sample (TH1) Knitted Tencel A100 Sample demonstrating that the reverse, unprinted side of the fabric appeared grey on the unprinted surface.

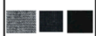
Further exploration of this effect was then carried out using the Synocron black RD dye; a black block print was screen printed on to the scoured, unbleached A100 fabric at light and medium shades onto both surfaces of the fabric at opposing ends with an overlap in the middle of the fabric where both surfaces had been printed. Results from this testing were used to inform further design development.

Test R53. Knitted Tencel A100 fabric sample TI was gently scoured before being screen-printed with black block print in 'light' shade onto the front left half surface of the fabric, air dried and then screen-printed with black block print in 'light' shade onto the reverse right half surface of the fabric, steamed, washed, air dried, and then assessed.

Test R54. Knitted Tencel A100 fabric sample TJ was gently scoured before being screen-printed with black block print in 'medium' shade onto the front left half surface of the fabric, air dried and then screen-printed with black block print in 'medium' shade onto the reverse right half surface of the fabric, steamed, washed, air dried, and then assessed.

Table 5.11. Shows the methods and swatch samples (TI to TJ) for each print test conducted (R53 to R54). The samples produced are presented in Figure 5.15.

Table 5.11. Methods and swatches for samples TI to TJ, print trials R53 to R54

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
TI FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Screen, solid Synocron Black RD 40g/1kg (LIGHT)	Front	Air dried	None	None	Screen, solid Synocron Black RD 40g/1kg (LIGHT)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TJ FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB for 30 minutes.	Screen, solid Synocron Black RD 60g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, solid Synocron Black RD 60g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C

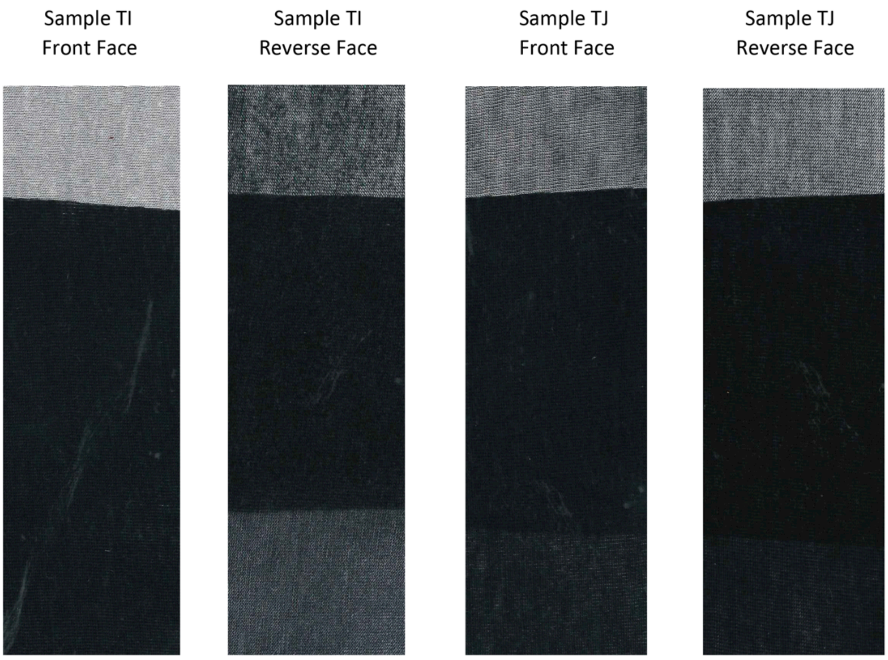


Figure 5.14. Samples (TI to TJ) from tests R53 to R54

On visual assessment of samples TI to TJ, it was observed that three shades of colour could be created through an illusion. This effect was created by screen printing onto both the front and reverse of the fabrics in different areas and then also overlapping the colour through printing in the same area on both the opposing surfaces of the fabric. The effect is clearly demonstrated on the reverse side of sample TI in Figure 5.14. The process was further explored using block and linear imagery for screen printing with Synocon black RD dye in light shade and the print conditions from TH1 presented in Table 5.10. The samples produced are presented within Figure 5.15; sample TK was printed only on the front face of the fabric and Sample TL was printed on both the front and reverse faces of the fabric. It was also observed that by layering two fabrics the effect can be furthered developed; Figure 5.16 shows the illusion created from combining samples TK and TL together.

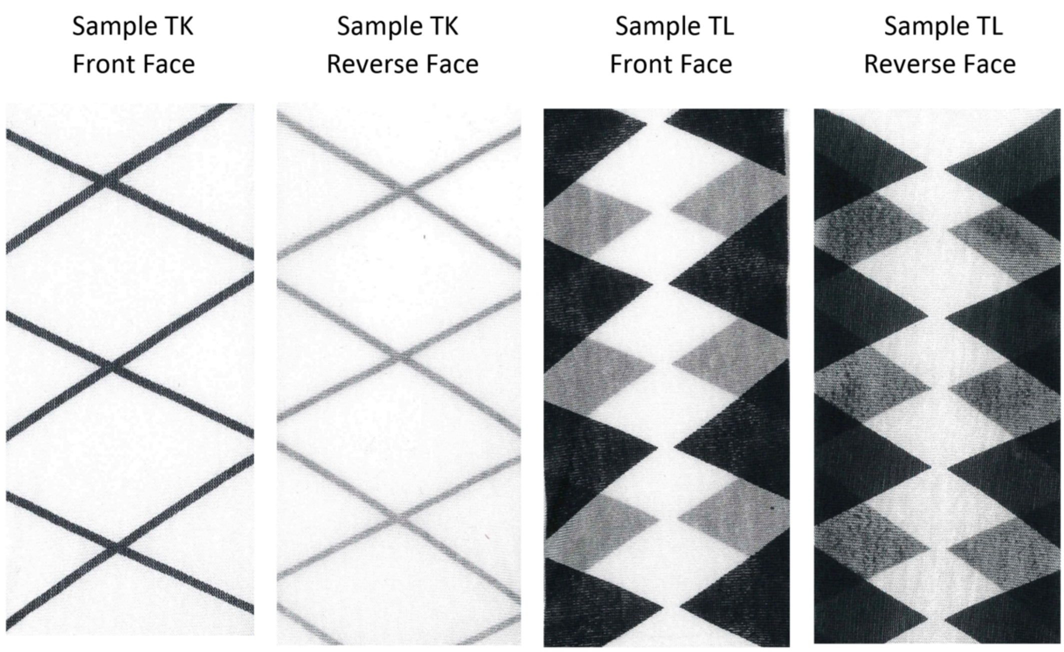


Figure 5.15. Samples (TK to TL) printed using test conditions from sample TH1

Sample TK & TL
Reverse face to Reverse

Sample TK & TL
Front face to Front

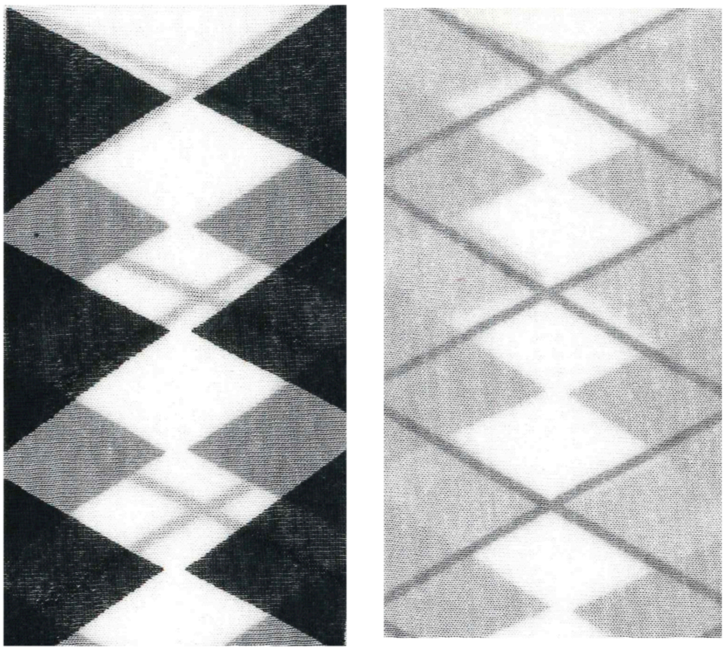


Figure 5.16. Samples (TK & TL) combined together through layering

Assessment of samples TI to TL demonstrated that the illusion of colour on the opposing side of the screen printed fabric surface can be produced successfully to create a variety of effects as shown in Figure 5.16 using black dye. The screen printing technique was then explored incorporating colour, in which medium shades of the KISCO RD Synocron colour palette, presented in Figure 5.12, were screen printed onto knitted Tencel A100 samples. Block colour was screen printed onto the front face of fabrics and a repeat bird motif was screen printed in the same colour onto the reverse face of fabrics.

Test R55. Knitted Tencel A100 fabric sample TM was gently scoured before being screen-printed with black block print in medium shade onto the front surface of the fabric, air dried and then screen-printed with black bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R56. Knitted Tencel A100 fabric sample TN was gently scoured before being screen-printed with navy blue block print in medium shade onto the front surface of the fabric, air dried and then screen-printed with navy blue bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R57. Knitted Tencel A100 fabric sample TO was gently scoured before being screen-printed with brillaint blue block print in medium shade onto the front surface of the fabric, air dried and then screen-printed with brilliant blue bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R58. Knitted Tencel A100 fabric sample TP was gently scoured before being screen-printed with rubine block print in medium shade onto the front surface of the fabric, air dried and then screen-printed rubine bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R59. Knitted Tencel A100 fabric sample TQ was gently scoured before being screen-printed with deep red block print in medium shade onto the front surface of the fabric, air dried and then screen-printed deep red bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R60. Knitted Tencel A100 fabric sample TR was gently scoured before being screen-printed with red block print in medium shade onto the front surface of the fabric, air dried and then screen-printed red bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R61. Knitted Tencel A100 fabric sample TR was gently scoured before being screen-printed with red block print in medium shade onto the front surface of the fabric, air dried and then screen-printed red bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Test R62. Knitted Tencel A100 fabric sample TS was gently scoured before being screen-printed with orange block print in medium shade onto the front surface of the fabric, air dried and then screen-printed orange bird motif in medium shade onto the reverse surface of the fabric, steamed, washed, air dried, and then assessed.

Table 5.12. Shows the methods and swatch samples (TM to TS) for each print test conducted (R55 to R62). The larger samples produced are presented in Figure 5.17.

Visual assessment of the samples (TM to TS) for print trials R55 to R62 concluded that the method of screen printing with colour on opposing surfaces of the fabric does create the illusion of paler and darker shades of colour. The methods established are: to create a paler shade on the front face of the fabric by screen printing on the reverse face of the fabric, to create a deeper shade screen print colour on the same area of opposing surfaces.

Table 5.12. Methods and swatches for samples TM to TS, print trials R55 to R62

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Prep. Method	2nd Print Method	Fabric face printed onto	Finished	Washed
TM FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Orange RD 15g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Orange RD 15g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TN FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Red RD 25g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Red RD 25g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TO FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Deep red RD 20g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Deep red RD 20g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TP FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Rubine RD 15g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Rubine RD 15g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TQ FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Brilliant blue RD 40g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Brilliant blue RD 40g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TR FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Navy blue RD 40g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Navy blue RD 40g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
TS FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C in a 0.1% solution of Exenol XB	Screen, solid Syncron Black RD 60g/1kg (MEDIUM)	Front	Air dried	None	None	Screen, bird motif Syncron Black RD 60g/1kg (MEDIUM)	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C

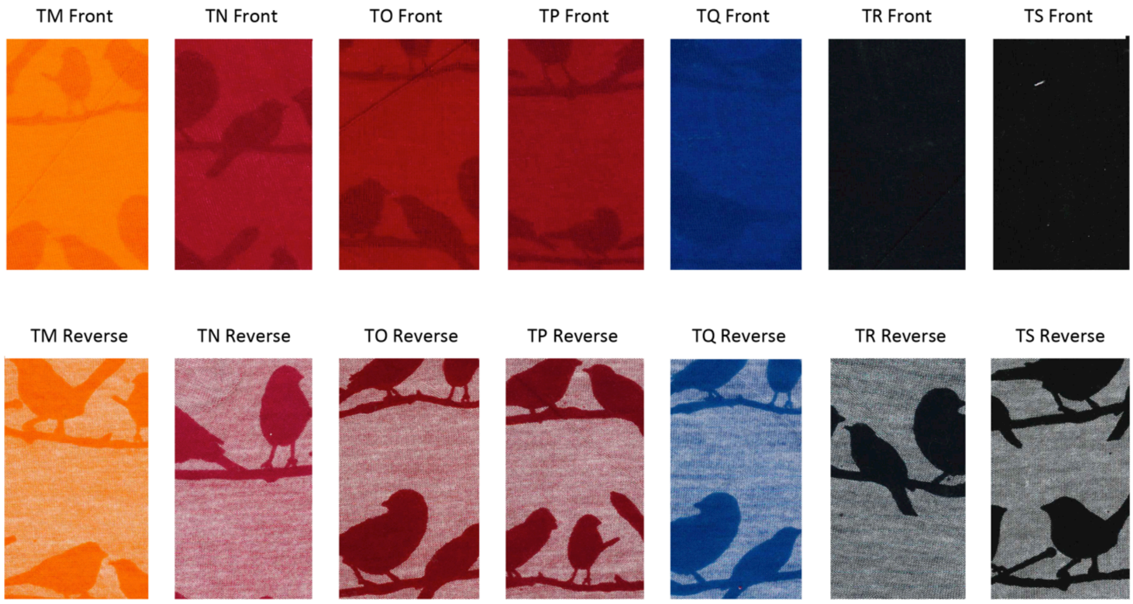


Figure 5.17. Large samples (TM to TS) from tests R55 to R62

Having established that paler and darker colour shades can be created through the method of screen printing onto the fabric surface, the 'responsible colour palette' that made up the remainder of the design colour palette, shown in Figure 5.12, were then visually assessed for the appearance of the reverse side of each fabric (the unprinted face). It was noted that in line with the results from the print trials (R55 to R62) a lighter colour palette may be achievable by incorporating the unprinted reverse side of the printed samples, thus compensating for the deficiencies of colours provided by the KISCO dyes. This extended palette is shown in Figure 5.18 and could be used along with the printing technique as a design tool by the designer in producing 'responsibly coloured' fashion and textiles.

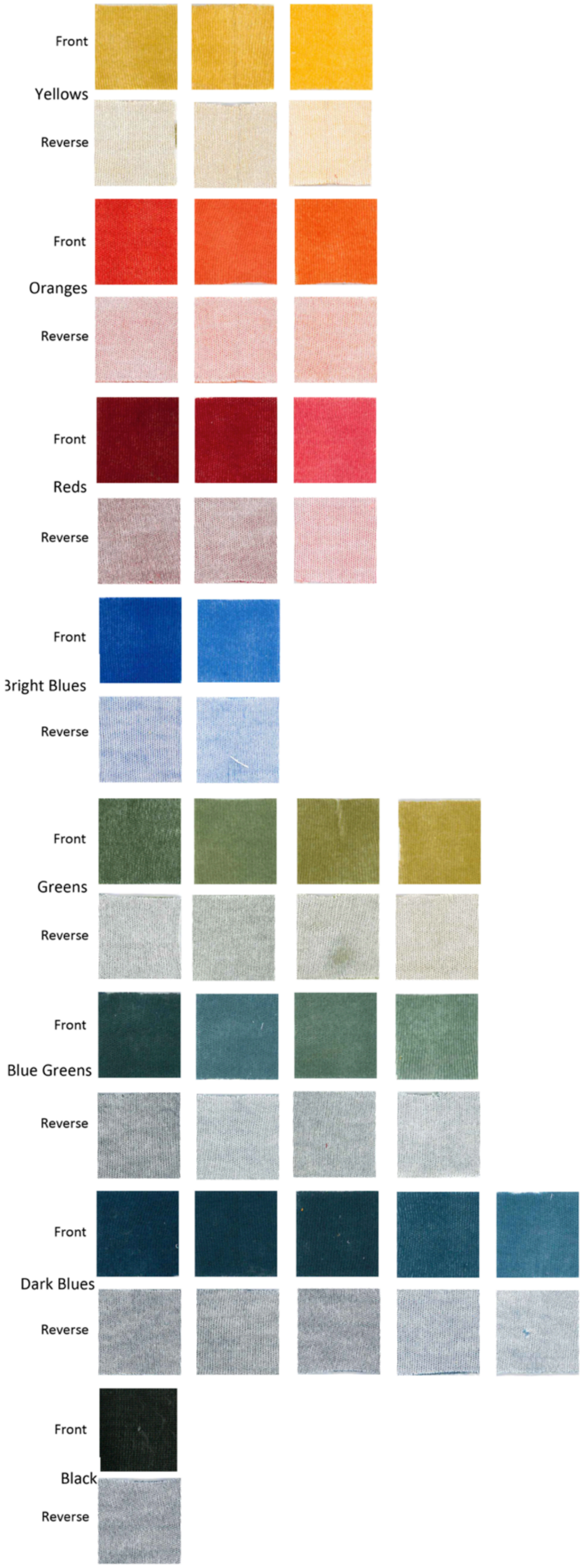


Figure 5.18 Extended colour palette incorporating both front face (printed surface) and reverse face (unprinted surface).

CHAPTER 6 LIFETIME EXTENSION

6.1 Introduction

In the previous chapters of this thesis, research has been described that has established methods for sustainable coloration (chapter 4) and environmentally responsible coloration (chapter 5) of Tencel fabrics. However, the outcomes of both lines of enquiry identified limitations in the range of colours achievable. In interweaving technical inquiry within the design process to enable informed design decisions based on environmental concerns for the fibre and dyestuffs used, it has been concluded that compromises are required in the aesthetic choice for colours available to the designer. The aim of the research described in this chapter was to address this compromise.

The research described thus far has concentrated on screen printing as a traditionally used, environmentally responsible method for applying colour to Tencel fabric. On the basis of the outcomes presented in Chapter 5, the ongoing screen-printing continued to use the same set of dyes, i.e., the Kisco Synocron reactive dyes that were identified as especially environmentally friendly. The research presented within this chapter progressed to explore the incorporation of digital printing technology within the research methodology that was developed for screen-printing of Tencel fabrics, established as described in Chapter 5. This modification was carried out as a means to provide an extended range of colours, as well as additional aesthetic tools for the designer, and to take advantage of the strong environmental credentials of digital printing technology. A further aim of the research described in this chapter was thus to use traditional screen print technology and modern digital inkjet print technology in complementary ways, so that the strengths are exploited and the weaknesses minimized.

Although the research described throughout this thesis aimed to employ the most responsible methods available for coloration, an inevitable environmental impact will occur due to the need to use synthetic dyes. In aiming to extend the colour palette, and thus the aesthetic tools available to the designer in producing coloured fashion and textiles, it is inevitable that there will be increased environmental impact. It is likely that the commercial inkjet inks used in this research contain the types of reactive dyes that are normally used for textile printing. Currently, there is no evidence for the commercial development of specific high fixation reactive dyes, such as the Kisco Synocron RD screen-printing range, for use in digital printing inks.

A strategy for reducing environmental impacts and resource usage of products throughout their life cycle is to use design as a method to extend product lifetimes (usage phase) within their life cycle. Through extending a product's lifetime the embedded energy from initial resources used in production are conserved and utilised as fewer products are consumed and waste is reduced (Cooper, 1994). The research outcomes presented within this chapter resulted from the aim to incorporate two processes, screen printing combined with digital printing, to provide a widened colour palette and additional aesthetic tools for the designer. In doing so, the exploration of life cycle extension for coloured fashion textiles through extended garment lifetimes was enabled.

The synthetic reactive dyes used within this phase of the research are 'permanent'; the research outcome from Chapter 4, described as the 'Cyclical Colour Model', owed its success to the use of an unmordanted natural dye that achieved the technical fastness properties of a synthetic equivalent. The fashion and textile industry strive for permanence in colour in order to be commercially successful. However, in achieving permanence in colour, garments are in a sense fixed in time. As fashion trends change, consumers desire and demand new seasonal colour palettes and surface patterns, and their existing wardrobe choices are deemed as 'old' and no longer on trend. These garments remain unworn, banished to the back of wardrobes or disposed of. This endless wasteful cycle of 'new' to 'old' within a matter of months wastes not only the physical materials that make up a garment but also the embedded energy used in their manufacture.

The research aims to overcome the issue of permanence by exploring how something apparently permanent can be made to change, in the form of a garment that can evolve over time to become a 'new' garment at a time when the consumer deems the original item to be 'old'. Garments are designed and produced to meet the aesthetic commercial trends at a point in time in order to achieve financial goals satisfied through the initial sale; this design and sale strategy results in garments that are 'aesthetically impoverished' (Champman, 2005b). Aesthetically, the garments capture and reflect the shape, pattern and colour trends from the season for which they are designed. Designing and producing garments that cannot transcend fashion seasons and occasion style, for example summer to winter, or casual to smart, prevents the consumer from engaging in long term relationships with the garments as they become unsuitable, old and forgotten, lost either to the depths of an unworn wardrobe or landfill. Fletcher & Grose (2012c) explain that the low cost and ease of purchase of garments is a significant factor in the consumer's behavior to discard clothing before the materials used to produce them are exhausted.

Essentially the aim of this section of research is to optimize the garment lifetime through designing and combining two garments within one. There has been a common approach to extending garment lifetimes through consumer engagement involving repairs and alterations. Though consumer interaction with garments in this way may create an emotional attachment, thus encouraging emotional durability, a disadvantage of this approach is the reliance on the consumer being equipped with the skills required to carry out the repair and alteration work that would either extend a garment's lifetime or change it into a new garment. It has been observed that there is little evidence of repair work being carried out on garments as a regular activity and that this could be due to the lack of skills by consumers (Gwilt, 2014). For this reason, the design approach within this research did not incorporate consumer engagement.

The 2004 Lifetimes Project conducted by Kate Fletcher and Mathilda Tham explored 'speed' and 'time' of garments, referring to garment lifetimes within a consumer wardrobe as the metabolism of the wardrobe, in order to illustrate the nature of consumer behaviour in regard to how often garments within their wardrobes are worn (Fletcher & Grose, 2012d). Their research demonstrated that an occasional item, a party top, is worn once and discarded, whereas a utility trouser is worn frequently. Fletcher and Grose present a scenario where, in the current wardrobe metabolic rate, garments are quickly consumed and disposed of to landfill, contrasting with a future scenario, the future wardrobe metabolic rate, where garments are re-used and shared essentially through a community wardrobe, incorporating ideas of garment leasing, recycling and sharing.

Inspired by this method of applying metabolic rates to the consumer wardrobe as a system, the design strategy used in the research described in this chapter applied the theoretical concept of metabolic rates to individual garments, to create garments that can transcend seasons and occasions through linking fast metabolic garments with slow metabolic garments. A fast metabolic garment categorises a garment worn rarely before being discarded, and slow metabolic rate categorises a garment worn repeatedly over time.

For example, a pair of jeans may be worn multiple times a week, whereas an occasion dress, for example a smart black dress, may be worn only once a quarter. Although consumers may not dispose of these items, they still constitute a waste of physical resources and embedded energy as they are in a sense discarded within the wardrobe to be worn only occasionally, if ever again. The garment metabolic rates are visualised in Figure 6.1.

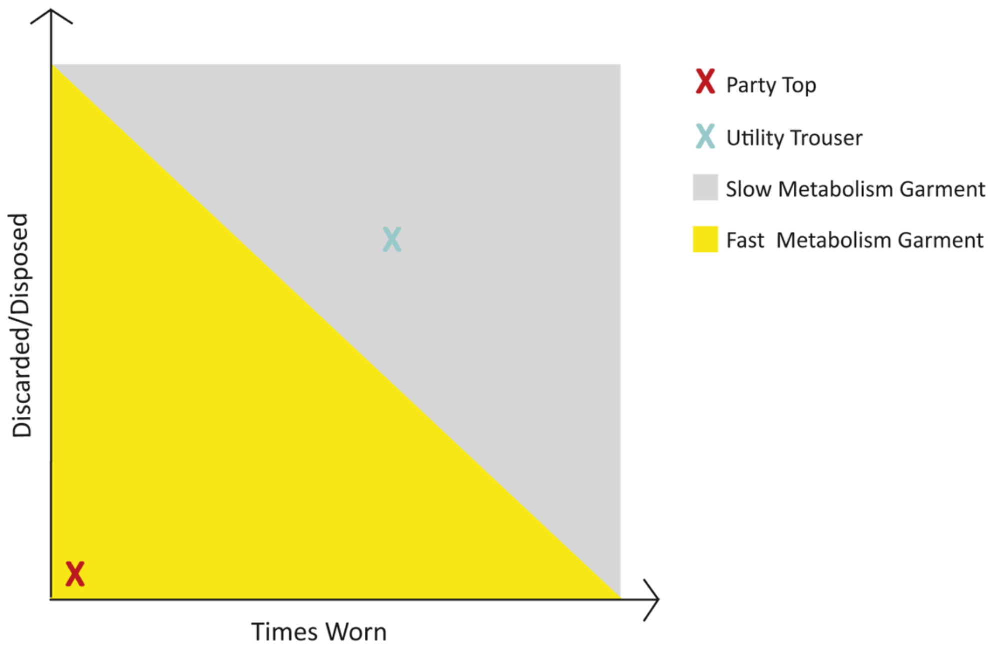


Figure 6.1 – Visualisation of garment lifetime metabolism

With a focus on the relationship between garment, colour and design, the research focused on developing a process of colour application that would allow the designer to create two garments within one, specifically linking the concepts of both high metabolic clothing and low metabolic clothing. The design approach used aimed to develop and link an 'on trend' garment, likely to be discarded in the following fashion season, with a timeless fashion garment. Alternatively, within the approach, a garment worn regularly may be incorporated within a garment worn rarely. The aim was to achieve all of these features within the initial design stage in a manner that did not require additional alteration by, or engagement with, the consumer.

6.2 Bifunctional Design

This design concept was inspired by a consideration of the bifunctional nature of the reactive dyes, as presented in Chapter 5. The technical development of these dyes aimed to create more functional groups on the dye molecule so as to increase fixation on the fabric, ultimately reducing environmental impact. Thus, a bifunctional approach to design was adopted leading to the research presented within this chapter for bi-surface fabrics, essentially to develop one fabric with two functional surfaces.

6.3 Digital Inkjet Printing

Digital inkjet printing involves the production of individual drops of ink deposited in a precisely controlled manner onto a substrate, and in doing so creating an image (Fralix, 2001). The depth of shade is controlled by how many dots of colour are deposited onto the substrate; pale shades are created by fewer dots of colour applied to the fabric so that the base fabric is more visible at certain points of the created image (Dawson, 2001,).

Stork first exhibited digital inkjet printing for textiles in 1991. However, the model of printer exhibited, the TruColour TCP2500 was designed as a sampling machine and could only print rectangular fabric swatches. At ITMA (an international trade show and conference for manufacturers and suppliers of textiles) in 1995, Stork introduced the ‘fashion jet’, a model of printer capable of continuously printing rolls of fabric, (Moser, 2003). Since this initial introductory interest in digital printing, further improvements in the technology and the capabilities of both computer hardware and computer-aided design software have continued to take place. Digital inkjet printing offers a method for creating effects that are reproducible and controllable, through the hand of the designer, assisted by the specifically-developed technology and the facilities provided by computer aided design.

6.3.1 Fabric Pre-Treatment for Digital Textile Inkjet Printing onto Cellulose Fibres

Applying a pre-treatment to fabrics prior to printing is essential to allow the dye applied to the substrate to fix and create a high quality image with good fastness properties (Provost, 1995a). The pre-treatment has to be applied to fabric rather than being incorporated together with the dye, as is the case with screen printing, for various reasons. A main factor is that inclusion of a thickener, an essential component of screen print pastes, with the dye into the digital printing ink creates difficulties in the release of the ink through the nozzles on the printhead. Also, some pre-treatment chemicals can cause corrosion of the sensitive printhead, including alkali in the ink, which is essential for the fixation of reactive dyes, causes hydrolysis of the dye and the solubility of the dye is reduced by the presence of salts in the inks (Hawkyard, 2006).

Tencel is a regenerated cellulose fibre and so a reactive dye is typically used for its coloration (Miles, 2003). The pre-treatment recipe used to coat the fabric prior to digital inkjet printing is largely based on the ingredients used within screen printing print paste recipes. This commonly involves the incorporation of urea, which absorbs moisture during steaming allowing dye to disperse into the fibres and facilitating high fixation, thickener to prevent ink spreading due to its low viscosity, and alkali for dye fixation. This coating is applied to the fabric, using either a padding or a screen print process, then allowing the fabric to dry prior to being inkjet printed (Provost, 1995b). Figure 6.2 illustrates the stages of digital inkjet printing.

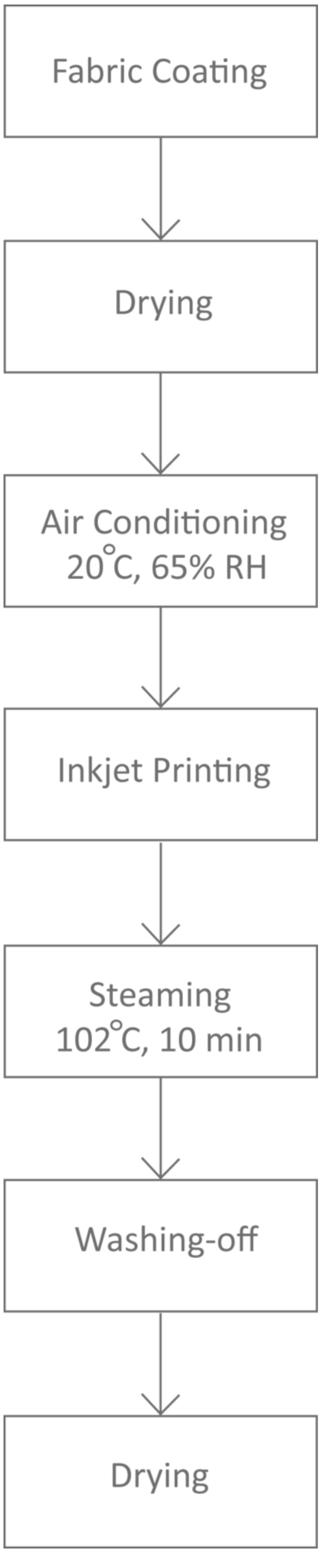


Figure 6.2. General Process for Inkjet Reactive Dye Textile Printing

6.4 Initial first stage Experimental Investigation

6.4.1 Initial Print Investigation

The purpose of the initial print trials was to establish whether it is possible to print successfully on both the front face and reverse face of Tencel A100 fabrics. Four sample fabrics were explored, one pair was prepared for screen printing and the second pair prepared for digital printing. One fabric from each pair of sample fabrics was printed on the opposing side to its partner, allowing a visual comparison to be conducted post finishing, aiming to establish whether both screen and inkjet printing is possible on both the front and reverse sides of the Tencel A100 fabrics. The initial print trials were as follows.

Test 1. Fabric sample A, screen-printed on the front face of the fabric, steamed, air-dried, washed, air-dried, assessed.
Test 2. Fabric sample B, screen-printed on the reverse face of the fabric, steamed, air-dried, washed, air-dried, assessed.
Test 3. Fabric sample C, digitally printed on front face of the fabric, steamed, air-dried, washed, air-dried, assessed.
Test 4. Fabric sample D, digitally printed on reverse face of the fabric, steamed, air-dried, washed, air-dried, assessed.

Table 6.1 presents the methods and illustrates initial swatch samples (A - D) for each print test conducted (1 - 4). Larger samples are shown in Figure 6.3.

Table 6.1. Methods and swatch samples from initial experimentation

Sample	Substrate	Preparation Method	Print Method	Fabric face printed onto	Finished	Washed
A 	Tencel A100	Scoured @ 40°C	Screen Printed	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
B 	Tencel A100	Scoured @ 40°C	Screen Printed	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
C 	Tencel A100	Scoured @ 40°C Coated for inkjet printing	Digital Inkjet	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
D 	Tencel A100	Scoured @ 40°C Coated for inkjet printing	Digital Inkjet	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C

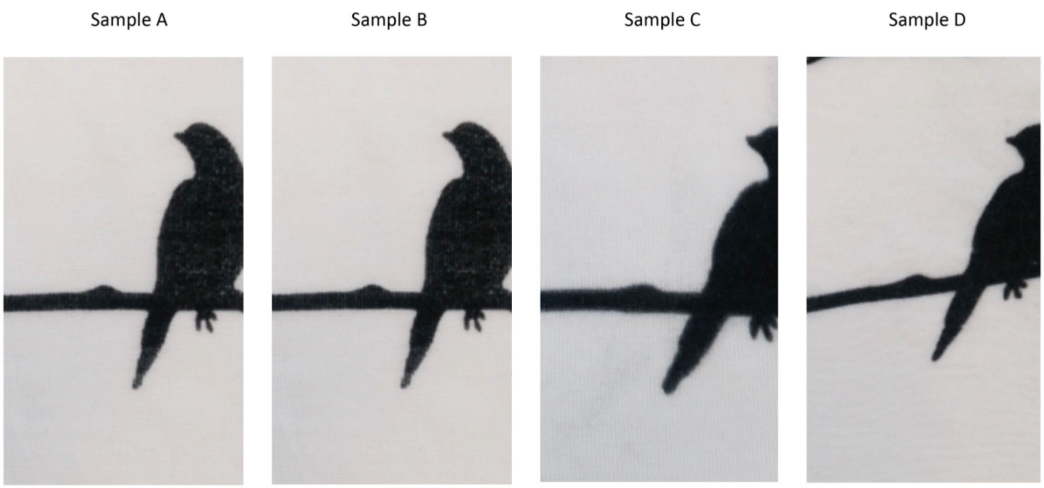


Figure 6.3. Larger samples (A – D) from tests 1-4.

