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Digital laser-dye patterning for PET textiles

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Abstract

A 'Digital Laser Dye' (DLD) patterning process was studied as an alternative textile coloration method within a textile design context, relevant to industrial textile procedures. To steer the investigation, the research question asked: 'How can a digital laser-dye process be developed in order to achieve new ways to colour and pattern polyester textiles for industry?' Carbon Dioxide (CO_2) laser technology was employed to modify polyester (PET) surface fibres for increased dye uptake via engineered tonal graphics using standardized woven and knitted fabrics. An interdisciplinary framework employed to carry out the study involved Optical Engineering, Dyeing Chemistry, Textile Design and Industry Interaction through collaboration with project partners, Society of Dyers and Colourists (SDC). In doing so, combined creative, scientific and technical aspects facilitated design innovation using a 'mixed method' approach involving quantitative and qualitative methods. Repeatability of the research results, parallel to design development, has established the potential to commercially apply the technique regarding an on-demand manufacture approach. Sportswear and intimate apparel prototypes generated, suggest suitable markets for processing polyester garments in this way. The work is positioned in a practice-led, design research environment, approached from a textile design perspective as a practitioner. Therefore, a practice-led methodology was employed.

Textile coloration, CO_2 Laser Technology, Digital demand dyeing, Laser-dye patterning, Polyester fabrics, Interdisciplinarity

This research considers a digital dyeing technique termed 'Digital laser-dye'. The technique was explored as a new coloration method for textile design. As the term laser-dye suggests, the process involved laser technology and dyeing practices. Standardized polyester (PET) knitted jersey and plain woven fabrics were modified with CO_2 lasers in order to graphically engineer dye onto the fabric surface as well as sportswear garments and intimate apparel. Patterns were generated by combining CAD, laser technology and dye methods. As such, laser technology was investigated as a method to modify surface fibres for dyeing in order to generate tonally varied high-resolution patterns on to the textiles, defined as 'laser-dye patterning'. The work considered the aesthetic possibilities, production opportunities and ecological potential of the process as an innovative surface design technique for textiles.

The effects of laser modification on the coloration properties of some synthetic fibres have been identified in previous academic studies such as Shahidi, Wiener, & Ghoranneviss (2013), Nourbakhsh & Ebrahimi (2012), Bahtiyari (2011), Yip, Chan, Sin, & Lau (2002) and Kan (2008a & 2008b). In particular, polyester/PET and polyamide/PA materials that have been found to display improved dye uptake capability when modified by laser beam energy. However, knowledge is limited in terms of creative exploration of the research results. Additionally, previous work does not incorporate industrial standard procedures (ISO) towards the commercial potential of techniques established. The digital laser-dye process discussed in this paper therefore addressed textile design and production aspects by integrating creativity (coloration and surface patterning), experimental rigour (technical and scientific methods and parameters) and ISO measurement and analysis (industry standard testing).

An interdisciplinary approach was employed and positioned within the framework of Textile Design practice. Textile design practice was embarked on as a 'T-shaped' practitioner (Design Council 2010, p. 14) (Figure 1), to facilitate 'crossing over' from one distinct specialist area – Textile Design – into other disciplines including Chemistry and Optical Engineering together with Industry involvement.

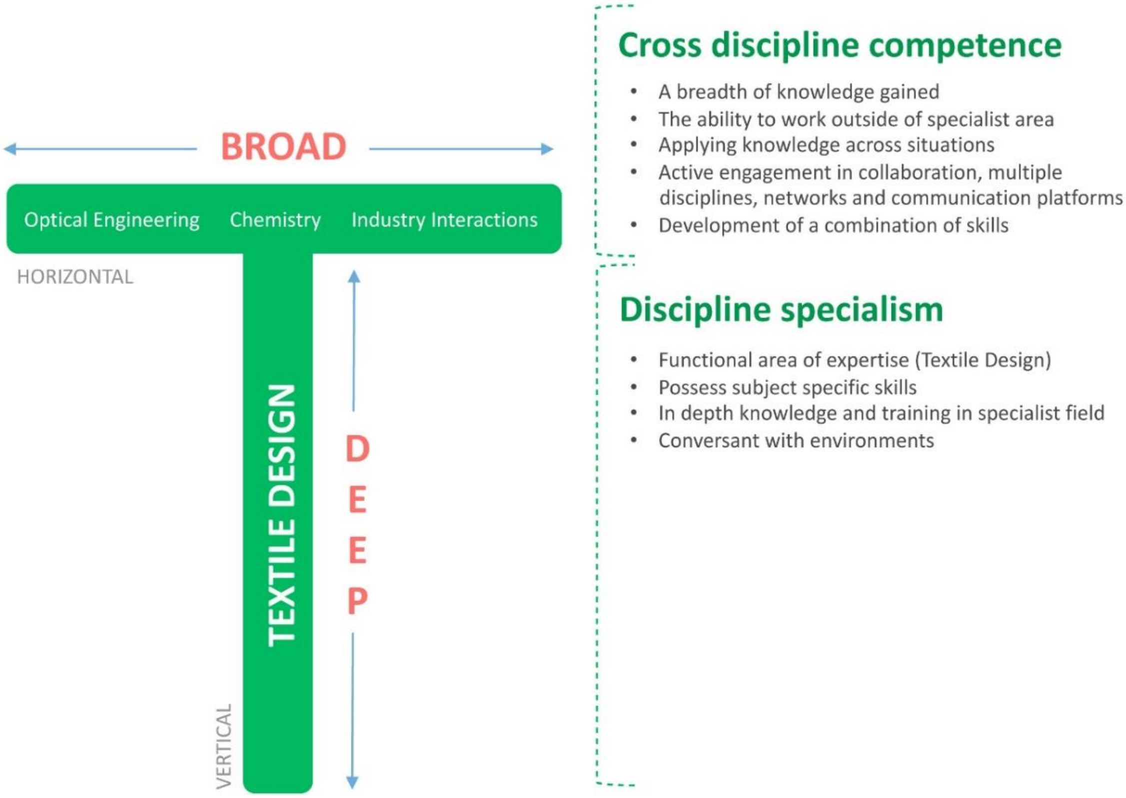


Figure 1: 'T-shaped' model used in this research

The purpose of this approach was to enable design innovation through the creation of novel surface effects with an ability to apply effects through ensuring repeatability and transferability in a way that is commercially relevant in terms of production. As such, these factors relate to controlled processing parameters in order to ensure reliable and consistent outcomes.

Through the approach taken, this research goes beyond current knowledge of laser-dye methods. It has enhanced design capability and commercial potential of combined laser/dye techniques through scientific understanding of the technology, experimental methods and procedures; commercial relevance of processes via industry involvement and integrated creative input from a textile design perspective. New knowledge generated by this work has led to an ability to control, specify and replicate novel surface effects as well as communicate the results through quantitative measurement and analysis and demonstrate the creative potential through textile/design collections and prototype garments and garment sections.

Background

Traditional textile design and coloration methods facilitate creativity when applying colour and pattern to fabric, as documented by Meller & Elffers (2002). Many textile designers and fabric producers embrace techniques based on conventions that are influenced by historical crafts, cultural references (Seivewright, 2007) and current technology. Long-established processes such as textile dyeing, print and pattern making combined with advanced technologies like digital inkjet printing and laser technology provide opportunities for experimentation and innovation (Bowles & Isaac, 2012, p.7; Clarke 2011, p.67; & Fish 2005, pp.81-90). This approach often leads to novel patterning for textile surfaces and new fabrication ideas. Laser technology in particular enables different effects to traditional and existing textile coloration/patterning techniques and production methods. Laser-dyeing explored in this research combined textile dyeing with CAD technology. In doing so, the work suggests a new digital patterning approach for synthetic (PET) textiles with dyes. An approach for precision dyeing with graphics has been established, not possible with conventional dyeing/coloration methods. Instead, the digital laser-dye process can be likened to digital textile ink-jet printing for example, based on the quality and intricacy of designs achievable due to the integration of CAD techniques. However, unlike digital printing whereby dyes sit on the textile surface, with laser-dyeing, the fibres are integrally dyed which was confirmed by carrying out microscopic analysis on treated fibres. This suggested the robustness of the process in terms of stable dye uptake, also supported by the results of ISO wash fastness tests carried out.

