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Carbon Dioxide Laser as a Sustainable Method for Producing a Pattern on Denim Fabric: Evaluation of Colour and Durability

Venkatraman PD*
Manchester Fashion Institute, Faculty of Arts and Humanities, Manchester Metropolitan University, Cavendish Street, Manchester, UK

***Corresponding author:** Prabhuraj D. Venkatraman, Manchester Fashion Institute, Faculty of Arts and Humanities, Manchester Metropolitan University, Cavendish Street, M15 6BG Manchester, UK

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Abstract

Laser treatment of denim fabrics was demonstrated as one of the methods of producing distressed effects and is continuing to attract textile and fashion designers to develop bespoke designs that appeal to all age groups. Two dark shaded indigo-dyed 100% cotton twill fabric with varying weights representing various garment applications were laser treated using a commercially available pulsed CO_2 laser of wavelength 10.62µm. Pulses per inch, which is the degree of closeness of laser irradiation, was maintained at 300 and 400 PPI. Treated denim fabrics were evaluated for tensile strength, colour measurements, including colour hue (H), saturation (S), brightness (B), reflectance, K/S (colour yield), CIE L* a* b*, fabric thickness and colourfastness after wash.

Results indicated that colour contrast of denim fabric enhanced with the increase in grayscale (tone density) for both the LW (lightweight) and HW (heavyweight) fabrics, mainly at lower laser speed (80%) and higher laser power (40%). At higher grayscale (30% GS), surface fibers charred due to laser and the oxidation of cellulose occurred, causing a distinct yellow tone compared to pristine denim. Fabric tensile strength was affected as grayscale and laser parameters increased, the variation from pristine denim for LW fabric was 40 - 45% at 30% GS, whilst for HW fabric, variation was 25-30%. Colourfastness tests revealed limited colour staining, and it removed charred fibers showing a distinct tone change. This research recommends a combination of fabric and laser parameters to produce patterns without affecting the overall quality of the fabric.

Keywords: Denim fabric; CO_2 laser; Colour change assessments; Tensile strength and colour fastness

Introduction

Denim fabric is a popular material for jeans and casual wear [1] and the market for denim fabric is expected to increase by $105 billion by 2023 from $90 billion in 2019 [2]. Approximately 300 denim mills Worldwide produce 6.4 billion meters of fabric, which could reach 8.2 billion meters by 2021 [3]. Due to the rise in awareness among consumers, the demand for innovation in a sustainable, ethically, and environmentally friendly process [1] is rising. Cotton fibre remains the preferred fibre for making denim jeans, and the finishing of denim is the essential aspect to suit consumers' needs. Indigo dye traditionally used in the dyeing of denim fabric (*Indigofera tinctorial* plant species) is insoluble in water. It is a vat dye, which provides a brilliant blue hue to the cotton fabric has low colour fastness [4], has a limited affinity to cellulose fibers [5], and it has to be reduced with chemicals to ensure the dye penetrates the fibers. However, synthetic indigo dyes (such as sulphur dyes) are common nowadays due to their better dye affinity to cotton fibers [4]. Traditional denim fabric is durable that has dyed warp yarns interlaced with undyed weft yarns, which has a distinct diagonal line due to warp yarn lifting over or remaining under two or more weft yarns.

Consumers look for some critical aspects when purchasing denim wear: colour/shade, fit, comfort, and finish - distressed or faded jeans. Hence, the finishing of denim is essential to suit consumer demands, and it can be classified as dry and wet finishing. Due to regulatory changes, and increased demand for eco-friendly denim wear [6], several initiatives (yarn dyeing, garment finishing, and use of organic fibers) have been carried out to make denim wear environmentally friendly [7]. Development of surface patterns or decoration or to increase aesthetic appearance is popular globally among all ages, particularly distressed, or faded denim or light washed for men's and women's wear [6]. Various finishing techniques enable to produce worn out, faded, or distressed effects, where the dyes are removed or fabrics are abraded or cut. Typical examples of dry finishing include – stone wash, whisker effect, grinding, ripping, etc [8]. Many of these processes are harmful to health, requiring several processing stages, time-consuming and arduous.