6.4.2 Initial Observations

Samples from the initial print investigations demonstrated no visual differences in dye coverage when screen-printed or digitally printed on the front and reverse faces of fabric samples. The success of these results led to the decision to continue investigating by combining digital print with screen print, and to optimize the method for printing on both front and reverse facing sides of fabrics with a focus on combining the two print methods onto one piece of fabric, the aim being to achieve a single layered reversible fabric with two contrasting surfaces (bi-surface fabric) on one single piece of fabric.

6.5 Experimental Section

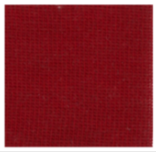
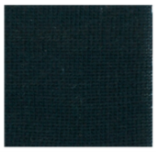
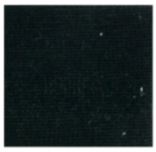
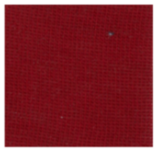
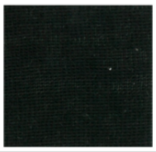
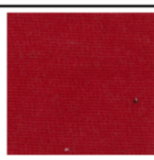
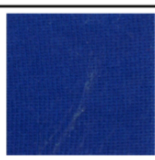
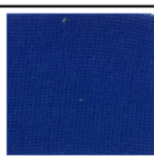
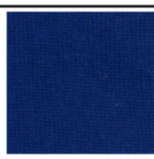
6.5.1 Materials

Reactive dyes for screen printing were provided by KISCO, 112-31 Yeomchang-Dong Kangseo-Gu, Seoul, 157-040, Korea as illustrated in Table 6.2. Lenzing AG, Austria, supplied knitted Tencel A100. For full fabric specification, refer to Table 4.1 (chapter 4). Exenol XB, described as an anionic/nonionic alcohol ethoxylate surfactant, was supplied by J. & W. Whewell Ltd, Manchester, UK. Manutex F 700, Urea, Matexil-Pal, and sodium bicarbonate were stock items in the Heriot-Watt University dyeing laboratory

6.5.2 Fabric Pre-Treatment

Knitted Tencel A100 was gently scoured at 30°C using a 0.1% aqueous solution of Exenol XB in accordance with the method developed in Chapter 5 described in Section 5.4.2

Table 6.2. List of Kisco Synocron RD Dyes

Kisco Dye	Colour Swatch		
	Light	Medium	Dark
Synocron Yellow RD			
Synocron Deep Red RD			
Synocron Navy Blue RD			
Synocron Orange RD			
Synocron Rubine RD			
Synocron Black RD			
Synocron Red RD			
Synocron Brilliant Blue RD			

6.5.4 Digital Printing

Fabrics were prepared for digital print by impregnating with a solution consisting of sodium bicarbonate, urea and water. This is a standard recipe for the coating of digital fabric, as provided in Table 6.3. Fabric must be pre-prepared in this way to provide the conditions that allow dye molecules to react with the fibre after inkjet printing. The dye molecules are then fixed to the fibre after printing using steam. Samples were digitally printed on a Mimaki Textile jet printer, then steamed at 100°C for 20 minutes, washed at the boil with a 0.1% aqueous solution of Exenol XB and air dried.

Table 6.3: Recipe and method used for coating fabric in preparation for digital inkjet printing

Recipe for 1 Litre	**Method**
100g Urea 25g Sodium Bicarbonate 875g Water	• Urea and sodium bicarbonate added to water in large clean vessel • Applied using roller padding, or for large quantities soak fabric for 10 minutes, and ensure evenly coated • Hung to air dry

6.5.5 ***Screen Printing***

Fabric samples were screen printed on a Zimmer magnetic print table with a single pass of the print paste across the fabric using a metal rod. The print paste was obtained following a standard recipe and method, provided in table 6.4. The samples were then steamed at 100°C for 10 minutes, subjected to a first hot rinse for 1 minute at 98°C, a second hot rinse for 1 minute at 98°C, a third rinse with a 0.1% aqueous solution of Exenol XB, a fourth rinse with 0.1% aqueous solution of Exenol XB, a final rinse with cold water at 40°C for 1 minute and finally they were air-dried.

Table 6.4 Screen print paste recipe, to make 500ml

Chemical	Quantity
Water	225ml
Manutex F 700	23g
Warm Water	150ml
Urea	50g
Matexil-Pal	5g
Cold Water	25ml
Kisco Synocron RD Dye	?
Sodium Bicarbonate	12.5g

6.5.6 *Second Stage Experimentation*

This second stage of experimentation focused on incorporating the two print methods, screen and inkjet onto the two opposing surfaces, front and reverse of a single piece of fabric. Knitted Tencel A100 fabrics were prepared for digital print and printed before being screen-printed following the recipes and methods, as is given in Tables 6.3 and 6.4.

Test 5. Fabric sample E was digitally printed on the front face of the fabric with a black bird motif, steamed, washed and air-dried. The fabric sample E was then screen-printed on the reverse face of fabric with a block print in black, steamed, washed, and air-dried. The sample was then assessed.

Test 6. Fabric sample F was digitally printed on the reverse face of fabric with the black bird motif, steamed, washed, and air-dried. The fabric sample F was then screen-printed on the front face of the fabric with the block print in black, steamed, washed, air-dried, and then assessed.

Test 7. Fabric sample G was digitally printed on the front face of the fabric with a black bird motif, steamed, washed, air-dried. Fabric sample G was then screen printed on the reverse face of fabric with a block print in black, steamed, washed, air-dried, and then assessed.

Test 8. Fabric sample H was digitally printed on the reverse face of the fabric with a black bird motif, steamed, air-dried, washed, air-dried. Fabric sample H was then screen printed on the front face of fabric with a block print in black, steamed, washed, air-dried, and then assessed.

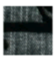
Visual assessment of samples E and F demonstrated that there was no apparent visual difference between the printed imagery on the two samples. Also, by comparison, no differences were observed between the digital printed image on the front facing side of sample E and the corresponding image on the reverse facing side of sample F. Similar observations were made by comparing samples G and H.

Table 6.5 shows the methods and initial swatch samples (E - F) for each print test conducted (5 - 6). Table 6.6 shows the methods and initial swatch samples (G – H) for each print test conducted (7 – 8). Larger samples with the visual comparison of the printed opposing faces are shown in Figures 6.4 and 6.5.

Table 6.5 Methods and initial swatches for samples E – F, print trials 5 - 6.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
E FRONT  REVERSE 	Tencel A100 Knit	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen, solid Synocron Black ED 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
F FRONT  REVERSE 	Tencel A100 Knit	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	solid Synocron Black ED 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Table 6.6 Methods and initial swatches for samples G – H, print trials 6 - 8.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
G FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen, solid Synocron Black ED 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
H FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	solid Synocron Black ED 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

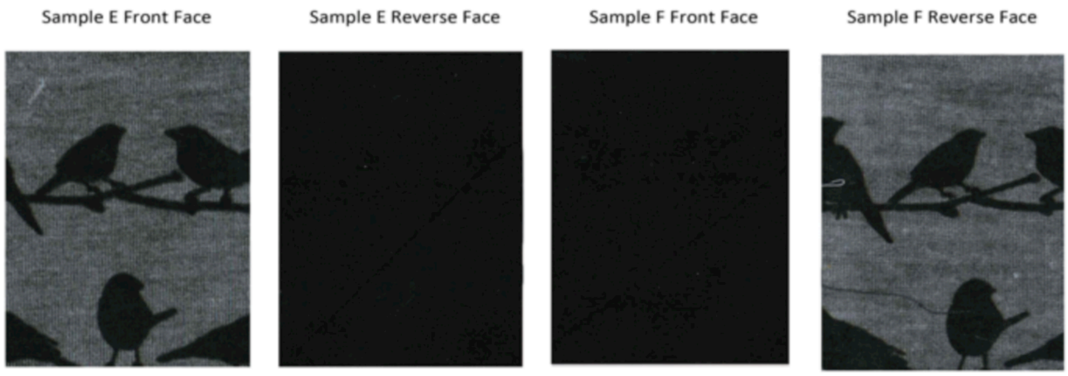


Figure 6.4. Larger samples (E - F) from tests 5 - 6.

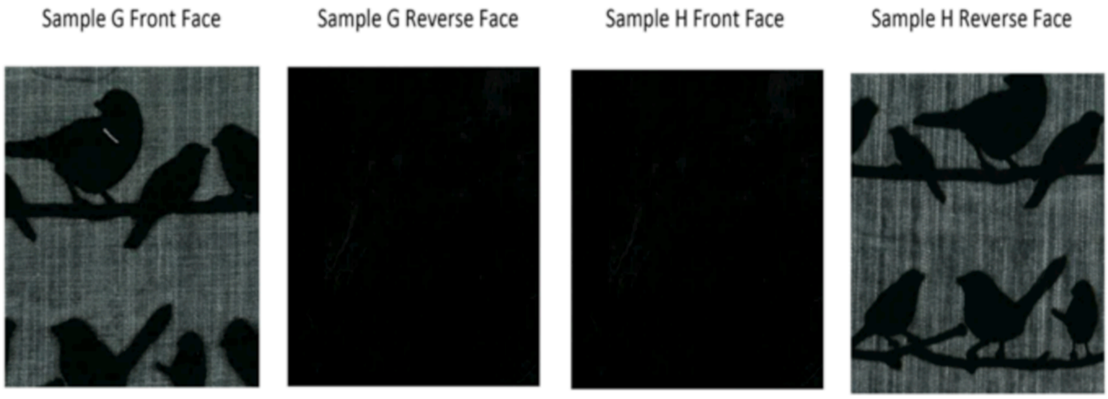


Figure 6.5. Larger samples (G - H) from tests 7 - 8.

On the basis of this investigation, it has been successfully demonstrated that combining digital and screen print processes within one piece of fabric using both the front and reverse sides is achievable. No differentiation of the print appearance was shown when either digitally or screen-printing on the front or reverse face of fabric samples. The experimentation so far has focused on establishing whether the design concept, to create bisurface fabrics through colour application, was technically achievable, with the experiments designed to test whether screen printed reactive dye and digital printed reactive dye can be applied firstly to both front and reverse faces of fabric, and secondly to the opposing faces on one piece of fabric. The colour applied in this initial phase of the investigation was black, and so it was decided to investigate the technique with a varied colour palette. Rather than using black for both digital and screen printed sides of the fabric, the next set of samples was produced using black on one face and grey on the other face to combine a varying depth and shade of colour on the two opposing sides. Black and grey where chosen as a standard to represent a dark and light colour combination. It was envisaged that the results from these trials might then be applicable to a range of dark and light colour combinations.

Test 9. Fabric sample I was digitally printed on the front face of the fabric with a grey bird motif, steamed, washed and air-dried. Fabric sample G was then screen printed on the reverse face of fabric with a block print in black, steamed, washed, air-dried, and then assessed.

Test 10. Fabric sample J was digitally printed on the reverse face of the fabric with a grey bird motif, steamed, air-dried, washed and air-dried. Fabric sample J was then screen printed on the front face of fabric with a block print in black, steamed, washed, air-dried, and then assessed.

Table 6.7 shows the methods and swatch samples (I and J) for each print test conducted (9 and 10). Larger samples with the visual comparison of the printed opposing faces are shown in Figure 6.6.

Table 6.7 Methods and swatches for samples I and J, print trials 9 and 10.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
I FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in grey	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen, solid Synocron Black ED 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
J FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in grey	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	solid Synocron Black ED 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

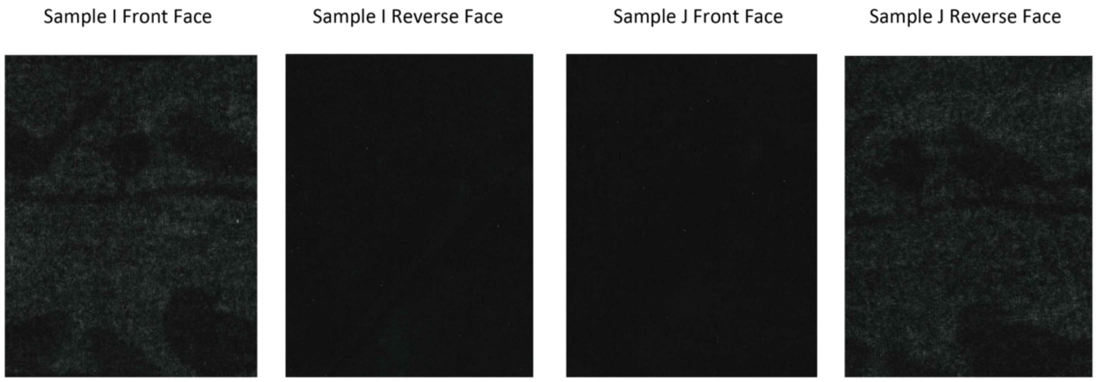


Figure 6.6. Larger samples (I and J) from tests 9 and 10.

Visual assessment of samples I and J demonstrated that the technique of printing on both sides of the fabric was less successful when a dark shade, in this case black, is combined with a lighter shade, in this case grey. Samples presented in Figure 6.5 demonstrate that when a darker shade is used to print on the opposing face of a lighter print, the image in the lighter colour becomes almost invisible, because it is obscured by the depth of the darker colour, in this case the black. This observation was found to be independent of which side of the fabric was printed with the lighter or darker shade.

Having established the viability of a technique to print on both sides of the fabric, and that a limitation in combining colours existed, the methods of fabric preparation and print were investigated further. Up to this point, the experimentation had been based on the existing knowledge and experience of the researcher and traditional recipes for preparing and printing the fabric, steaming and finishing at each individual stage of colour application, before proceeding to the next. Figure 6.7 illustrates the stages of printing. Thus far, fabrics have been scoured by a multi-stage process, prepared for digital print, digitally printed, steamed, washed, air dried, then screen printed with the standard recipe for reactive dyes, then steamed, washed and air dried.

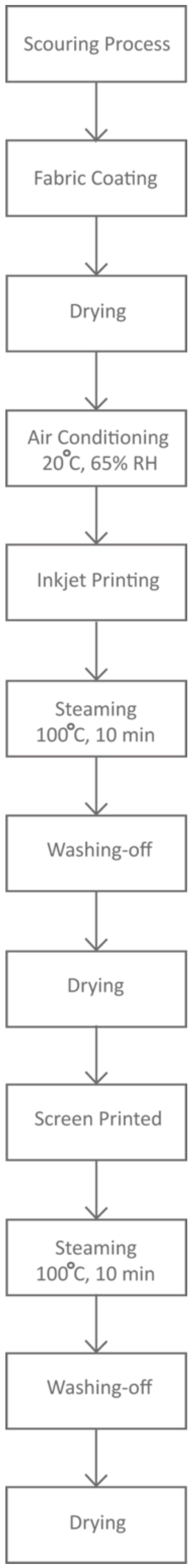


Figure 6.7. Sequence of processes used in the combined printing process

There are significant benefits for the designer following this phase of the research, as it has provided a design tool in which the designer may use more than one surface of the fabric for the design of fashion garments. However, this feature alone does not necessarily lead to environmental benefits, beyond the benefit created by the possibility identified for the designer to employ life cycle extension in their initial design process through creating a second garment within the first.

When the print method shown in Figure 6.7 was analyzed, it was evident that multiple stages of preparation and finishing were being repeated, as highlighted in Figure 6.8, thus impacting on the overall water, energy and synthetic chemical usage within the process. If these stages could be combined and streamlined, then it was envisaged that a new method might be developed in which the overall environmental impact of this process would be greatly reduced. The next stage of experimentation therefore focused on repeating tests 5 and 6 that produced samples E and F, which demonstrated the successful combination of screen print and digital print, with no observed disparities in the front or reverse facing prints, either digital or screen printed, but using a streamlined method. The aim was to combine the two printing stages into one and to prepare fabric only once, steam and wash once. Figure 6.9 presents an illustration from the research work book that demonstrates how the two separate processes cross over and thus identifies opportunities for them to be streamlined.

The illustration demonstrates the key areas where the two processes could be joined, through appropriate use of the synthetic chemicals used in printing and combining preparation and finishing processes into one, rather than two separate stages. The streamlined process is shown in Figure 6.10. The only repeating stage that was not eliminated or reduced, or incorporated within another, was the drying. Ensuring that the fabric is dry prior to conducting a printing process is vital to the quality and fastness properties of final fabrics. However, an air drying technique was used that would not use additional energy or repeat chemical usage to add to waste concerns.

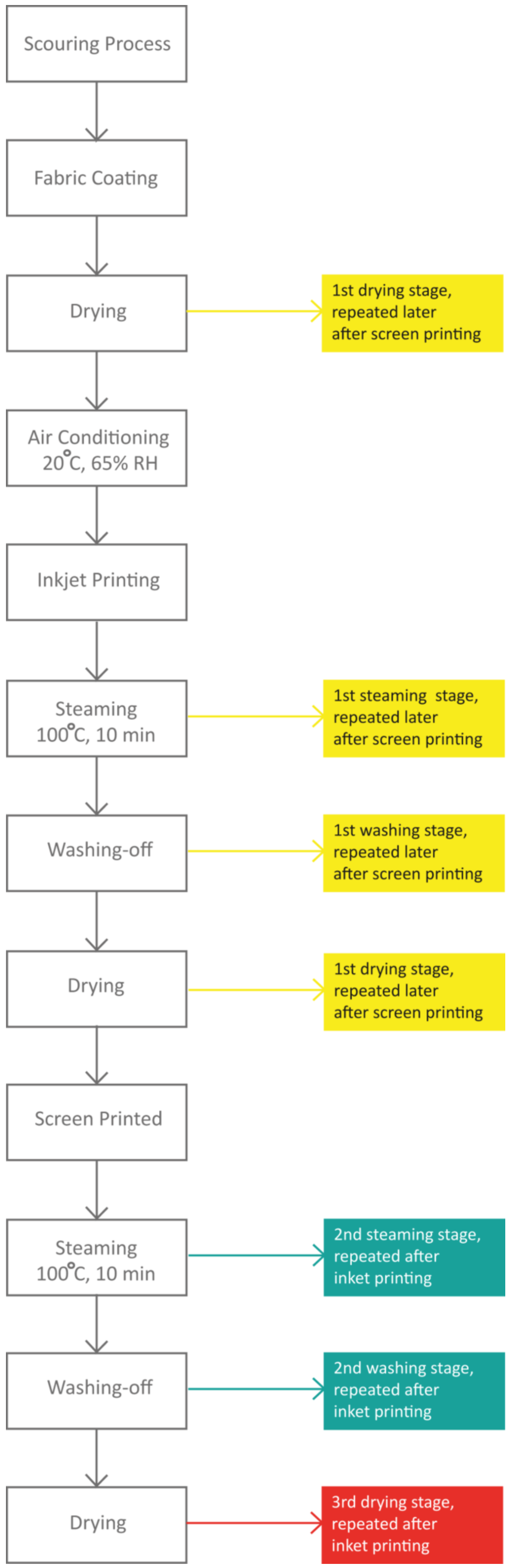


Figure 6.8 Identification of repeated stages for possible combination

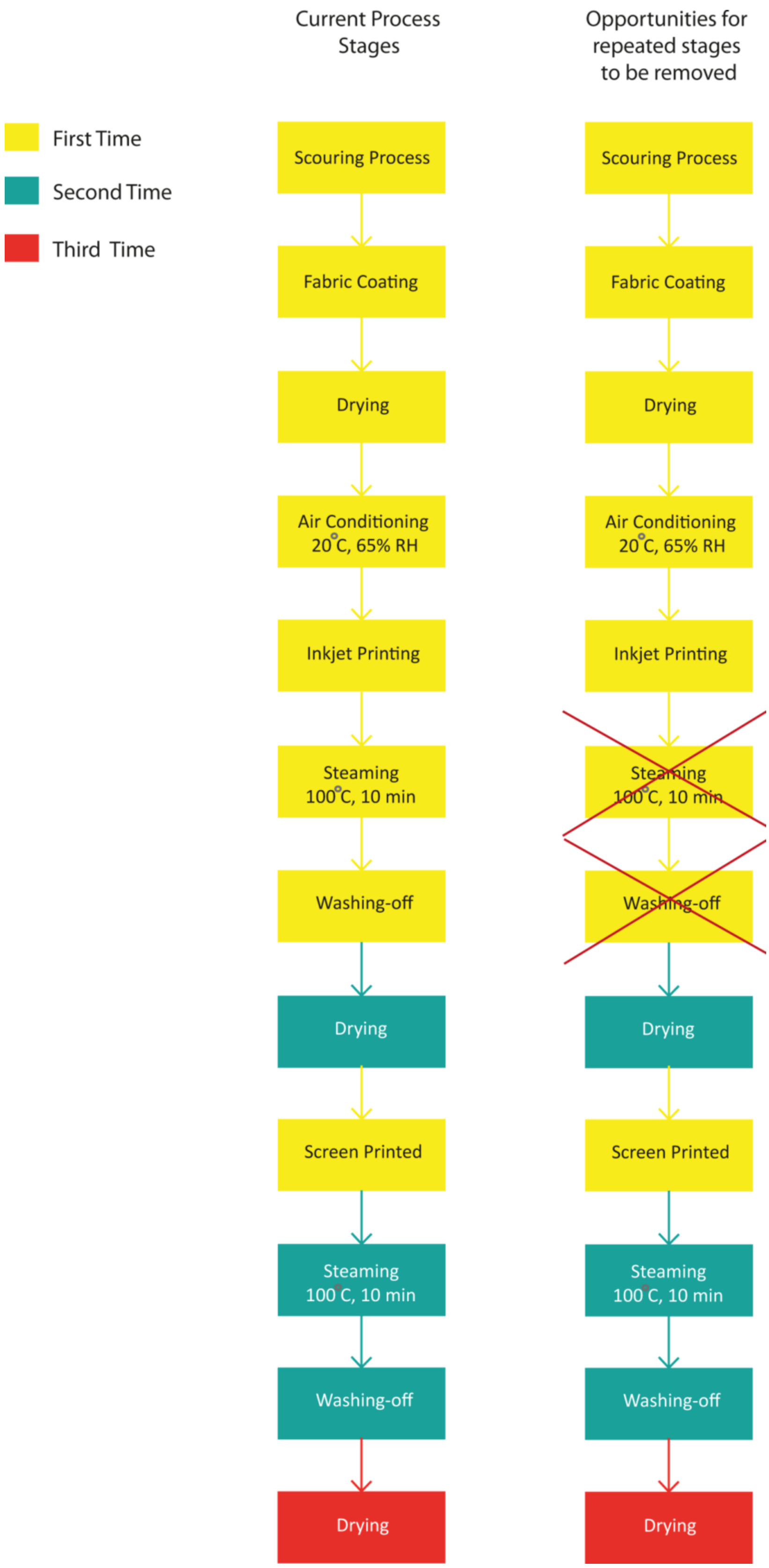


Figure 6.9. Repeated processes for possible removal in developing a more streamlined and reduced environmental impact process.

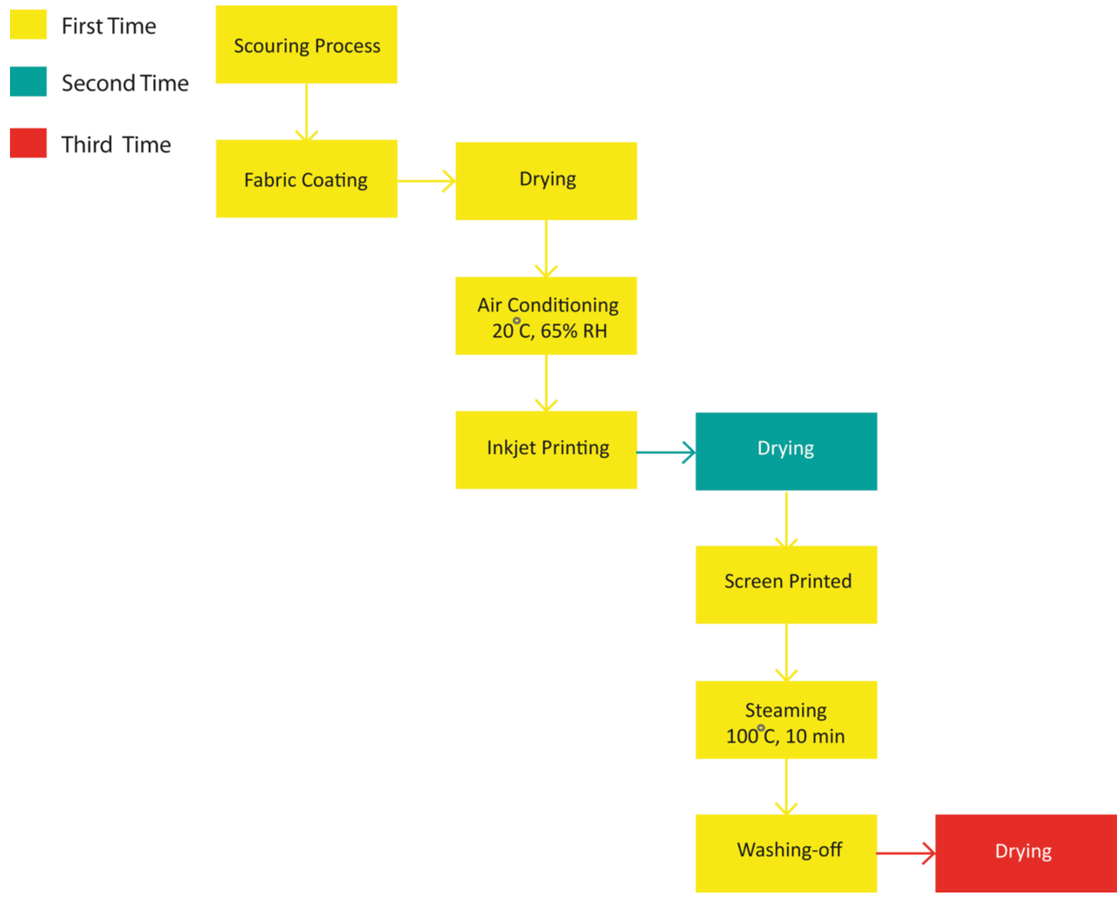


Figure 6.10. The streamlined process

It was noted that the particular chemicals applied to the fabric in order to prepare it for digital printing are the same as used in the screen-printing paste recipe, as illustrated in Figure 6.11. These chemicals are Manutex, which is a thickening agent used to ensure that the screen print paste is of the correct consistency, urea which enhances penetration of the dye into the fibre, and sodium bicarbonate, which provides the alkaline conditions under which the reactive dye fixes to the cellulosic fabric. Fabric is coated for digital print so that, after the dye is applied by printing, it is induced to react with the fibre and becomes fixed during steaming. The screen printing ink contains these same chemicals, but in that case they are applied to fabric during printing. However, if the fabric is already coated with these chemicals then, hypothetically, they do not need to also be included in the screen print paste. An exception is the Manutex, which still needs to be incorporated to thicken the screen print paste. The presence of urea and sodium bicarbonate also shortens the life of the print paste, making it viable for only 48 hours after which it is no longer fit for purpose, and so if they can be omitted from the print paste then less paste will also be wasted.

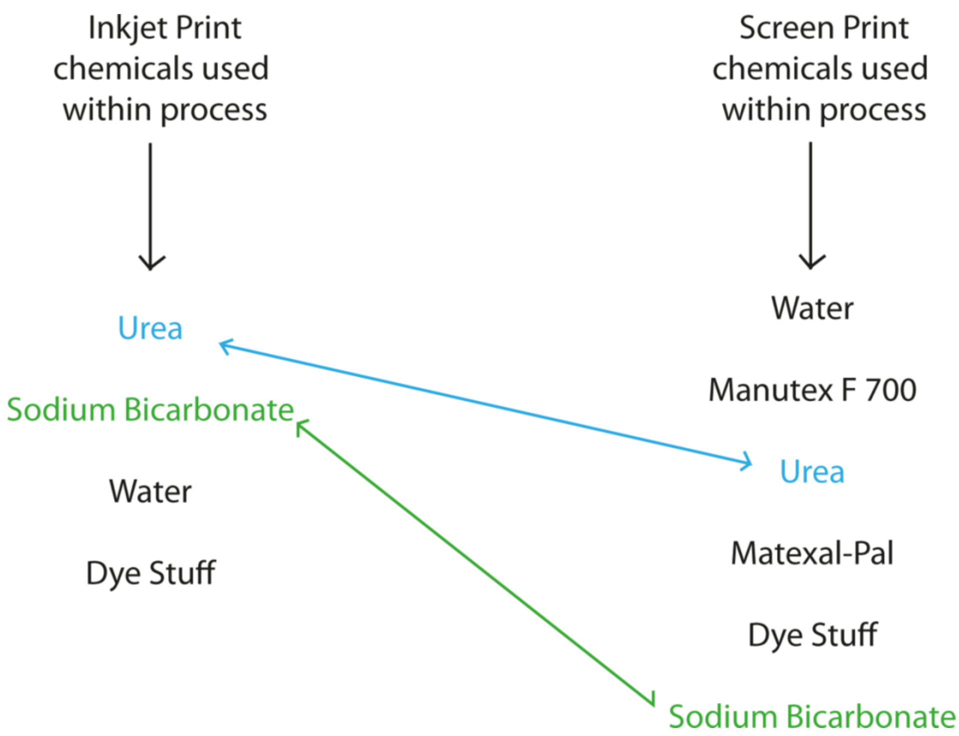


Figure 6.11. Chemical crossover of digital and screen print

The experimentation carried out so far on the two stage process leads to removal of the chemicals applied during fabric preparation for digital printing by steaming and washing, before fabrics are screen printed, and so the print paste has also required the additional chemicals. The experimentation in tests 11-14 involved an investigation that omitted steaming and washing after the digital print, and used only dye and Manutex, the thickening agent, to create a screen print paste. Samples E-H from print tests 5-8, produced using the original non-streamlined traditional methods and processes, were used as a comparison with the samples produced during this stage, K-M from tests 11-14, using the streamlined process developed for visual assessment to evaluate whether the process was successful. Flow diagrams showing the processes with and without the repeated chemicals are shown in Figures 6.12 and 6.13.

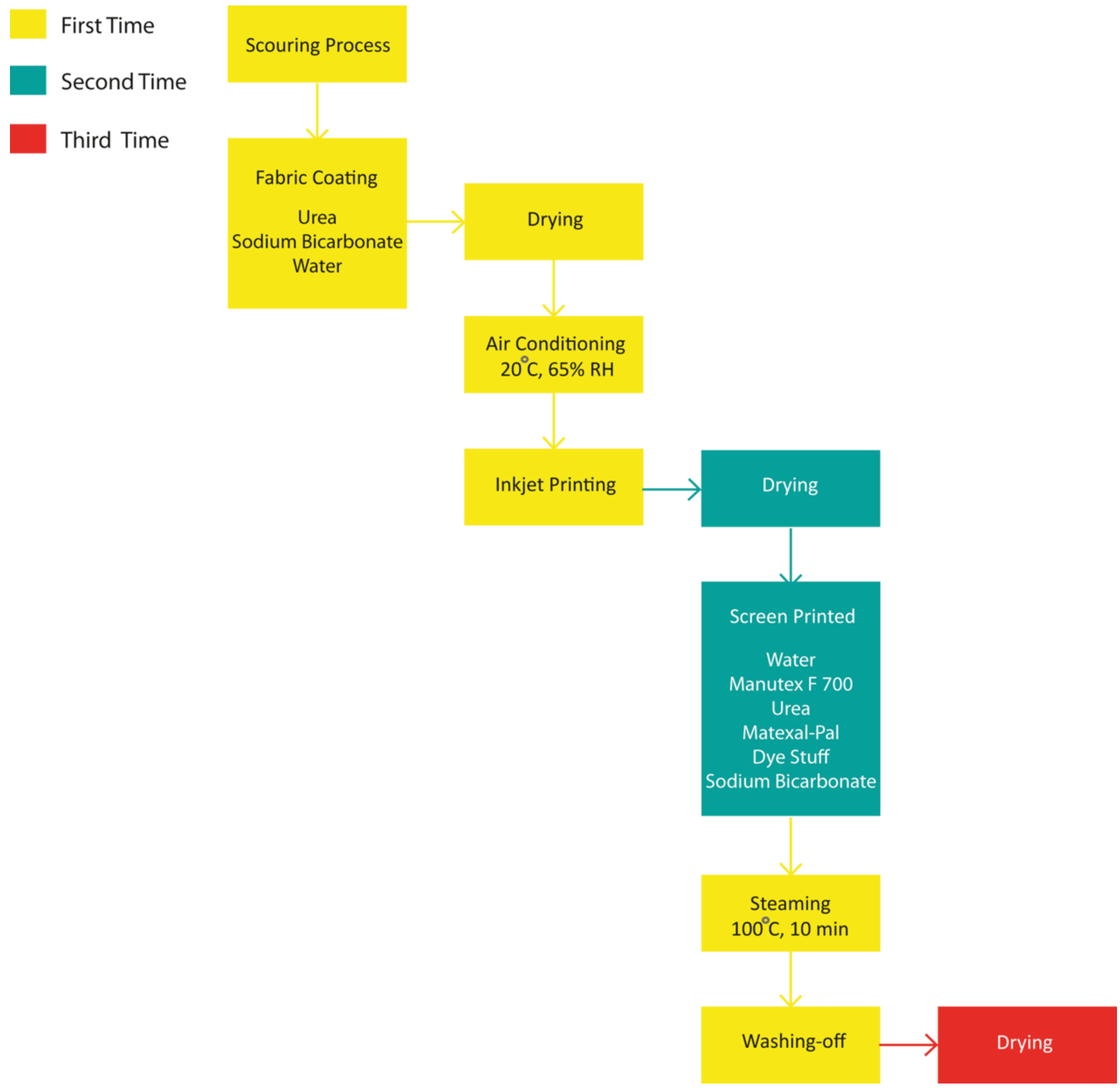


Figure 6.12. Flow diagram of the process with repeated chemicals used firstly for inkjet printing and added again later for screen printing

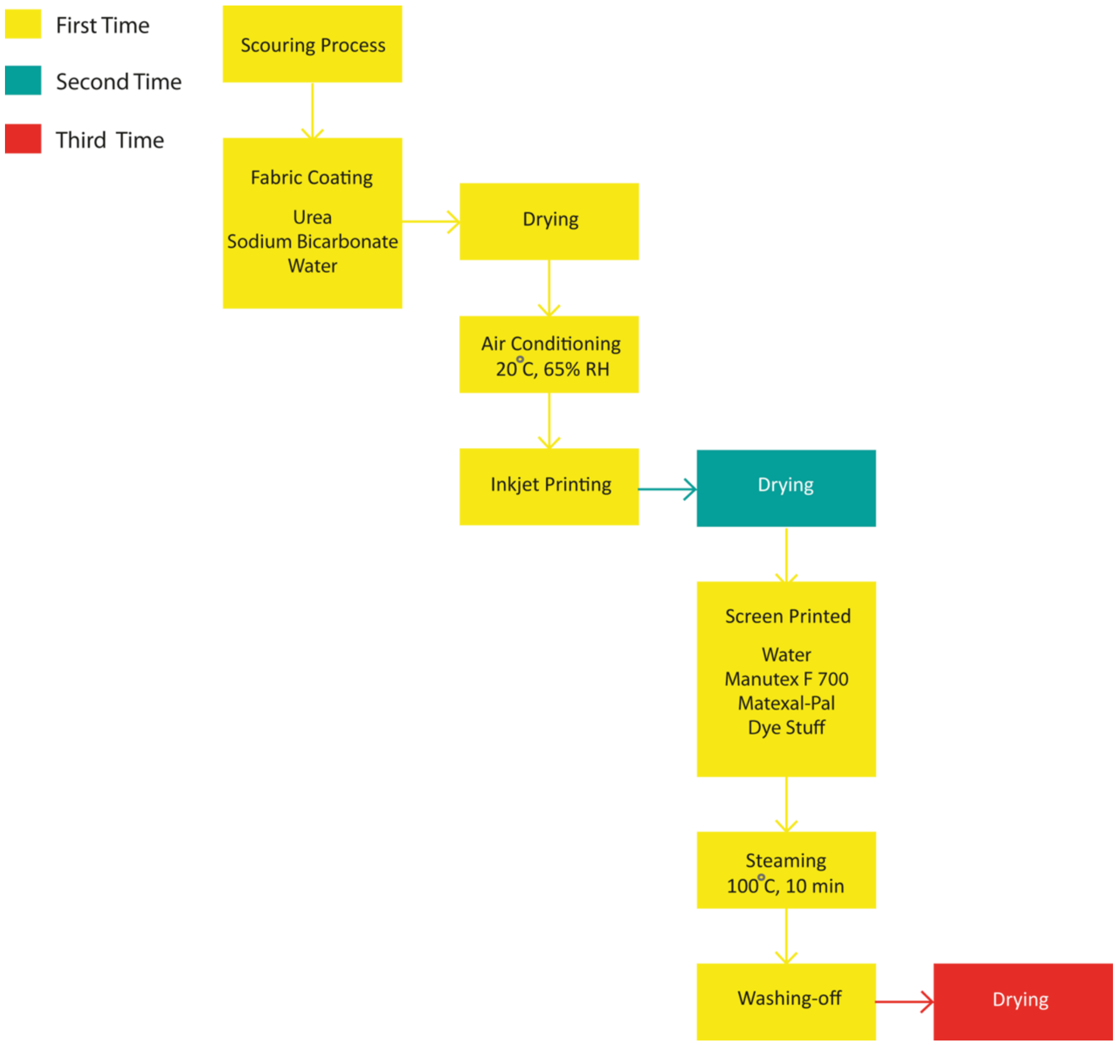


Figure 6.13. Flow diagram of a process with repeated use of chemicals removed and incorporated into a single stage. The chemicals are added only at the inkjet printing stage, fabric not steamed after inkjet printing, resulting in the chemicals urea, and sodium bicarbonate still embedded in the fabric, and thus not requiring a second batch to be used within the screen print paste.