Conventionally, the coloration of synthetic textiles places high demand on resources in processing such as energy and water use involving solvents, as documented by Shamey & Shim (2011). Typically, polymers like PET are difficult to dye especially to yield deep/dark shades. Laser technology, as a method to modify surface fibres for improved dyeing is a low energy, dry and efficient approach that does not involve chemicals. This in turn promotes sustainability for textile manufacture. The technology is therefore considered environmentally beneficial – an aspect also raised by Yip et al. (2002, p.78), Shahidi et al. (2013, p.42) and Wong (2003, p.114).

From technical and scientific perspectives, current knowledge about laser modified textiles is centred around synthetic fibres regarding the effect on dyeing properties as investigated by

Yip et al. (2002); Kamel, Raslan, Helmy, & Al-Ashkar (2012); Bahtiyari (2011); Lau et al. (1997); Shahidi et al. (2013), for example. These polymer materials are preferable due to their affinity with laser irradiation – a reaction enabled by exposure to the beam changes the fibre/yarn structure, affecting the dyeability of laser treated surface fibres. Consequently, this results in deeper colour strength due to increased dye absorption.

The use of laser technology in textile design and manufacture to achieve a range of creative goals has increased in recent years (Gabzdyl, 2008, p.21-22 & Clarke, 2011, pp.106-107, pp.130-131). At present, it is mainly used to cut and mark a range of textile materials for aesthetic effect. Designers and manufacturers have adopted laser processes to produce innovative materials that display the capability of the technology as a creative tool. In the textile industry, denim fabrics represent the vast majority of laser-etched goods (Lockman & Clayson, 1996; Ondogan, Pamuk, Ondogan, & Ozguney, 2005). Laser cutting enables precise incisions with a variety of materials suitable for interior/exterior environments and the body, explored by Boontje (Clarke, 2011, pp.106-107) and Hur (Mix A/W 2010/11, p.22; Braddock Clarke & Harris, 2012, p.54), for example. This digital process facilitates repeatable effects and enables production speed due to digital automation. As such, laser material processing is considered efficient.

Within the textile design research communities, practitioners have used lasers to enhance the visual and tactile characteristics of cloth to create new structures and surfaces often by combining conventional textile techniques with laser processing. For example: Stoyel (1996; 1999) explored laser technology to manipulate synthetic and natural fabrics for decorative surface effects in the form of patterns and textures; Kane (2008a & 2008b) has generated unique surface effects by integrating laser technology and nonwoven materials; Addrison (2009a & 2009b) and Bartlett (2006) began to combine surface modification methods with wet techniques; Goldsworthy (2009) employed laser technology as a creative environmental alternative to finish polyester substrates; Matthews (2011) has developed novel laser processes to form three-dimensional textiles; Schlaepfer et al. (Clarke, 2011, pp.130-131) explored this technology as a tool for fine work to create laser embellished metalized fabrics; and Weedlun (2011) investigated laser-engraving techniques to create decorative dual colour appliqué textile designs.

Research problem: identifying and addressing gaps in current knowledge

Scientific and technical approaches rather than a design perspective currently dominate this laser/dye research area (Nourbakhsh & Ebrahimi, 2012; Kan, 2008a & 2008b). Investigation typically occurs in disciplines such as Textile Chemistry, Textile Engineering and Material Science, for example. In these research contexts, an inherent scientific language has led to sufficient know-how of common issues regarding experimental methods, materials, data handling and analysis. Investigation from within creative textile disciplines is apparent, demonstrated by Addrison (2009a & 2009b) and Bartlett (2006), but is less developed from a scientific or technical perspective. Therefore, design innovation and commercial relevance of a combined laser/dye process was limited in these studies. The potential was there but, the means to apply/extend/transfer techniques, methods, procedures and results is not evident. Although some creative insights are offered, artistic development through an in depth study of methods and techniques alongside consideration of commercial context were absent.

Both Addrison and Bartlett's work (2009a; 2009b, & 2006 respectively), reached a point that identified opportunities to achieve modified dye and pattern effects using the laser. However, the work was limited in terms of combining both creative and technical perspectives to achieve robust laser/dye processes for textile design and coloration development. In order to address such gap through this laser-dye study, the following research question together with an aim and objectives facilitated focused in depth experimentation and steered developments:

- **Research question***:* How can a digital laser-dye process be developed in order to achieve new ways to colour and pattern polyester textiles for industry?
- **Aim**: To establish a new digital laser-dye surface patterning method for textile design by investigating digital laser-dyeing as a transferable creative graphic approach for textile designing with dyes
- **Objectives**: To…
    1. explore a range of experimental parameters regarding fabric, laser machines/equipment and design aspects by employing different fabric structures, laser processing methods and design approaches involving CAD techniques;

2. embed industry standard (ISO) methods and procedures into experimentation as well as incorporate ISO measurement and analysis including wash fastness, colour assessment and textile performance testing;
3. identify the design possibilities of the process for specific markets by producing a specified range of prototypes that exploit the process in terms of textile design innovation and market potential; and
4. develop an awareness of the environmental aspects identified in existing studies regarding laser modified textiles for improved dyeability applicable to the digital laser-dye process in order to further understand the environmental advantages of processing fabric in this way.

This paper focuses mainly on objectives 1 and 3 in terms of the experimental methods, approach and results of the research discussed, demonstrating the interplay between disciplines – Textile Design; Dyeing Chemistry; Optical Engineering; and integrated Industry aspects of the work.

Methodology

A practice-led research methodology involving mixed methods (quantitative and qualitative), as discussed by Creswell (1994) was employed to carry out the digital laser-dye study discussed. An interdisciplinary approach undertaken describes the crossing over into different disciplines and departments within academia (Loughborough University) from the standpoint of a textile design practitioner. Collaboration in this work describes the partnership with an industry organisation, Society of Dyers and Colourists (SDC) that facilitated considerations for commercial potential of the digital laser-dye process. This framework facilitated the scientific, technical and creative aspects of the project, as explained in Table 1.

Table 1: Descriptions for the Scientific, Technical and Creative aspects of the research

Aspects of the research	Description
Scientific	Quantitative experimental methods, data handing (based on precision, mathematical or computational approaches), measurement and analysis involving methodological statistical procedures that can be repeated and graphically presented or explained; approaches include: structured experiments (relating to laser processing, CAD, dyeing and testing), ISO dyeing procedures, digital microscopy (fibre/surface analysis), colour assessment and ISO textile performance tests.
Technical	Experimentation involving a range of varied processing parameters required in order to explore laser-dye techniques attributed to laser machines and associated equipment (e.g. laser power meters), computer software: laser and CAD related, infrared dye machine/dye profiles and elements of fibre and colour analysis such as equipment, settings and computer software e.g. microscopes, reflectance spectrophotometry and ISO performance testing machines.
Creative	Design practice based on artistic input, encompassing discipline specific skills and an awareness of creative elements. This involved being experimentally engaged scientifically, technically and creatively as to identify and exploit opportunities presented by the laser-dye process from a textile design perspective by focusing on colour and pattern surface development; creative aspects represent a qualitative approach that embodies individual thought (intuition and tacit knowledge) and expression which aids design innovation.

Qualitative and quantitative 'mixed methods' outlined in Figure 2 assisted the creative focus of the inquiry centred on development of digital laser-dyeing techniques for textiles.