Problems with mechanical processing of developing faded denim are high and pose severe health hazards during denim fabric's surface abrading [8]. Sandblasting (uses sand containing silica) potentially causes silicosis or lung cancer; potassium permanganate spray used to produce colour change can damage the respiratory system; hand scrapping (flying lint, dyes) is another potential health hazard [8,9]. Therefore, conventional denim processing has a negative impact on

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the environment. Several water-free denim processing technologies have been attempted to counteract these adverse effects, including plasma treatment that produces distressed or faded denim by affecting the dye molecules, ozone treatment (fabric bleached with ozone gas), and enzyme finish. Although these processes have some advantages in reducing water consumption, energy, chemicals, laser processing remains an ideal tool for producing colour fading with good evenness and accurate reproduction [10]. The possibility of developing subtle tonal effects and intricate design patterns or cuts on denim using laser is growing, attracting several designers, and has become a future of denim finishing [11]. Laser systems in textiles use raster marking where laser beam moves in rows successively to produce the marking using a laser beam [12]. The laser beam removes the dye or degrades the fabric surface [13] and produces a localized burning effect on the surface when using a CO_2 laser [14].

Various studies have reported the use of laser in apparel for manufacturing [13], fading [15-18], improve appearance [43], changes in the seam properties [44], and producing patterns on denim fabric [19]. Laser application was reported as a cleaner production process for denim processing [17] due to its low hazard, saving energy and time, reducing various processes, and being chemical-free. When using different laser beams, Nd:YAG at 532nm was noted to produce the best effect, and CO_2 laser affected textile fibers and produced a distinct effect on the fabric [20]. Much similar to the above, a study that compared three different types of laser beams (Nd:YAG laser 1064nm; CTH: YAG laser 2.09μm; and CO_2 laser 10.6μm) indicated pulsed CO_2 had a high efficiency, where dimensional shrinkage and tearing strength of laser-treated denim fabrics were not affected. The colourfastness of treated samples revealed that colour change was minimal and that little or no colour transfer was observed [15]. The durability of the fabrics is vital during usage; hence fabric properties such as tensile and tearing strength have been reported. Laser treated denim fabric produced differences in tensile strength, particularly in warp and weft directions [21]. This was attributed to the direction of the laser beam falling on the fabric surface. Owing to these developments, researchers studied various laser variations or equipment to produce surface effects as the process was environmentally friendly compared to conventional methods [17]. Some studies [17,22,23] reported the effect of laser treatment on denim fabrics using pixel time and dots per inch (dpi) as one of the main parameters determining the colour contrast difference between pristine denim and treated denim and affecting other physical properties of the fabric.

Interestingly, when using laser on polyester or polyamide fabrics, increased surface roughness and dye adsorption [24] were noted. Although surface motifs to enhance the appearance of polyester fabrics were also observed at 50dpi and 180μs, any increase in laser parameters melted the fabric [25]. Modification of surface morphology of the fabric structure was of interest to many when applying laser beam. An increase in wetting time (s) of the laser-treated bleached cotton samples were noted when compared to the raw cotton treated sample. Wetting time was zero for bleached cotton laser-treated fabric compared to raw samples [26]. This was attributed to an increase in the porosity of fabric due to fibre loss and the formation of the cellular structure due to laser resulting in increased wetting. In addition, denim treated fabrics, when washed, can produce back staining during denim washing, where removed indigo dye can redeposit on the fabric surface affecting the appearance of the fabric [27].

Some of the shortcomings of previous studies are that most have used higher laser parameters which could affect the durability or performance of the fabrics (that could modify the fabric texture, causing difficulty in handling the fabric during manufacturing or consumer use). Other shortcomings can be limited to one fabric type, use of different equipment, or lack of comparison with different fabric densities or a combination of the above parameters resulting in heterogeneous literature. In this study, we report the application of CO_2 laser at a low laser power to create changes in the shade without compromising the fabric properties. Such a comprehensive assessment will serve as a tool for various professionals who apply laser for surface modification, decoration or fading, particularly for lightweight fabrics (shirts, tops, blouses) and heavyweight fabrics (trousers, jackets).

Objectives of the research

Laser patterning using a commercially available CO_2 laser was used to identify a set of laser parameters for developing a pattern using indigo-dyed denim fabrics. Three distinct laser parameters (laser speed, power, and pulses per inch) were varied along with the tone density (grayscale) to determine an ideal combination of laser parameters for differing fabric area densities to produce a distinct contrast in indigo-dyed denim fabric without affecting the durability of the fabric (Figure 1). This research builds on the previous study [19] that reported the potential of producing patterns using a fixed laser speed and pulses per inch laser patterning. In addition, the study adds new information for precisely producing contrast at a lower grayscale (10-30%), which does not affect its physical properties, fabric thickness and tensile strength. Grayscale denotes the tone density, where 10% represents the low tone, and 100% indicates the higher tone density.