Test 11. Fabric knitted sample K was scoured, prepared for digital printing, digitally printed on the front face of fabric with a black bird motif, and air-dried. Sample K was then screen-printed on the reverse with a black block print, steamed, washed, air dried, and then assessed.

Test 12. Fabric knitted sample L was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with a black bird motif, and air-dried. Sample L was then screen-printed on the front with black block print, steamed, washed, air dried, and then assessed.

Table 6.8 shows the methods and swatch samples (K and L) for each print test conducted (11 and 12). The larger samples produced are presented in Figure 6.14.

Table 6.8 Methods and swatches for samples K and L, print trials 11 and 12.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
K FRONT  REVERSE 	Tencel A100 Knit	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Front	Air dried	None	None	Screen, solid Synocron Black RD 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
L FRONT  REVERSE 	Tencel A100 Knit	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Black RD 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

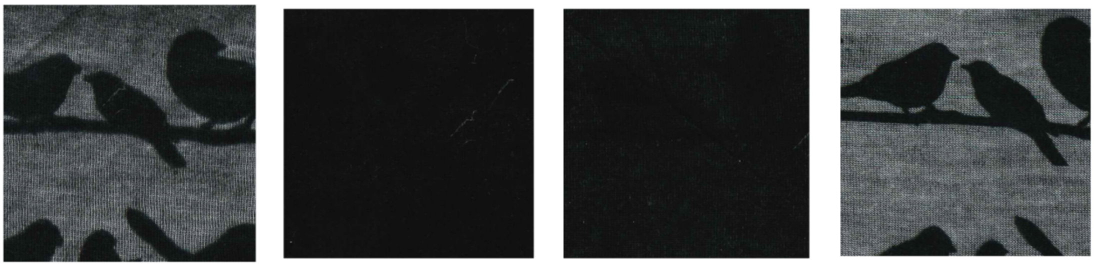


Figure 6.14 Larger samples (K and L) from tests 11 and 12.

Test 13. Fabric woven sample M was scoured, prepared for digital printing, digitally printed on the front face of fabric with a black bird motif, and air-dried. Sample M was then screen-printed on the reverse with a black block print, steamed, washed, air dried, and then assessed.

Test 14. Fabric woven sample N was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with a black bird motif, and air-dried. Sample N was then screen-printed on the front with a black block print, steamed, washed, air dried, and then assessed.

Table 6.9 shows the methods and swatch samples (M and N) for each print test conducted (13 and 14). The larger samples produced are presented in Figure 6.15.

Table 6.9 Methods and swatches for samples M and N, print trials 13 and 14.

Sample	Substrate	1^{st} Preparation Method	1^{st} Print Method	Fabric face printed onto	Finished	Washed	2^{nd} Preparation Method	2^{nd} Print Method	Fabric face printed onto	Finished	Washed
M FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Front	Air dried	None	None	Screen, solid Synocron Black RD 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
N FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Black RD 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Sample M Front Face Sample M Reverse Face Sample N Front Face Sample N Reverse Face

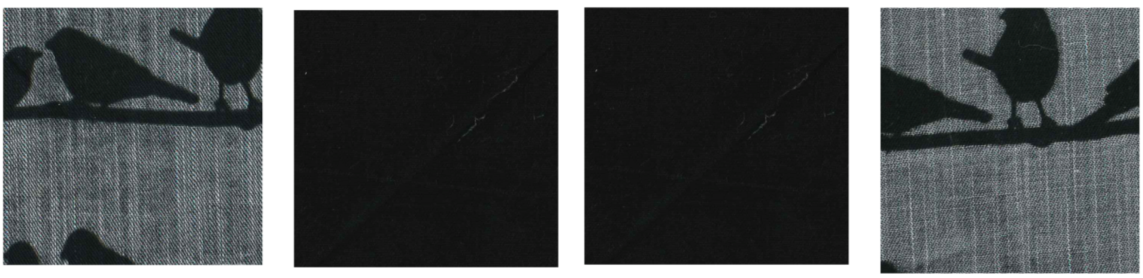


Figure 6.15. Larger samples (M and N) from tests 13 and 14.

It was concluded, based on visual assessment, by a comparison of samples K -N with samples E and F, which had used separate stages for printing and finishing, that there was no visual differentiation. The visual comparison is illustrated in Figure 6.16 for the knitted samples and Figure 6.17 for the woven samples. Combining the separate stages within one process was thus successful, providing not only a useful tool for the designer but also reducing the environmental impact of printing through combining the two stages within one. In addition, the process uses a screen print paste with a longer lifetime. The combined bisurface printing technique developed through incorporating inkjet and screen print technologies is illustrated in Figure 6.13

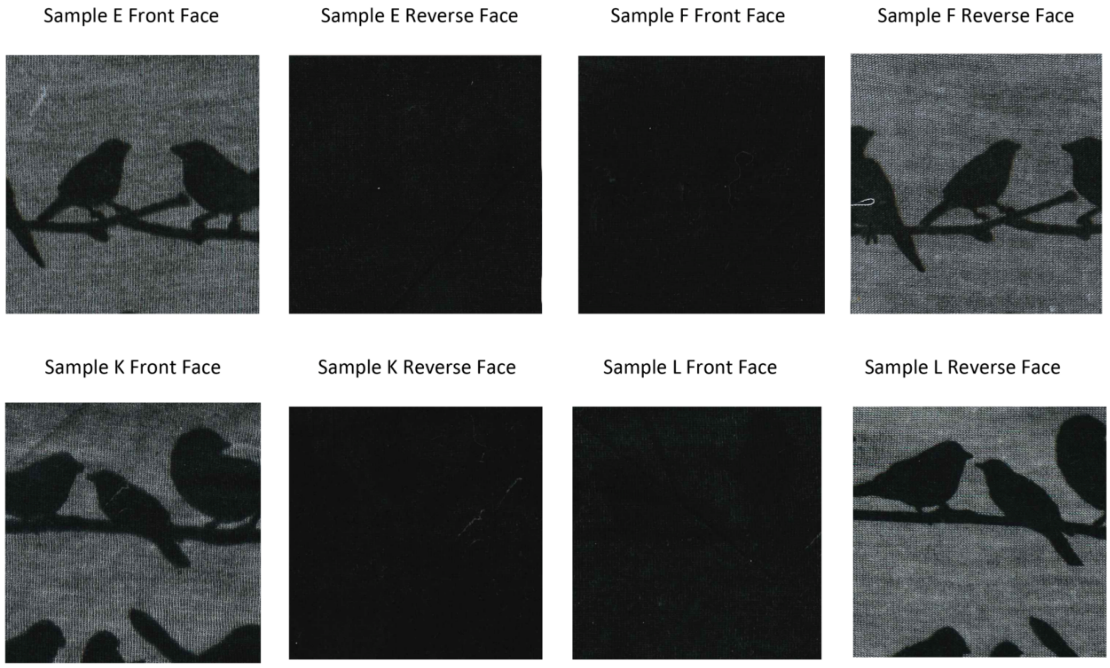


Figure 6.16. Visual comparison of samples K and L, using the streamlined process of printing (tests 11 and 12) for knitted Tencel with samples E and F for knitted Tencel, which had used separate stages for printing and finishing (tests 5 and 6)

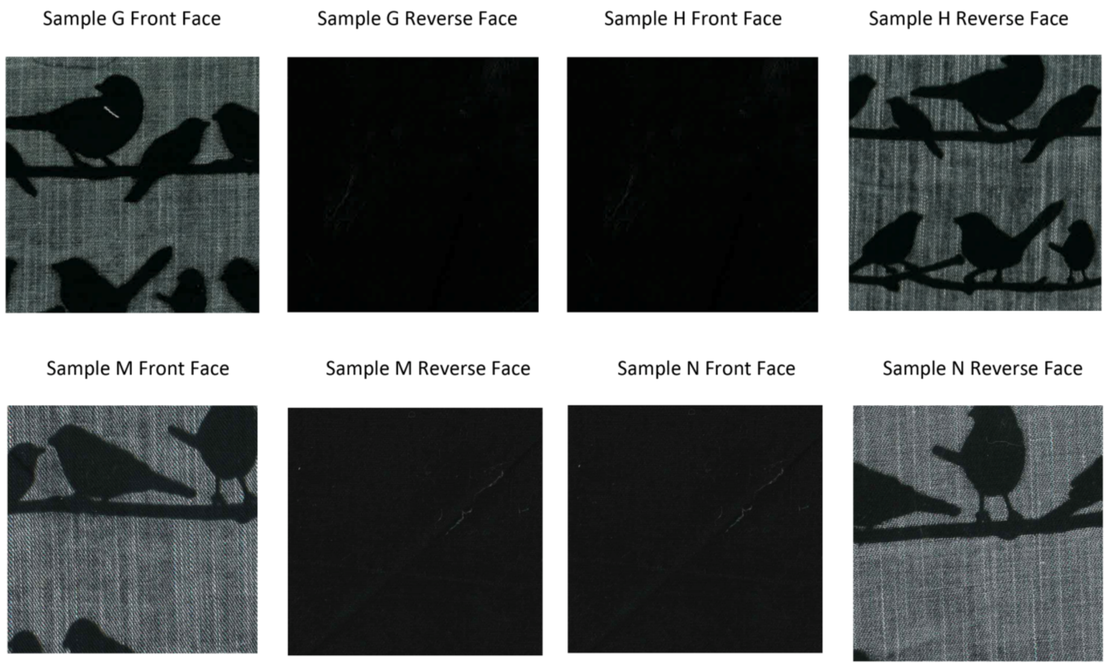


Figure 6.17. Visual comparison of samples M and N, using the streamlined process of printing (tests 13 and 14) for woven Tencel, with samples G and H for woven Tencel, which had used separate stages for printing and finishing (tests and to 8)

The research progressed subsequently to exploring the possibility of combining colours within the process, and also varying the depths of colour. The first experiment in this stage revisited combining black with grey. Initial investigations in tests 9 to 10 that produced samples I and J demonstrated that combining the deep shade of black with the lighter shade of grey was unsuccessful. Because this creates limitations for the designer in adopting this printing technique, the samples were revisited at this stage of the research. Samples G and H were produced initially using a black print paste mixed at dye ratio of 60g/1kg (dye to print paste). Thus, in aiming to achieve success in this combination of light and dark colour, the strength of dye in the black print paste was reduced to 40g/1kg.

Test 15. Fabric sample O was scoured, prepared for digital printing, digitally printed on the front face of fabric with the grey bird motif and air-dried. Sample O was then screen-printed on the reverse with black block print, steamed, washed, air dried, and then assessed.

Test 16. Fabric sample P was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the grey bird motif, and air-dried. Sample P was then screen-printed on the front with black block print, steamed, washed, air dried, and then assessed.

Table 6.10 shows the methods and swatch samples (O and P) for each print test conducted (15 and 16). The larger samples produced are presented in Figure 6.18.

Table 6.10 Methods and swatches for samples O and P, print trials 15 and 16.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
O FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in grey	Front	Air dried	None	None	Screen, solid Synocron Black RD 40g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
P FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in grey	Reverse	Air dried	None	None	solid Synocron Black RD 40g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

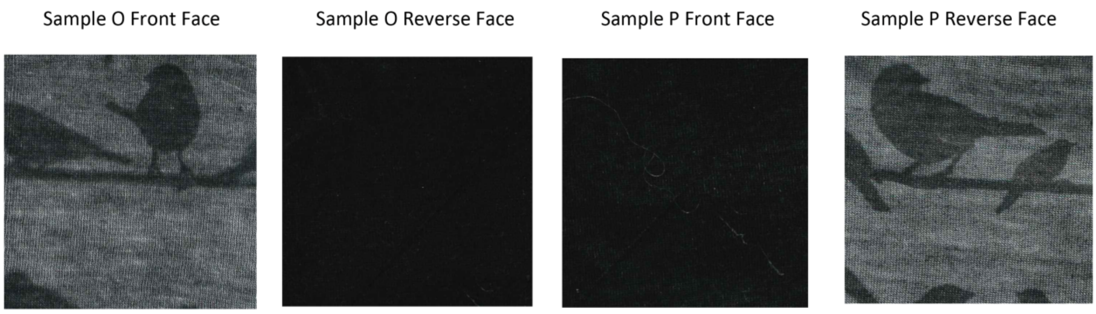


Figure 6.18. Larger samples (O and P) from tests 15 and 16.

Visual assessment demonstrated a much more successful appearance for sample O and P when compared to the earlier samples I and J as shown in Figure 6.19, in that the lighter print was clearly visible, through reducing the dye strength of the screen print paste mixture.

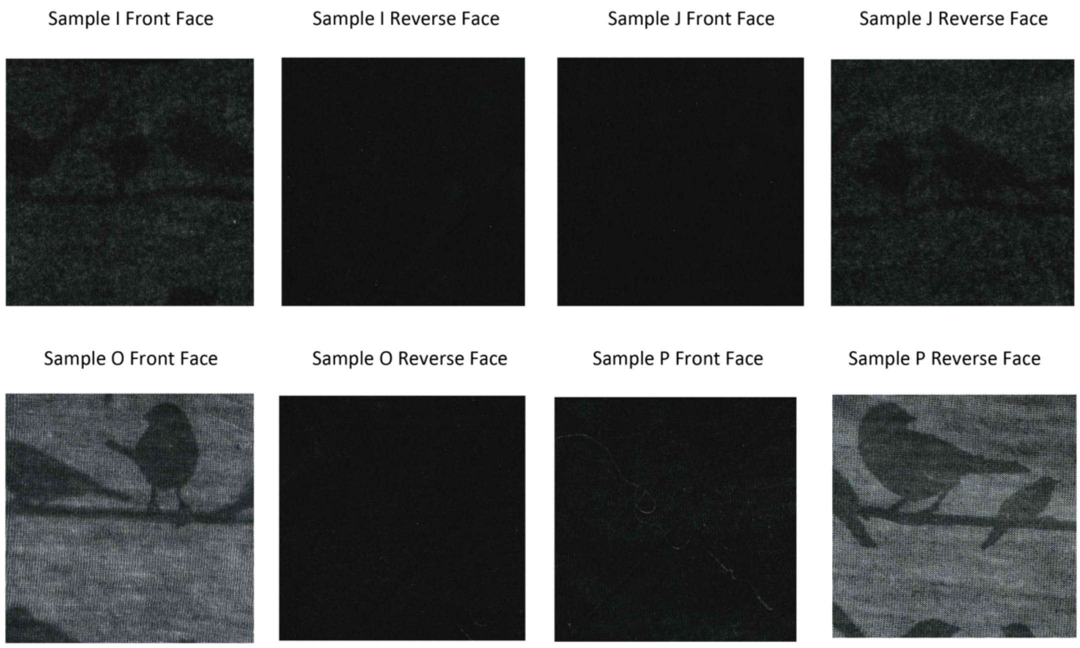


Figure 6.19. Visual comparison of samples I and J (tests 9 and 10) with O and P (tests 15 and 16)

The results demonstrated a successful approach to the incorporation of colour, though had only focused on incorporating monochrome shades into the streamlined print process. At this stage, a wider variety of colour was then introduced further into the experimentation. Samples were produced by screen printing using the Kisco Synacron RD colour palette, for medium and dark shades demonstrated earlier in this chapter (Figure 6.2). Samples were digitally inkjet printed on to the reverse side of the fabric and the block screen print colour was printed on to the front face of the fabric. This was due to the simplicity of the digital print imagery used proving in earlier experimentation to be unproblematic in the inkjet print process and the block printing of colour on to the knitted fabrics was deemed to be more suited to the front face of the fabrics for this combination of imagery.

Test 17. Fabric sample Q, scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample Q was then screen-printed on the reverse with yellow block print, medium shade, steamed, washed, air dried, and then assessed.

Test18. Fabric sample R, scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif, and air-dried. Sample T was then screen-printed on the front with yellow block print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.11 shows the methods and swatch samples (Q and R) for each print test conducted (17 and 18). The larger samples produced are presented in Figure 6.20.

Table 6.11 Methods and swatches for samples Q and R, print trials 17 and 18.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
Q FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Yellow RD 20g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
R FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Yellow RD 40g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Sample Q Front Face | Sample Q Reverse Face | Sample R Front Face | Sample R Reverse Face

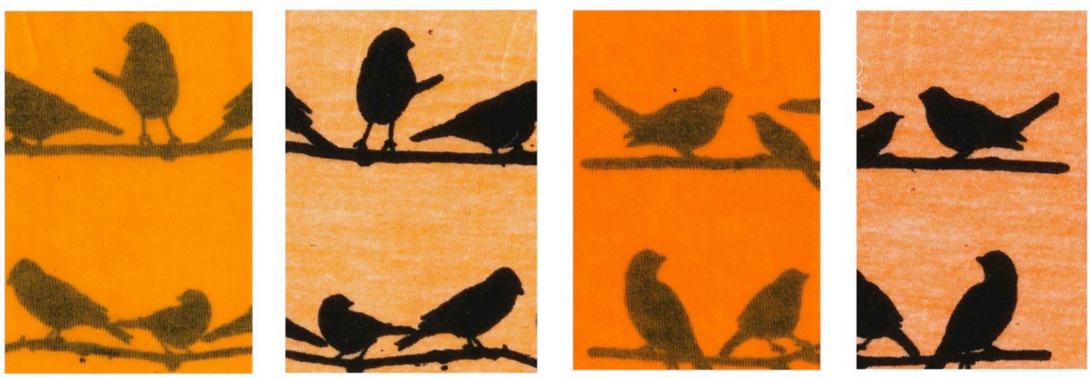


Figure 6.20. Larger samples (Q and R) from tests 17 and 18.

Test 19. Fabric sample S was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample S was then screen-printed on the reverse with orange block print, medium shade, steamed, washed, air dried, and then assessed.

Test 20. Fabric sample T was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif, and air-dried. Sample T was then screen-printed on the front with orange block print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.12 shows the methods and swatch samples (S and T) for each print test conducted (19 and 20). The larger samples produced are presented in Figure 6.21.

Table 6.12 Methods and swatches for samples S and T, print trials 19 and 20.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
S FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Orange RD 15g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
T FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Orange RD 30g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

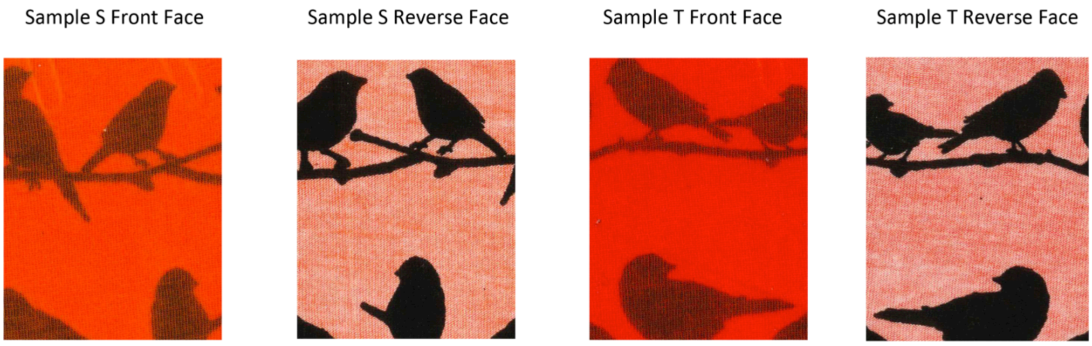


Figure 6.21. Larger samples (S and T) from tests 19 and 20.

Test 21. Fabric sample U was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample U was then screen-printed on the reverse with red block print, medium shade, steamed, washed, air dried, and then assessed.

Test 22. Fabric sample V was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif, and air-dried. Sample V was then screen-printed on the front with red block print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.13 shows the methods and swatch samples (U and V) for each print test conducted (21 and 22). The larger samples produced are presented in Figure 6.22.

Table 6.13 Methods and swatches for samples U and V, print trials 21 and 22.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
U FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Red RD 25g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
V FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Red RD 50g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Figure 6.22. Larger samples (U and V) from tests 21 and 22.

Test 23. Fabric sample W was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample W was then screen-printed on the reverse with deep red block print, medium shade, steamed, washed, air dried, and then assessed.

Test 24. Fabric sample X was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample X was then screen-printed on the reverse with deep red block print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.14 shows the methods and swatch samples (W and X) for each print test conducted (23 and 24). The larger samples produced are presented in Figure 6.23.

Table 6.14 Methods and swatches for samples W and X, print trials 23 and 24.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
W FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Deep Red RD 20g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
X FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Deep Red RD 40g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Sample W Front Face Sample W Reverse Face Sample X Front Face Sample X Reverse Face

Figure 6.23. Larger samples (W and X) from tests 23 and 24.

Test 25. Fabric sample Y was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample Y was then screen-printed on the reverse with rubine block print, medium shade, steamed, washed, air dried, and then assessed.

Test 26. Fabric sample Z was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample Y was then screen-printed on the reverse with rubine print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.15 shows the methods and swatch samples (Y and Z) for each print test conducted (25 and 26). The larger samples produced are presented in Figure 6.24.

Table 6.15 Methods and swatches for samples Y and Z, print trials 25 and 26.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
Y FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Rubine RD 15g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
Z FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Rubine RD 30g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Sample Y Front Face · Sample Y Reverse Face · Sample Z Front Face · Sample Z Reverse Face

Figure 6.24. Larger samples (Y and Z) from tests 25 and 26.

Test 27. Fabric sample A1 was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample A1 was then screen-printed on the reverse with brilliant blue block print, medium shade, steamed, washed, air dried, and then assessed.

Test 28. Fabric sample A2 was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample A2 was then screen-printed on the reverse with brilliant blue block print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.16 shows the methods and swatch samples (A1 and A2) for each print test conducted (27 and 28). The larger samples produced are presented in Figure 6.25.

Table 6.16 Methods and swatches for samples A1 and A2, print trials 27 and 28.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
A1 FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Brilliant Blue RD 40g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
A2 FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Brilliant Blue RD 80g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

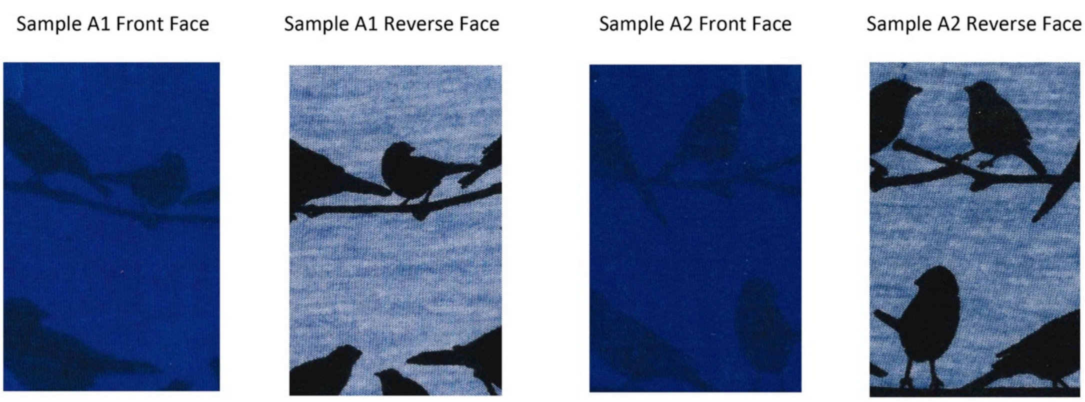


Figure 6.25. Larger samples (A1 and A2) from tests 27 and 28.

Test 29. Fabric sample A3 was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample A3 was then screen-printed on the reverse with navy blue block print, medium shade, steamed, washed, air dried, and then assessed.

Test 30. Fabric sample A4 was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the black bird motif and air-dried. Sample A4 was then screen-printed on the reverse with navy blue block print, dark shade, steamed, washed, air dried, and then assessed.

Table 6.17 shows the methods and swatch samples (A3 and A4) for each print test conducted (29 and 30). The larger samples produced are presented in Figure 6.26.

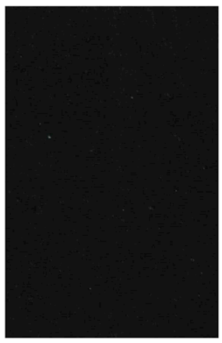
Table 6.17 Methods and swatches for samples A3 and A4, print trials 29 and 30.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
A3 FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	Screen, solid Synocron Navy Blue RD 40g/1kg (Medium)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
A4 FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, bird motif in black	Reverse	Air dried	None	None	solid Synocron Navy Blue RD 80g/1kg (Dark)	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Sample A3 Front Face

Sample A3 Reverse Face

Sample A4 Front Face



Sample A4 Reverse Face

Figure 6.26. Larger samples (A3 and A4) from tests 29 and 30.

6.6 Interdisciplinary Design Development

The results have demonstrated the successful incorporation of colour into the streamlined print process. On this basis, the technical research carried out may now be used as a tool to integrate with and inform the design process. Although no visual disparity was found between screen or digital printing applied on either the front or reverse side of fabrics, it was decided to use the front face as standard for digitally printing and the reverse face as standard for screen printing from this point forward within the research. Digital print can be more sensitive to the fabric surface being printed on to, due to the nature of the print head used to release the drop of colour onto the substrate. Thus, to safeguard the quality of print and reduce risk of waste through print error, printing on the front face of the fabric using digital inkjet was selected as a personal preference.

As described in the previous section, the technique involving a streamlined combination of digital and screen print process was demonstrated to be successful technically, with colour also introduced successfully. In the next research phase, the process was then used to explore the potential for designing. Imagery for digital print was explored first. The driving force for creating bi-surface printable fabrics was so that the designer could essentially create two garments within one to combine a slow metabolic garment with a fast metabolic garment.

For this purpose, a popular textile choice for casual garments, denim was chosen and linked to a smart, formal block colour garment choice. Both denim and solid block coloured fabric would normally be prepared by dyeing, and the alternative to prepare either of these items by printing was already a novel concept. Denim dyeing, which traditionally uses indigo, has negative environmental features in terms of chemical, energy and water usage, which might potentially be reduced by the use of print techniques. Also, to combine them into one garment was a significant design challenge.

Denim in itself is an industry that is hugely environmentally impacting. Five billion pairs of jeans are manufactured globally every year using 35% of world cotton production (Musante, 2013). The production of standard denim jeans is water, chemical and energy intensive, from initial fibre cultivation through to manufacturing processes, causing significant environmental impact. The French Environment and Energy Management Agency (ADEME) has produced the document 'An Environmental Product

Declaration of Jeans'; this document provides a collection of environmental information based on life cycle analysis conducted according to international ISO 14040 standards. The aim of the document is to inform sustainable purchasing behavior through highlighting the potential for areas of improvement, such as consumer choice at point of purchase. For example, the document suggests that choosing organic cotton over standard cotton will have a positive environmental impact. Data within the ADEME report suggests that the detrimental environmental impact of jeans occurs in two main areas of the product life cycle; 59% arises during cotton cultivation and product manufacturing/finishing processes, and 41% is due to utilization/end of life (ADEME).

The denim brand Levi Strauss and Co. also conducted a life cycle assessment (LCA) in order to understand the environmental impact of their denim products throughout an entire life cycle. The LCA data for a pair of Levi's 501 jeans highlighted three key areas of impact. The first of these was specifically water usage. More than 3,000 liters of water are used during the full product cycle for a single pair of jeans. 49% of this water is used in growing the cotton, 45% is used when consumers wash their jeans, and the remaining 6% is used during the manufacturing process of the jeans (Levi Strauss & Co, 2015). The life cycle analyses data for denim jeans highlights that the main environmental impact of denim production is caused by cotton cultivation, followed by coloration and finishing processes. The research described in this chapter aimed to address all three of these areas. Further research would be worthwhile also to address consumer behavior, aiming to decrease environmental impact during the use and end of life stages of the garments.

The denim imagery was developed first. It was decided that the denim imagery would be digitally printed as the imagery required was more complex and less well suited to screen printing than to create the opposing solid coloured surface, which could easily be produced through screen printing. Arguably, screen print is likely to produce a better quality of solid colour. Digital inkjet printing provides opportunities to explore an alternative coloration method for denim, which would combine two separate finishing processes used in traditional denim production aiming to reduce energy, chemical and water usage, namely the initial coloration stages of indigo dyeing and finishing stages such as stone washing, bleaching, treatment with enzymes or sulphuric acid, and laser treatment. The comparison of inkjet printed denim with traditionally produced dyed denim is shown in Figure 6.27.