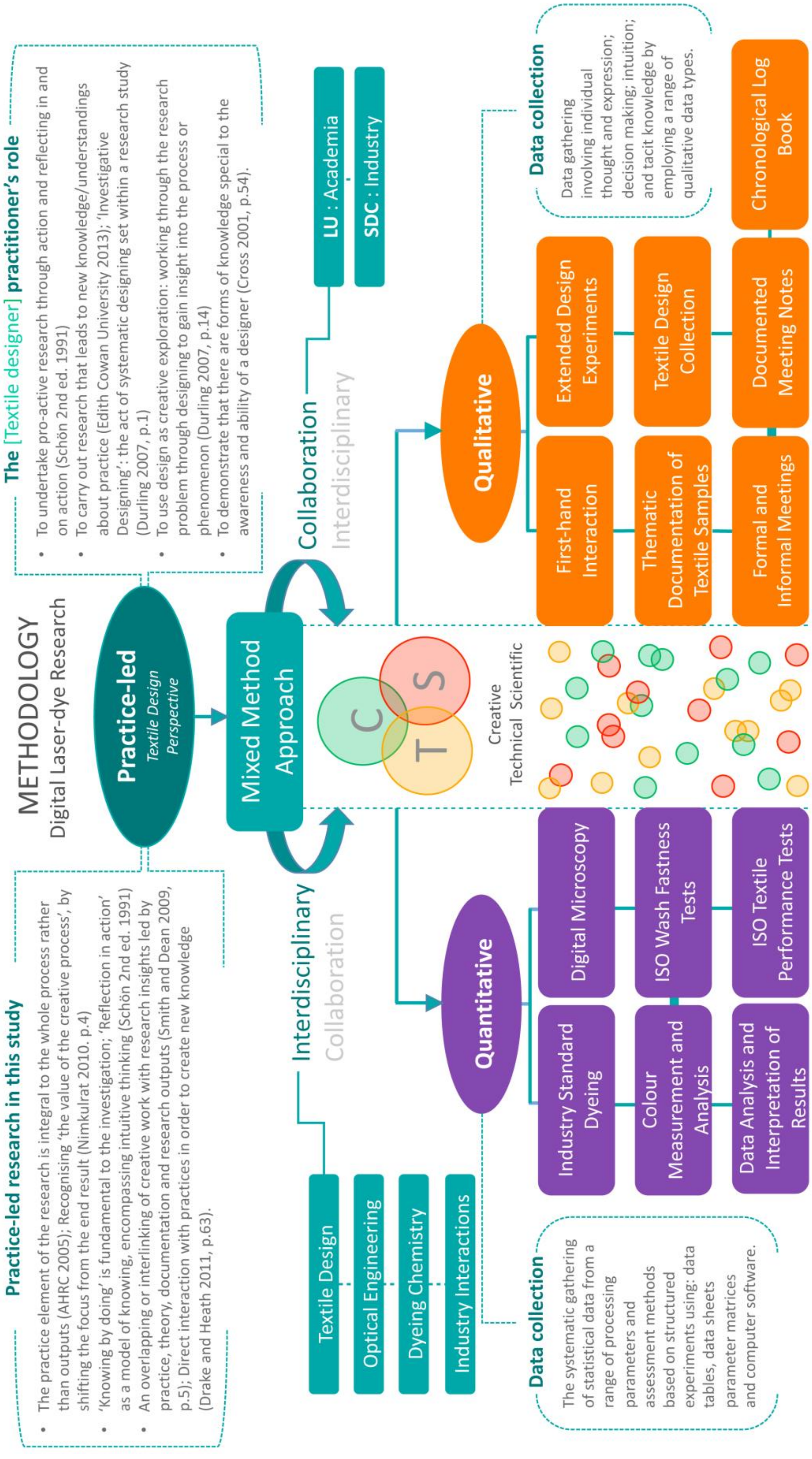


Figure 2: Practice-led methodology: a 'mixed method' research approach

Flow of work conducted using mixed methods

Figure 3 demonstrates the flow of work conducted in this research regarding the digital laser-dye process and in relation both qualitative and quantitative methods carried out. Three digital laser-dye approaches were identified and explored in this study – Fibre-laser (FL) involving the textile and laser only; Fibre-laser-dye (FLD) whereby fabrics were laser treated first then dyed; and Fibre-dye-laser which denotes fibres/fabrics were dyed first then laser modified. This work flow of the laser-dye process (Figure 3) outlines how practical work happened in terms of the sequence in which specific activities occurred corresponding with each of the approaches explored (FL; FLD; and FDL).

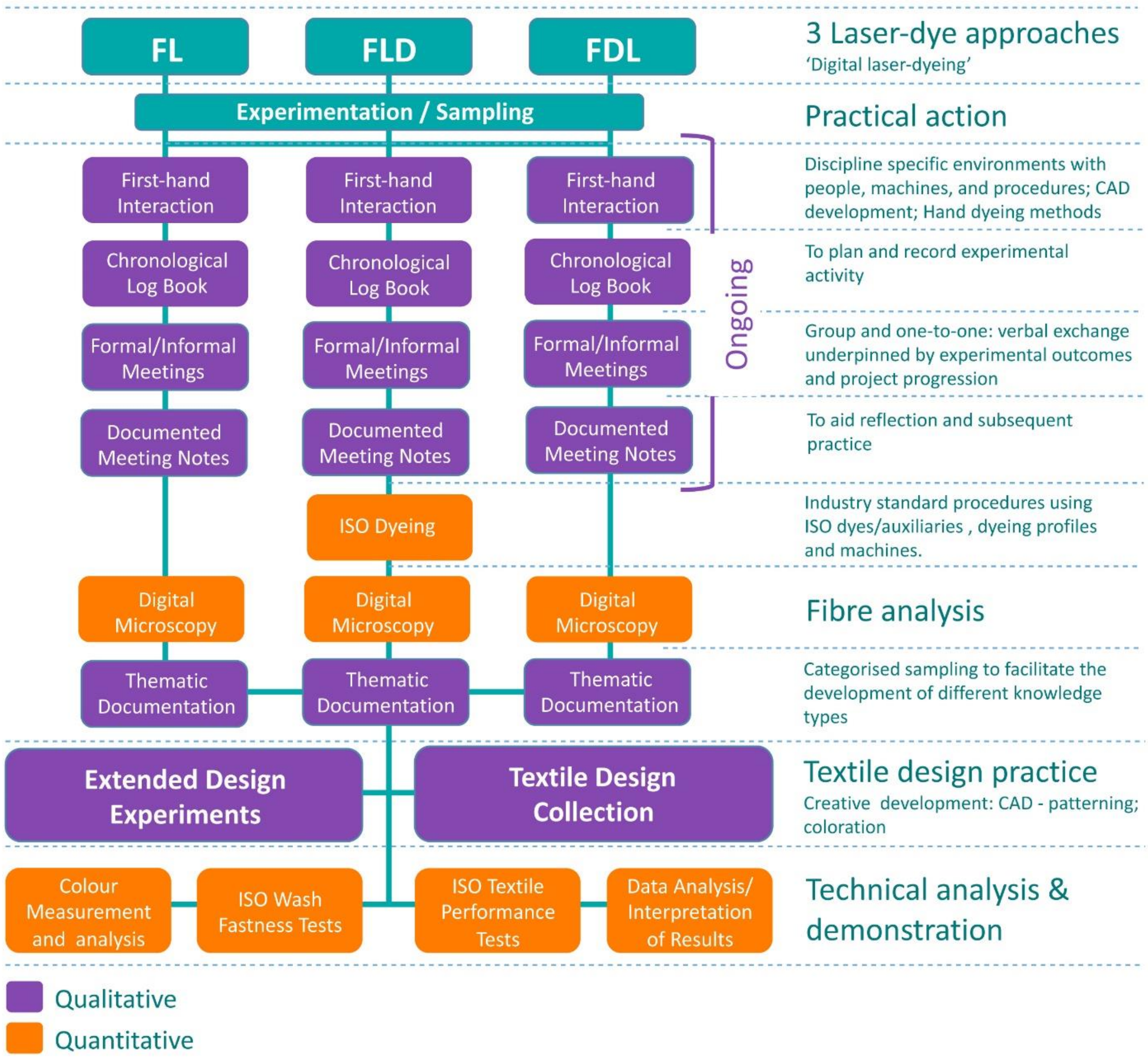


Figure 3: Flow of work using mixed methods

Experimental parameters, methods and approaches

A combination of parameters relating to fabrics, laser-processing methods, dyes, dyeing procedures and design aspects were explored. The work carried out enhanced design capability through scientific understanding and integrated creative input, and the ability to replicate effects goes some way towards commercial validation of Digital laser-dyeing (DLD) where production reliability is paramount.

Industry Standard specification fabrics

Table 2 outlines the ISO standardized specification PET fabrics employed.

Table 2: Textile fibres used for experimental sampling in this research

Fabric	Supplier	Composition	Construction
Polyester	*Society of Dyers and Colourists*	Polyester staple fibre (undyed)	**1/1/ Plain Weave**: Warp: 23,5 per cm, Weft 20,5 per cm; Yarn: Warp: 7,5tex Z 1000 X 2 S 800; R 15 tex, Weft: 20 tex S 800
Polyester	*Crystal Martin*	97% Polyester, 3% Elastine (piece dyed off-white)	**Single Jersey Knit**: 28 gauge, 17Dex 180 gm per sqm2; 57 courses, – 3cm, 49 wales – 3cm

Standardization ensured consistency between each fabric batch and individual test samples in relation to their unique specification data regarding fibre composition and textile construction.