Materials and Methods

In this research, denim fabric with a twill weave structure (2/1) of varying fabric weights was chosen and was supplied by Rofinor Texteis, Portugal. Prior to evaluating samples, the laser-treated denim fabrics were conditioned in the laboratory for 24h (20±2°C and relative humidity 65%), and the results are shown in Table 1. Universal Laser equipment ILS12.57 CNC based on the CO_2 method with a laser wavelength of 10.62μm and power range 10-75 W, pulsed wave mode was used in this research. Further to laser treatment, colour change was measured using SF600 DCI Spectraflash from Datacolour spectrophotometer. The following parameters were examined colour hue (H), Saturation (S), Brightness (B), K/S (colour yield) and reflectance. Colour change was evaluated using D65 illuminant and 10° standard observer in a visible spectrum 400-700 nm. K/S represents the colour yield, where K is the absorption coefficient, and S is the scattering coefficient, following Kubelka Monk theory [28].

Commission Internationale d'Eclairage [29] developed the colour space l* a* b* that gives a numerical value to identify the colour precisely. The colour change (ΔE) depends on L, a and b parameters, L* indicates the lightness of the sample; the higher the value, the lighter the shade; it is a ratio scale ranging from 0 (black) to 100 (white); a* indicates position between red and green (positive values designate red, negative values designate green); b* indicates the position between yellow and blue (positive values designate yellow and negative value blue). In HSL colour space, colour hue (H) signifies the base colour, 0-360 in a colour wheel, from red-yellow-green-cyan-blue-magenta-red. Colour saturation (S) denotes the degree to which hue differs from 0% (natural grey) to 100% fully saturated. Colour brightness denotes how bright the colour is. For instance, 0 % refers to no colour (black), and 100% refers to maximum brightness and is white (HSL colour space) [30]. The fabric performance was evaluated for its durability, including tensile strength [31], Fabric surface thickness [32], and colourfastness to washing [33]. Tensile strength was evaluated using a constant rate of extension tensile testing machine [CRE] that has a stationary clamp and other movable clamp maintained at a rate of extension of 100mm/min [31]. A gauge length of 200mm was maintained, and three samples were evaluated for each type of lasered fabric. A thickness gauge (Mitutoyo 7301, range 0-10 mm and accuracy ±0.015mm) was used to measure the fabric thickness, which consists of an immovable bottom plate and a top plate that is movable [using a lever that has a spring-loaded plunger] and is also called presser foot [10mm diameter]. It measures the fabric thickness when placed horizontally without any creases between the plates.

For colourfastness assessments - greyscale for assessing colour change [34] and grayscale for assessing staining [35] was reported using a 5-step scale. Samples were washed using a Gyrowash machine at 40°C for 30 minutes using a standard soap. A greyscale consists of five pairs of colour chips that show perceived colour fastness rating, where 5 represents no change between the pristine and washed denim; fastness rating 1 represents the greatest contrast. All these assessments are carried using a lightbox with standard lighting conditions. The colour change ratings were obtained by comparing the difference between pristine denim samples and washed and lasered denim sample with the difference observed between two colour chips on the greyscale. For assessing staining, the lasered denim sample was sewn onto a multi-fibre fabric strip (acetate, cotton, polyamide, polyester, acrylic and wool), and a different scale was used that has one pair of white and four pairs of grey and white colour chips. Fastness rating 5 indicates no staining, whilst 4 to 1 have increasingly darker colour chips that correspond to increased staining, whereas a fastness rating 1 indicates heavy staining [36,37]. Both the fabrics were treated to varying laser parameters as shown below in Table 2. Statistical analysis was carried using IBM SPSS Ver. 26.0. A repeated one way ANOVA (analysis of variance) was conducted to determine the difference between various denim samples with the assumption that the dependent variable (tensile strength) is at a continuous level and the independent variable has three or more categorical levels (laser patterns) drawn from the denim sample.

Table 1: Fabric parameters.

Parameter	Light weight fabric (LW)	Heavyweight fabric (HW)
Fabric weight (g/m²)	285 (±5.0)	495 (±1.5)
Thickness (mm)	0.66 (± 0.0)	1.1 (±0.0)
Fabric count (warp/inch x weft/inch)	86 x 48	64 x 44
Yarn count (Tex)		
Warp	35	82
Weft	56	108
Yarn turns per metre		
Warp	420	440
Weft	210	220
Cover factor K=k1 (warp)+ k2(weft)	51 + 36	58 + 46
Tensile strength§ (N)		
Warp	940.39 (±51.5)	1261.1 (±65.5)
Weft	461.7 (±70.95)	439.22 (±88.27)
Elongation (mm)		
Warp	31.65 (±0.57)	36.01 (±1.08)
Weft	11.68 (±0.33)	10.64 (±0.37)

§Gauge length: 200mm; rate of extension 100mm/min; number in brackets indicates standard deviation; yarn count (Tex) - weight (g) of 1000m of yarn, the lower the tex, finer the yarn.