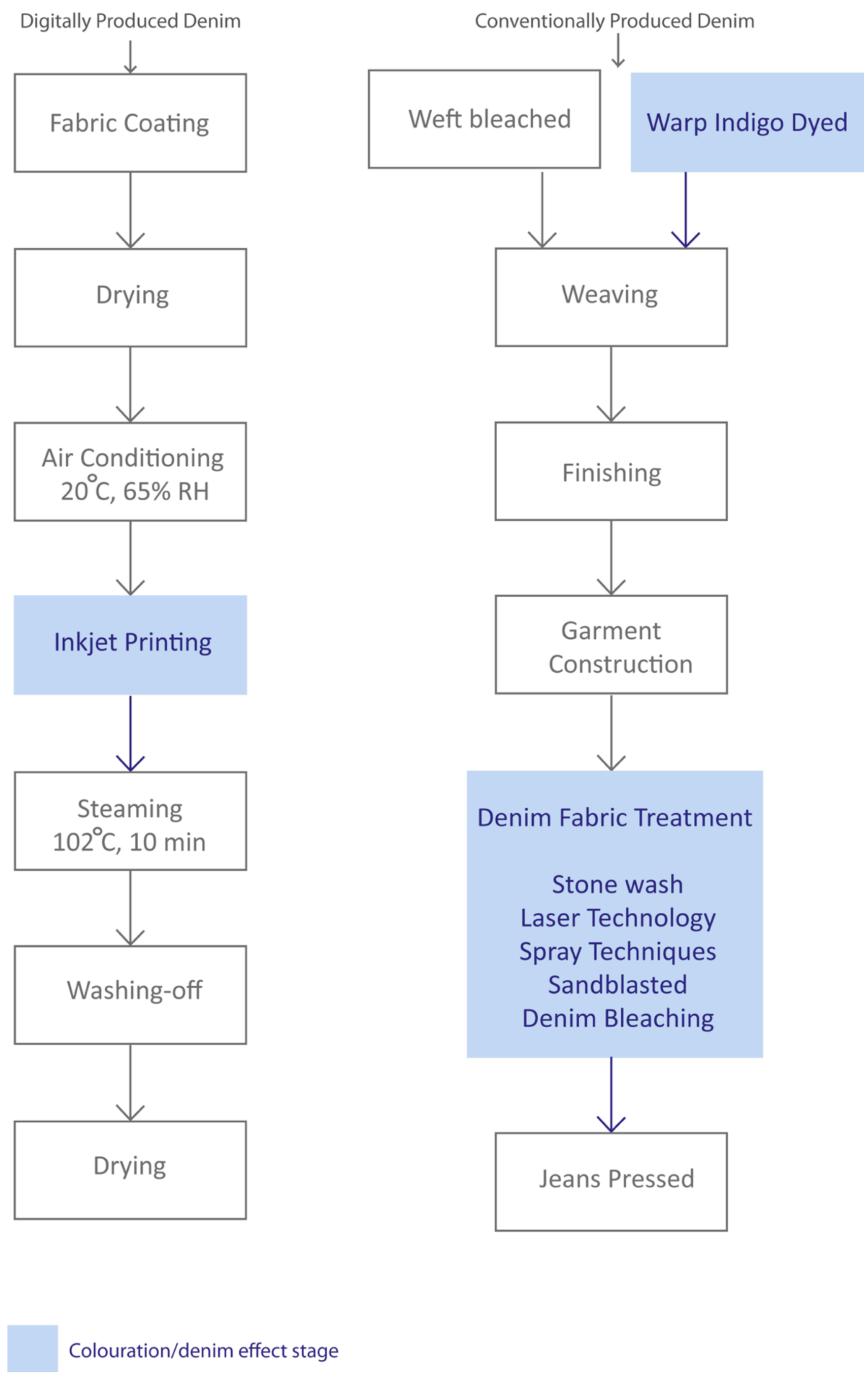


Figure 6.27. A comparison of methods for denim production

In aiming to reduce energy, chemical and water usage, digital inkjet printing provides the opportunity for the initial coloration stages of indigo dyeing to be incorporated with the finishing stages, such as stone washing, laser technology, spray techniques, sand blasting and denim bleaching, which are all used to create a design aesthetic, such as an 'old, worn, denim look' in new garments, but which cause additional environmental impact during production.

6.6.1 Re-designing Denim; Combining Coloration and Finishing Processes

Digital inkjet printing provides opportunity to explore an alternative coloration method for denim, which would combine two separate finishing processes of traditional denim production to reduce energy, chemical and water usage, these being the initial coloration stages of indigo dyeing and finishing stages such as stone washing, bleaching, treatment with enzymes, laser treatment or sulphuric acid. Printing allows colour to be applied in a localized design or pattern to a textile material, in this case, fabric. Digital inkjet printing refers to the creation of individual drops of ink deposited in a precisely controlled manner onto a substrate in doing so creating an image (Fralix, M, T. 2001).

Digital inkjet printing for textiles was first exhibited by stork in 1991 though the model exhibited, the TruColour TCP2500 was designed as a sampling machine and could only print rectangular fabric swatches. At ITMA (an international trade show and conference for manufacturers and suppliers of textile) in 1995 Stork introduced the 'fashion jet', a model of printer capable of continuously printing rolls of fabric, (Moser, 2003). Since the initial introductory interest in digital print, improvements in technology and capabilities of both computers and computer-aided design soft-wear programs have continued to grow. Digital inkjet printing offers a method for creating denim effects that are reproducible and controllable, through the hand of the designer, technology and computer aided design that is readily available on a commercial scale

6.6.2 Digital Denim

Before the combined digital and screen-printing process was applied, it firstly needed to be established whether denim could be simulated using digital printing. 'Irregular Twill' fabric was specifically woven from Tencel A100 for the purpose of the research. The change from cotton, used in traditional denim, to Tencel avoids the negative environmental features of cotton, and takes advantage of the positive environmental features of Tencel, as described in Section 2.3.2. The fabric was prepared for digital print by impregnating with a solution of sodium bicarbonate, Metaxil p-AL and urea in water as described in Section 6.2.4. Fabric must be pre-prepared in this way to allow reactive dye molecules to penetrate into the fibre during inkjet printing, and to cause them to be fixed to the fibre by chemical reaction after printing using steam.

To create the denim imagery for printing, a selection of denim swatches were scanned into Photoshop using a high-resolution setting (300 dpi). The digital imagery was required to replicate both the structural twill effect of denim as a result of the traditional construction method which interweaves blue and white yarns, and the unique 'blue' colour achievable on dyeing with indigo. In the case of digital print, indigo cannot be used as the dye, and so was replaced with reactive dye and the denim twill (usually structural) was replaced by a digital effect. Four traditional denim fabric swatches varying in colour, shade, and depth were selected for further design development. Trials were carried out in which the digital images from each of these swatches, placed in a repeat pattern, were printed on to the pre-treated Tencel. Figure 6.28 shows the initial inkjet printed samples of the four denim swatches used as tiles to create the denim fabric. It was decided, based on visual inspection of the printed fabric, that samples B and D provided the most realistic denim appearance.

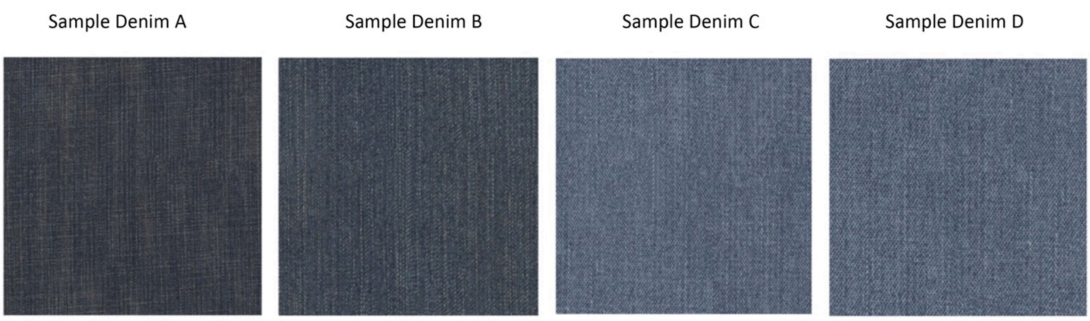


Figure 6.28. Initial digital denim imagery developed.

The digital denim swatches shown in Figure 6.28 were imported into Lectra (Kaledo Style) software, and then developed into a repeat image. The main challenge faced with digitally printing denim is creating a fading effect (worn look) in the desired area of the jeans. To attempt to achieve more precision in placing the worn effects a pattern for the final jeans was drafted to a sample size 10 sizing specification. A traditional paper pattern was made to ensure the pattern pieces fitted accurately then the pattern was digitally drawn into Lectra (Modaris CAD software program for patternmaking, grading and 3D digital prototyping). The benefit of developing a digital pattern is that it allows the designer to work with accurate scale pattern pieces digitally on the computer screen which is vital in creating faded denim areas. This method allowed the desired denim effect to be directly placed onto each pattern piece whilst retaining the scale. The designer can work into the plain denim pattern pieces to create the 'worn effect' on focused areas of the pattern piece.

At this stage the combined imagery and pattern pieces were tested by digitally printing a selection of colours and fading effects. Four legs were then printed as test samples (as show in Figure 6.29). The denim imagery developed demonstrated in samples B and D in Figure 6.28 was further developed into a denim jean leg shape to explore whether the denim effect worked on a larger scale. The denim imagery was used to create a pattern piece for the front leg of a denim jean. The imagery was printed both without and with an additional fading effect. This allowed initial investigation into incorporating both coloration processes with the finishing process. The results of the trials are demonstrated in Figure 6.29.

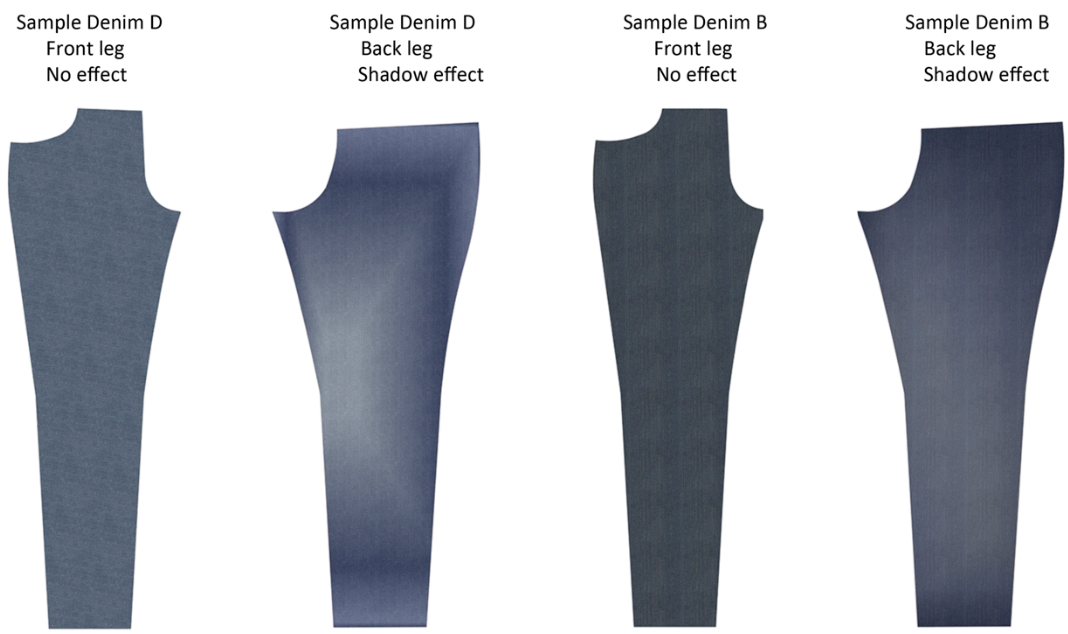


Figure 6.29. Developing digital denim imagery into a garment shape and adding a 'worn, aged, effect' at the inkjet printing stage.

Once the jeans were digitally printed as pattern pieces, figure, 6.30, a standard steam finish process (100°C for 20 minutes) was used in order to fix the reactive dye to the fabric. The jeans were then constructed, as a standard pair of jeans would be as shown in Figure 6.31. Figure 6.32 shows the pocket area faded effect created by digitally printing.

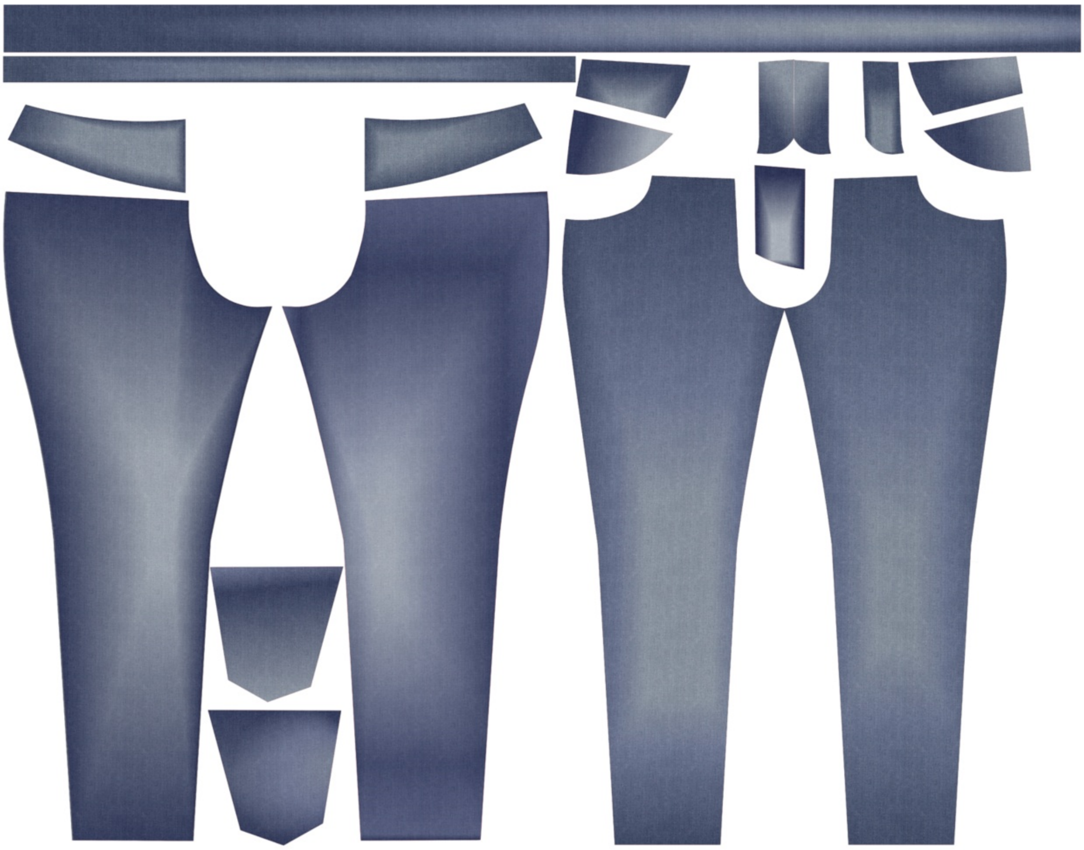


Figure 6.30. Lectra digital trouser pattern digitally printed with developed denim imagery

Figure 6.31. ‘Denim-less Denim’ trouser front and back view

Figure 6.32**.** A close up of the pocket showing the digital print effect creating a faded, worn look.

To develop a larger colour palette for denim sample B, the darker of the more successful digital denim fabrics, manipulation was carried out in Adobe Photoshop by using the curve tool, a tool designed to increase and decrease colour tone. The varying shades of denim produced using this method are shown in the inkjet printed samples shown in Figure 6.30, along with the original fabric sample used, sample B, and the curve input and output numbers used to create the new swatches.

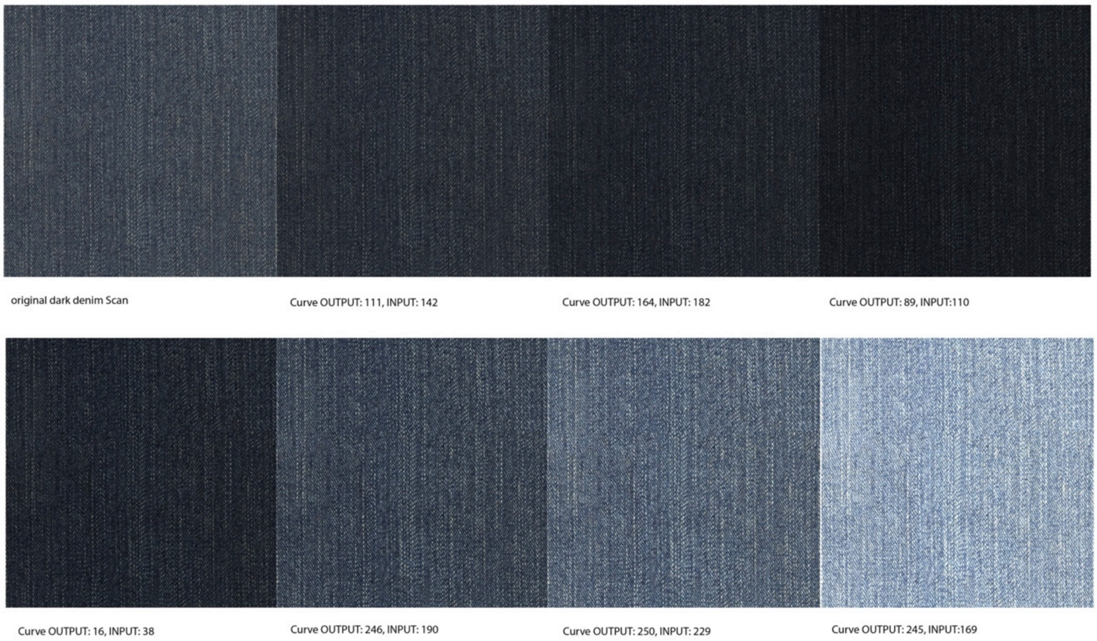


Figure 6.33. Developing a digital colour palette by exploring the effect of manipulating colour depth through using the Adobe Photoshop curve tool.

6.6.3 Digital denim assessment

The imagery produced by digitally printing denim, as described in the previous section, was judged visually to be successful in simulating a traditional denim fabric. However, when denim leg pattern pieces produced for initial experimentation, as presented in Figure 6.29, were constructed together to give the impression of a denim jean trouser leg, the reduced weight of the Tencel garment in comparison to a traditional cotton jean was evident in the drape of the garment. Thus, it was concluded that the weight of the 100% woven Tencel used to produce the final pair of jeans ideally needed to be heavier, more similar to a 'denim weight'. Tencel is a lighter fibre than cotton and so it was clear that development towards creating a heavier density of yarn would need to be conducted in order to produce heavier and thicker Tencel denim, comparable to that of cotton denim. As a fashion fabric, Tencel is commonly marketed for its luxurious qualities, such as a smooth drape. However, these are not desirable qualities in a fabric choice for producing denim jeans for women. Generally, a heavier fabric weight made up by incorporating a blend of cotton with a small percentage of elastane (Lycra) is used. The fabric used to create the Tencel jeans had no elastane content, which is commonly a component of the fabric used to construct women's denim jeans to provide some elasticity that aids both the fit and the look of the garment. A decision was made not to incorporate elastane within the Tencel jeans at this stage, due to the potential environmental repercussions both in producing elastane and in recycling or disposing of the garment at the end of life stage. This initial assessment of the digital denim fabric led to the decision that if the denim imagery was incorporated into a garment design, alternative applications for the digital denim, rather than a trouser, that are more suited to the weight of the 100% Tencel fabric used, would need to be explored.

Having successfully produced an inkjet 'denim look' fabric, the next stage of research used this outcome to explore the incorporation of the digital denim process, within the method developed for combining screen with digital print. Subsequently, the research was continued to investigate the potential for both knitted and woven fabric applications for garment designs.

6.6.4 Bi-surface denim

A series of 100% Tencel woven fabric samples was tested to establish whether the digitally printed denim imagery could be combined successfully with screen-printing. The first set of tests, 31 and 32 (samples D1 and D2) compared printing on the front and reverse of the fabric with the denim imagery. The second set of tests, 33 and 34 (samples D3 and D4) focused on incorporating the imagery into the streamlined printing process and also compared printing on the front and reverse surface of the fabric.

Test 31. Fabric sample D1 was scoured, prepared for digital printing, digitally printed on the front face of the fabric with the denim imagery, and air dried. Sample D1 was then screen-printed on the reverse of the fabric with the black bird print, steamed, washed, dried and then assessed.

Test 32. Fabric sample D2 was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the denim imagery, and air-dried. Sample N was then screen-printed on the front of the fabric with the black bird print, steamed, washed, dried and assessed.

Table 6.18 shows the methods and swatch samples (D1 and D2) for each print test conducted (31 and 32). The larger samples produced are presented in Figure 6.34.

Table 6.18 Methods and swatches for samples D1 and D2, print trials 31 and 32.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
D1 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, denim sample B	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen bird motif Synocron Black RD 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
D2 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, denim sample B	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen bird motif Synocron Black RD 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

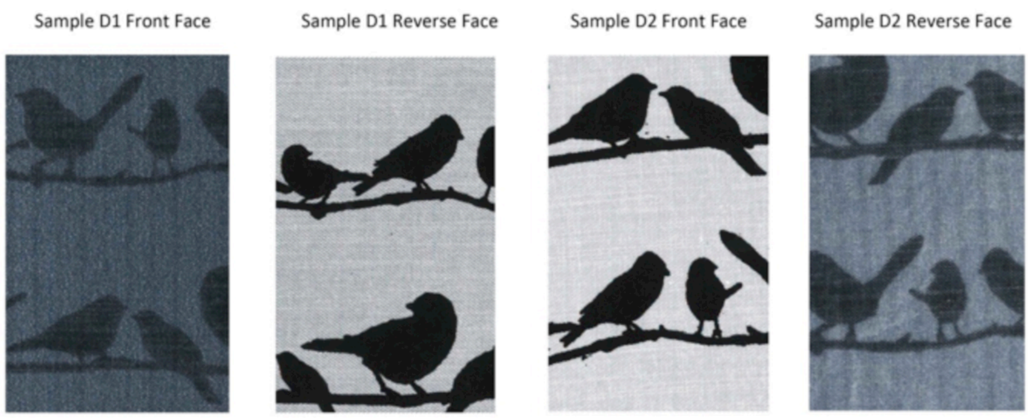


Figure 6.34. Larger samples (D1 and D2) from tests 31 and 32, for visual comparison.

Test 33. Fabric sample D3, scoured, prepared for digital printing, digitally printed on the front face of the fabric with the denim imagery, and air dried. Sample 31 was then screen-printed on the reverse of the fabric with the black bird print, steamed, washed, dried and then assessed.

Test 34. Fabric sample D4, scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the denim imagery, and air-dried. Sample D4 was then screen-printed on the front of the fabric with the black bird print, steamed, washed, dried and assessed.

Table 6.19 shows the methods and swatch samples (D3 and D4) for each print test conducted (33 and 34). The larger samples produced are presented in Figure 6.32.

Table 6.19. Methods and swatches for samples D3 and D4, print trials 33 and 34.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
D3 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital Denim imagery	Reverse	Air dried	None	None	Screen bird motif Synocron Black RD 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C
D4 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital Denim imagery	Front	Air dried	None	None	Screen bird motif Synocron Black RD 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Sample D3 Front Face | Sample D3 Reverse Face | Sample D4 Front Face | Sample D4 Reverse Face

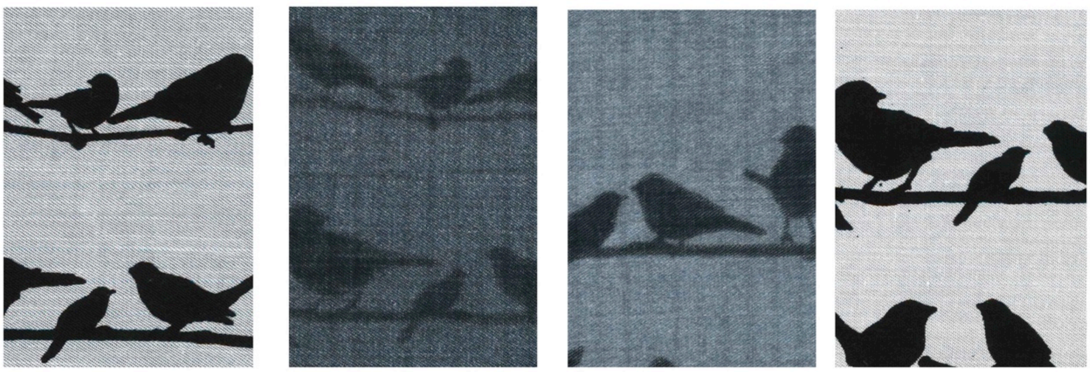


Figure 6.35. Larger samples (D3 and D4) from tests 33 and 34, for visual comparison.

Visual assessment of the samples D1 and D2, as shown in Figure 6.35, demonstrated that the denim imagery was successfully produced, no matter whether printed on the front or the reverse side of the fabric samples. The samples also clearly show a difference in colour among the denim imageries printed on the four samples. This was attributed to the inkjet printer used, as the image quality is not reduced, but the colour strength is weaker. It was also observed that the black screen print can be seen on the side opposite to which it is printed, a feature that adversely affects the appearance in trying to create printed surfaces with two different images within one piece of fabric. However, a positive feature was that the samples were successfully prepared, printed and finished in one continuous process, demonstrating that the technique developed can be successfully applied and is reliably repeatable.

To overcome the observed issue of pattern being seen through the inkjet printed surface the technique, used for earlier samples, of screen printing block colour was explored. The first set of tests, 35 and 36 (samples D5 and D6) compared combining the digital inkjet denim imagery with the block screen print using the non-streamlined process, samples were digitally printed on either the front or reverse of the fabric with the apposing surface then block screen printed. Fabrics were dried, steamed and washed after the first stage of printing and then compared with the second set of tests, 37 and 38 (samples D7 and D8) that repeated the printing stages of tests 35 and 36, but focused on incorporating the imagery into the streamlined printing process and also compared printing on the front and reverse surface of the fabric.

Table 6.20 shows the methods and swatch samples (D5 and D6) for each print test conducted (35 and 36). The larger samples produced are presented in Figure 6.36.

Table 6.20. Methods and swatches for samples D5 and D6, print trials 35 and 36.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
D5 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim inagery	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen, solid Synocron Black RD 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
D6 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim inagery	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C	None	Screen, solid Synocron Black RD 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

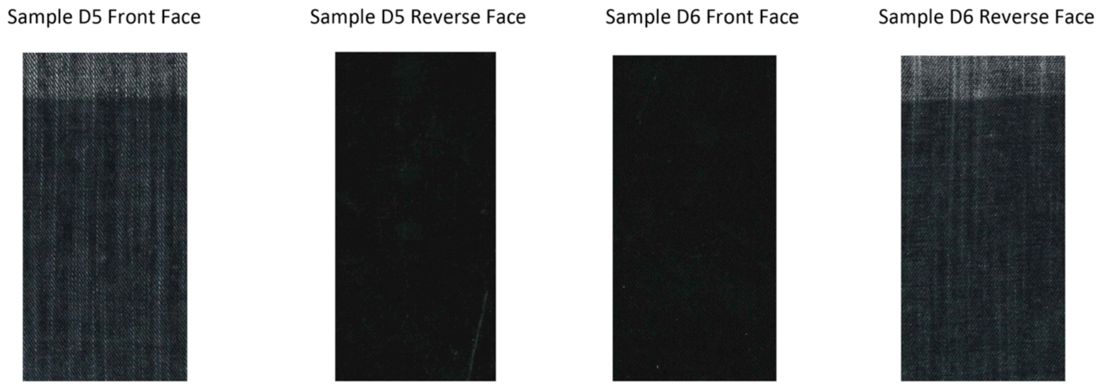


Figure 6.36. Larger samples (D5 and D6) from tests 35 and 36, for visual comparison.

Test 37. Fabric sample D8 was scoured, prepared for digital printing, digitally printed on the front face of the fabric with the denim imagery, and air dried. Sample D7 was then screen-printed on the reverse of the fabric with the black block print, steamed, washed, dried and then assessed.

Test 38. Fabric sample D8 was scoured, prepared for digital printing, digitally printed on the reverse face of fabric with the denim imagery, and air-dried. Sample D8 was then screen-printed on the front of the fabric with the black block print, steamed, washed, dried and assessed.

Table 6.21 shows the methods and swatch samples (D7 and D8) for each print test conducted (37 and 38). The larger samples produced are presented in Figure 6.37.

Table 6.21. Methods and swatches for samples D7 and D8, print trials 37 and 38.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
D7 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	Screen, solid Synocron Black RD 60g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
D8 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Reverse	Air dried	None	None	solid Synocron Black RD 60g/1kg	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

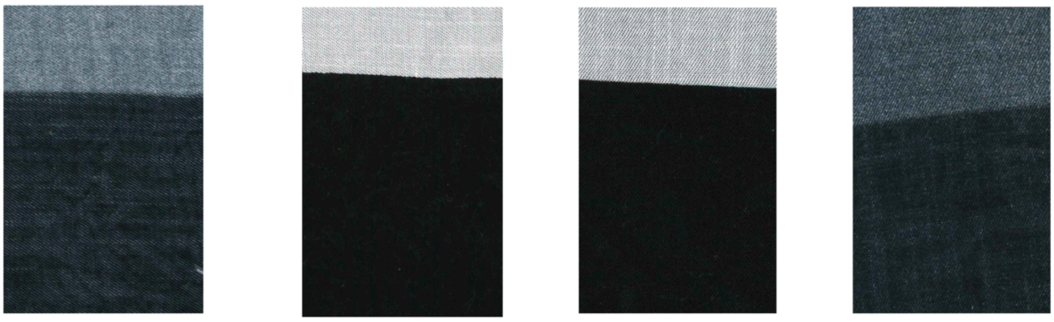


Figure 6.37. Larger samples (D7 and D8) from tests 37 and 38, for visual comparison.

From the visual assessment, the samples demonstrated two opposing fabric surfaces. The denim imagery is darkened by the block screen print and so this effect has to be considered during the design process. Essentially, the design must use the two sides to inform the appearance of one another. This technique could be used either to create two surfaces that work together to inform each other of an opposing appearance, or to inform each other's appearance, depending on whether the designer is aiming either to hide each side from the other or alternatively, and in contrast, to make each side visible from the other to a certain extent. This may be used, for example, to create a shadow effect or a sense of depth.

To provide the design process with the full range of Tencel fabrics available within the research, the technique developed to digitally inkjet print the denim imagery and combine it with screen-printing in the streamlined printing method was tested using the knitted Tencel fabric. Assessment of the resulting samples K1 and K2 concluded that the technique is suitable for both the knitted and woven fabrics.

Test 39. Fabric sample K1 was scoured, prepared for digital printing, digitally printed on the front face of fabric with the denim imagery, and air-dried, steamed, washed, dried and assessed.

Test 40. Fabric sample K2 was scoured, prepared for digital printing, digitally printed on the front face of fabric with the denim imagery, and air-dried. Sample K2 was then air-dried, screen-printed with block imagery on the reverse face of fabric, steamed, washed, dried and assessed.

Table 6.22 shows the methods and swatch samples (K1 and K2) for each print test conducted (39 and 40). The larger samples produced are presented in Figure 6.38. and show how screen printing can be used to manipulate the digitally printed surface.

Table 6.22. Methods and swatch samples (K1 and K2) for the print trials 39 and 40.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
K1 FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C
K2 FRONT  REVERSE 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	Solid Synocron RD Yellow 5g/1kg mixed Deep Red 40g/1kg	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Figure 6.38. Larger samples (K1 and K2) from tests 39 and 40 for visual comparison

6.6.5 Surface Design

An advantageous surface design opportunity was also noted during the experimentation as illustrated in samples D9, figure 6.34. When the fabrics are first digitally printed with the denim imagery, it was found by accident that the dye can be easily manipulated on the fabric surface using only water before steaming which is used to allow fixation of the dye to the substrate to occur. This takes advantage of the unfixed condition of the dye that allows the dye to 'bleed', since it is not fixed on the fabric at this stage. This feature, created using print test 35 with methods and swatches that are presented in Table 6.21, provided interesting effects within the denim imagery, similar to the effects obtained when denim garments are bleached in a commonly-used finishing process to create surface effects on commercially produced denim. Thus, new design development opportunities are offered through exploring the technique of using water to manipulate the surface of the digital print after printing and before steaming to create unique surface effects.

Test 41. Fabric sample D9 was scoured, prepared for digital printing, digitally printed on the front face of fabric with the denim imagery, and air-dried. Sample D9 was then air-dried, hot water dropped on the front face of fabric, steamed, washed, dried and assessed.

Table 6.23 Methods and swatch sample (D9) for the print trial 41.

Sample	Substrate	1^{st} Preparation Method	1^{st} Print Method	Fabric face printed onto	Finished	Washed	2^{nd} Preparation Method	Surface manipulation Method	Fabric face onto	Finished	Washed
D9 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	Water dropped in single blob onto fabric surface	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

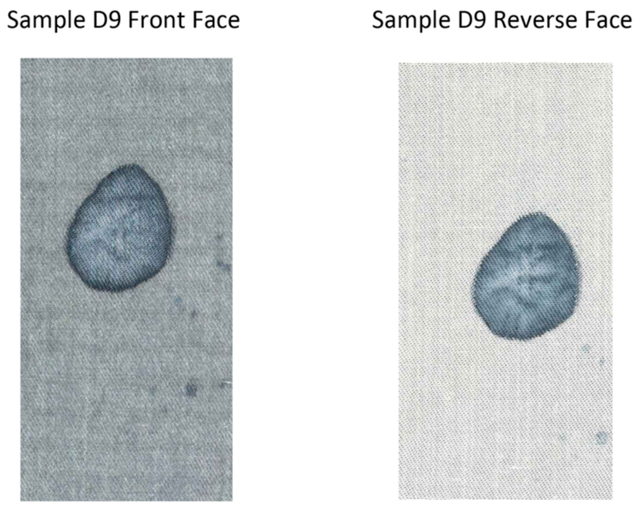


Figure 6.39. Larger samples (D9) from test 41 for visual comparison

It was observed from the previous research finding that the screen printed block colour created an interesting effect on the reverse (unprinted) side of the fabric and it was considered that the technique of dropping hot water on to unfinished fabric surfaces may create an interesting effect when applied to a screen printed surface. As the desired effect was to create a denim-like fabric the Synocron Navy Blue dye was chosen to explore the technique of applying hot water to the fabric surface using screen printed samples. This allowed for comparisons between the digitally printed and screen printed samples. It was observed that the screen-printed imagery, shown in Figure 6.39, creates a denim effect on the fabric surface that no colour was applied to, i.e., the unprinted front surface of the fabric.

Test 42. Fabric sample D10 was scoured, screen-printed on the reverse face of the fabric with block colour was air-dried. Hot water was splashed on the front face of fabric, which was then steamed, washed, dried and assessed.

Table 6.24 Methods and swatch sample D10, print trial 42.

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	Surface manipulation method	Fabric face onto	Finished	Washed
D10 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C	Screen, solid Synocron Navy Blue RD 60g/1kg	Reverse	Air dried	None	None	Water splashed in multiple small drops onto screen printed fabric surface	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C

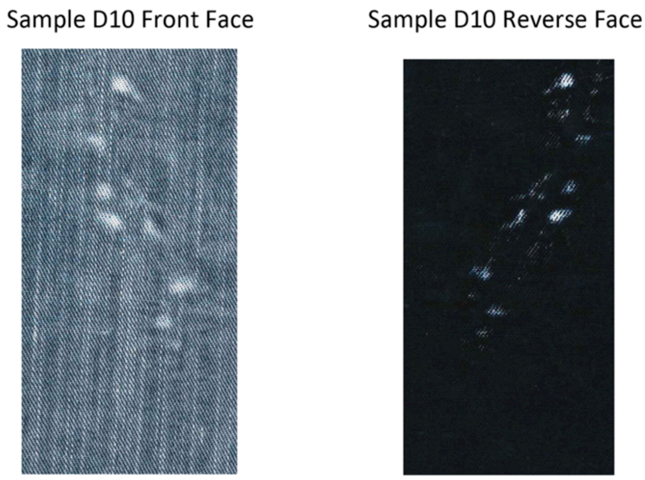


Figure 6.40 Larger samples (D10) from test 42, for visual comparison.