Carbon Dioxide (CO_2) lasers used in this study

Table 3 sets out the lasers machines employed. Figures 4-5 show the two main types employed.

Table 3: CO^2 Lasers used in this research

CO^2 Laser system	Power (W)	Computer Software	Machine location (Dpt.)
Laser bed *(Flat bed cutter used for etching in this study)* The laser is directed around the bed by a nozzle; the nozzle is taken to the location where the textile is taped into position on the bed	58	APS-Ethos	School of the Arts
Synrad laser marker A galvanometer mirror driven system used for etching textiles in this study; the beam is directed by oscillating mirrors	10	Winmark Pro	Wolfson School of Mechanical and Manufacturing Engineering
Synrad laser marker A galvanometer mirror driven system used for etching textiles in this study; the beam is directed by oscillating mirrors	60	WinMark Pro	Wolfson School of Mechanical and Manufacturing Engineering

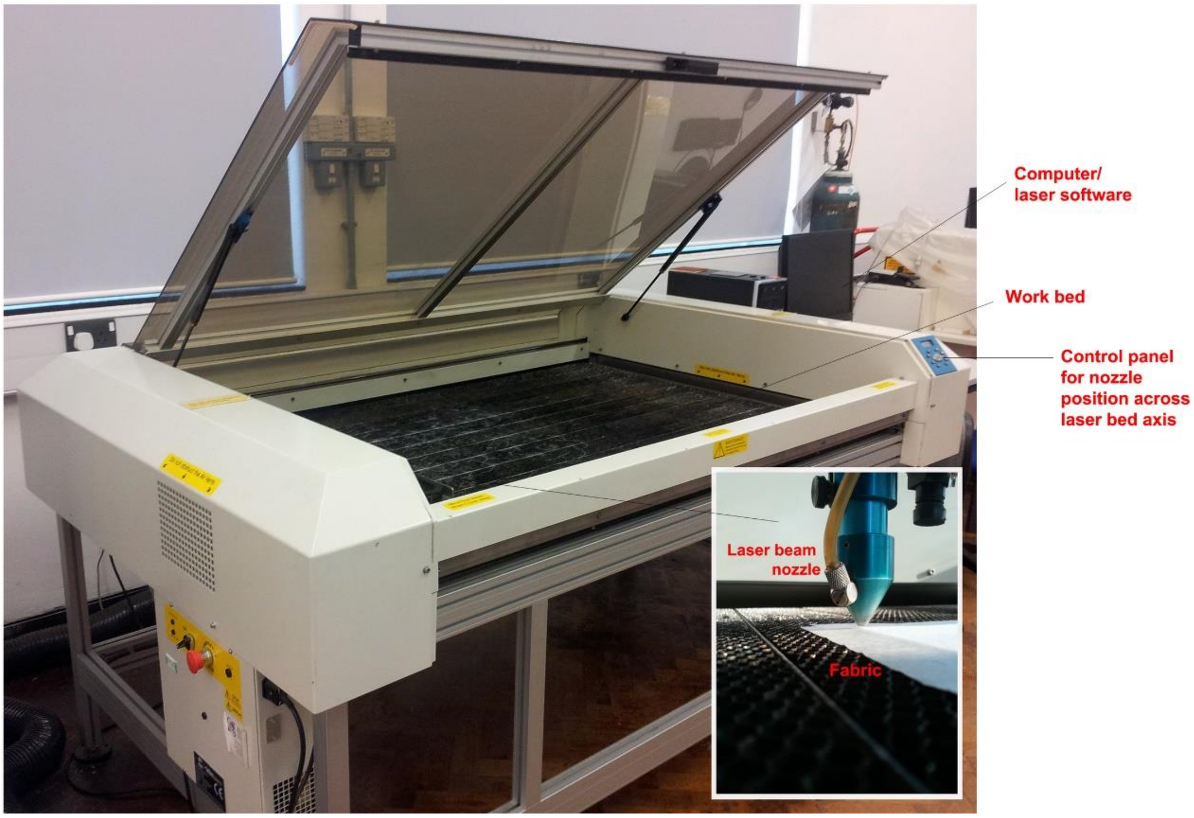


Figure 4: 58W CO2 Laser bed system

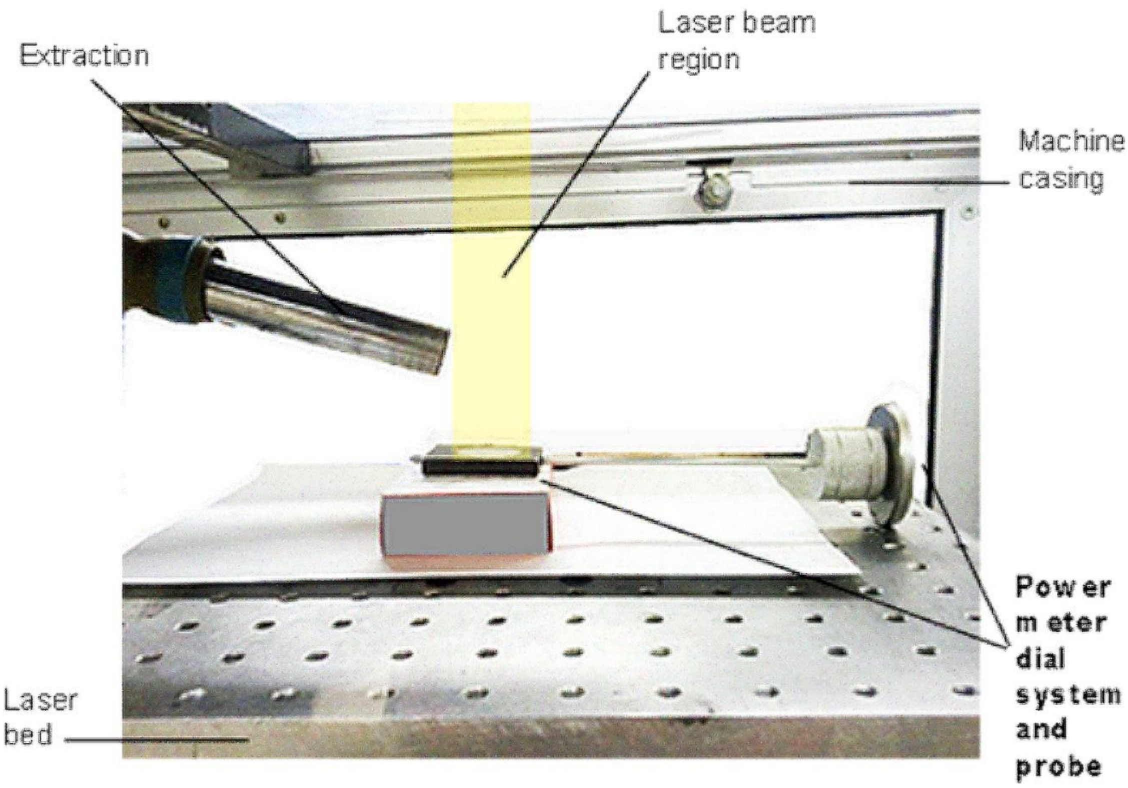


Figure 5: CO2 Synrad 10W laser marker system – measuring laser power output

Laser textile processing: defining energy density in this study

The experimental results discussed in this paper are based on an approach that has been termed ‘energy density’. This refers to the amount of power or joules/units of laser energy transferred to the fabric surface per cm^2 via beam delivery, represented as J/cm2. Figure 6 sets out equation used to calculate energy density relevant to laser treated textile samples. Actual energy output released from the laser nozzle was used to modify fibre with different levels of laser surface treatment. To achieve specific laser-dye effects, energy parameters were investigated by employing controlled technical procedures with the laser in relation the scientific chemical/physical structural changes of the fibre. Interactions between laser beam energy and textile fibres were studied as a way of generating tonally varied dye uptake on the textile surface in the form of high resolution patterns that depict sharp graphic qualities and well-defined forms enabled by CAD technology. The overarching purpose of this approach was to identify the creative opportunities of the process in a way that was commercially relevant in terms of reproducibility - an important factor for industrial development of the DLD process.

$$\text{Total energy (J)}^{[1]} = \text{Power (watts)}^{[2]} \times \text{Time (sec)}^{[3]}$$

$$\text{Energy density (J/cm}^2)^{[5]} = \frac{\text{Total amount of energy (J)}}{\text{Laser treated area (cm}^2)^{[4]}}$$

1 Total Energy
UNIT MEASUREMENT
A unit of energy in Joules

2 Power
LASER SETTING
Refers to operational power attributed to the laser machine or a percentage of operational power by selecting a value (1-100%) via laser computer software

3 Time
VELOCITY SETTING
The speed/time taken for the laser beam to scan an area/design (cm2) in seconds

4 Laser treated area (cm2)
SIZE OF DESIGN/SPACE
The size of the processing area. This alters the time taken (sec) and energy density (J/cm2) between designs/effects in relation to the size of the design or sample and the level of detail and intricacy embedded into a CAD file. However, once specified, time/velocity and laser power settings remain constant and are not affected by the above mentioned factors.