Results and Discussions

Universal laser equipment used in this study is reliable, accurate, and is user friendly. The equipment is safe to operate, as the laser beam cannot be operated without closing the platform with a glass enclosure/window. The heavy charred dust or cut fabrics are collected beneath the platform, and fumes collected during the laser-treated process are filtered safely. 'Air assist' develops an air pressure around the optics, and the compressed air keeps the debris or particulate away from the material processed and improves the quality of processing. The software connected to the equipment is user friendly, and designs or patterns can be transferred *via* drawing software (Corel draw). It also enables to change of various laser parameters - raster, speed, power, pulses per inch, cut, mark, or pattern and provides an estimated time required to complete the design [38]. The process is chemical-free and safer than any conventional method making it sustainable processing of denim. Figure 2 and 3 illustrate typical laser-treated denim with various combinations showing the visible colour change between 20-30% grayscale.

Spectrophotometer - colour change assessments

The higher the reflectance value (%), the lighter the shade of the lasered denim. For lightweight denim fabric, at 10% grayscale, higher reflectance was noticed in the range 420-440 for all fabric samples LW1-8 and at 700nm LW1, LW3 - LW8 (Figure 4). It could be observed that at 10% GS for LW1-LW8 the reflectance values were higher than standard fabric (pristine denim), meaning that the treated fabric was pale compared to standard fabric. For 20% grayscale, higher reflectance was noticed between 680 and 700 nm, and reflectance values were different to the standard fabric. This showed the removal of indigo dyes from the fibers, resulting in a pale shade, particularly for LW3 and LW7 sample, which was treated at 40% laser power, 80% laser speed, and 400/300 PPI, respectively. Peaks for reflectance at 30% grayscale were observed between 680-700 nm for LW3, LW7 and LW8 samples. As the laser speed is lowered from 100 to 80%, there is increased degradation of the fabric surface removing indigo dye, resulting in a lighter shade compared to pristine denim. Based on the above, it could be inferred that grayscale and laser speed and laser power affect the reflectance levels, producing pale effect on the denim fabric. 30% grayscale produced pale fabric compared to 10 and 20% grayscale.

Table 2: Various laser parameter combinations.

Fabric sample ID	Laser parameter variations	Fabric sample ID	Laser parameter variations
LW/HW 1	40% laser power; 400 PPI; 100% laser speed	LW/HW 5	40% laser power; 300 PPI; 100% laser speed
LW/HW 2	30% laser power; 400 PPI; 100% laser speed	LW/HW 6	30% laser power; 300 PPI; 100% laser speed
LW/HW 3	40% laser power; 400 PPI; 80% laser speed	LW/HW 7	40% laser power; 300 PPI; 80% laser speed
LW/HW 4	30% laser power; 400 PPI; 80% laser speed	LW/HW 8	30% laser power; 300 PPI; 80% laser speed