The effect of applying water to un-finished screen printed fabrics to create a denim like surface was further explored by painting, rather than dropping or splashing, hot water on to the surface and screen printing both the front and reverse of fabrics, and applying water to the opposite side to allow for a visual comparison aiming to determine any differences in the two methods.

Test 43. Fabric sample D11 was scoured, screen-printed on the reverse face of the fabric with block colour and air-dried. Sample D11 then had hot water brushed onto the front face of fabric, which was then steamed, washed, dried and assessed.

Test 44. Fabric sample D12 was scoured, screen-printed on the front face of the fabric with block colour, air-dried. Sample D12 then had hot water brushed onto the reverse face of fabric, which was then steamed, washed, dried and assessed.

Table 6.25 Methods and swatches for samples D11 and D12, print trials 43 and 44,

Sample	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	Surface Manipulation method	Fabric face onto	Finished	Washed
D11 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C	Screen, solid Synocron Navy Blue RD 60g/1kg	Front	Air dried	None	None	Water applied in zigzag pattern to reverse fabric surface with standard paint brush	Reverse	Steamed at 100°C 10 minutes	Hot wash @ 95°C
D12 FRONT  REVERSE 	Tencel A100 Woven	Scoured @ 40°C	Screen, solid Synocron Navy Blue RD 60g/1kg	Reverse	Air dried	None	None	Water applied in zigzag pattern to front fabric surface with standard paint brush	Front	Steamed at 100°C 10 minutes	Hot wash @ 95°C

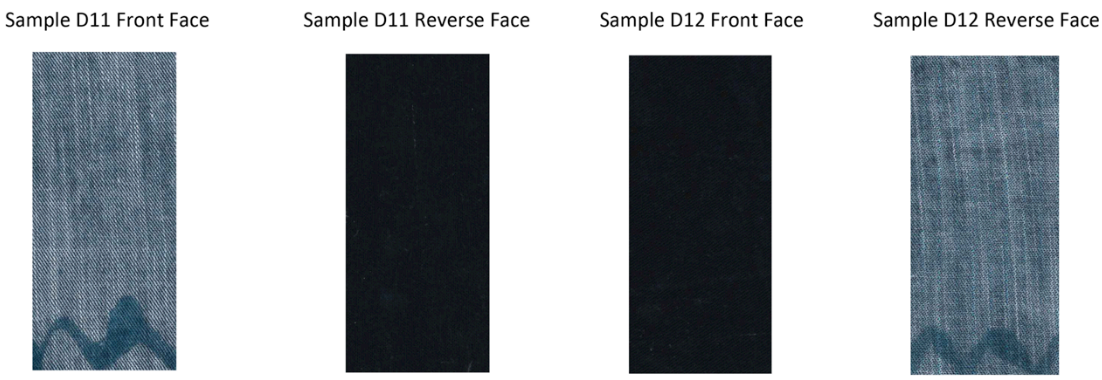


Figure 6.41. Larger samples (D11 and D12) from tests 43 and 44, for visual comparison.

Tests 39 to 44 demonstrate that the denim imagery can be created on both knitted and woven Tencel fabric, and that, on the woven Tencel denim effect fabric, it can be produced either through digital inkjet printing or screen printing. The woven denim bi-surface fabric can be created through printing on only one surface of the fabric and using water to manipulate the unfixed dye to create a surface effect similar to bleached denim, providing a denim-like surface that has had no colour applied directly to it.

6.7 Bi-surface garment application

Two methods of creating a double surface, both of which provide a bi-surface fabric that can be used to design and produce reversible garments, have been explored within the research described in this thesis. The first method, explored as described in Chapter 4, during the evolving garment design utilized an existing, traditional method of attaching two pieces of fabric together via their reverse faces to create two front facing sides of a garment. This method was first discussed in Section 4.5 of this thesis. With the progression of the research and a continuing focus on utilizing resources in a way that minimized environmental impact, the second method that involved creating a reversible surface has been developed as described through this chapter where the focus was on creating a bi-surface single fabric.

The initial denim imagery development, described in Section 6.6.2, demonstrated that when the printed samples were constructed to give the impression of a denim trouser leg, the weight of the woven Tencel was found to be problematic in terms of the drape and in creating a heavy denim-like fabric, which could result in problems with garment design. Thus, a consideration of the two methods of creating reversible fabrics was used to inform the next phase of research that concentrated on extending a garments lifetime by incorporating two garments within one. Heavier weighted garments such as trousers or dresses may be more suited to the first method, by using two lightweight fabrics in combination together to produce a heavier weighted fabric. Lighter weight garments such as T-shirts may be more suited to the second method, by using one piece of fabric to create two surfaces.

This phase of research focused on using the conclusions of the experimentation using the printing methods within the design process to achieve the design concept of optimizing garment lifetimes through combining two garments within one. It was envisaged that these items would then be used to create multiple outfits or 'looks' through how they change and interact with each other, depending on which surface is used as outward facing. The design concept was devised in such a way that the garments could change from 'on trend' fashion items to classic basic items or 'smart' garments to 'casual' garments, thus ensuring that they are always wearable. This approach would allow the designer to design an initial garment with a fast metabolism, so that it may only be desirable to the consumer for a short period of time before being discarded, but which may be transformed into a longer lasting garment that can be worn for a longer period of time, by designing the linked opposing garment as a slow metabolic garment, i.e., a garment worn repeatedly over time. For example, a bright colour or bold pattern within a garment can be dated to a certain fashion trend and, when the next fashion season replaces this, the consumer will no longer want to wear it and the garment thus becomes obsolete. Within this research, the garment that becomes obsolete is linked with a garment that is not dated to a fashion trend or colour, but rather is associated with classic or casual timeless design.

The four garment shapes chosen for this development were trouser, dress, skirt, and top. This selection allowed the incorporation of both the woven and knitted Tencel, as well as the use of methods for creating double sided surfaces, the traditional method of attaching two reverse faces together and the printing method, developed as described in this chapter, for bi-surface fabrics. Each garment was designed to have two different appearances, with one side seen as a fast metabolic garment, and the other as a slow metabolic garment worn over a longer period of time. These features allow the items to move from short to long life garments, hence extending their lifetime through increasing wearability for the consumer. The slow metabolic garment surface used the digital inkjet denim imagery within each of the four garment designs, whilst the fast metabolic garment surface used the screen print technique.

In creating reversible garments, the use of fastenings can become problematic due to the fact that one garment is always adjacent to the body. Thus, linings or binding, which may be used to soften the feel of fastenings in single sided garments, cannot be used in this case. The fastenings also have to be functional on either faces or sides of the garments.

For this reason, the range of patterns used within the four garments was kept to a minimum and the need for reversibility was specified within the designs, so that any fastening used within the design could be used for both faces of the garments. The need for fastenings generally increases the environmental impact of garments, and so it was also consistent with the aim of the research not to use them unless it was absolutely key to the functionality of the garments. Within the four-piece garment collection that was assembled, only one fastening was ultimately required and this was in the trouser, which required a zip to aid putting on and removing the garment. The other garments were all designed without fastenings. The patterns used were also simplified and the pattern lays created so as to minimize waste. All of these issues are explained in the following section describing the research process, in which the concept, design and production method for each garment are presented.

Garment 1 –Trouser.
Design Concept – To incorporate a slow metabolism, long-life trouser - a classic design of denim jeans with a fast metabolism, short life fashion trouser using a bold print. Evaluation described previously had highlighted concerns over the weight and drape of the fabric and so it was decided to use two pieces of fabric attached reverse face to reverse face to create a reversible, bi-surface garment as this method would provide a heavier weighted garment than a single piece of fabric, used for the bi-surface fabric printing, would produce. Two pieces of woven Tencel were attached to each other. The pattern for the trouser was simplified to four pieces. The simple four-piece pattern developed incorporating only a two-way recyclable plastic zip, a fastening that was necessary for fit and to allow reversibility of the garment design.

Garment 1 Surface A; the digital denim imagery was developed directly into the pattern pieces using the adobe creative suite to create a digital trouser design. The image developed as illustrated in Figure 6.42 also shows the incorporated digitally printed seaming and pockets as well as the faded denim areas. Physically adding pockets or traditional denim seams is not possible with a reversible garment, as they would affect the fit and drape of the garment making it look and feel bulky. Thus, the printing method was used to make the trouser appear to be an authentic denim item dyed with indigo and faded over time, and also simulating pockets and seams.

Garment 1 surface B, a bold black and white print was selected for use, as the trouser also needed to fit with other items from the four-piece collection and it was considered that a black base for the trouser print would allow this. In using a black and white print, the research also took advantage of the bright, natural whiteness of Tencel. The fabric used in the white part of the print was simply left unprinted, rather than having to use a discharge method of printing that bleaches out the selected area after screen printing, the black parts of the fabric, a method that would be required with cotton. This feature provided another environmental advantage in using Tencel A100 compared with cotton in this case. Surface B, illustrated in Figure 6.43 was produced using the screen print method presented in Chapter 5. Methods and swatches for producing surface A and B for garment 1, the trouser, are shown in Table 6.26. Once the two sides of the garment were printed and finished, the garment was then constructed.

Table 6.26 Methods and swatches for Garment 1, surfaces A and B

Garment 1 TROUSER	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
Surface A 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C
Surface B 	Tencel A100 Woven	Scoured @ 40°C	Screen print Synocron Black RD 40g/1kg (LIGHT)	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C

Figure 6.42. Design development Garment 1, Surface A

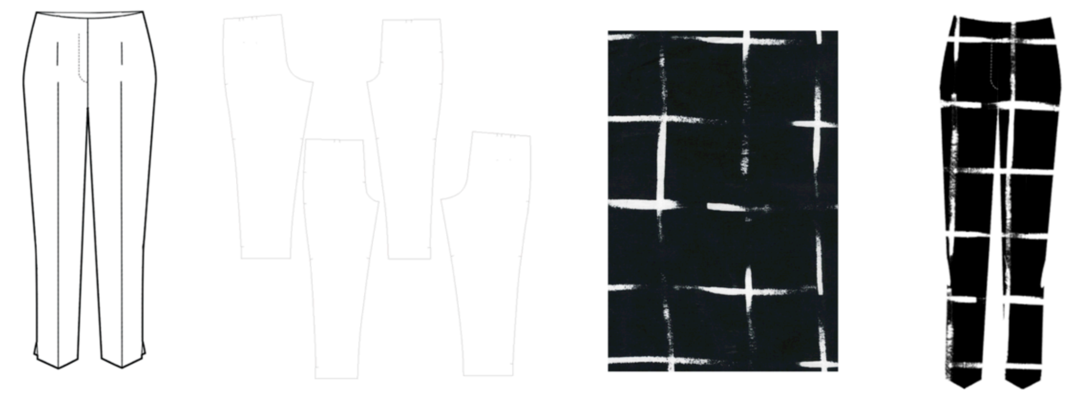


Figure 6.43. Design development Garment 1, Surface B

Garment 2 – Dress

Design Concept – To incorporate a slow metabolism, a long-life dress that is not often worn with another slow metabolism, a long-life dress but that is often worn. The dress will change from smart to casual incorporating a classic ‘little black dress’ with a casual denim dress. ‘The little black dress’ is part of most women’s wardrobes though not often worn; it epitomizes a smart sophisticated look. The opposite of this in terms of casual classic style would be denim jeans and a t-shirt. Thus, it was decided to use the digital denim technique to design a denim dress. The imagery developed used to produce garment 1, the trouser, provided the technique for creating the images of pockets and seams. Though effective, it was considered that such simulated effects would appear more credible on a dress rather than on a trouser.

The shape of the dress was designed to be a flattering, classic, easily wearable shape that allowed room within the pattern for changes in body shape over time. The garment had to be suitable for casual, smart and formal occasions and so the length could not be too short and the shoulders needed to be covered. The developed dress design was an A-line mid-thigh length with a boat neck and three-quarters sleeves. A black dress would normally be produced from high quality, medium weight, dyed black fabric. In this case, woven Tencel was used. Since the lighter weight of a single piece of fabric did not produce the desired drape on the dress when worn, the method for producing a reversible garment, discussed in Chapter 4, was again selected for use, involving printing two separate pieces of fabric and sewing them together, reverse face to reverse face.

Garment 2 Surface A; the digital denim imagery was developed directly into the pattern pieces using the adobe creative suite to create a digital dress design as with garment 1. The denim imagery developed incorporated digitally printed seaming and pockets as well as a printed zip fastening to the centre back of the dress on the neck line. Other digital details added to the print through the use of CAD on the pattern lay included two pockets drawn onto the front of the dress and seam detail was added to the front side, neck and bottom seam lines to provide the effect of denim seaming and pocket detailing. The design development is illustrated in Figure 6.44.

Garment 2 Surface B; The solid black surface of the fabric, illustrated in Figure 6.45. was screen printed with the technique presented in Chapter 5. Based on the depth of black colour achieved during sampling, it was concluded that screen-printing was capable of providing the same effect as dyeing, and would have a reduced environmental impact. Methods and swatches for producing surface A and B for garment 2, the dress, are shown in Table 6.27. Once the two sides of the garment were printed and finished, the garment was then constructed, reverse side to reverse side.

Table 6.27 Methods and swatches for Garment 2, surfaces C and D

Garment 2 DRESS	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
Surface C 	Tencel A100 Woven	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C
Surface D 	Tencel A100 Woven	Scoured @ 40°C	Screen print Synocron Black RD 40g/1kg (LIGHT)	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C

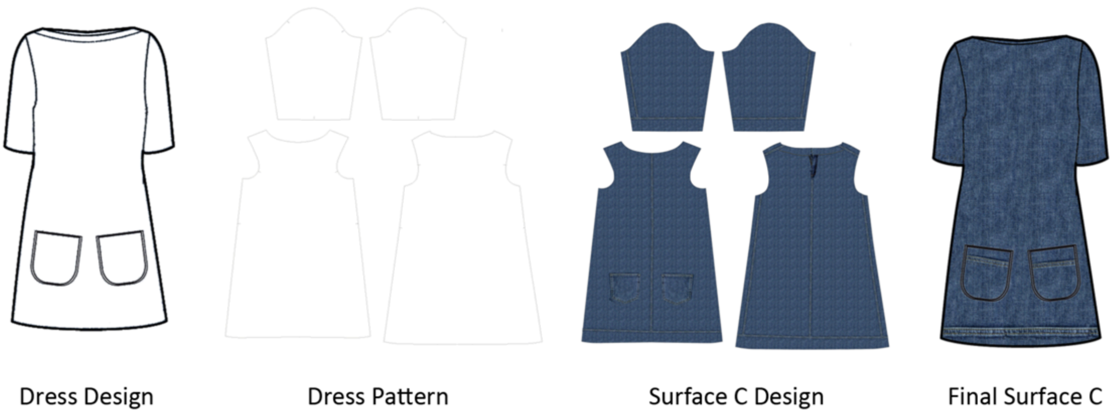


Figure 6.44. Design development for Garment 2, Surface C

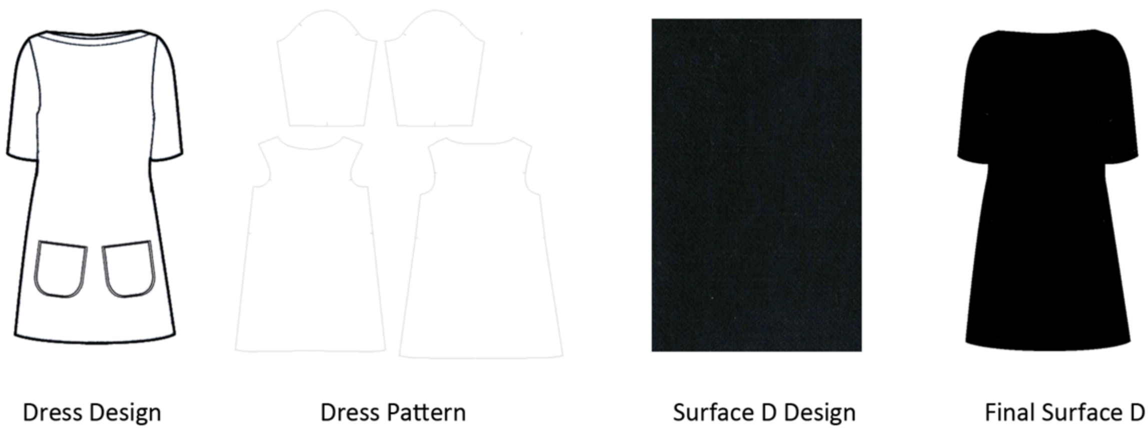


Figure 6.45. Design development for Garment 2, Surface D

Garment 3 – Skirt

Design Concept – To incorporate a slow metabolism, long-life skirt within a fast metabolism, short-life skirt. The skirt design, developed as described in Chapter 4 for the evolving garment design, was utilized for the shape of garment 3. This decision was based on the multiple ways of wearing that the design had previously provided, and efficiency in terms of minimized waste resulting from the pattern lay being only two pieces. The skirt was constructed from the knitted Tencel A100 as this fabric provided flexibility in the garment and may allow for changes in body shape over time.

The garment originally developed from this pattern in Chapter 4 used the double-layered fabric method of producing bi-surface garments. For garment 3 it was considered appropriate to use the single layer of fabric with the second method of printing on both surfaces of the fabric to produce a bi-surface fabric. However, following sampling, though the printing process created a bi-surface fabric, it was decided that the lighter weight, single fabric would not be suitable for the skirt design and so the method of incorporating two fabrics, printing on both front faces, within one garment was used.

Garment 3 Surface A; the imagery selected incorporated the digital denim approach that had been developed, but was seen as a one-season trend rather than being used as a long life classic imagery. Digital denim imagery was developed onto the pattern pieces for the skirt using the adobe creative suite and the curve tool, to create a black denim rather than indigo blue. The fabric was then digitally printed on the front face. The imagery used when printed onto the garment, rather than providing a classic long life look, appeared more suited to a short life fashion look, as in this case it was applied to a knitted fabric, which changed the appearance of the denim. Rather than looking authentic, as was the case with the digitally printed woven denim fabric, the knit created an edgier more fashion-oriented garment.

Garment 3 Surface B; the classic longer life side of the garment was produced using a block screen print, printed onto the front face of the fabric. The red colour chosen was informed by both fashion trends of classic colours and also the experimental work conducted as described in Chapter 5. Methods and swatches for producing surface A and B for garment 3, the skirt are shown in Table 6.28. Once the two sides of the garment were printed and finished, they where sewn together reverse face to reverse face as the garment was constructed.

Table 6.28 Methods and swatches for Garment 3, surfaces E and F

Garment 3 SKIRT	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
Surface E	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C
Surface F	Tencel A100 Knitted	Scoured @ 40°C	Screen print Synocron Deep Red RD 40g/1kg (Dark)	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C

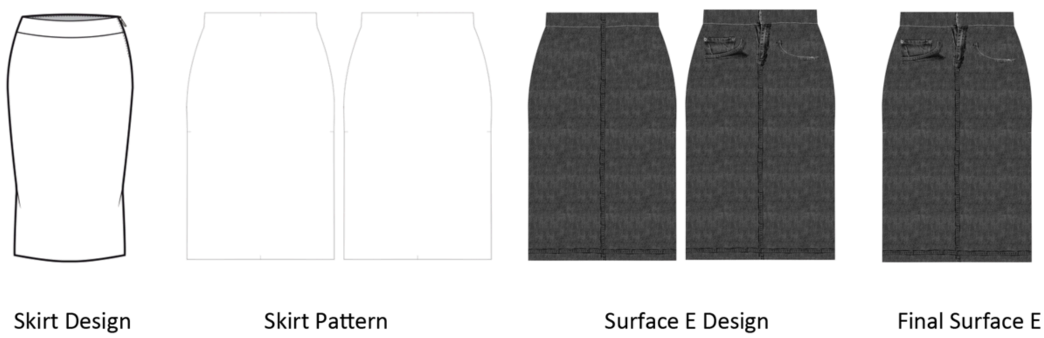


Figure 6.46. Design development Garment 3, Surface E

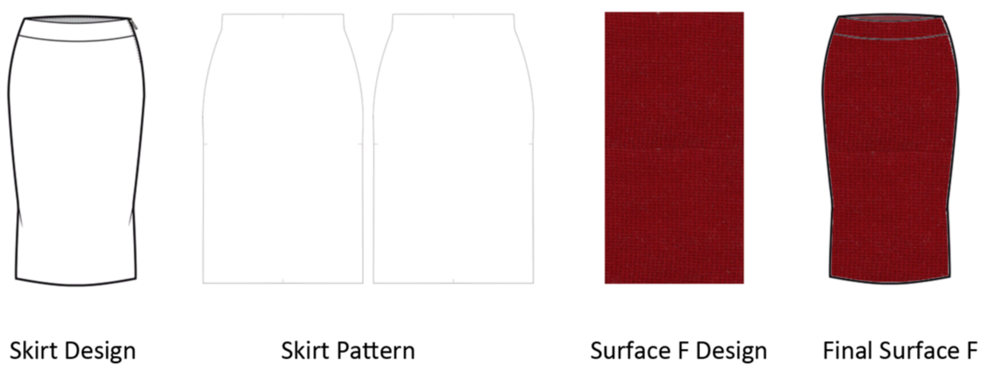


Figure 6.47. Design development Garment 3, Surface F

Garment 4 – T-Shirt.

Design Concept – To incorporate a slow metabolism, long-life T-shirt within a fast metabolism, short-life T-shirt. The T-shirt design, developed as described in chapter 4 for the evolving garment design, was utilized for the shape of garment 4. This garment from chapter 3 benefitted from the research that had already demonstrated the garment design versatility. The method of coloration incorporated the bi-surface printing method, digital with screen print using a single piece of fabric. The fabric used was the same as that used for the matching skirt, knitted Tencel A100.

Garment 4 Surface G; Digital denim imagery was developed onto the pattern lay for the T-shirt. The fabric was then digitally printed on the front face.

Garment 4 Surface H; The shorter life side of the garment was produced using an unprinted surface, the inkjet printed denim surface informed the unprinted surface giving the impression of faded, bleached denim. Methods and swatches for producing surface G and H for garment 4, the T-shirt are shown in Table 6.29. Once the two surfaces of the fabric were printed and finished, the garment was then constructed.

Table 6.29 Methods and swatches for Garment 4, surfaces G and H

Garment 4 T-Shirt	Substrate	1st Preparation Method	1st Print Method	Fabric face printed onto	Finished	Washed	2nd Preparation Method	2nd Print Method	Fabric face printed onto	Finished	Washed
Surface G 	Tencel A100 Knitted	Scoured @ 40°C Coated for inkjet printing	Inkjet, Digital denim imagery	Front	Air dried	None	None	None	None	Steamed at 100°C 10 minutes	Hot wash @ 95°C
Surface H 	Tencel A100 Knitted	None	None	None	None	None	None	None	None	None	None

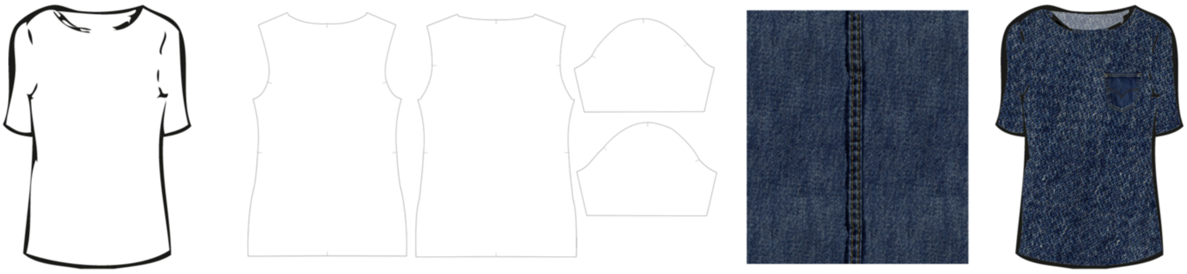


Figure 6.48. Design development Garment 4, Surface G

Figure 6.49. Design development Garment 4, Surface H

6.8 Conclusions

The bi-surface printing method proved to be successful using a variety of colour and imagery on Tencel textile samples illustrated, in Figure 6.44 with methods shown in Table 6.29. However, when the process is applied to garment construction problems with fabric weight, and the technicalities of constructing bi-surface garments were highlighted. This resulted in the primary method for producing the bi-functional garment as the traditional method, presented in Chapter 4, of using two reverse faces sewn together. To develop the bi-surface printing method developed in this chapter further for successful garment application, research would also need to be carried out on garment pattern drafting, construction methods and fastenings for single fabric reversible garments.

CHAPTER 7: Research Summary, Conclusions, Future Suggestions

7.1 Research Summary

The aim of this research was to explore methods to reduce the environmental impact of coloured fashion and textiles, questioning if colour for fashion and textiles can be sustainable? The thesis established that all current methods of coloration for cellulosic fibres, whether using dyes from a natural or synthetic source, have some negative environmental impact. The research provides new solutions, a long-term approach based on cyclical design for sustainable coloration where waste streams within existing commercial models of production are utilized. Contrasted with the more immediate solutions offered through responsible coloration where market available synthetic dyes are explored, fabric preparation treatments for coloration optimized for environmental performance and design strategies incorporated to extend textile and garment longevity.

In meeting the research aims an interdisciplinary research approach, which incorporated technical inquiry within the design process to generate interdisciplinary knowledge within the researcher and research outputs was developed. The study demonstrates that, to reduce the environmental impact of coloured fashion and textiles, exploring the lifecycle relationship between fibre, dyestuff and textile/garment through the associated disciplines within the design process is key. This relationship identified through the life cycle 'hotspots' presented in chapter 3, provided the basis for the interdisciplinary exploration within the thesis. The research was presented in reflection of this relationship, starting with fibre choice, progressing to dyestuff production/selection and concluding with application/use of colour to fashion and textiles. The diagram in Figure 7.1 demonstrates, only when the three key elements of this cyclical relationship are symbiotic can either sustainable or environmentally responsible coloured fashion and textiles be designed and developed. The research outcomes for sustainable colour and responsible colour are mapped onto this diagram, presented in figures 7.3 and 7.4 later in the chapter when the specific research outcomes are discussed

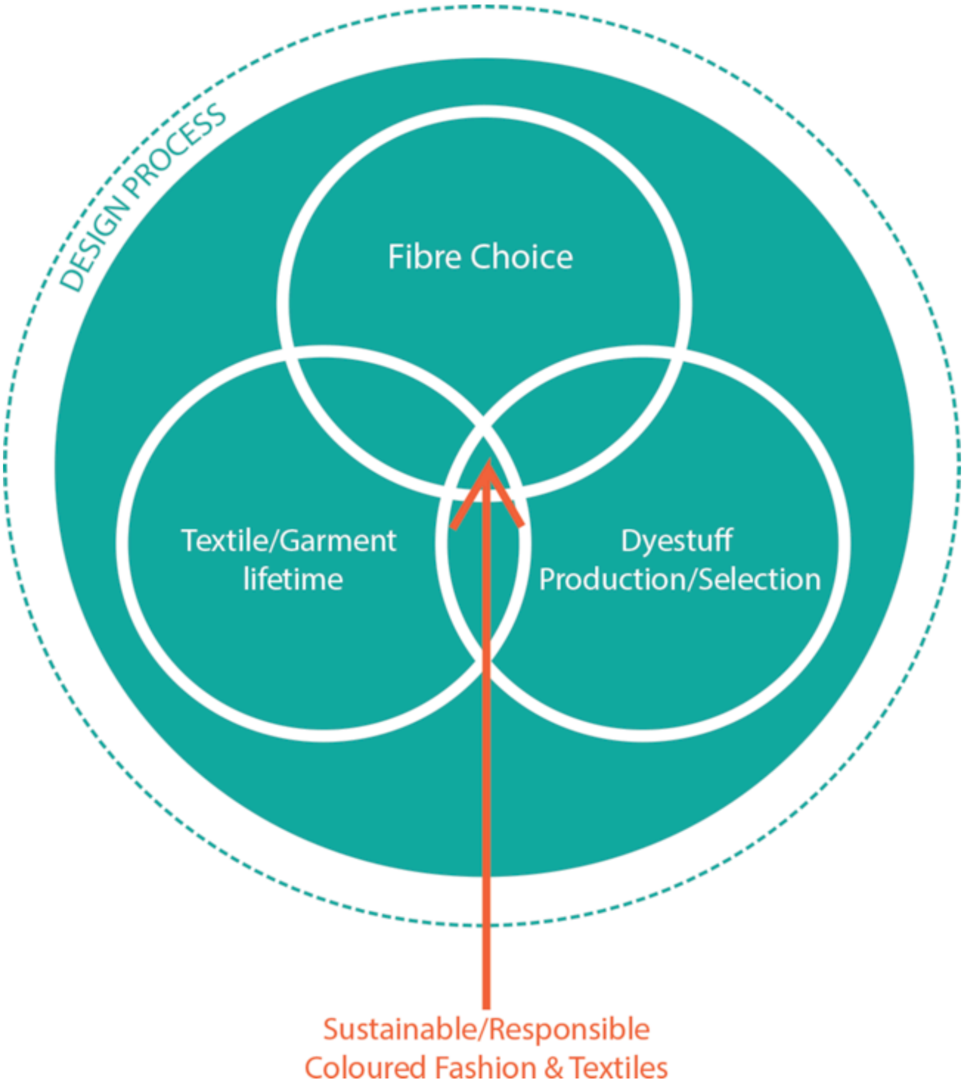


Figure 7.1. Sustainable and Responsible Coloured Textiles and Fashion Diagram

7.2. The research

In exploring the environmental impact of coloured fashion and textiles, the design process was evolved from a linear process into a cyclical process with a view to achieving the following original aims of the thesis, as discussed in chapter 1:

1. To establish the current state of knowledge regarding the range of approaches that are used in the coloration of cellulosic fibres for fashion and textiles.
   The fast pace, economic enormity and environmental impact of fashion and textile production were discussed. Through life cycle assessment data, the fibre, coloration and finishing and garment use/end of life stages were identified as areas within the lifecycle producing the biggest environmental impact. Large amounts of chemicals, water and energy are used and waste streams created at each stage. Consumer behavior was identified as feeding this unsustainable cycle due to demand for 'fast fashion'; consumers dispose or disregard garments only worn a handful of times in replacement of 'new' items to reflect current fashion trends.

   The literature identified research approaches within sustainable design focused largely on fibre selection, where science and technology have developed sustainable fibres for use within design, reducing waste at pattern stages, packaging and transportation. Developing solutions to reduce the environmental impact of colour largely being left to science and technology was a key finding in the literature. Though positive steps toward more sustainable coloration of polyester fibres were presented in the literature, equivalent solutions for cellulose fibres, of which sustainable fibres, such as the lyocell fibre focused on within this research are available on the commercial market are not available. Stakeholders discussions with the fibre company, Lenzing, at there Grimsby and Austrian production facilities confirmed this 'gap' in sustainable coloration processes required for the sustainable fibres available is preventing sustainable coloured fashion and textiles being achieved on the commercial scale required, and hence, was the focus of this research.

2. To establish the current state of knowledge regarding approaches to environmentally responsible coloration of cellulosic fibres for fashion and textiles.
   Focusing specifically on the coloration of regenerated cellulose fibres the literature identified that in terms of preparation of fabric for coloration stages the regenerated celluloses, such as, Viscose, Modal, and Tencel are generally prepared using the same specification as cotton cellulose. This involves an intensive scouring and bleaching

treatment; this was of interest as regenerated cellulose fibres are produced as explained in the literature through a chemical process, essentially much cleaner than the process cotton is produced within.

Approaches to reducing the environmental impact of cellulosic fibres splintered into a natural *vs* synthetic debate within the literature. It was concluded that whether from natural or synthetic source, all colour currently has a level of environmental impact. In relation to natural dyes, while the source though theoretically sustainable as it is natural, the land, water and chemical used in agriculture and extraction of dye along with the mordants used in application of dye, the poor technical performance for fastness impacting on the short life expectancy of the dyes on textiles affects both their sustainability credentials and suitability for fashion and textile application. Approaches to increasing the environmental performance of natural sources of dye have focused on utilizing by-products. However, in terms of extraction and application the additional chemical and processes are still required and fixation performance remains problematic. In terms of the synthetic dyes they are from an unsustainable source due to being derived from oil, and require auxiliary chemicals during application to help dyes penetrate fibres. Approaches to increasing the environmental performance of the dyes involves re-visiting bi-functional or tri-functional reactive dyes. As presented in the chapter 5, the bi-functional group of reactive dyes have increased fixation resulting in the use of less dye at the initial coloration stage and also less dye lost in the effluent during washing off stages.

Through both the literature and discussion with both fibre and dye company stakeholders at industrial trade shows and site visits, the research identified that in terms of colour two sources of chemical were available, natural or synthetic. It was concluded that within current production and application process neither offer solutions for sustainability.

3. To explore the sustainability credentials of lyocell as a cellulosic fibre, especially in comparison to cotton.

   Analyses and review of existing field to factory gate life cycle analyses, presented in chapter 2, demonstrated that at each stage of the fibre production lyocell has a superior environmental performance when compare with cotton.

   The creative inquiry presented in chapter 4, designing coloured fashion and textiles with in a life cycle demonstrated that lyocell offered increased sustainability through printing with colour extracted from fibre production waste. Technical inquiry supported this finding with colourfastness properties concluded to be excellent. Technical experimentation, focusing on the environmental performance of lyocell compared to Tencel in relation to colour application, presented in chapter 5, including a research field trip to work with the Korean dye company KISCO concluded that in the pre-creative stages (preparing for colour application) and creative stages (colour application) the use of lyocell rather than cotton reduces the environmental stages required for applying colour to fabric. Unlike cotton it was concluded that lyocell does not require harsh scouring processes or bleaching stages. An environmentally responsible method for preparing lyocell for coloration was developed and presented in chapter 5.