5 Energy Density
ACTUAL ENERGY USAGE PER DESIGN
This calculation provides the specific amount of energy used to process an effect, design or pattern – a known value based on operational/percentage of selected power (watts), the processing time taken (sec) and the size of the laser scanned area (cm2). This value aids repeatability and transferability of the laser-dye process. Once known, the value can be reapplied or employed to use for different CO2 lasers with different operational power, in order to achieve replicable outcomes.

Figure 6: Energy density equation

Actual power output was measured using a digital laser power meter – 0-10W Coherent LM10 Probe. This ensured accuracy when identifying and maintaining optimal processing energy to modify fabrics according to specific parameters and repeatable effects regarding patterning, dye uptake and controlled surface treatment.

Energy density was identified as a quantifiable method to calibrate laser power against levels of colour i.e. tones. An ability to know, understand and manipulate energy output and distribution when processing a piece of fabric was fundamental to the digital laser-dye process. This concerned raster and vector beam scanning approaches investigated (later discussed in this paper). A mechanical know-how of methods enabled even, level dye uptake making it possible to create a range of tonal densities using a single dye colour in a way that could be repeated or altered by specification. Energy density provided a 'common language' and quantifiable procedure for a digital laser-dye process in order to achieve controlled, repeatable tonal colour range and pattern precision.

Laser patterning methods

Digital laser-dyed patterns were formed with multiple dye shades generating a tonally varied shade depth spectrum using a single dye. High-resolution capability of the laser beam spot when modifying textile fibres facilitated patterning likened to 'dots-per-inch', as in digital printing processes. Two approaches were explored in this research – vector and raster laser beam scanning. *Adobe Photoshop* and *Illustrator* CAD software were used to create files and *APS-Ethos* and *Winmark Pro* software was used for laser processing.

Vector beam scanning method

Using a vector method, consistent beam scanning in relation to a specified grid pattern was enabled. Linear vector grids were generated to provide a 'blueprint' path to direct beam movement different to a raster method that performs an automated beam scanning motion. Vector lines were created using *Adobe Illustrator* CAD software compatible with the laser software.

Beam spot size was accounted for when applying a vector approach for laser processing. It was therefore possible to control beam overlap during scanning in order to determine even dye uptake on the textile surface. Level surface modification such as this is not always achievable with a beam overlap tendency in raster processing and can be difficult to avoid.

The consistent distance between repeated lines in a vector grid influenced energy density. Distances less than the beam width diameter activated beam overlap causing greater fibre/laser interaction and deeper dyeing as the fibre was modified twice, creating a visible undesired streaking effect. Larger gaps discouraged this effect reducing interaction and encouraging weaker dye uptake. Subtler surface effects occurred due to reduced energy density. Therefore, a method for plotting energy density against tonal density was identified and a correlation between line space distance and colour intensity was understood. This knowledge facilitated calibration values between vector line space distance (mm), total energy (J) and energy density (J/cm^2).

By specifying incremental vector grid variables, a relatively extensive tonal range from a single dye was produced. Results therefore suggest that a vector approach demonstrates a finely tuned affinity to the DLD process regarding tonal capability, identified in this study.

Raster beam scanning method

By employing a raster beam scanning method, this approach facilitated imported CAD files in the form of high-resolution shapes, patterns and designs etc. from *Adobe Photoshop* to the laser computer software for processing. In order to modify the PET textiles, a series of closely spaced parallel beam scans interacted with surface fibres by 'filling' a predetermined area of the fabric in a continuous vertical zigzag motion.

Digital greyscale (GS) features linked to both CAD and laser software facilitated image depiction and variable modification levels to the textile surface. A greyscale design approach was explored in the development of graphics and engineered repeat patterns were initiated by combining CAD data with creative authority in the form of percentages of black (GS %) e.g. 50%, 70%, and so on. GS% influenced energy density and as such, this technique facilitated controlled variable power output in laser processing. When combined with specified laser parameters, this system determined differential dye uptake based on variable fibre modification linked to grey data.

Greyscale CAD designs were converted to a halftone image via laser software for raster scanning. Each GS% generated a unique halftone pattern altering the energy density and power output of the laser beam during processing. Varied fibre modification levels were enabled using this technique and an understanding of actual power output in relation to digital design information (i.e. GS%) and processing parameters such as energy in watts, velocity, spot size etc., made it possible to digitally calibrate data to produce repeatable effects. Sufficient knowledge of the DLD process meant that the outcomes could be manipulated to alter surface treatment, colour appearance and patterning effects.

Industry standard dyeing: dyes and procedures

ISO *Itosperse* disperse dyes were adopted for this research consisting of shades: Yellow 3G; Yellow Brown SERL 150%; Rubine CGL 150%; Red 2BE 200%; Blue 3RL 150%; and Navy CD2G 200%. In this paper, fabric samples dyed with Blue 3RL 150% are presented and discussed.

Dry laser modified fabrics were dyed using ISO dyeing procedures. Dye baths were prepared from a 0.4% aqueous stock solution at a 1:9 dye/water ratio to achieve a 1% shade. In addition, 0.5% shade depths were also explored in this research. Deionised water was used to eliminate impurities. Auxiliary agents from a 0.4% stock solution were added to aid dye-to-fibre permeation at 0.5% on the weight of fabric. The pH acidity of each bath was maintained at 4.5 to ensure dye stability in terms of colourfastness.

Dyeing was carried out using a *Coloursmith* infrared dyeing machine. This machine type is routinely used in industry dye-houses for sample dyeing. It is a low-liquor, controllable system capable of dyeing polyester at high temperatures. The machine-facilitated batch dyeing, therefore multiple samples were dyed simultaneously in separate beakers.

In this research, a high temperature dyeing method was explored, in line with commercial requirements for the coloration of PET textiles. An industry standard cycle for dyeing polyester was employed (Table 4) reaching a maximum temperature of 140ºC. The dye bath and fabric sample were added to a beaker. Multiple beakers were then loaded inside the machine.

Table 4: Polyester dye cycle used with infrared dye machine

PROGRAM No 2	PROGRAM NAME - SDC POLY				
ROTATION				REVERSAL TIME	
Anti Clockwise		Clockwise		Anti Clockwise	Clockwise
ON	20 RPM	ON	20 RPM	5 Minutes	5 Minutes

STEP No	**TARGET TEMP ºC**	RATE OF **RISE º/MIN**	DWELL **MIN & SECS**	MESSAGE	STATUS
1	50	7.0	05.00		OFF
2	80	1.5	10.00		OFF
3	140	0.8	59.59		OFF
4	80	7.0	02.00		OFF
5	40	2.0	10.00	END	ON
6					OFF
7					OFF
8					OFF
9					OFF
10					OFF

After dyeing, samples were rinsed in hot water and a reduction clearing after treatment was carried out. This procedure removed any unabsorbed dye by heating the fabric in 500mls of water containing 2g of Sodium Hydrosulphite and 2g of Sodium Hydroxide, compliant with ISO methods. The mixture was raised to 80ºC and constantly stirred for 45 minutes - 1 hour. Afterwards, the sample was rinsed thoroughly in cold water until no trace of residual dye was found.

Textile design development: patterning

A combination of hand drawn material and CAD methods were used to formulate digital patterns towards final designs. *Adobe Photoshop* and *Adobe Illustrator* computer design software assisted this development. Computer graphics were interpreted via laser beam or spot to enable image creation with dyes. An ability to digitally generate and manipulate imagery as a textile designer specialising in print and surface pattern aided the designing stage. Tonal capability of the laser-process enhanced the appearance of patterns through an ability to achieve subtle, dramatic or gradient shifts and shade depths on the cloth surface. Dye/colour was imperative to the DLD process, primarily concerned with the coloration of laser modified textile fibres via graphic methods.