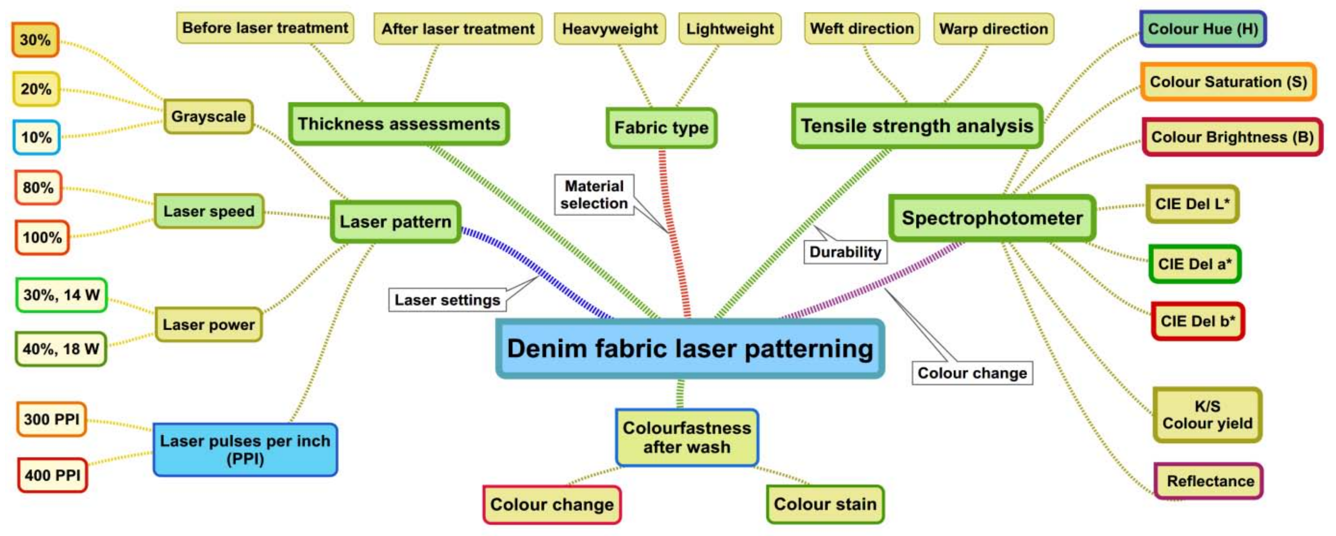

Figure 1: Overview of research.

For HW fabric, the reflectance values were lower than LW fabric across all three grayscales. Peaks were observed in the range of 420-440 nm for all samples at 10% grayscale, whilst higher reflectance was noted in wavelength 680-700 nm for 20 and 30% grayscale. In addition, treated samples for 20 and 30% grayscale showed a distinct difference in shade from pristine denim, as shown in Figure 4. Heavyweight fabrics showed lower reflectance than lightweight fabrics, and it is attributed to higher fabric density of fibers in the heavyweight fabric that has more fibers dispersed with indigo dye, resulting in a darker shade than LW fabrics. Therefore, lasered lightweight fabrics had a distinct contrast or light shade or hue compared to heavyweight fabrics at higher grayscale.

Figure 5 reveals that colour yield (K/S) was higher for 10% grayscale for HW fabrics than LW fabrics. It could be noted from Figure 5 (i) colour yield decreases for all samples of lightweight fabrics as the laser treatment increases from 20 to 30% grayscale. LW 3 and LW 7 samples have a low colour yield across all the grayscales, which means that colour change is visible compared to standard fabric. For heavyweight fabrics, laser-treated samples show a distinct difference from the standard fabric observed in Figure 5 (ii), where the laser-treated samples had a low colour yield (K/S) compared to the standard fabric. The HW7 sample (40% laser power; 300 PPI; 80%; laser speed) produced a lower colour yield compared to other samples at 10 and 20% grayscale. This also shows that lower laser speed and higher laser power produced low colour yield that differed from pristine fabric. This could be attributed to the removal of indigo pigment from the fabric surface. Overall, it can be suggested that colour yield (K/S) was affected at a low level at 10% grayscale; however, this was more pronounced at 20% and 30% grayscale.

Colour components HSB

In the case of the colour brightness, the overall trend for all LW fabrics was marginally higher for 30% grayscale compared to 10 and 20% (Figure 6). This shows the influence of grayscale that had removed the indigo dyes resulting in an increase in brightness and is different from standard fabric (0% grayscale). For LW3 and LW7 samples, colour brightness was higher compared to other samples. There is a distinct difference in colour brightness between laser-treated samples (heavy weight fabrics, across all the grayscales and samples) and standard fabric. At 10% grayscale, HW1 and HW7 had higher brightness and were different from standard fabric, meaning that fabric begins to show a faded effect at a lower grayscale. Sample HW1, 5 and 7 had higher brightness at 20% grayscale, whilst at 30% grayscale, HW1, HW3, HW5, and HW7 produced a faded effect compared to standard fabric. Overall, it can be inferred that colour brightness is higher for lightweight fabric than heavyweight fabric for similar laser settings. Hence, it could be suggested that 20% grayscale can be ideal for lightweight fabric and 30% grayscale for heavyweight fabric for producing contrast effect from standard indigo dyed fabric.