4. To apply an interdisciplinary approach towards the development of novel methods for sustainable, or environmentally-responsible coloration of fashion and textiles.
   The life cycle 'hot spots' identified through literature, fibre, coloration/finishing stages and garment/textile were used to inform the interdisciplinary research relationship between textile technology, colour chemistry and design. An interdisciplinary methodological framework was developed based upon this relationship discussed and presented in chapter 3. The full framework with the research outcomes mapped onto is represented in figure 7.5 at the end of this chapter.

5. To explore printing on lyocell as a means to reduce the environmental impact of coloration techniques, especially in comparison with cotton.
   Informed by the literature observation that Tencel is treated in the same way as cotton in preparation for coloration, the research presented in chapter 5 compared the performance of Tencel against cotton to develop an optimized, tailored scouring process that was developed for lyocell and it was concluded that the bleaching stages are not required. The process illustrated in figure 7.4 was developed.

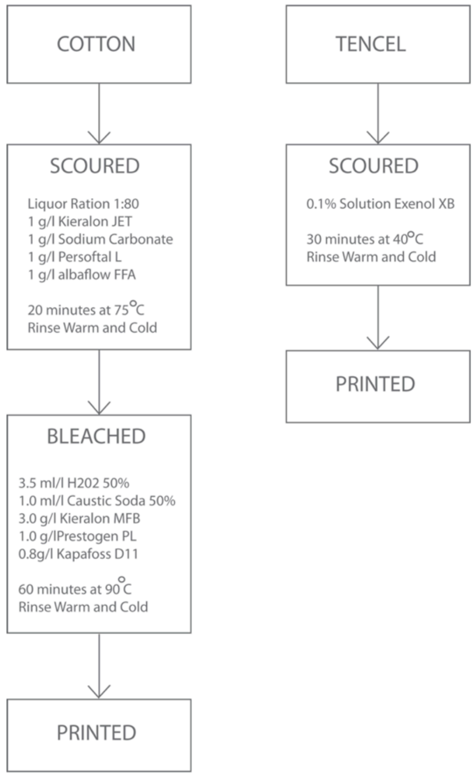


Figure 7.2 Comparison of the stages of preparation for cotton and Tencel to the point of screen-printing: cotton stages based on industry methods, Tencel stages as the process developed within the research.

6. To investigate the use of design methodology as a means to lower the environmental impact of coloration techniques applied to lyocell fibres for fashion and textiles.

   The research conducted within the developed interdisciplinary framework led to the garment designs presented in chapter 6. The creativity of design was used to solve the problem of environmental impact occurring through the use of additional finishes, in which a print technique for denim was developed rather than the use of bleaching or laser treatments and material for pockets or other sources of materials rather than lyocell being added for fastenings. The research demonstrates that fewer elements in the garments equate to reduced environmental impact. Design strategies were also used to extend the garment lifetime within the lifecycle through incorporating the bi-surface coloration technique into garment design.

7.3 Stages of research

In addressing these aims, two key phases of the research carried out are presented within the thesis. The first phase, presented in chapter 4, involved an exploration that aimed to answer the primary research question: can colour for textiles be sustainable? In the course of this research phase, methods for producing and using sustainable colour were developed. The second stage of research was informed by this conclusion from the first section of research, in terms of the limitations in creating sustainable colour, the primary limitation from this study being the colours currently achievable using the method. As a result, the focus of research progressed from creating sustainable colour to exploring environmentally responsible colour. The second phase of research initially involved a technical exploration of how colour may be used responsibly, in the form of carefully selected synthetic dyestuffs, as described within chapter 5, and then addressed how colour may be applied and designed for use within garment life cycles, as described within chapter 6, focusing on the use of design to extend garment longevity.

These two phases of research, presented in figure 7.2, created three key interdisciplinary research outcomes that can be used to reduce the environmental impact of coloured fashion and textiles; these have been defined as 'Sustainable Colour', 'Responsible Colour' and 'Bi-surface Colour'. The technical knowledge derived from the experimentation conducted was incorporated into and interwoven within the design process to inform the practical textile outcomes of this study that have been presented throughout the thesis. These outcomes include a physical collection of work obtained in parallel with the research documented photographically throughout the thesis.

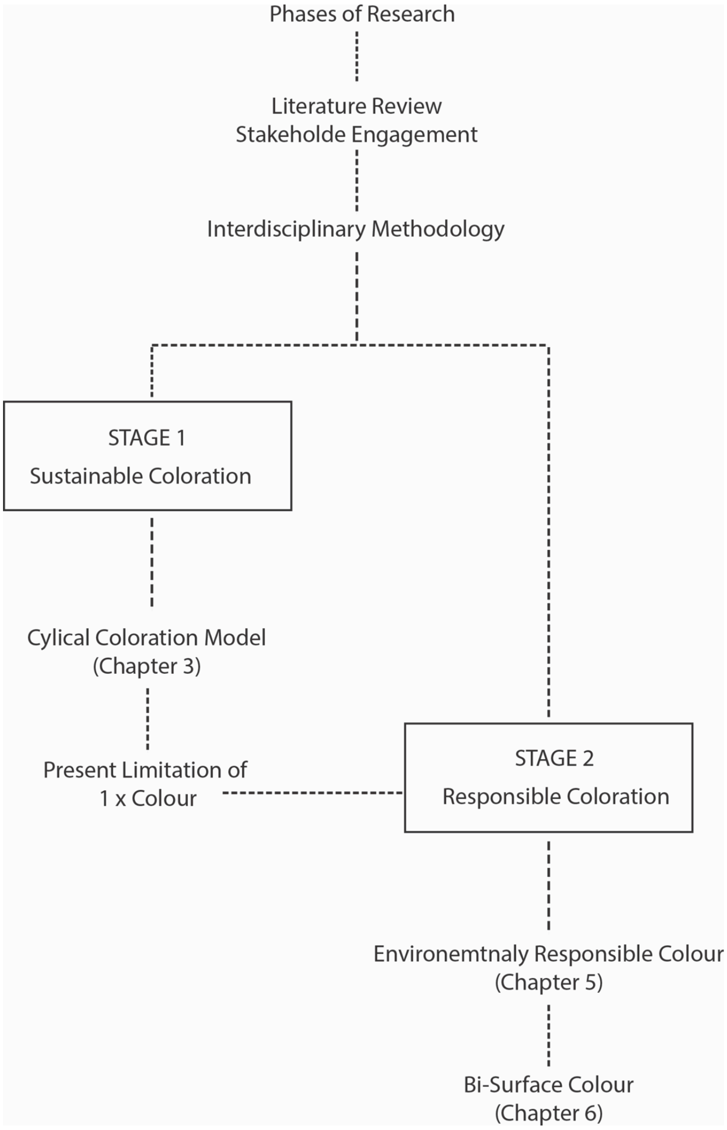


Figure 7.3. Phases of research diagram

7.4 Research Outcomes / Contribution to Knowledge

7.4.1 Cyclical Design; An Interdisciplinary Framework

Through developing a logical interdisciplinary framework for the research, initially presented in chapter 3, and fully presented with research outcomes in figure 7.4 the creative and intuitive nature of the design process and creative experimentation were interwoven within the factual nature of the science established by technical experimentation to create an iterative loop in which one stage informs another.

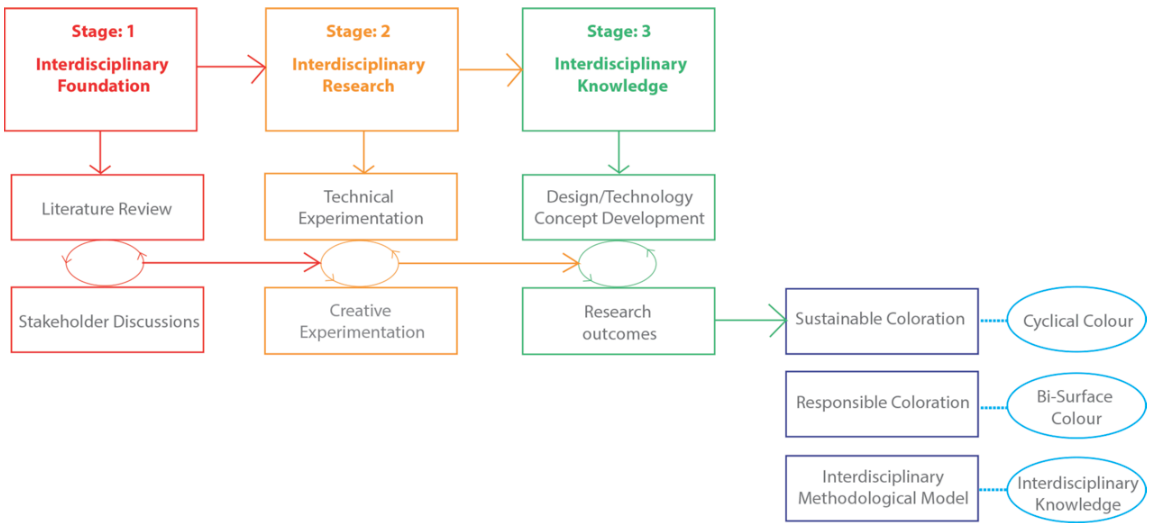


Figure 7.4. Developed model for interdisciplinary research

This framework was essential to establish 'interdisciplinary knowledge' for both the researcher and research outcomes, and ultimately it is the knowledge gained through undertaking the process that can be fed back into the research cycle. The framework was structured into three sections, stage 1 interdisciplinary foundation, Stage 2 interdisciplinary research, stage 3 interdisciplinary knowledge. The interdisciplinary framework developed for 'interdisciplinary knowledge. is presented in figure 7.5.

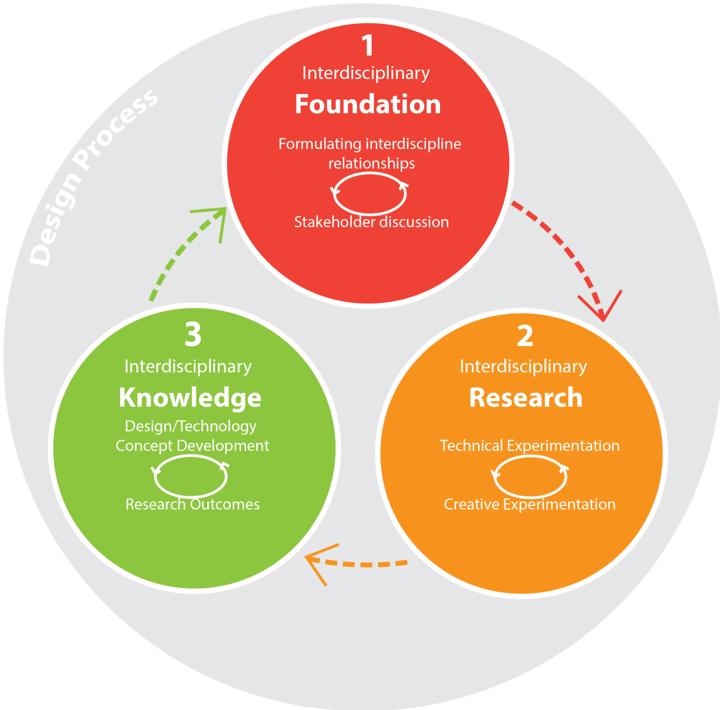


Figure 7.5. ‘interdisciplinary framework’

Upon completion of the research process it was observed by the researcher that the framework can be used at varying intersection points to further inform/develop research findings. For example, having acquired interdisciplinary knowledge the researcher may be required to re-formulate the interdisciplinary relationship, or use the acquired new knowledge to feed back into the research and technical/creative inquiry within the same interdisciplinary relationship to create an alternative research outcome; examples of the various ways the framework can be explored within an interdisciplinary cyclical design once the first cycle is completed and ‘interdisciplinary knowledge’ is developed is presented in figure 7.6.

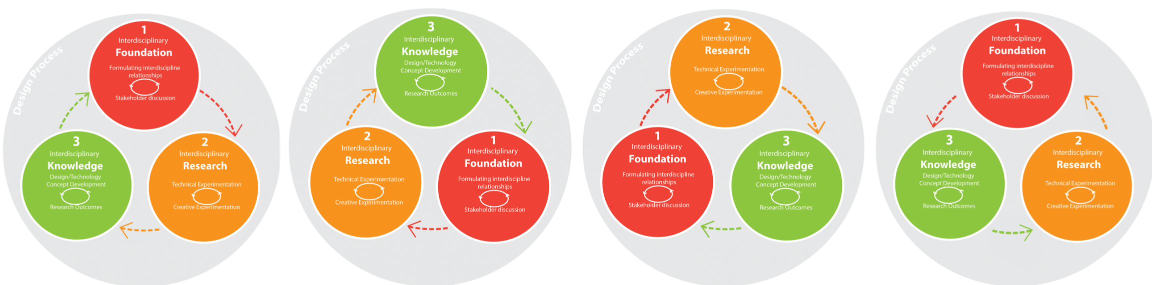


Figure 7.6. ‘interdisciplinary framework’

7.4.2 'Sustainable Colour' through 'Cyclical Coloration'

The first research outcome provided an example of 'Sustainable colour'. This was based on a natural dye that was produced using a by-product of lyocell fibre production, Eucalyptus leaves and bark. The dye was demonstrated to provide a set of technical fastness properties comparable to those of the synthetic dyes that are commonly used to produce a similar colour. This outcome makes a significant contribution to knowledge, as arguably the most sustainable method of coloration reported. It is the first example of colour being produced within a closed loop cycle, with water required for extraction of the dye only, and no mordant used for fixation, yet excellent technical performance was achieved. This result is proposed as providing a potential long-term solution for colouring textiles without the use of synthetic dyes that are reliant of petrochemicals. It has been categorized within the thesis as a method for creating sustainable colour, defined as 'Cyclical Coloration'.

Cyclical coloration: a method, which incorporated life cycle design thinking into the creative process, was developed as an approach to creating sustainable coloured fabric, potentially achievable on an industrial scale. This design process was integrated into the closed loop production process of lyocell, which ensured sustainability. Natural colour is produced within the product life cycle by extraction of dye from the leaves and bark of the eucalyptus from which the fibre is derived. Screen prints produced from these dyes show remarkably good technical performance. The research provides an example of the potential to utilize by-products or waste from industrial scale manufacturing in an existing system for textile production to produce sources of colour. Creating sustainable colour through the use of by-products generated within fibre production provides a longer-term solution for the production of sustainable coloured fashion and textiles with many avenues for future research. Lenzing, expressed the view that 'this research could be feasibly introduced into commercial industrial practice. The simple extraction process to produce the dye would be easily achievable on an industrial scale. Lenzing are manufacturers of the fibres, not fabrics, and so are not in a position to utilise the possibilities directly, but would be supportive of proposed developments in the fabric production industry to commercialise the concept' (Taylor 2013).

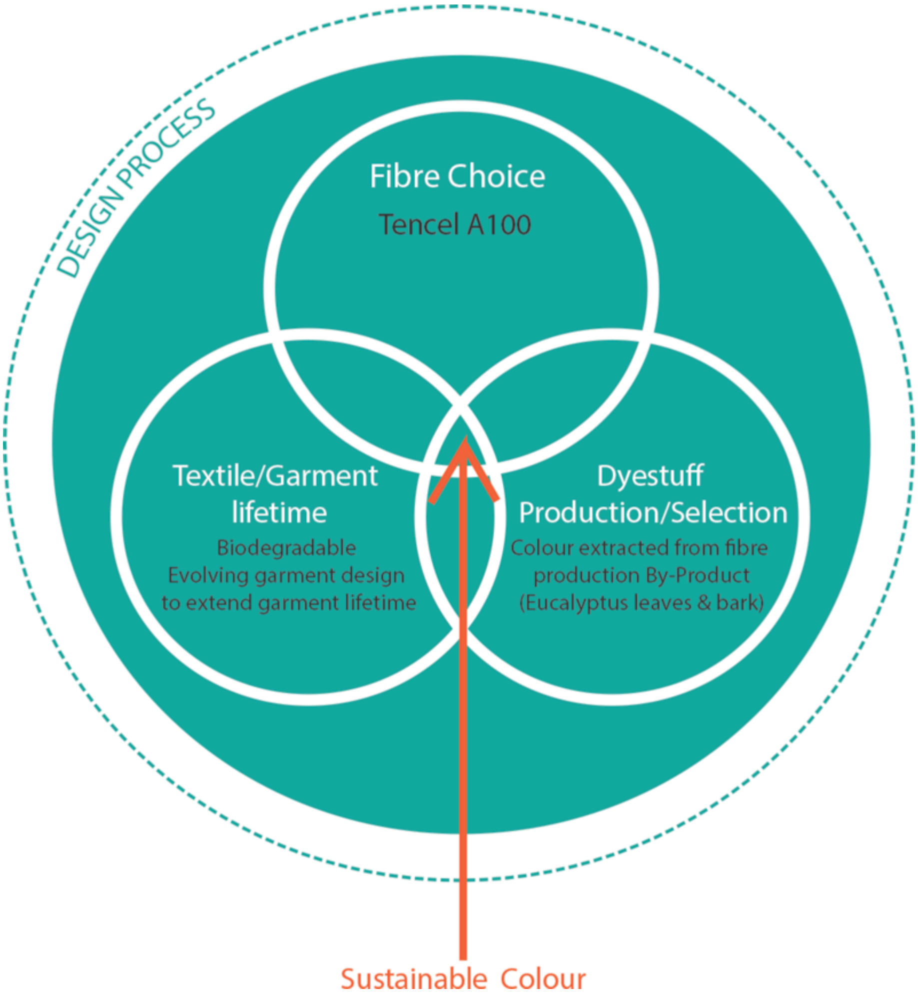


Figure 7.7. Sustainable Colour mapped onto the Sustainable and Responsible Coloured Textiles and Fashion Diagram.

7.4.3 'Responsible Colour'

In contrast to 'sustainable colour', 'responsible colour' offered a more immediate, short-term approach to reducing the environmental impact of coloured fashion and textiles. The limitations of the Cyclical Colour Model, in terms of the restricted colour possibilities presently achievable, led to questioning the possibility of methods that might provide more immediately applicable solutions. As described in chapter 4 the definition of 'sustainable' developed for the research within this thesis was: learning to leave in harmony with our planet and to take from it only what we are able to give back to it without causing harm. In accepting that, by exploring the inevitable use of synthetic dyes, truly sustainable outcomes would not be achievable according to this research definition, the focus of the research moved to developing methods for coloration that were as environmentally responsible as possible. Synthetic dyes where explored and Kisco's improved fixation reactive dyes, Synocron RD range, was selected for use based on their environmental credentials.

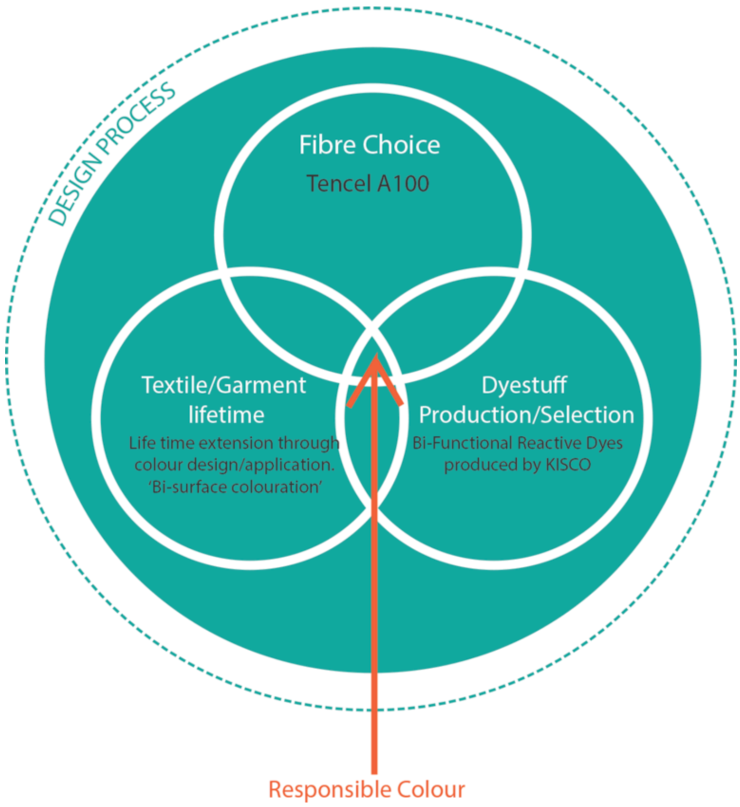


Figure 7.8. Responsible Colour mapped onto the Sustainable and Responsible Coloured Textiles and Fashion Diagram

7.4.4 'Bi-surface Colour'- designing with colour to extend garment longevity

Having established the technically and environmentally most efficient synthetic dyes for application, design methods and methods of colour application were then explored aiming to further reduce the environmental impact of coloured fashion garments. The design concept of creating a surface that could have more than one face showing colour was inspired by consideration of the bi-functional nature of the reactive dyes. Colour technologists developed the bi-functional dyes to reduce environmental impact through increasing the number of functional groups within the dye molecule. The researcher was inspired by this concept to increase the functionality of fabrics by utilizing both surfaces, front and back, of fabrics. This feature allows garments to change their appearance simply through how the user decides to wear them. Outcomes from this phase of research explored creating bi-surface garments, in which both surfaces of fabrics have colour applied. Screen print and digital print stages were combined, and the processes streamlined, to provide a single fabric with two surfaces. This coloration method was then used alongside the traditional method of creating double-sided garments used as described in chapter 6 to create a collection of prototype garments that had an extended lifetime through creating two garments within one.

7.5 Overall Research Conclusions

Sustainable colour is achievable, exploiting the current existing commercial scale production of lyocell fibre, by extracting colour from natural by-products of the fibre production. In principle, this method can be adapted reasonably quickly by industry for commercial production. However the colour range achievable is currently limited and further research and development into the process would be needed to ensure commercial success. On the basis of this approach, it has been concluded that when design thinking is used to create a circular method of design, rather than the linear process that is normally used, environmental impact can be reduced and sustainable solutions developed.

The research led to the conclusion that, whether achieving sustainable colour or responsible colour, in aiming to reduce the environmental impact of coloured fashion and textiles, the designer has to compromise on the aesthetic colour range achievable.

Neither natural nor synthetic sources of colour can provide the infinite rainbow of choices available to a designer, when care for the environmental impact of the final product is a prime motivator.

7.6 Limitations of the research

The research was focused on the use of Tencel fibres, manufactured and provided by Lenzing as a result of their collaboration. This fibre was selected on the basis of the positive environmental credentials of the lyocell process used to manufacture Tencel, and the positive approach of the company towards the environment. The industrial scale of production that is currently used would allow the research outcomes from this thesis, in principle, to be industrially feasible. However, although the decision to use lyocell was fundamental in establishing and conducting this initial research, there is scope to develop the approach further by exploring other emerging alternative sustainable fibres, although there are no others that offer the closed loop process of lyocell.

The research described in this thesis highlighted a gap in terms of sustainable coloration solutions for cellulosic fibres. Thus, a major focus of the work was on cellulosic fibres and reactive dyestuffs, the most commonly used dyestuff class for these fibres. The specific technical research outcomes are limited to this fibre and dyestuff combination. However, the design principles and outcomes are not limited in this way, and so could also be explored using other fibre and dyestuff combinations.

7.7 Recommendations for future work

7.7.1 'Sustainable Colour'

It would be useful to explore the expansion of the colour range within the existing 'cyclical colour model' established in this thesis for the lyocell process. Examples of a range of colours, from turquoise blue through to orange and yellow, have been demonstrated by artisans using dyes extracted from eucalyptus plant species; this suggests the possibility to extract alternative colours from the by-product used to create the yellow shade as presented in Chapter 4. Possible experimentation could include varying the temperature and/or method of dye extraction.

In moving towards renewable sustainable sources of colour for fashion and textiles and the possible industrial scale use of natural dyes, for this proposal to be sustainable and realistic, the sources of colour available from existing and future developed processes would need to be based on the use of by-products of the agricultural and fibre industry. Methods of dye extraction using a closed loop water process, as explained in Chapter 4, would need to be developed and incorporated into large scale production. Application of colour without bleaching or mordanting fabrics needs further investigating, while ensuring that the final coloured fabrics meet the fastness standards that can be achieved with competing synthetic dyes.

7.7.2 'Responsible Colour' to reduce environmental impact

The conclusions from the phase of research presented in Chapter 5, established that the designer is also limited in the choice of available colours within the range of dyes currently on the market, based on the group of reactive dyes, produced using bi-functional chemical structures, which have been demonstrated to reduce environmental impact by increasing fixation, thus also requiring a reduced amount of initial dyestuff.

In progressing the research further, interdisciplinary exploration should be conducted with a designer working in collaboration with a colour chemist to build upon these findings and develop solutions together working in parallel between a laboratory and design studio.

7.7.3 'Bi-surface Colour': designing with colour to extend garment longevity

The final stage of research, presented in Chapter 6, explored ways aiming to overcome the technical limitations identified in Chapter 5 through how colour is used within the design process and applied for use within a garment's lifetime. This process requires to be tested through consumer involvement and wearer trials, aiming to further refine and develop the process and the product. It will also be important to establish whether the method does indeed extend the wearability and lifetime of a garment.

Further manipulation of digital prints with water after printing and before steaming, an effect described in Chapter 6, offers the potential to 'flip' the process whereby the printed digital aesthetic can be modified by hand. In effect, the digital print provides the canvas for further manipulation. There is potential to explore the use of this technique as an alternative means of producing simulated bleaching finishes on denim.

The final design outcomes from this research should be used within a consumer research setting to test, under 'real world' conditions, the strengths and weaknesses of the processes. The data obtained from wearer trials would be fed back into the design process aiming to revise and improve the methods, and then lead to the production of second stage research outputs that have been further refined, ultimately inching closer to providing the industry with solutions to reduce the environmental impact of colour for textiles.

Appendix A

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Coloration Technology
Society of Dyers and Colourists

An approach to sustainable coloration of lyocell fabrics by screen printing using extracts of leaves and bark from eucalyptus

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This paper presents an initial study from a more extensive programme of research at the design/technology interface that is focused on the use of design methodology as a means to lower the environmental impact of fashion clothing. The leaves and bark that are byproducts of the responsibly farmed eucalyptus used in the manufacture of lyocell fibres were extracted with water to provide a source of natural colour. Lyocell fabric, which required minimal preparation, was screen printed with an aqueous paste containing only the extracted colour and a natural thickener to provide attractive golden-yellow prints. The printed fabrics demonstrated surprisingly good fastness towards light, washing and rubbing. A mordanting pretreatment of the lyocell with alum modified the colour of the naturally coloured prints to become stronger and duller, but provided no advantage in terms of technical performance. The outcome presents a potentially useful model for the development of sustainably coloured fashion textile products.

Introduction

Society is becoming increasingly concerned with protection of the environment. The major issues that are under constant debate include the impact of climate change, the destruction of the rainforests, water and air pollution, waste disposal and depletion of non-renewable sources of energy and materials. The global textile industry faces significant challenges in addressing its responsibility towards a wide range of environmental issues. In aiming towards economic success, the industry has developed a dependency on non-renewable resources, consumes large quantities of chemicals (some of which present serious human health issues), energy, and water, and generates large volumes of waste. The attitude of sections of society towards fashion also has an impact on the environment. For example, the desire to follow rapidly changing fashion trends commonly leads to premature disposal of garments, which inevitably end up in landfill, a situation that is unsustainable [1]. As an awareness of this impact has been growing, the use of 'sustainable' in the context of design and fashion has been steadily increasing [2]. It has been said that there are more than 70 definitions of the term 'sustainability'. It is thus unsurprising that there is frequent confusion over its meaning, and also that the term is commonly misinterpreted [3,4]. The Oxford English Dictionary cites the meaning as 'able to be maintained at a certain rate or level' and, in an environmental sense, as 'conserving an ecological balance by avoiding depletion of natural resources'. There have been a number of specific initiatives to address the issues in the context of textile products, for example that they may be labelled as 'sustainable' if the raw materials originate from organic farming and if the manufacturing processes comply with ecologically and sociably acceptable production methods [5]. This statement, while well intentioned, is rather specific in that it may exclude other valid alternatives, including the approach described in this paper. In the context of the programme of research that has led to this paper, we have adopted the concept that the essence of sustainability concerns 'learning to live in harmony with our planet and to take from it only what we are able to give back to it', which is our modification of an original suggestion in a Design Council paper [6]. On the basis of this principle, textile and clothing designers are encouraged to incorporate environmental value into their design process, making informed choices based not only on aesthetic, tactile, and technical qualities, but equally on the environmental credentials of the materials and processes used [7]. It may be anticipated that consumers, as they become more environmentally aware, will consciously choose to support fashion brands that project a profile that promotes sustainability. It has been suggested that 80–90% of the life cycle costs of a product are determined by design prior to its production [8]. Designers thus have the opportunity to significantly reduce the environmental impact of manufactured garments by early intervention.

Fibre selection is of prime importance in the design of a textile product, in ensuring not only the desired qualities but also in determining the environmental impact. Cotton is by far the most important natural fibre. However, it presents some negative features in terms of sustainability. Most prominently, its cultivation has traditionally required the use of large areas of arable agricultural land, large quantities of water, and high levels of pesticides, although this needs to be balanced against a variety of initiatives that have significantly improved its environmental profile in recent years [9]. Lyocell, marketed as 'Tencel' by the manufacturers, Lenzing AG (Austria), is a regenerated cellulosic fibre that has strong environmental credentials [10,11]. The manufacturing process uses as its raw material wood pulp derived from eucalyptus species, particularly *Eucalyptus Grandis*, *Urophylla*, *Nitens* and *Dunnii*, all of which are hybrids. These species are farmed on land described as 'marginal', i.e. unable to sustain agricultural crops. They are fast growing and have low requirements for water and pesticides. The manufacture of lyocell involves dissolving the pulp in *N*-methylmorpholine-*N*-oxide (NMMO) containing a small amount of water. The fibres are formed by a dry-jet wet spinning process in which the viscous, concentrated solution of cellulose is extruded through a spinneret into a water bath. The organic solvent, which is claimed to be essentially non-toxic and biodegradable, is recovered at a rate of 99.5% [11]. Unlike other regenerated cellulosic fibres, such as viscose, there is no chemical conversion involved, and the cellulose content of the pulp used to feed the lyocell process remains chemically unchanged in the final product.

Colour is the most immediately visible feature in the design of a textile product and is often the main aesthetic concern. It is not unreasonable to suggest that all methods of textile coloration have some undesirable environmental consequences. A recent study expressed the opinion that 'the perfect t-shirt' would be constructed from unbleached and undyed organic cotton [12]. While there is some justification for this conclusion, it is questionable as to whether the plain light beige 'eco-fashion' look would appeal widely to consumers who have higher expectations in terms of colour. The textile dyes currently used in the industrial coloration of textiles are almost exclusively synthetic products of the chemical industry, manufactured from finite, non-renewable petrochemical sources [13]. Application of the synthetic dyes to the textiles generally involves intense use of chemicals, water, and energy, with inevitable environmental consequences [14]. While it may be argued that natural dyes may offer some environmental benefit compared with synthetic dyes, for example in terms of biodegradability and low toxicity, their use is not free of environmental impact. The cultivation of plants specifically for the production of natural dyes would require the use of a significant area of arable land, for which food production is a higher priority [15]. In addition, natural dyeing of textiles commonly requires treatment with a mordanting agent, usually a metal salt, the purpose of which is to fix the dye to fibres for which many natural dyes have little direct affinity, with inevitable environmental consequences [16]. In addition, natural dyes provide a limited range of colours and commonly show inferior fastness properties compared with their synthetic counterparts. There is, however, evidence of recent re-investigations of natural dyeing processes that aim to address some of these negative issues [17].

The research reported in this paper involves a collaboration between two textile designers (DE and SR) and a colour chemist (RC) operating at the design/technology interface and inspired by the concepts of sustainable design and the possibilities that they offer, while employing important scientific underpinning. This paper presents results from an initial study in a wider programme of research that involves engagement in product design from concept to end of life, taking responsibility for the environmental consequences of design decisions. The objective is to demonstrate the potential to design, ideally within a sustainable life cycle model, coloured textiles that might be used for fashion garments. The paper explores specifically the potential to utilise byproducts of the eucalyptus species farmed for lyocell production as a source of natural colour.

Experimental

Materials

Fresh eucalyptus leaves and bark were supplied by the supplier of wood pulp to Lenzing (Sappi, South Africa). The leaves and bark were allowed to dry in sunlight for 2 weeks before crushing in a blender. Lyocell fabrics were supplied by Lenzing AG, Austria. Both fabrics, Tencel A100 (1.4 dtex, staple length 38 mm, 168 g m^{-2}) and standard Tencel (1.3 dtex, staple length 38 mm, 125 g m^{-2}), were weft knitted from 1/30s ring-spun yarns in an interlock structure. Exenol XB, described as an anionic/nonionic alcohol ethoxylate, was supplied by J & W Whewell Ltd, UK. Gum tragacanth was supplied by Makebake, UK. Potassium aluminium sulphate (alum), calcium carbonate, and tannic acid were obtained from Sigma-Aldrich, UK. Alpro unsweetened soya long-life milk was purchased at a local supermarket.

Dye extraction

The dried leaves and bark were extracted separately. The material was slurried in water (*ca.* 10 g leaves and 20 g bark per litre of water). This mixture was raised to the boil and refluxed for 1 h. The slurry was then filtered and the water removed from the filtrate by rotary evaporation to provide a brownish-orange crystalline powder. A further quantity of dye was obtainable from a second extraction.

Fabric pretreatment

The lyocell fabrics were scoured using a 0.1% solution of Exenol XB in water at 40 °C for 30 min, rinsed with cold water, and then air dried at room temperature.