Results and discussion

By employing a linear vector grid method, a ‘colour chart’ of 25 shade depths was generated using disperse dye Blue 3RL 150% (Figure 7). Each tone represented a different grid pattern, as illustrated in Figure 6, for example. Incremental differences to line spacing per grid begun with a distance of 0.2mm/Vector grid 1, increasing by 0.01mm through to 0.44mm/Vector grid 25. This system determined variable energy density, also achievable with different dye shades.

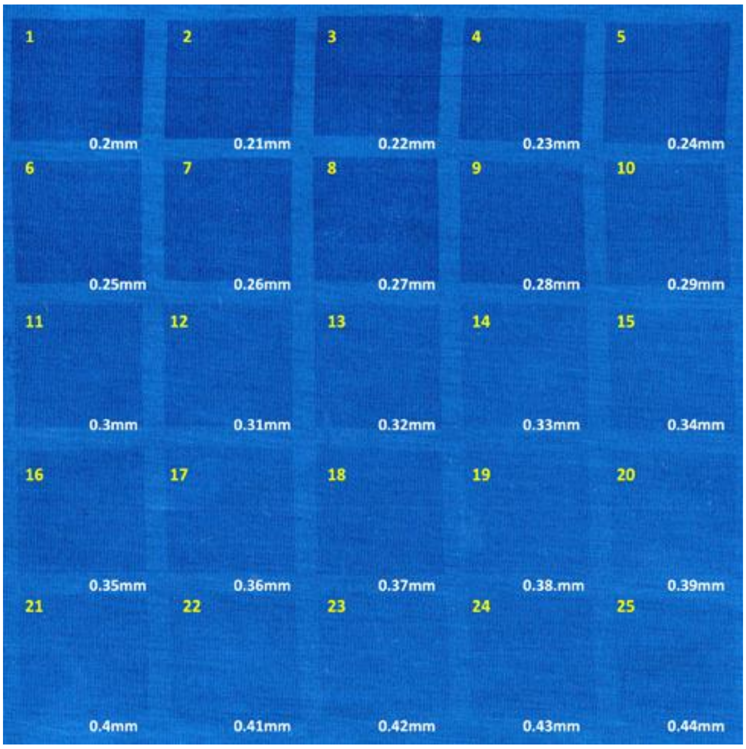


Figure 7: Laser-dyed tonal colour chart: knitted polyester fabric sample

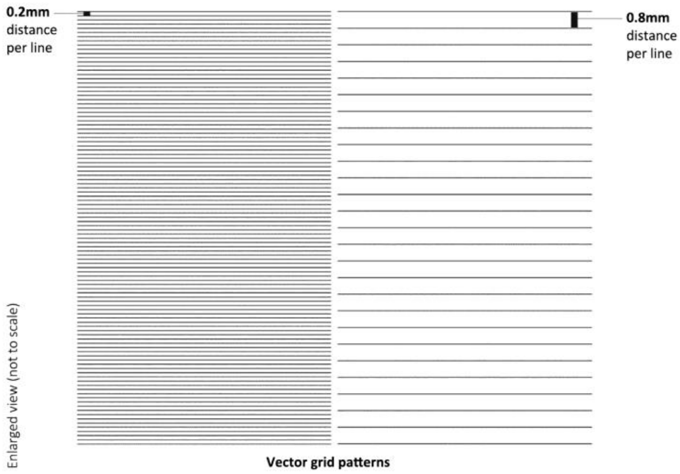


Figure 8: Vector generated linear grid patterns

A line spacing distance of 0.3mm/Vector grid 11, matched the optimum focal beam diameter (also 0.3mm) for modifying polyester fabric, as investigated in this study. Within these parameters, Beam overlap was avoided, as demonstrated in Figure 9. Instead, energy output was evenly distributed across the textile surface during the scanning process. Alternatively, 0.21mm/Vector grid 2 for example, had a distance less than 0.3mm. This relationship between beam and vector grid lines induced deeper dyeing due to greater fibre/laser interaction attributed to beam overlap. Significant spacing such as 0.43mm/Vector grid 24 reduced interaction as the laser beam scanned the fabric less due to larger gaps between individual vector lines. Here, overall energy density was reduced producing subtler surface effects linked to limited modification and consequently reduced dye uptake.

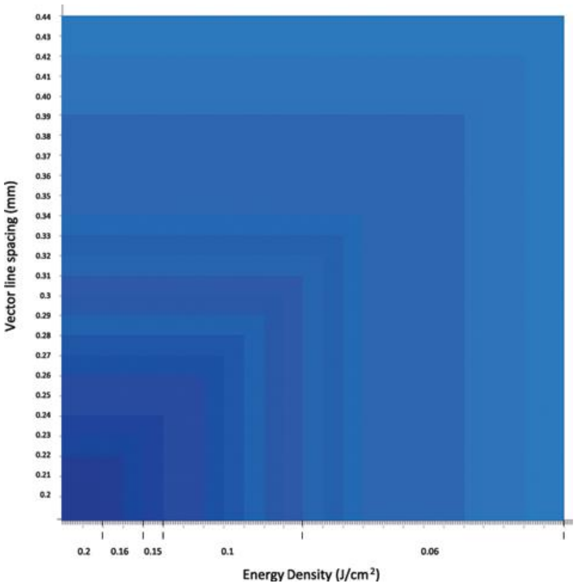
Figure 9: Diagram showing the position of a 0.3mm laser line vector grid

Table 5 shows the calibration values attributed to the fabric colour chart (Figure 7) in relation to the laser processing parameters explored based on 4.5W of beam energy. Vector line space (mm), Total energy (J) and Energy density (J/cm^2) values are given in relation to each digital laser-dyed area.

Table 5: Calibration values

Grid	Vector line space (mm)	Total energy (J)	Energy density (J/cm^2)
1	0.2	1.8	0.2
2	0.21	1.8	0.2
3	0.22	1.4	0.16 (0.2)
4	0.23	1.4	0.16 (0.2)
5	0.24	1.4	0.15 (0.2)
6	0.25	0.9	0.1
7	0.26	0.9	0.1
8	0.27	0.9	0.1
9	0.28	0.9	0.1
10	0.29	0.9	0.1
11	**0.3**	**0.9**	**0.1**
12	0.31	0.9	0.1
13	0.32	0.5	0.06 (0.1)
14	0.33	0.5	0.06 (0.1)
15	0.34	0.5	0.06 (0.1)
16	0.35	0.5	0.06 (0.1)
17	0.36	0.5	0.06 (0.1)
18	0.37	0.5	0.06 (0.1)
19	0.38	0.5	0.06 (0.1)
20	0.39	0.5	0.06 (0.1)
21	0.4	0.5	0.06 (0.1)
22	0.41	0.5	0.06 (0.1)
23	0.42	0.5	0.06 (0.1)
24	0.43	0.5	0.06 (0.1)
25	0.44	0.5	0.06 (0.1)

The overall trend shows energy density values declined from grid 1-25. The rate of change reflected marginal changes in line distance. It is therefore acknowledged that tonal variance was largely dependent on vector line spacing due differences in laser power output between grid patterns. When referring to the fabric colour chart, tonal density decreases as line spacing distance increases. The greatest difference in energy density was recorded between vector grids 1 and 25, which can be understood. Colour data was configured both visually and numerically demonstrating the relationship between a specific vector grid, tonal density and energy density (Figures 10 and 11).



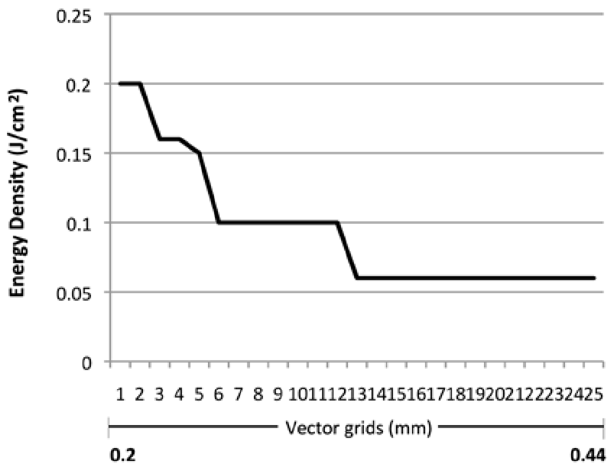


Figure 10: (Left) Colour configured data: Energy density/Vector line spacing parameters; Figure 11: (Right) Diagram showing an energy density decline as line spacing increases per vector grid

Levels of colour defined by energy density were employed in order to build an image with variable tones. A greyscale raster approach enabled the creation of graphics for textile patterning using a digital laser-dye process. Grey percentages (GS %) were used to generate engineered repeat patterns. These patterns were translated creatively and quantitatively by combining design and technical data. CAD files, seen in Figure 12, determined the energy density required to achieve specific tonal effects (Figure 13), also linked to other laser processing parameters such as actual output power, based on a specific halftone pattern (Figure 12) and velocity.