For LW fabric, the colour hue at 10% GS produces some colour variation compared to the pristine sample and has a predominantly blue shade. However, for 20% grayscale, it could be noted that except for LW2, LW4, and LW6, the remaining samples had a lower colour hue compared to the standard fabric (Figure 7). For 20% GS, LW3 and LW7 have a very light colour hue (210-220º), and for 30% grayscale, the samples had a low colour hue in the range 125-135º, indicating

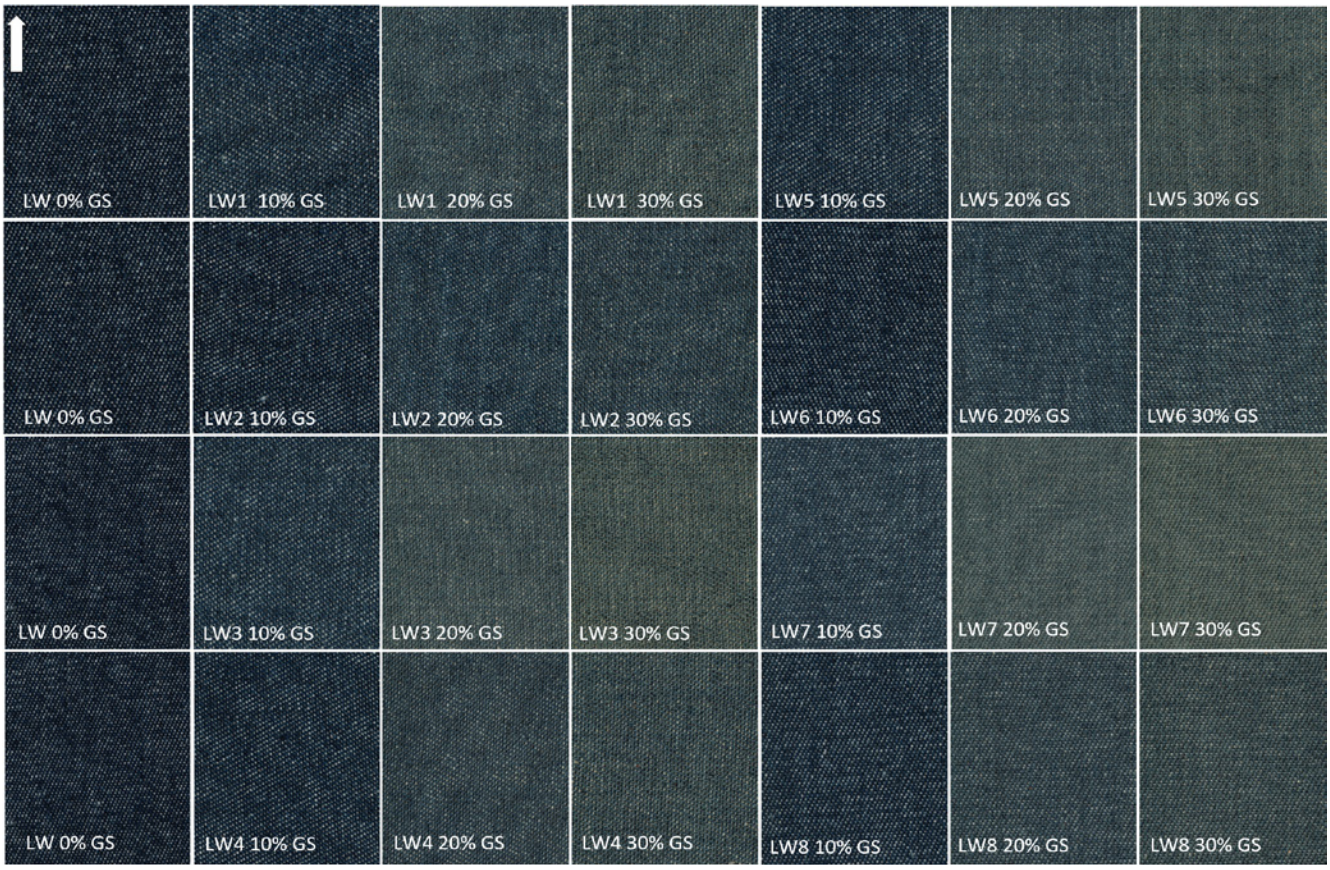

Figure 2: Light weight denim laser treated samples.

that fabric has a green shade and due to oxidation of cellulose and indigo dye reacting to laser light. It could be inferred that indigo dye on the fibre surface starts to deteriorate at higher laser power (40%) and lower laser speed (80%) compared to other samples, producing a distinct contrast on the fabric surface. For heavyweight fabric, sample HW1 and HW7 had low colour hue across all the three grayscales, at 10% GS, these two samples had a mild blue effect (265-267°) and at 20% GS further mild blue shade (236-233°), but at 30% GS fabric a low colour hue (186-189°) revealing green/cyan shade. This also shows that higher laser power has a more significant influence on affecting colour hue, where deterioration of surface fibers occurs, resulting in a lighter shade and is in line with a previous study [39].