Mordanting

The scoured fabric was treated separately with the mordants – alum, calcium carbonate, soya milk, and tannic acid. An aqueous solution of the mordant at a concentration of 20% owf using a liquor ratio of 15:1 was poured over the fabric (12 g) as it was passed through a two-bowl BVHP padder (Roaches Engineering, UK).

Screen printing

The print pastes were obtained by dissolving the extracted dye in a solution of gum tragacanth in water (40 g l^{-1}) at concentrations of 2, 4, 8, and 16%. These concentrations refer to the total amount of extracted solids, which are likely to be complex mixtures of naturally occurring components. Fabric samples were printed on a Zimmer (Austria) magnetic print table with a single pass of the print paste across the fabric using a metal rod. The samples were then steamed at 100 °C for 20 min, washed with a 0.1% aqueous solution of Exenol XB, initially cold and then increasing to 40 °C, then with water, and finally air dried.

Assessment

Samples were evaluated for wash fastness in accordance with ISO:105, part C10 [18], for colour fastness to rubbing in accordance with ISO:105, part X12, and for colour fastness to light in accordance with ISO:105, part BO1 [19,20]. Colour measurement was carried out on a Datacolor Spectraflash SF600 spectrophotometer and processed using Datamatch (USA) 3.1 software, employing the small aperture for the 10° observer with specular reflectance included and the UV component excluded, under D65 illumination. The instrument was calibrated using a black trap, white tile, and green tile respectively according to the manufacturer's recommendations. Samples were folded four times, and measurements were made on the back of the fabric. An average of three measurements from different parts of the fabric were obtained in each case. Reflectance measurements in the UV region were obtained using a PerkinElmer (USA) Lambda 35 UV/vis spectrometer equipped with a labsphere RSA-PE-20 reflectance spectroscopy accessory.

Results and Discussion

Lyocell was selected as the textile substrate for this study, as an example of a fibre that has sound environmental credentials and also because certain fabrics constructed from the fibre offer attractive and interesting aesthetic and tactile qualities from a textile designer's perspective. Lyocell also offers environmental advantages in terms of coloration, especially in reactive dyeing [21]. The version of the fibre of particular interest in this respect, Tencel A100, is prepared by treatment with the crosslinking agent trisacryloylhexahydrotriazine (TAHT) [22]. The open fibre structure of Tencel A100 has a positive influence on its dyeing performance. High colour yields are obtained from reactive dyes, attributed to the high natural affinity of the dyes for the fibre, a high rate of exhaustion, and a high degree of fixation. This feature means that the amount of dye that needs to be applied initially and the level of certain chemical auxiliaries required for the dyeing process may be minimised [23,24]. In aiming towards a future 'zero-emissions, zero-waste society', consideration of the use of renewable resources for textile coloration has been proposed, especially by making use of byproducts from agricultural processes and ensuring that all parts of the plant are utilised in some way [25]. At this initial stage of the investigation, a potentially sustainable source of natural colour for application to lyocell was identified as the leaves and bark of the particular species of eucalyptus used in its production. Currently, the trees are debarked in the field, and the leaves and bark are left there as natural compost. There are several previous reports of the use of colour extracted from species of eucalyptus in natural dyeing [26–29], and it is used to a certain extent in craft-based natural dyeing processes.

For the present study, quantities of fresh bark and leaves of the species of eucalyptus that are used in lyocell manufacture were obtained from the farms in South Africa where they are grown. It was found that a simple extraction of the dried leaves and bark using boiling water, with no additives, in both cases provided a reasonable quantity of an orange-brown crystalline material after evaporation of the water [26]. In principle, the solid residue from the leaves and bark after the extraction process could continue to fulfil their purpose as a composting material. As the method of colour application to the Tencel A100 fabric, screen printing was selected in view of its simplicity and the fact that localised coloration and creative pattern selection might be used to produce attractive colour effects while minimising the use of dyes and auxiliary chemicals. The traditional screen preparation procedure involves an initial application of a coating of a photosensitive emulsion on the screen. An acetate film containing the image is then placed over the screen, and the system is subjected to a photochemical curing process, after which uncured material is washed off to reveal the image. To avoid the environmental consequences of this chemical process, the print imagery was derived from stencils formed using lyocell fabric, which were then placed on the fabric to be printed beneath an open screen. It is envisaged that the lyocell fabric used for this purpose might, in principle, be reused in stencil production as a structured piece of fabric by sewing or bonding, or recycled in some other way.

Print pastes were prepared simply using gum tragacanth as a natural thickening agent dissolved in water, in which solution the dye extract dissolved readily. Other auxiliary chemicals common in print paste formulation, the most obvious of which is urea used as a fibre-swelling agent to promote dye uptake, were avoided to minimise environmental impact. Initial print trials using this print paste on untreated Tencel A100 gave prints that exhibited a degree of non-uniformity. Consequently, a light scouring of the fabric at 40 °C was carried out using a dilute aqueous solution of a particular surfactant recommended for its low environmental impact. This process contrasts with the rather vigorous scouring procedure, often supplemented by bleaching, that is commonly employed as a print pretreatment for cotton fabric. Screen prints of the scoured Tencel A100 with the pastes derived from the eucalyptus extracts were finished by a traditional steaming process to promote fixation. Attractive golden-yellow prints on a clean white fabric background were produced. The colours of the prints derived from extracts of the eucalyptus leaves and bark were virtually identical, presumably because the compositions of the coloured materials from the two sources were similar. Previous studies of eucalyptus extracts have identified the principal coloured components as flavonoid species, found in association with tannins and polyphenols [28].

A graph illustrating the variation in K/S values with wavelength in the visible region for scoured Tencel A100 printed with leaf and bark extracts at a concentration of 4% in the print paste, obtained by reflectance spectrophotometry, is given in Figure 1. The yellow colour is due to the absorption at low wavelengths. It was confirmed that this visible absorption is an extension of absorption in the UV region from the reflectance curves shown in Figure 2. Undyed Tencel A100 shows around 40–50% reflectance in the UVA region, while the reflectance is <10% in the printed samples. The UV absorption properties of fabrics treated with extracts of eucalyptus have been reported previously [29].

The effect of dye concentration in the print paste derived from eucalyptus leaves and bark on the colour strength of printed Tencel A100 is illustrated in Figure 3. The expected increase in colour strength with concentration is shown. A concentration of 4% was considered to be the most reasonable practically, as higher concentrations (8 and

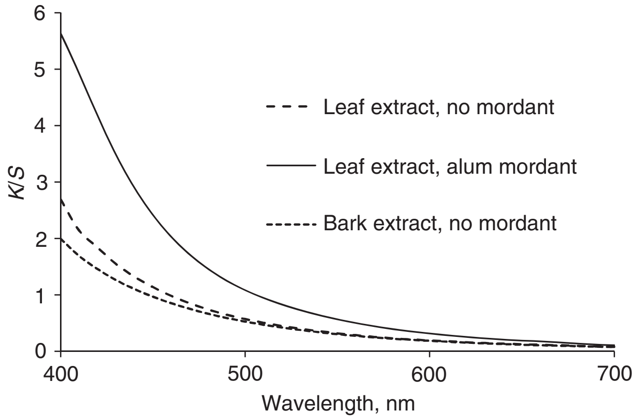

Figure 1 *K/S* curve for Tencel A100 printed with eucalyptus leaf extract, at 4% concentration in the print paste.

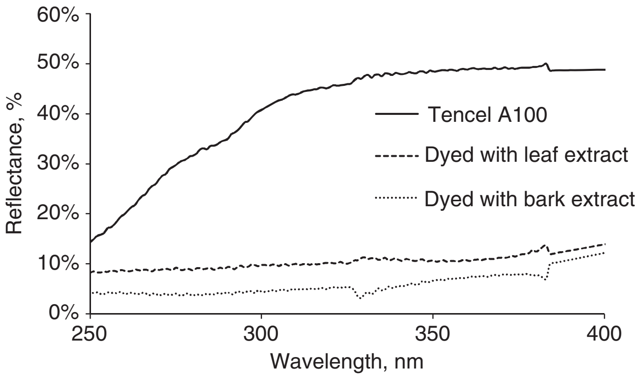

Figure 2 Reflectance (%) of Tencel A100, undyed and dyed with leaf and bark extracts.

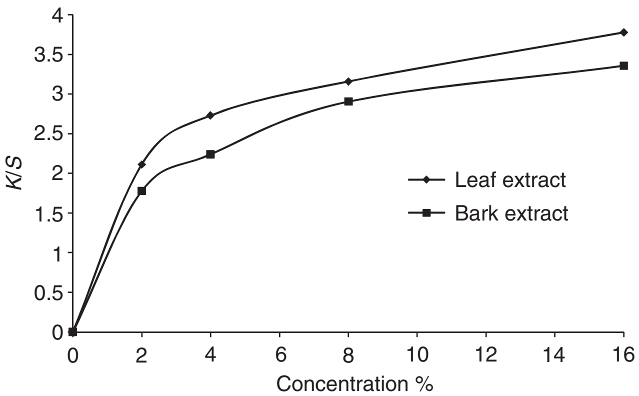

Figure 3 Relationship between the concentration of dye in the print paste and colour developed, as the *K/S* value at 400 nm.

16%) did not lead to proportionately higher colour strength, and there was significant colour loss into the wash liquors observed at these higher concentrations during the wash-off procedures employed after steaming. Consequently, all subsequent investigations were carried out at a concentration of 4%.

In view of the fact that natural dyes commonly require a mordant treatment for adequate fixation on textiles, printing was also carried out on a range of fabric samples pretreated with a selected group of mordants. The mordants selected included alum, which is traditionally the most commonly used and most effective mordant, although its use introduces some environmental consequences as a metal-containing agent [31]. The other mordants used were tannic acid, proposed recently as a natural botanical alternative to metal-containing mordants [32], calcium carbonate, and soya milk, which are commonly used in natural craft dyeing, in particular for eucalyptus [33]. The *K/S* values at 400 nm for each of the Tencel A100 samples printed with eucalyptus leaf and bark extracts, at a concentration of 4% in the print paste, are given in Table 1 as a measure of the colour strength. Mordanting with alum provides a stronger, although less attractive brownish-yellow colour in the printed samples, which is evident from the *K/S* curve as illustrated in Figure 1. In contrast, none of the other mordants modified the colour significantly.

Wash fastness results based on a set of 40 °C standard laundering conditions are given in Table 2. The wash fastness ratings for both colour change and staining on all of the adjacent fibres were excellent, rated at 4–5 or 5 throughout. The most interesting result is the excellent wash fastness provided by printing on fabric that has received no mordanting treatment. An explanation for this observation may be proposed that is based on previous observations that eucalyptus extracts contain natural tannins which are capable of acting as dye fixing agents [28]. Thus, it is conceivable that the extracts from the eucalyptus leaves and bark in this case contain both the flavonoid colouring materials and also tannins and are therefore 'self-mordanting'.

Rub fastness results are given in Table 3. The dry rub fastness is excellent, rated at 5 for all samples. There is, in some cases, slightly inferior wet rub fastness. Interestingly, the unmordanted fabric proved to be superior compared with the alum treated fabric in this respect.

The ability to withstand the effect of light is a key attribute of coloured textiles. Light fastness is frequently reported as a deficiency in naturally dyed fabrics. It has been suggested that light fastness ratings of naturally dyed textiles rarely exceed a grading of 4 when assessed against the blue wool scale standards [15]. The light fastness data for the printed samples obtained by a standard Xenotest exposure procedure are given in Table 4. It is of considerable interest that light fastness ratings up to 5–6 are provided by the printed fabric, a level comparable with that provided by many traditional synthetic dyes. It is especially interesting that the optimum light fastness was provided by the printed fabric with no mordant pretreatment. In view of this rather unexpected outcome, this particular assessment was repeated several times to provide verification, and the result was demonstrated to be consistent and reproducible. A potential explanation for the good light resistance is that the UV absorption in the extract, as demonstrated in Figure 2, may provide the coloured species

Table 1 *K/S* values at 400 nm for Tencel A100 samples printed with eucalyptus leaf and bark extracts at 4% concentration in the print paste

	Unmordanted	Alum	Tannic acid	Calcium carbonate	Soya milk
Leaf extract	2.7	5.6	1.8	2.2	3.1
Bark extract	2.0	3.5	1.8	1.8	1.7

Table 2 Wash fastness assessment of Tencel A100 fabrics printed with eucalyptus leaf and bark extracts at a concentration of 4% in the print paste

			Staining											
	Colour change		Cellulose acetate		Cotton		Nylon		Polyester		Acrylic		Wool	
Mordant	Leaf	Bark	Leaf	Bark	Leaf	Bark	Leaf	Bark	Leaf	Bark	Leaf	Bark	Leaf	Bark
None	4–5	4–5	5	5	4–5	5	5	5	5	5	5	5	5	5
Alum	5	5	5	5	4–5	5	5	5	5	5	5	5	5	5
Tannic acid	4–5	4–5	5	5	4–5	4–5	4–5	4–5	5	4–5	5	5	5	5
Calcium carbonate	5	4–5	5	5	4–5	4–5	5	5	5	5	5	5	5	5
Soya milk	4–5	4–5	5	5	4–5	4–5	5	5	5	5	5	5	5	5

Table 3 Rub fastness assessment of Tencel A100 fabrics printed with eucalyptus leaf and bark extracts at a concentration of 4% in the print paste

Mordant	Dry rub fastness (leaf)	Wet rub fastness (leaf)	Dry rub fastness (bark)	Wet rub fastness (bark)
None	5	4–5	5	4–5
Alum	5	4	5	3–4
Tannic acid	5	4–5	5	4–5
Calcium carbonate	5	4–5	5	4
Soya milk	5	4	5	4

Table 4 Light fastness of Tencel A100 fabrics printed with eucalyptus leaf extract at a concentration of 4% in the print paste

Mordant	Light fastness (leaf)	Light fastness (bark)
None	5–6	5–6
Alum	5	5
Tannic acid	4	4–5
Calcium carbonate	5	5
Soya milk	5	5

Table 5 Properties of unmordanted standard Tencel fabrics printed with eucalyptus leaf and bark extracts at a concentration of 4% in the print paste

	Leaf	Bark
K/S at 400 nm	2.3	2.7
Wash fastness		
Colour change	4	4
Staining		
Cellulose acetate	5	5
Cotton	5	5
Nylon	5	5
Polyester	5	5
Acrylic	5	5
Wool	5	5
Rub fastness		
Dry	4–5	4
Wet	4–5	4
Light fastness	5	5

with a degree of protection from the damaging effect of UV radiation [29,30].

The selection of Tencel A100 as the fabric for this investigation was based on its particular suitability for coloration. However, there is a potential environmental issue associated with this version of lyocell fibre in that it is manufactured using a chemical treatment to provide cross-linking. It was thus decided to investigate the performance of standard Tencel, which has not been subjected to a comparable chemical treatment, under the same established screen printing conditions. A comparison of the results of this investigation, given in Table 5, with those presented in Table 1 for printed Tencel A100 demonstrates that the dye extracts perform similarly in terms of the strength of colour developed, as represented by the *K/S* values, on the two versions of lyocell. The range of fastness properties of the printed standard Tencel fabrics were acceptable, as illustrated in Table 5, although marginally inferior in some cases compared with the comparable results given by Tencel A100 (see Tables 2–4). It appears that the location of the coloured species within the open crosslinked structure of Tencel A100 may provide a marginal enhancement in fastness performance.

Conclusions

Natural colouring materials may be extracted using a simple water-based process from the leaves and bark that are byproducts from the responsible farming of the eucalyptus species used to produce the wood pulp from which lyocell fibres are manufactured. Thus, they represent a potentially renewable resource of colour. Screen prints were produced successfully on fabrics constructed from two commercial grades of lyocell, which required only a mild scouring pretreatment using print pastes containing only the extracted colour, a natural thickener, and water. The prints provided an attractive golden-yellow colour on a clean white background. The performance of the prints, in terms of fastness to washing, rubbing, and light, was good to excellent, rather unexpectedly, and was marginally superior to the performance of the prints on fabric that had received an alum mordant treatment. The alum pretreatment gave rise to enhanced colour strength but a less attractive brownish-yellow colour, presumably owing to metal complexation. Explanations have been proposed for the excellent set of technical properties on unmordanted fabrics, based on the probable presence in eucalyptus extracts, supported by previous literature reports, of ingredients that provide both self-mordanting properties and a degree of UV protection. On the basis of the colours being natural, it is anticipated that they would be biodegradable.

The attractive colour and the level of technical performance of the process described in this paper offer distinct possibilities for the design of fashion fabrics, and the process offers significant advantages in terms of sustainability. In our opinion, this may well be the most sustainable approach to coloured textiles that has been reported to date. A significant limitation is that the process is restricted at this stage to the single colour. However, in our ongoing programme of research, we are actively exploring ways to extend the range of colours, utilising a range of design practice concepts and methods to offset environmental impact. This investigation has wider implications in potentially providing a model system for sustainable design. It is our hope that the focus on life cycle considerations that we have adopted will encourage other designers to think beyond the immediacy of the creative and technical processes and demonstrate an awareness of the wider context in which a fashion textile product exists. Making informed, responsible design choices at the initial stages of the development of a textile product will provide a positive impact on its environmental credentials.

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Better than Beige: Sustainable colour for Lyocell

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Abstract

This paper introduces initial findings from a more extensive programme of research at the design/technology interface carried out in the School of Textile and Design, Heriot-Watt University, in collaboration with Lenzing, Austria. The PhD research is focused on the use of design methodology as a means to address the environmental impact of colour for fashion textiles, addressing the challenges and limitations in creating sustainable colour.

Recent literature commentary in the area of sustainable textile design reinforces our opinion that all forms of coloration, using either natural or synthetic colours, have some adverse environmental impact. On the basis of a previously-reported research project, it has been suggested that the most sustainable way to produce garments is to use unbleached, undyed organic fabrics. We are programmed to react to colour on a psychological and physiological level. Removing variety of colour on the grounds of sustainability is effectively suggesting that a world consisting only of light beige would be acceptable. However, from the perspective of both designer and consumer this conclusion, though environmentally-justifiable, sacrifices any textile design influence. Such textiles would not be enough to satisfy our human desire for colour. This paper raises the importance of exploring the environmental impact involved in creating colour for textiles through ‘how we use and design with colour’, an area which is rarely addressed within sustainable design.

This paper illustrates a textile designer’s approach to these specific colour-associated issues, carried out in collaboration with Lenzing, global fibre manufacturers. The emphasis of the project was to explore innovative ways of colouring textiles through sustainable coloration methods. The research was underpinned by textile and coloration technology working in parallel with the design approach in establishing sustainable options for coloration.

The use of Lyocell fibres (Tencel) enabled exploitation of their strong environmental credentials and provided the basis of a cyclical model for sustainable colour involving life-cycle design thinking. The model is focused on the life-cycle of the Lyocell manufacturing process. Natural colour was extracted from the leaf and bark, which are by-products of the sustainably-forested eucalyptus from which the fibres are derived. No harmful chemicals were used at any stage and only water was used in the extraction process. Colour was applied to fabrics by screen-printing using gum tragacanth as a natural thickening agent for the print paste. The process was evaluated both with and without the use of mordants. Technical evaluation of the printed fabrics demonstrated a surprisingly good set of fastness properties, at a level comparable with those provided by many synthetic dye classes.

The research has highlighted that for sustainable design to be successful, it must incorporate and balance aesthetic value with environmental value, rather than sacrificing one for the other. The collection of textile design samples produced using a cyclical (life-cycle) method concludes that the natural eucalyptus-based dye may be suitable for commercial use. The process presents future potential for innovative design development and illustrates how the incorporation of traditional craft knowledge within current production processes can create solutions for sustainability. The paper concludes by suggesting future applications for this research.

Keywords

Sustainable, textiles, design, colour, Lyocell, life-cycle

Introduction

Textiles for fashion, at many stages of their life-cycle, contribute significantly towards environmental pollution, for example in terms of extensive consumption of chemicals, energy, water, and generation of waste. As an industry, fashion textile production is heavily reliant on diminishing, non-renewable natural resources. With increased awareness surrounding the use of these finite resources, there is ongoing debate, particularly in the scientific community, as to how much longer chemicals based on fossil fuels will continue to be available for use. While opinions range from 50 to 500 years, it is agreed that the reserves are limited and that research into new energy and material resources for textile production will be essential to satisfy future needs (Bechtold and Mussak 2009).

This growing awareness within the industry has led to a developing vocabulary for fashion and textile products that aim to be more environmentally responsible throughout the life cycles of clothing items. Terms such as bio, eco, natural, organic, slow, conscious and responsible are being used to categorize a variety of features of this type of 'green fashion'. Research in the area of sustainable design has gained momentum in recent years, aiming to provide innovative solutions for an industry that needs to evolve into more responsible and efficient systems of production. The focus of research and development has generally been to address fibre choice, garment design and production processes. In contrast, approaches to introducing colour have been largely overlooked. Developments in the area of textile coloration have been led by scientists and technologists with focus primarily on the chemistry involved, for example aiming to reduce the requirements for water, energy and raw materials used for dyeing and printing processes.

Colour is the most immediately visible feature in the design of textiles. It is often the main aesthetic concern for both the designer and consumer. It can also be the reason for financial success or failure of products within the marketplace. The main motivation for the use of colour within design is to create desirable aesthetics to ensure the commercial appeal and financial success of the product. Designers commonly demonstrate only a limited understanding of, or regard for, the environmental impact caused by the production of colour and its application to textiles. The global textile industry uses more than 700, 000 tonnes of dye each year. Depending on the particular dye class used, the percentage of dye that remains unfixed to the fibre during the dyeing process and finds its way into the effluent ranges from 5 to 50 per cent (Hardin 2007: 191).

There are two broad sources of chemicals which may be used to create colour: natural and synthetic. It is a common misconception to presume that natural inevitably means good and synthetic bad in terms of its effect on the environment. Until the mid-nineteenth century, when the development of synthetic dyes began, all textiles were coloured using dyes from natural sources (Cardon 2007: 20). The lower cost, better reliability, reproducibility, and larger scale of operation that was achievable with synthetic dyes, together with the development of new technologies that have taken place over the years, have meant that the traditional processes used for natural dyeing and knowledge and experience of the methods have been largely eliminated. Modern industrial processes use natural dyes only in specific niche markets. The dyes currently used for the industrial coloration of textiles are almost exclusively synthetic products of the chemical industry, manufactured from finite, non-renewable petrochemical sources (Christie 2001: 118). Application of these synthetic dyes to textiles generally involves intense use of chemicals, water and energy, with inevitable environmental consequences (Bide 2007: 74).

Current opinion within the research community is increasingly concluding that all methods of coloration of textiles have environmental consequences (Better Thinking 2006). The current systems for introducing colour must be considered as unsustainable over the longer term. This leads to the fundamental questions which have motivated the research programme reported in this paper: how would we produce colour without the use of chemicals derived from fossil fuels, and what happens when reserves run out?

While it may be argued that natural dyes offer some environmental benefit compared with synthetic dyes, for example in terms of cultivation from renewable natural sources, biodegradability and low toxicity, their use is not completely free of environmental impact (Glover 1998: 4). The cultivation of plants specifically for the production of natural dyes would require the use of a significant area of arable land, for which food production is a higher priority. In addition, natural dyeing of textiles commonly requires treatment with a mordanting agent, usually a metal salt, to fix the dye to fibres as many natural dyes have little direct affinity for fibres, and this mordanting process has inevitable environmental consequences (Bechtold and Mussak 2009: 319). Commonly, natural dyes also show inferior fastness properties, limiting their suitability for use on textiles, especially fashion. In aesthetic terms, the range of colour and depth of shades that are capable of being produced from natural dyes is limited, and in no way comparable with the rainbow of possibilities achievable from the use of the modern range of synthetic dyes.

There is, however, evidence of recent re-investigations of natural dyeing processes aiming to address some of these negative issues (Bechtold et al. 2003). It is proposed that, in striving to achieve sustainable colour, we must re-consider the use of renewable resources for textile coloration, and in doing so incorporate the aim towards a future zero waste, zero emissions society. The development of agricultural production of plants used purely as a source of colour, and the use of the currently established methods both for extraction of natural colour and its application to textiles, do not provide alternatives to dyeing with synthetic dyes that are necessarily sustainable or environmentally responsible. This paper provides an example of a new approach to sources of colour that incorporate the utilisation of waste and by-products. The broad aims of the research programme are essentially to design processes which link production with design so that they incorporate life-cycle thinking in order to produce sustainable colour, and to establish a model from which opportunities and limitations for creating colour within a product life-cycle may be evaluated.

Sustainable beige?

It has been suggested that 'the perfect t-shirt', in terms of sustainability, would be constructed from unbleached, undyed organic cotton (Black 2011: 82). While there is technical and social justification for the conclusion from this study (Gwilt and Rissanen 2011: 79), the removal of colour from the process of design for textiles is arguably unsustainable from a design perspective, based on the very nature of design. After all, how desirable can beige be? It is questionable as to whether the plain light beige 'eco-fashion' look would appeal widely to both designers and consumers who have higher expectations in terms of colour. This approach to colour prioritises environmental concerns over aesthetic value.

In striving for a solution beyond beige and also questioning whether sustainable colour can be created, the research described in this paper has explored definitions for the meaning of sustainable. It is suggested that the term has more than seventy definitions (Holmberg and Sandbrook 1992: 20). The use of 'sustainable' in the context of design, fashion and textiles has been steadily increasing, and this has resulted in frequent confusion and misinterpretation in terms of its meaning (Galvic and Lukman 2007). The *Oxford English Dictionary* cites the meaning of the word sustainable as 'able to be maintained at a certain rate or level' and, in an environmental sense, as 'conserving an ecological balance by avoiding depletion of natural resources'. There have been a number of specific initiatives to address the issues in the context of textile products, for example that they may be labelled as 'sustainable' if the raw materials originate from organic farming and if the manufacturing processes comply with ecologically and socially acceptable production methods (Ganglberger 2009: 353). This statement is rather specific in that it may exclude other valid alternatives, including the approach described in this paper.

In questioning whether sustainable colour can be created we have adopted the concept that the essence of sustainability concerns 'learning to live in harmony with our planet and to take from it only what we are able to give back to it', which is our modification of an original suggestion in a Design Council paper (Thompson 2011: 2). On the basis of this principle, the textile designer is encouraged to balance aesthetic and environmental value of products.

A cyclical approach towards sustainable colour

To establish a method for sustainable coloration an experiential methodological approach was used in which life-cycle design thinking was incorporated into the creative practice of the printed textile designer. In engaging with product design from concept to end of life, the designer gains experience and understanding of environmental implications of design decisions, incorporating this new knowledge into the future design process.

In aiming to unite aesthetic value with environmental value within the design process, design decisions are made not only on the basis of aesthetic, tactile and technical qualities of materials, but also on the environmental credentials of raw materials used to produce sustainable products (Hallet and Johnston 2010: 167). Fibre selection is the first decision that impacts on both aesthetic and environmental performance of textile products. An important approach to sustainability within the fibre industry involves mimicking the natural regenerative cycle of nature by production methods in closed loop systems. Closed loop fibre production has provided the initial foundation for the cyclical process that is required within the research described in this paper from which to achieve sustainable colour.

Lyocell, marketed as Tencel by the manufacturers, Lenzing AG (Austria), is a regenerated cellulosic fibre which has strong environmental credentials (Taylor 1998: 191; Mather and Wardman 2011: 115). The manufacturing process uses as its raw material wood pulp derived from eucalyptus species, particularly *Eucalyptus Grandis*, *Urophylla*, *Nitens* and *Dunnii*, all of which are hybrids. These species are farmed on land described as 'marginal', i.e. unable to sustain agricultural crops. They are fast growing and have low requirements for water and pesticides. The manufacture of Lyocell involves dissolving the pulp in N-methylmorpholine-N-oxide (NMMO) containing a small amount of water. The fibres are formed by a dry-jet wet spinning process in which the viscous, concentrated solution of cellulose is extruded through a spinneret into a water bath. The organic solvent, which is claimed to be essentially non-toxic and biodegradable, is recovered at a rate of 99.5 per cent (Mather and Wardman 2011: 115). Unlike other regenerated cellulosic fibres, such as viscose, there is no chemical conversion involved and the cellulose content of the pulp used to feed the Lyocell process remains chemically unchanged in the final product.

Thus, sustainability may be claimed for Tencel as a fibre, until coloration and finishing stages. However, there is inevitable environmental impact occurring at the stage in the life-cycle when colour is applied to the fabric, with a consequent effect on sustainability. In the approach to sustainable coloration of Tencel adopted in this research, it was considered a requirement that no exterior materials should be brought into the production process, and that the colour should ideally be derived from materials already existing within the closed loop production process.

Analysis of the Lyocell process for Tencel identified a potentially sustainable source of natural colour as the leaves and bark of the particular species of eucalyptus used for its production. Currently, the trees are debarked in the field and the leaves and bark are left there as natural compost. Precedent for the use of eucalyptus as a source of colour for textile dyeing was evident from publications in the colour technology area (Ali et al. 2007: 559; Mongkholrattanasit et al. 2009: 319; 2010: 272), as well as its use in craft-based natural dyeing processes (Flint 2008).

As these by-products are being utilised as natural fertiliser within the production process, the aim was to optimise the resource by extracting colour from them before they are returned to the ground as fertiliser. Working in collaboration with the Tencel fibre manufacturer Lenzing, quantities of fresh bark and leaves of the species of eucalyptus that are used in Tencel manufacture were obtained from the farms in South Africa where they are grown.

For a successful method leading to sustainable coloration, it is important that the colour available within the closed loop is able to be extracted and stored for later application on to fabric when desired. A simple extraction of the dried leaves and bark using boiling water, with no additives in both cases, provided a reasonable quantity of an orange-brown crystalline material after evaporation, a process adapted from a previous report (Ali et al. 2007: 560). The process is illustrated in Figure 1. In principle, the solid residue from the leaves and bark after the extraction process could be returned into the life-cycle to fulfil their purpose as a composting material.

Figure 1. Images of the extraction process

A popular method for producing naturally dyed textiles is to combine the plant source with boiling water in a large vessel to create a dye bath. The dyeing process as a method of coloration, using either natural or synthetic dyes, is water and energy intensive and in terms of natural dyeing it is more suited to small-scale production. As an alternative method for colour application, screen printing was used in this research. Using this method, localised coloration and creative pattern formation may be achieved to create attractive colour effects while minimising the use of dye. The print paste was prepared simply using gum tragacanth as a natural thickening agent. This material selected as a natural gum is obtained from the dried sap of the plant species *Astragalus Tragacanthus*. It is biodegradable and readily available at low cost and it was found that the dye extract dissolved readily in an aqueous solution of the gum to provide a paste suitable for screen printing.

The grade of fibre known as Tencel A100 was selected because it is known to be highly receptive to coloration. Initial print trials using this print paste on untreated Tencel gave prints that exhibited a degree of non-uniformity, creating a blotchy appearance across the fabric surface. Consequently, a light scouring of the fabric at 40°C was carried out using a dilute aqueous solution of an environmentally-responsible surfactant. This process contrasts with the rather vigorous scouring procedure, often supplemented by bleaching, that is commonly employed as a print pre-treatment for other natural cellulosic fabrics, such as cotton.

Screen prints of the scoured Tencel A100 with the pastes derived from the eucalyptus extracts were finished by a traditional steaming process to promote fixation. Attractive golden-yellow prints on a clean white fabric background were produced, as shown in Figure 2. The colours of the initial prints derived from extracts of the eucalyptus leaves and bark were virtually identical, as shown in Figure 3, presumably because the compositions of the coloured materials from the two sources are similar. Previous studies of eucalyptus extracts have identified the principal coloured components as flavonoid species, found in association with tannins and polyphenols (Monkholrattanasit et al. 2010: 346).

Figure 2. Images of print samples
1 x pull of print paste across fabric   2 x pulls of print paste across fabric

Leaf   Bark

Figure 3. Images of printed colour samples

In view of the fact that natural dyes commonly require a mordant treatment for adequate fixation on textiles so that they are resistant to washing, rub-off or fading with exposure to light, printing was also carried out on a range of fabric samples pre-treated with a selected group of mordants. The mordants selected included alum, which is traditionally the most commonly-used and most effective mordant, although its use introduces some environmental consequences as a metal-containing agent (Cardon 2007: 20). The other mordants used were tannic acid, proposed recently as a natural botanical alternative to metal-containing mordants (Burkinshaw and Kumar 2009: 53), calcium carbonate and soya milk, which are commonly used in natural craft dyeing, in particular for eucalyptus (Flint 2008: 87).

Technical evaluation of the printed fabrics found that there was essentially no difference between the performance of fabrics treated with the range of mordants and the unmordanted fabric. This is an extremely important result in the context of sustainability as the need for mordanting is one of the main negative environmental consequences of natural dyeing. An explanation for this observation is provided by reports that eucalyptus contains natural tannins, which are capable of acting as fixing agents for the dyes (Mongkholrattanasit et al. 2010: 346).

A visual evaluation of the effect of dye concentration in the print paste on developed colour showed that the optimum level for dye strength was 4 per cent. Higher concentrations (8 per cent and 16 percent) did not produce an increased colour depth and there was evident undesirable colour loss into the effluent during wash-off. Optimised samples for technical testing were printed using unmordanted fabric with print pastes at a concentration of 4 per cent of the dye obtained from both leaves and bark. Results of a technical investigation into the dye performance demonstrated that the printed fabrics showed excellent fastness to washing and rubbing with very good light-fastness, remarkable results for unmordanted natural dyeing, and comparable with the level given by many traditional synthetic dyes (Ellams et al. 2013: 5). Figure 4 illustrates an example from the final prints produced.

Figure 4. Image of print sample – striped vest

Cyclical coloration: Designing beyond beige

A method which incorporated life-cycle design thinking into the creative process has been developed as an approach to creating sustainable coloured fabric on an industrial scale. This design process was integrated into the closed loop production process which ensures that the coloration was sustainable. A transferable model which may be referred to as 'cyclical coloration' was developed. Natural colour is produced within the sustainable product life-cycle by extraction of natural dyes from the leaves and bark of the eucalyptus from which the fibre is derived, and screen prints produced from these dyes show remarkably good technical performance. The research provides an example of the potential to utilise by-products or waste from industrial scale manufacturing in an existing system for textile production to produce sources of colour.