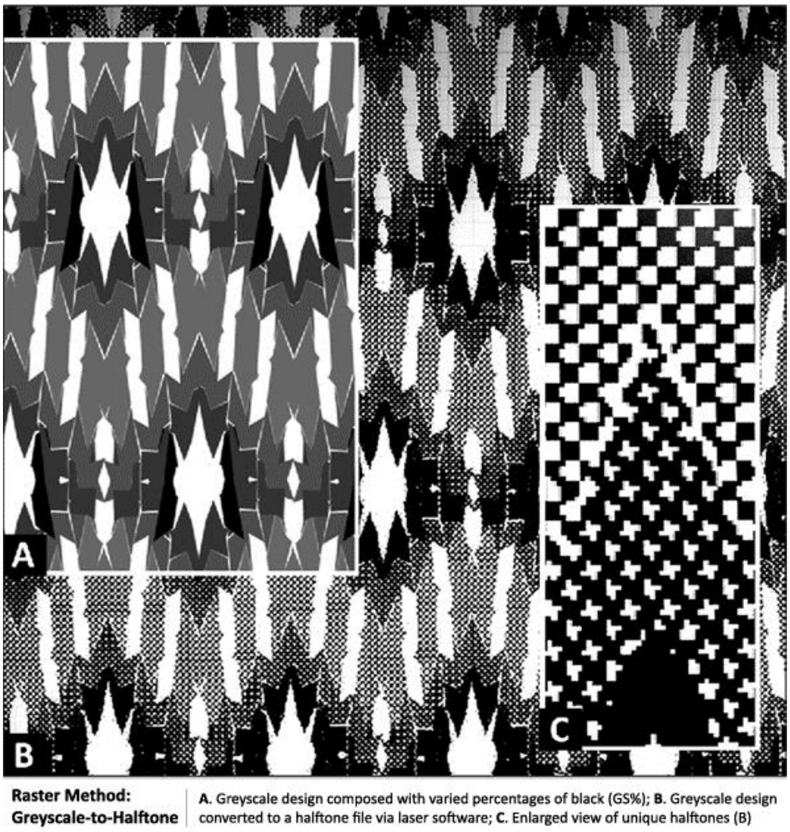


Figure 12: Digital design file containing a range of grey tones (GS %)

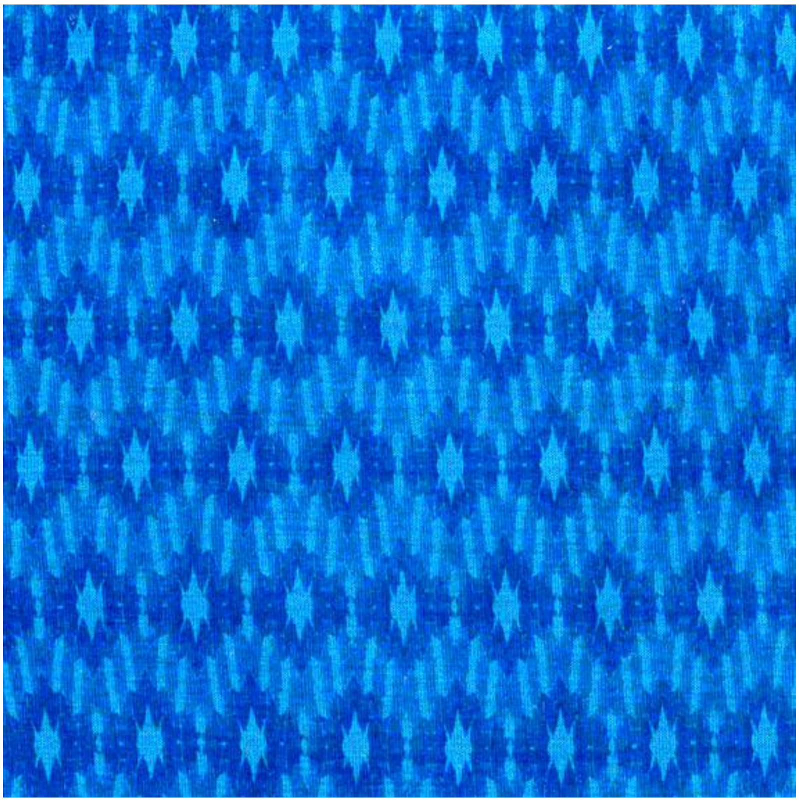


Figure 13: Digital laser-dyed knitted polyester textile sample

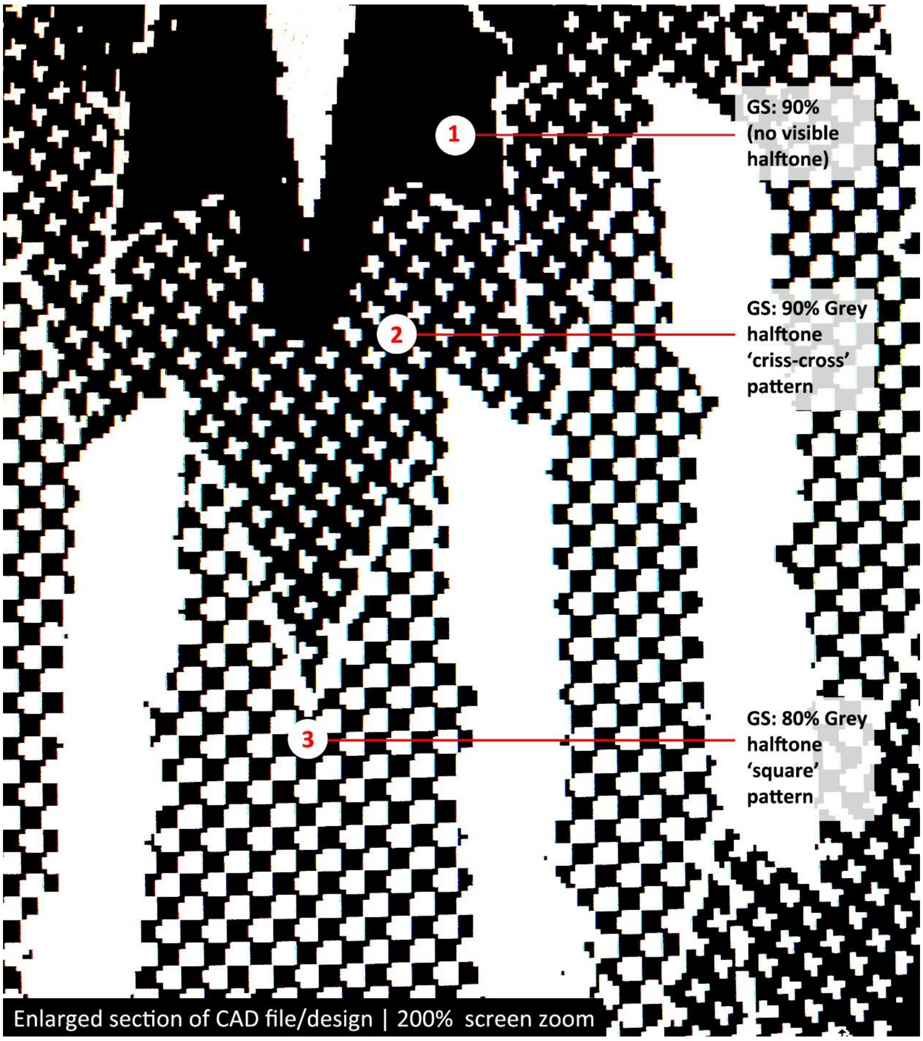


Figure 14: Halftone reduction CAD file showing pixelated grids based on different GS% in a pattern

Experimentation presented opportunities for processing finished garments (Figures 15 and 16). The laser beam was able to scan across seams, stitching and three-dimensional forms whilst retaining high-resolution graphic qualities and tonal definition. This is not achievable with conventional image-based coloration approaches on to finished garments. With digital printing processes, the flat fabric is printed by the metre and the garment is constructed after printing and fixing the dye to the fabric. In screen-printing, the bulkiness of a finished garment when laid flat interferes with application and evenness of the print due to an irregular surface. Garment dyeing typically involves total submersion of the item in a dye vat or equivalent container. These approaches do not facilitate patterning, focusing on coloration of the whole garment in a single even shade to achieve a uniform distribution of dye colour. As such, this work proposes a DLD system for textiles relevant to industrial manufacture and commercial goods.