For LW fabric, the colour saturation at 10% grayscale is much higher for all the samples and at 20% and 30% grayscale colour saturation is much lower compared to 10% grayscale and standard fabric, indicating that laser treatment affected the fabric producing a lighter tone compared to the standard fabric at higher grayscale (Figure 8). The above trend was applicable for heavyweight fabrics, but the colour saturation was higher than lightweight fabric. On the other hand, samples HW2 and HW7 had lower colour saturation at 20% and 30% grayscale, producing a light effect on denim fabric when compared to standard fabric. Therefore, it could be noted that 20-30% grayscale affects the fibre, removes indigo dyes from its surface, and exposes the lighter shaded part of the yarns resulting in a distinct contrast in the shade from the standard denim fabric.

ΔL^* indicates the lightness of the sample (Figure 9). For LW fabric as grayscale increases from 10-30% the fabric is lighter as noticed in ΔL^*values. This trend was noticed for all the LW samples and was clearly different from untreated denim sample. LW3 sample had marginally higher ΔL^* values indicating laser light removed the indigo dyes from the fabric surface.

For HW fabric, the trend was like LW fabric where ΔL^* values were higher for 30% grayscale compared to 10% grayscale. However, ΔL^* values were higher for heavyweight fabric compared to lightweight fabric, indicating that colour change is noticeable resulting in a lighter blue shade as compared to standard fabric.

Δa^* indicates position between red and green (+) values indicate red, (-) values designate green). Laser light causes oxidization of cellulose resulting in yellowing of fabric, and any remaining indigo dyes combined with yellowing of cellulose gives a green shade. For LW fabric, the negative values indicated that fabric is greener compared with pristine denim. LW 3 and 7 had higher Δa^* values. For 10% grayscale, LW6 sample was red in shade due to charring effect of cellulose caused by laser light. For HW fabric, Δa^* was higher for LW1, LW3, and LW7, indicating that the fabric had greener shade. Such green-yellow shade was also noted with the increase in laser parameters [17].

Δb^* values for both LW and HW fabric indicated that as the grayscale increases, the fabric is yellower compared to pristine fabric.