The process presents potential for future innovative design development and illustrates how the embedding of traditional craft knowledge within current production processes can create adaptive processes and solutions for sustainability. It has subsequently been demonstrated successfully that the technology is transferable to modal, another regenerated cellulosic fibre produced by Lenzing from beech; screen printing of modal using the natural colour extracted from the beech leaves and bark in this case provided an interesting nude pink colour.

In our opinion, and that of Lenzing, this research could be feasibly introduced into commercial industrial practice. The simple extraction process to produce the dye would be easily achievable on an industrial scale. Lenzing are manufacturers of the fibres, not fabrics, and so are not in a position to utilise the possibilities directly, but they would be supportive of proposed developments in the fabric production industry to commercialise the concept (Taylor 2013).

Better than beige, but no rainbow?

A significant limitation of the system developed is that it is capable of providing only one colour, although the attractive colour and the level of performance offer exciting design possibilities leading towards fashion fabrics, and a process which offers significant advantages in terms of sustainability. Currently, in terms of colour variation it is possible only to vary shade depth through altering the number of passes across the fabric during screen printing, illustrated in Figure 2. Research is ongoing into extending the range of colours available, while taking due consideration of sustainability.

The research presented in this paper provides a foundation model that has been used to inform subsequent stages of ongoing research with the focus progressing on to the relationships between fibre, structure, colour and their use in the garment life-cycle. It explores the role that design can play in limiting environmental impact through life-cycle extension utilising a range of design practice concepts to address the environmental issues and evolving the design process in order to incorporate responsible, informed design decisions with production processes at the outset of a life-cycle.

It is envisaged that this focus on incorporating colour into life-cycle considerations and encouragement of designers to make informed, responsible design choices at the initial stages of development will impact positively on the environmental credentials of a textile products.

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Appendix B

Jeans can be hard enough to get on when they are made of cotton, so 'wooden denim' sounds like a torturous invention. Yet creator Dawn Ellams was working for the good of mankind when she created a pair of jeans using Tencel®, a sustainable wood fibre made by Lenzing AG. The PhD researcher at Heriot-Watt University believes her application could cut the carbon emissions of the global jeans industry. Manufacturing a pair of cotton jeans uses on average 42 litres of water and an array of harmful chemicals. Dawn's version have cotton-like qualities and are printed to look like denim: but only use one fifth of the water, energy and chemicals needed to manufacture more conventional jeans. Michael Kininmonth, Business Development Manager for Lenzing AG, thinks the idea could have a future: "Innovation is the life's blood of today's denim industry and there are strong environmental reasons why this production route, if honed, might have a chance of being adopted commercially."
www.hw.ac.uk, www.lenzing.com

Appendix C

KISCO

A.T.B Test Report

TO :

CLASSIFICATION : Reactive / printing

TESTER : Devin Han / Advanced Textile Business

TEST TITLE : **Reactive Printing**

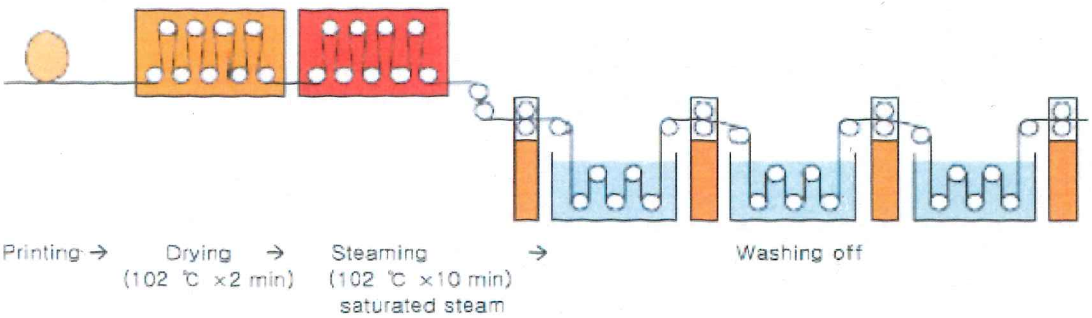
1. Dyestuff list

Synocron Yellow RD
Synocron Orange RD
Synocron Red RD
Synocron Deep Red RD
Synocron Rubine RD
Synocron Brill. Blue RD
Synocron Navy Blue RD
Synocron Black RD

2. Printing conditions

◎ Material : Cotton Knit, Tencel A 100, Modal, Standard Tencel

◎ Depth : 2/1, 1/1, 1/2 (40, 60, 80g/kg for Black RD)



	Chemical	Amount
Printing Paste	Synocron RD	X g
	Urea	150g
	Alginate Thickener	550g
	Reduction Inhibitor	10g
	Sodium Bi-carbonate	20g
	Balance(water)	Y g
	Total	1000g/kg

3. Test Result

Synocron Yellow RD

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
10g/kg	Tencel A 100	153	-3.61	3.46	2.3	3.68	-1.94	5.5	2.35
	Modal	81	-1.13	-0.5	-6.83	-6.22	-2.86	6.94	2.94
	ST'D Tencel	108	-1.83	1.07	-1.61	-0.9	-1.71	2.66	1.51

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
20g/kg	Tencel A 100	147	-4.23	4.11	-0.6	1.65	-3.81	5.93	3.49
	Modal	75	-1.01	-1.27	-7.73	-7.26	-2.94	7.9	3.24
	ST'D Tencel	97	-1.58	0.29	-3.41	-2.77	-2.01	3.77	1.91

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
40g/kg	Tencel A 100	109	-4.45	0.38	-6.52	-5.1	-4.08	7.9	4.22
	Modal	62	0.73	-3.95	-8.05	-8.87	-1.29	9	2.96
	ST'D Tencel	80	-1.45	-2.11	-6.8	-6.8	-2.13	7.27	2.83

Synocron Orange RD

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
7.5g/kg	Tencel A 100	238	-7.54	8.15	4.68	8.54	-3.92	12.05	5.38
	Modal	148	-3.3	4.08	2.68	4.52	-1.83	5.89	2.55
	ST'D Tencel	183	-5.41	6.26	3.38	6.37	-3.16	8.93	4.1

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
15g/kg	Tencel A 100	193	-7.91	6.57	-2.72	2	-6.82	10.63	6.74
	Modal	134	-3.53	3.08	-0.89	1.17	-2.98	4.77	2.97
	ST'D Tencel	153	-5.47	4.08	-1.88	1.03	-4.37	7.08	4.39

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
30g/kg	Tencel A 100	143	-8.13	3.15	-10.26	-5.39	-9.28	13.46	8.42
	Modal	106	-3.15	0.59	-5.24	-3.57	-3.87	6.14	3.58
	ST'D Tencel	116	-4.81	1.4	-6.9	-4.24	-5.63	8.53	5.15

Synocron Red RD

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
12.5g/kg	Tencel A 100	127	-3.41	-2.82	3.92	-1.7	4.52	5.91	3.18
	Modal	73	-0.02	-6.02	-4.94	-6.86	-3.68	7.79	3.22
	ST'D Tencel	95	-1.16	-3.34	-0.23	-3.3	0.54	3.54	1.36

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
25g/kg	Tencel A 100	111	-3.46	-5.51	0.47	-5.09	2.17	6.53	3
	Modal	69	0.61	-4.61	-6.36	-6.06	-4.99	7.87	3.74
	ST'D Tencel	90	-1.24	-4.25	-2.34	-4.74	-1.03	5.01	1.97

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
50g/kg	Tencel A 100	94	-2.42	-6.81	-3.73	-7.71	-0.93	8.13	3.37
	Modal	53	3.38	-3.44	-9.9	-6.27	-8.4	11.01	6.42
	ST'D Tencel	84	-0.25	-3.34	-4.52	-4.72	-3.05	5.63	2.71

Synocron Deep Red RD

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
10g/kg	Tencel A 100	169	-5.27	-1.93	5.3	0.35	5.63	7.72	4.53
	Modal	104	-1.76	-3.58	-0.45	-3.5	0.87	4.01	1.69
	ST'D Tencel	129	-3.15	-2.25	2.52	-1.12	3.19	4.62	2.66

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
20g/kg	Tencel A 100	144	-5.1	-4.92	0.42	-4.29	2.46	7.1	3.76
	Modal	91	-1.04	-4.54	-2.68	-5.23	-0.68	5.37	2.11
	ST'D Tencel	112	-2.7	-4.37	-0.89	-4.35	0.97	5.21	2.37

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
40g/kg	Tencel A 100	108	-3.99	-7.99	-5.04	-9.38	-1.08	10.25	4.63
	Modal	81	0.13	-4.53	-3.4	-5.55	-1.11	5.67	2.33
	ST'D Tencel	95	-2.07	-6.16	-3.91	-7.25	-0.84	7.59	3.23

Synocron Rubine RD

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
7.5g/kg	Tencel A 100	350	-11.98	4.59	10.88	7.2	9.36	16.82	8.91
	Modal	194	-7.22	1.59	5.41	2.68	4.96	9.16	4.88
	ST'D Tencel	250	-9.36	3.25	7.39	4.82	6.48	12.36	6.5

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
15g/kg	Tencel A 100	277	-9.68	-0.12	8.19	2.24	7.88	12.68	7.43
	Modal	152	-4.61	-1.57	3.67	-0.63	3.94	6.1	3.61
	ST'D Tencel	201	-7.02	-0.26	5.51	1.18	5.39	8.93	5.23

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
30g/kg	Tencel A 100	264	-10.4	-5.41	4.49	-3.81	5.91	12.58	7.53
	Modal	181	-6.31	-3.13	4.25	-1.76	4.97	8.22	5.09
	ST'D Tencel	222	-8.37	-3.52	4.62	-2	5.46	10.19	6.24

Synocron Brilliant Blue RD

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
20g/kg	Tencel A 100	169	-6.96	4.23	-0.38	1.25	4.06	8.16	4.7
	Modal	72	3.4	-2.25	4.22	-4.51	-1.59	5.87	2.79
	ST'D Tencel	121	-3.23	1.12	1.97	-1.73	1.46	3.94	2.12

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
40g/kg	Tencel A 100	158	-6.56	2.77	3.11	-2.3	3.47	7.77	4.7
	Modal	64	4.92	-3.93	4.16	-4.82	-3.08	7.54	4.13
	ST'D Tencel	108	-2.02	-0.97	4.25	-4.36	-0.01	4.8	2.12

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
80g/kg	Tencel A 100	130	-4.37	-1	6.43	-6.43	0.99	7.84	3.97
	Modal	49	8.46	-6.96	4.09	-5.58	-5.83	11.69	7.33
	ST'D Tencel	91	0.38	-3.29	4.62	-5.34	-1.91	5.68	2.55

Synocron Navy Blue RD
Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
20g/kg	Tencel A 100	159	-5.92	2.88	6.4	-6.93	1.09	9.18	6.67
	Modal	88	1.09	0.87	2.39	-2.54	0.12	2.77	1.94
	ST'D Tencel	115	-2.15	1.32	3.31	-3.55	0.3	4.16	2.96

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
40g/kg	Tencel A 100	142	-3.59	1.69	6.13	-6.3	0.85	7.3	6.12
	Modal	85	1.61	0.33	1.13	-1.18	0.13	2	1.78
	ST'D Tencel	107	-0.77	0.6	2.86	-2.92	0.09	3.02	2.44

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
80g/kg	Tencel A 100	120	-1.2	-0.3	2.93	-2.88	0.6	3.18	3.38
	Modal	89	1.11	-0.23	-0.27	0.22	-0.28	1.16	1.17
	ST'D Tencel	104	-0.07	-0.4	1.65	-1.7	-0.01	1.7	1.8

Synocron Black RD
Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
40g/kg	Tencel A 100	111	-0.54	0.37	1.53	-1.53	0.38	1.67	2.1
	Modal	79	2.66	-0.74	0.54	-0.3	-0.87	2.82	2.88
	ST'D Tencel	101	0.15	-0.22	1	-0.93	-0.41	1.03	1.32

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
60g/kg	Tencel A 100	104	0.09	-0.39	0.52	-0.65	0.07	0.66	0.91
	Modal	79	2.49	-0.94	-0.08	-0.24	-0.91	2.66	2.77
	ST'D Tencel	97	0.52	-0.67	0.11	-0.41	-0.55	0.86	1.09

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
80g/kg	Tencel A 100	101	0.37	-0.43	0.33	-0.54	0.09	0.66	0.84
	Modal	87	1.49	-0.66	0.29	-0.71	-0.11	1.66	1.77
	ST'D Tencel	97	0.61	-0.36	0.39	-0.49	0.2	0.81	0.95

Pantone Color Matching

Standard = Cotton Knit at D65

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
18-1856 TC	Tencel A 100	156	-5.19	-2.72	5.37	-1.1	5.92	7.94	4.35
	Modal	76	-0.31	-6.8	-3.59	-7.41	-2.04	7.69	2.93
	ST'D Tencel	113	-3.04	-4.14	0.85	-3.8	1.85	5.2	2.33

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
15-0953 TC	Tencel A 100	168	-7.67	-0.54	-2.83	-2.84	-0.52	8.19	3.43
	Modal	83	-1.45	-1.91	-7.49	-7.67	-0.96	7.87	2.88
	ST'D Tencel	115	-4.29	-2.39	-4.95	-5.47	0.48	6.97	2.69

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
19-3519 TC	Tencel A 100	158	-4.83	-5	3.81	-6.16	-1.24	7.93	5.48
	Modal	66	5.72	-1.45	3.24	-3.3	1.3	6.74	4.93
	ST'D Tencel	108	-0.5	-2.91	3.29	-4.38	0.17	4.42	2.84

	Ill/Obs	Strength	DL	Da	Db	DC	DH	DE	CMC DE
19-4125 TC	Tencel A 100	211	-9.69	3.19	3.98	-4.97	1.13	10.95	7.19
	Modal	90	0.99	1.51	2.09	-2.55	0.36	2.76	1.96
	ST'D Tencel	148	-5.33	1.84	2.32	-2.91	0.57	6.1	4.01

KISCO

SYNOCRON YELLOW RD SHADE

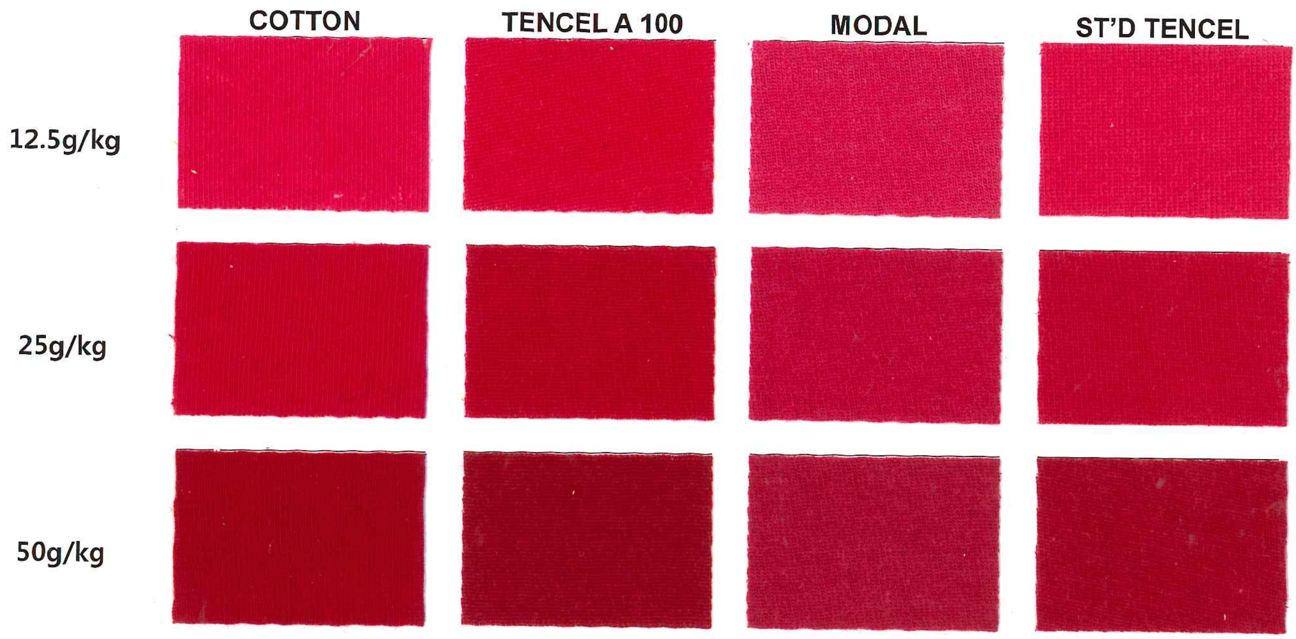
	COTTON	TENCEL A 100	MODAL	ST'D TENCEL
10g/kg				
20g/kg				
40g/kg				

SYNOCRON ORANGE RD SHADE

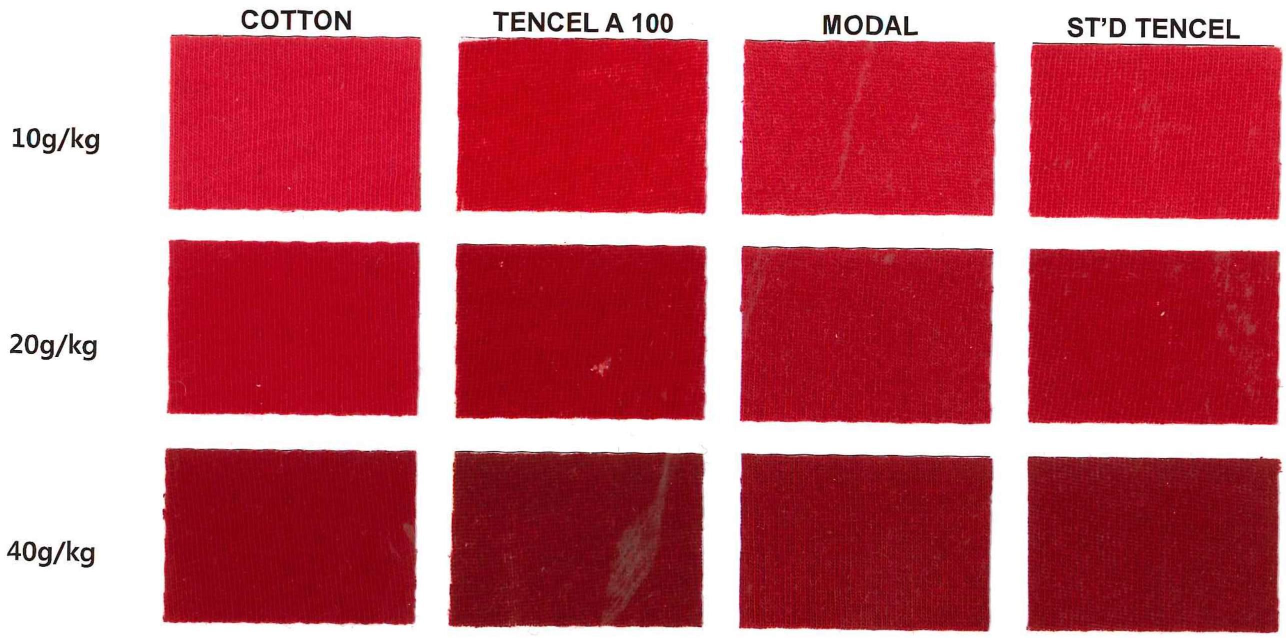
	COTTON	TENCEL A 100	MODAL	ST'D TENCEL
7.5g/kg				
15g/kg				
30g/kg				

KISCO

SYNOCRON RED RD SHADE

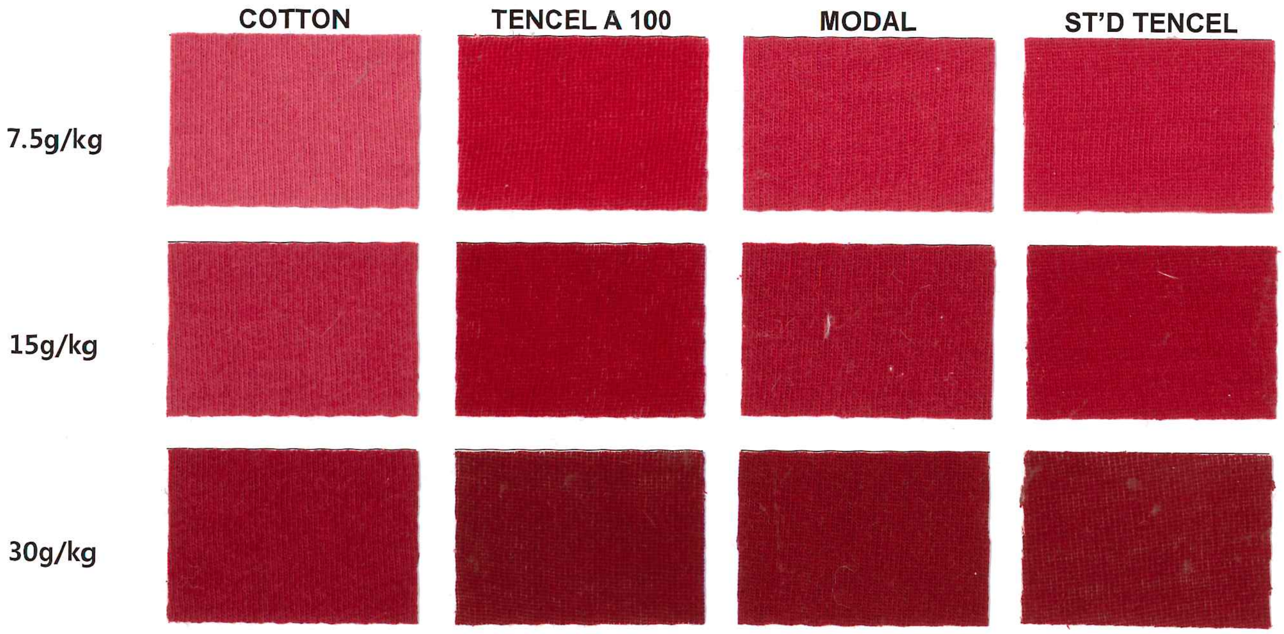


SYNOCRON DEEP RED RD SHADE

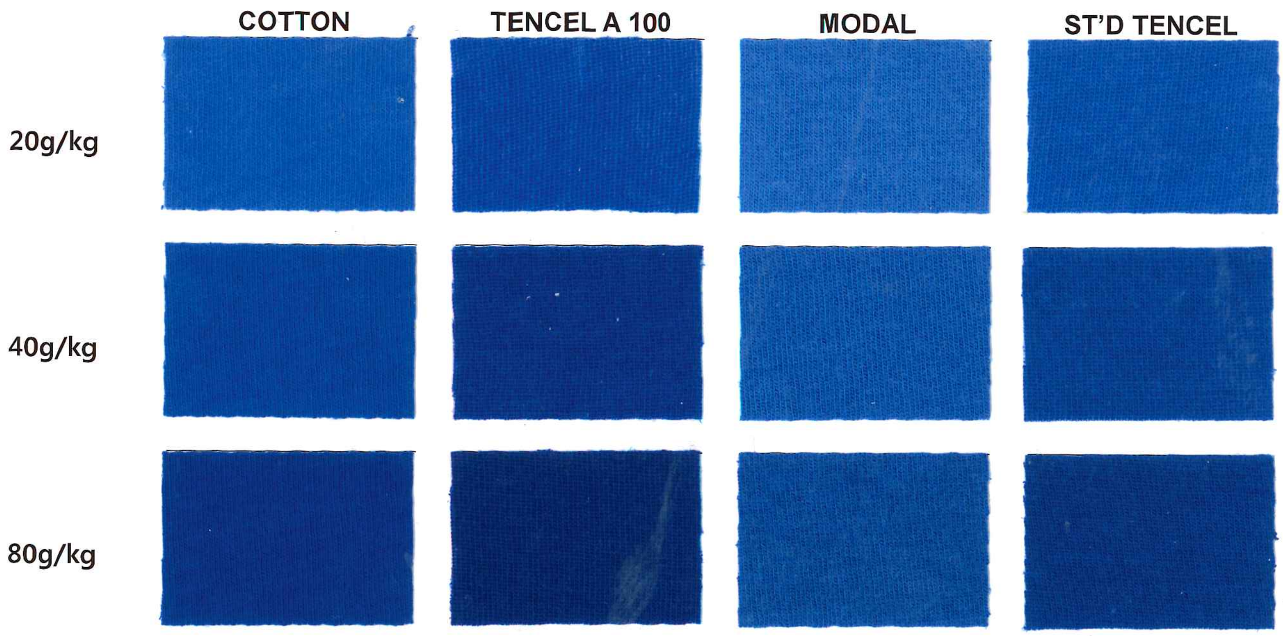


KISCO

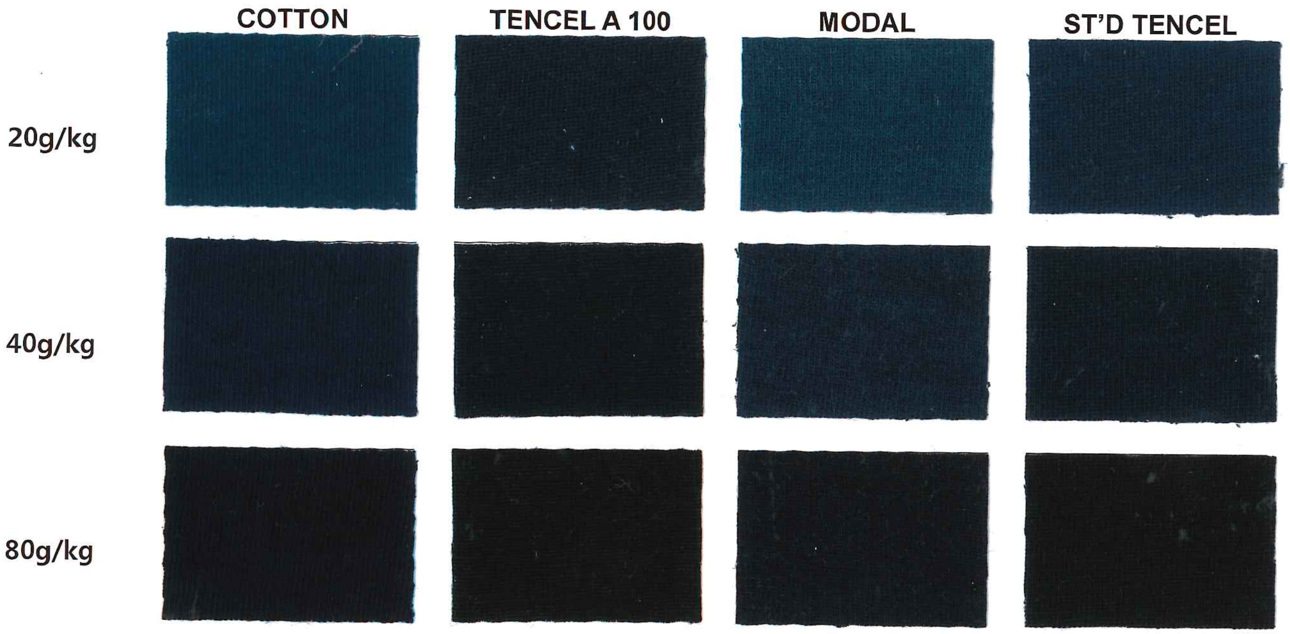
SYNOCRON RUBINE RD SHADE



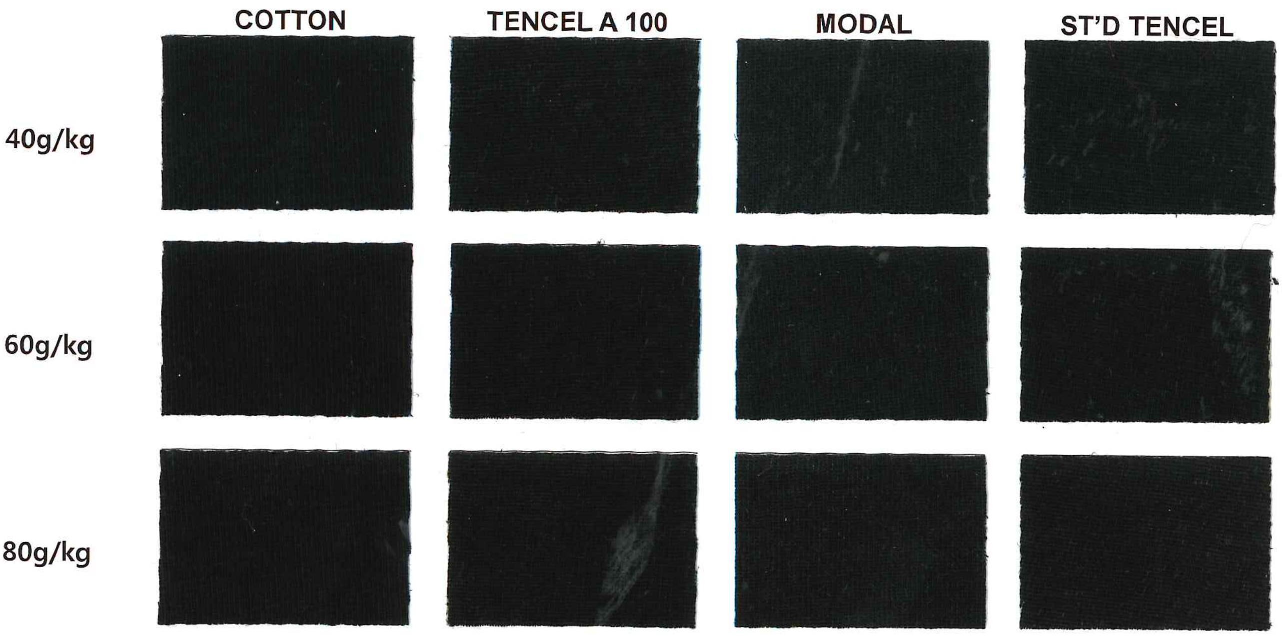
SYNOCRON BRILL. BLUE RD SHADE



SYNOCRON NAVY BLUE RD SHADE



SYNOCRON BLACK RD SHADE



PANTONE 19-3519 TC			
Synocron Yellow RD	2.6g/kg	Synocron Golden Yellow P-2R	3.3g/kg
Synocron Red RD	7.5g/kg	Synocron Red P-BN	13.4g/kg
Synocron Brilliant Blue RD	23.32g/kg	Synocron Blue P-3R	31.6g/kg
Total	33.3g/kg	Total	48.3g/kg

PANTONE 18-1856 TC			
Synocron Red RD	13.5g/kg	Synocron Red P-6B	7g/kg
Synocron Orange RD	0.5g/kg	Synocron Golden Yellow P-2R	1.7g/kg
Total	14g/kg	Synocron Red P-BN	10.8g/kg
		Total	19.5g/kg

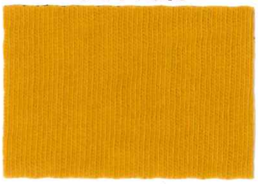
PANTONE 15-0953 TC			
Synocron Yellow RD	9.5g/kg	Synocron Golden Yellow P-2R	10.4g/kg
Synocron Brilliant Blue RD	0.6g/kg	Synocron Orange P-2R	0.6g/kg
Total	10.1g/kg	Synocron Blue P-5R	1.1g/kg
		Total	12.15g/kg

PANTONE 19-4125 TC			
Synocron Yellow RD	0.9g/kg	Synocron Golden Yellow P-2R	2.9g/kg
Synocron Rubine RD	0.7g/kg	Synocron Navy Blue P-2R	13g/kg
Synocron Navy Blue RD	11.4g/kg	Synocron Blue P-3R	25g/kg
Total	13g/kg	Total	40.9g/kg

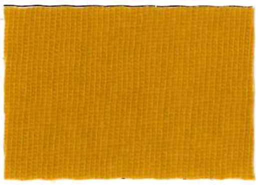
PANTONE COLOR MATCHING

PANTONE 15-0953 TC	
Synocron Yellow RD	9.5g/kg
Synocron Brilliant Blue RD	0.6g/kg

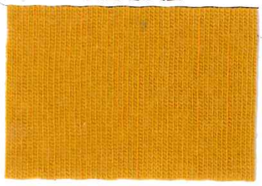
COTTON



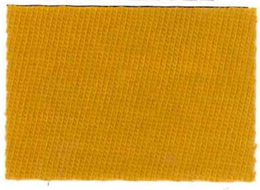
TENCEL A 100



MODAL



ST'D TENCEL



PANTONE 19-4125 TC	
Synocron Yellow RD	0.9g/kg
Synocron Rubine RD	0.7g/kg
Synocron Navy Blue RD	11.4g/kg

COTTON

TENCEL A 100

MODAL

ST'D TENCEL

DISCHARGE PRINTING

PANTONE
19-4125 TC

KISCO

PANTONE COLOR MATCHING

PANTONE 19-3519 TC	
Synocron Yellow RD	**2.6g/kg**
Synocron Red RD	**7.5g/kg**
Synocron Brilliant Blue RD	**23.2g/kg**

COTTON **TENCEL A 100** **MODAL** **ST'D TENCEL**

PANTONE 18-1856 TC	
Synocron Red RD	**13.5g/kg**
Synocron Orange RD	**0.5g/kg**

COTTON **TENCEL A 100** **MODAL** **ST'D TENCEL**

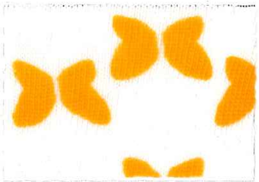
Test Report

1. Fastness Test

Back Staining

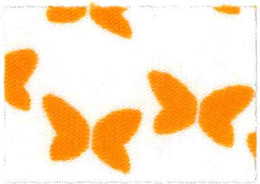
Cotton

Tencel A 100



Modal

Tencel Standard



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