Figure 15: Digital laser-dyed finished garments including 3D clothing (construction and surface)

Figure 16: Digital laser-dyed sports bra tops

Industry Standard (ISO) wash fastness tests

ISO wash fastness tests were carried out on laser-dyed and untreated fabrics samples for comparison. After washing, ‘Change in colour’ and ‘Assessment of staining’ were recorded. Results obtained provided summative data about the robustness of a laser-dye process explored relevant to conventional dyeing methods. Such information enabled further understanding about the potential of the process for commercial use. In consultation with the SDC, it was agreed fabric samples dyed with shade depth less than 1% would not undergo after-treatment post dyeing as such process would affect the shade and appearance of colour. Therefore, these results implied loose dye particles remained on the fabric (represented by a rating of *3-4*, Table 6) limiting wash fastness, which is understood. Overall, results indicate stability of the laser-dye process explored in this study, represented by a rating of *5* (highest) or *4* (Table 6). Outcomes therefore suggest as a textile coloration approach, digital laser-dyeing is technically robust in terms of wash fastness.

Table 6: Wash fastness results table

		Sample		Change in Colour	Assessment of Staining: Acetate	Cotton	Nylon 6.6	Polyester	Acrylic	Wool
		DES 1 / COLL1: DRK BLUE/PUR								
C1:S1	1	**1**	Not Trtd - 1% Shade	4-5	5	5	4-5	5	5	5
	2	**2**	GS: 70% - 1% Shade	4-5	5	5	4-5	5	5	5
	3	**3**	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
	4	**4**	Not Trtd - 0.5% Shade	4-5	5	5	4-5	5	5	5
	5	**5**	Patterned - 0.5% Shade	4-5	4	4-5	3-4	4	4-5	5
		DES 5 / COLL1: AUBERGINE								
C1:S2	6	**1**	Not Trtd - 1% Shade	4-5	5	5	4-5	5	5	5
	7	**2**	GS: 70% - 1% Shade	4-5	5	5	4-5	5	5	5
	8	**3**	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
		DES 3 / COLL1: LT. ORNG/YELL								
C1:S3	9	**1**	Not Trtd - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
	10	**2**	GS: 70% - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
	11	**3**	GS: 100% - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
	12	**4**	Patterned - 1% Shade	4-5	4-5	4-5	4	4-5	4-5	4-5
		DES 4 / COLL1: GREY-GREEN								
C1:S4	13	**1**	Not Trtd - 1% Shade	4-5	5	5	4-5	5	5	5
	14	**2**	GS: 70% - 1% Shade	4-5	5	5	4-5	5	5	5
	15	**3**	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
		DES 1 / COLL2: BLUE								
C2:S5	16	**1**	Not Trtd - 1% Shade	4-5	5	4-5	4-5	4-5	5	5
	17	**2**	GS: 70% - 1% Shade	4-5*	5	5	4-5	4-5	5	5
	18	**3**	GS: 100% - 1% Shade	4-5**	5	5	4-5	5	5	5
	19	**4**	Patterned - 1% Shade	4-5	5	5	4-5	5	5	5
		DES 5 / COLL2: RED								
C2:S6	20	**1**	Not Trtd - 1% Shade	4-5	5	5	5	5	5	5
	21	**2**	GS: 70% - 1% Shade	4-5	5	5	5	5	5	5
	22	**3**	GS: 100% - 1% Shade	4-5	5	5	5	5	5	5
	23	**4**	Patterned - 1% Shade	4-5	5	5	5	5	5	5
		DES 2 / COLL2: MAGENTA								
C2:S7	24	**1**	Not Trtd - 1% Shade	4-5	4-5	5	4-5	5	5	5
	25	**2**	GS: 70% - 1% Shade	4-5	4-5	5	4-5	5	5	5
	26	**3**	Patterned - 1% Shade	4-5	4-5	5	4-5	5	5	5
	27	**4**	Not Trtd - 0.5% Shade	4-5	4-5	5	4-5	5	5	5
	28	**5**	Patterned - 0.5% Shade	4-5	3-4	4-5	3-4	4	4-5	4-5
		DES 3 / COLL2: GREEN								
C2:S8	29	**1**	Not Trtd - 1% Shade	4-5	5	5	5	5	5	5
	30	**2**	GS: 70% - 1% Shade	4-5	5	5	5	5	5	5
		DES 3 / COLL1: RED								
C3:S9	31	**1**	Patterned - 1% Shade	4-5	4-5	5	5	5	5	5
	32	**2**	Patterned - 0.5% Shade	4-5	4	4-5*	4	4-5	5	5
		DES 4 / COLL2: PURPLE								
C3:S10	33	**1**	Not Trtd - 1% Shade	4-5	5	5	5	5	5	5
	34	**2**	GS: 70% - 1% Shade	4-5	5	5	5	5	5	5
	35	**3**	Patterned - 1% Shade	4-5	5	5	5	5	5	5
		DES 3 / COLL2: GREEN								
C3:S11	36	**1**	GS: 100% - 1% Shade	4-5	4-5	5	4-5	5	5	5
	37	**2**	Patterned - 1% Shade	4-5	4-5	5	*4-5	5	5	5
	38	**3**	Not Trtd - 0.5% Shade	4-5	4-5	5	4-5	5	5	5
	39	**4**	Patterned - 0.5% Shade	4-5	4-5	5	4-5	5	5	5

Ratings	
(orange)	5
(green)	4-5
(red)	4
(yellow)	3-4

Key	
Red	Industry Standard assessment are
*/**	No official assessment for result
C:S	Cycle:Set

Conclusion and further work to be undertaken

Digital laser-dyeing (DLD) explored in this study involved laser technology, CAD methods and dyeing. This research assisted the development of textile coloration and patterning for PET textile materials. Knitted and woven fabrics as well as sportswear garments were studied. The interdisciplinary nature of the investigation facilitated textile design and apparel development. A range of processing parameters were investigated enabling different design possibilities in relation to the fabric structure. A controlled experimental approach not only facilitated new creative effects, but aided variants of an outcome, achieved through adjusting individual parameters. This design flexibility further supports the on demand and customization potential of the process. In doing so, the research presented and discussed in this paper has contributed new knowledge to the fields of laser material processing, textile engineering, textile coloration, textile design/CAD technology and apparel manufacture by:

- Establishing a system for laser-dyed textiles, termed 'digital laser-dye', to enable tonally varied dye uptake with high-resolution graphics based on an energy density approach;

- Establishing digital laser-dyeing as a commercially relevant laser-dye patterning tool for textiles through industry standard (ISO) procedures, colour measurement and analysis and textile performance testing;

- Suggesting new ways to process finished garments by applying colour and pattern using the digital laser-dye process; and

- Demonstrating the design potential of the digital laser-dye process.

Quantitative procedures identified in this study including an energy density method, calibration systems, laser processing parameters, colour assessment and so on supports the transferability of information, results and practices involved. For example, colour data (graphs, charts, tables and diagrams) may be considered a type of 'know-how guide' and model for laser processing textiles in this way. Scientific approaches adopted enable communication and application of the digital laser-dye process in different environments, particularly relevant to commercial situations significant to this research. As such, an ability to replicate effects and achieve consistent results has been achieved. This work therefore demonstrates a rigorous laser-dye approach explored with PET textiles, also relevant to the coloration and patterning development of other fibres, textile structures, dye types and shades.

Further work aims to advance the design potential of the DLD process in terms of pattern and colour development in relation to garment finishing opportunities. It will also aim to extend eco capability of a laser-dye process integrating ecological assessment in practice, based on low water utilization and low energy processing factors in addition to functionality with regard to textile performance. Therefore, the technology may be seen as an ecological alternative to traditional textile patterning techniques. An ability to achieve deep dyeing with digital laser-dyeing suggests the potential to reduce high temperatures at which synthetic PET fabrics are conventionally dyed. This could potentially reduce energy consumption and negate the demand for additional chemicals used in printing processes, for example. These considerations are also acknowledged in previous work in this research field.

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