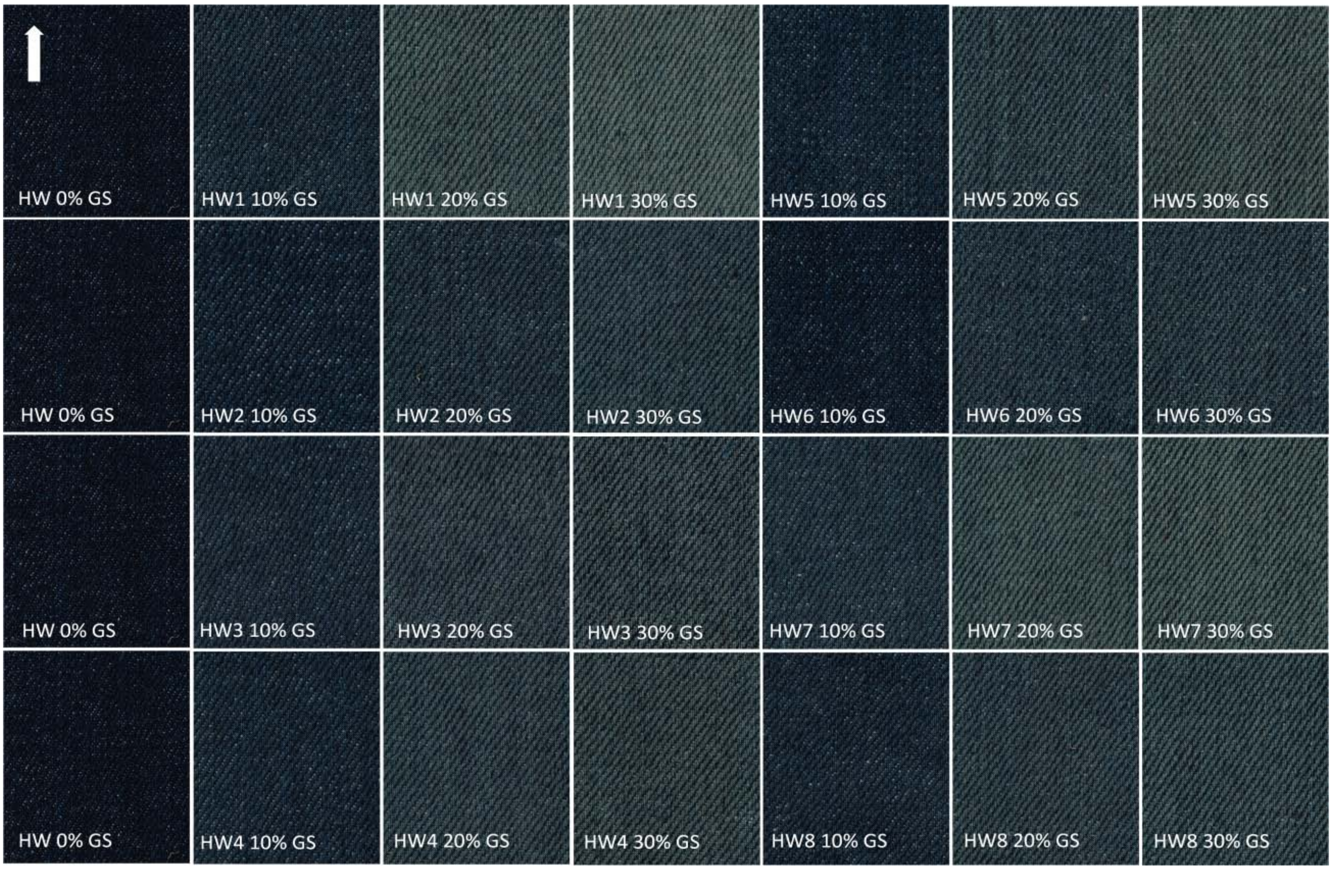

Figure 3: Heavy weight denim laser treated samples.

This was more prominent for LW3 and LW7 at 20 and 30% GS. For HW1, HW3 and HW7, the samples produced yellow shade compared with other samples and pristine fabric, indicating that laser light produced a burning effect and oxidation of cellulose of fibers creating a change in shade. At 10% GS, the fabric is relatively light blue in shade or mild yellow shade. For HW2 and HW6 sample laser effect was minimum due to low laser power and higher laser speed.

Evaluation of tensile strength and thickness

The tensile strength of fabrics in the warp direction is higher than the weft direction; this can be noticed for HW1-8 samples at 10% grayscale (Figure 10). However, the tensile strength (warp direction) for heavyweight fabrics were higher than lightweight fabrics. Generally, the loss of strength is more in warp direction than weft, which is confirmed when laser pulse increases [21,23]. The tensile strength depends on fibers, yarns, and fabric [40]. Generally, the twill woven fabric has higher strength in lengthwise direction than the cross-direction. This is due to several factors. One of them is a higher fabric count [denotes the number of warp or weft threads per unit area], i.e., more warp yarns per inch than weft yarns. It can be observed from Table 1 that the fabric count for both LW and HW samples have more warp yarns per inch than weft yarns per inch. The other factors which could affect the strength of fabrics are yarn fineness turns per meter of yarns, fabric structure, cover factor (denotes area of the fabric covered by a set of threads) and fabric weight. Generally, warp yarns are finer and have a higher twist than weft yarns. The high twist in the yarns holds the fibers together and has higher frictional force [40]. HW fabric had finer yarns, a higher cover factor in the warp direction, and higher yarn turns per meter resulting in a higher tensile strength than the weft direction. The above trend applies to LW fabric.

There were marginal differences in tensile strength for LW and HW fabrics, particularly weft direction. This trend was similar in 20% and 30% grayscale for both LW and HW fabrics, where heavyweight fabrics in the warp direction had higher tensile strength than lightweight ones. For HW fabrics, there was a decrease in tensile strength at 10% GS, and the difference between pristine sample and treated sample for HW1 (3.5%), HW5 (5%) and HW8 (5%); at 20% GS, the difference between pristine and laser-treated sample were HW3(13%), HW7 (19%) and HW8 (18%) and at 30% GS, the higher difference was observed for HW3(26.3%), HW7 (28%) and HW8 (30%). On the other hand, there were marginal differences in tensile strength for other HW samples at 10% GS. For 20 and 30% GS, HW2 and HW6 had the lowest difference between pristine and laser-treated samples, and this also meant that lower laser power (30%); higher laser speed (100%) and 400/300 PPI (laser pulses per inch) caused minor damage to the surface fibers and warp yarns contributing to the tensile strength of the fabric.

For LW fabrics, the decrease in tensile strength was noted for 10% GS between pristine and treated sample, mainly for LW4 (6.28%) and LW7 (6.17%); at 20% GS, LW1 (12%), LW5 (15.3%) and LW7 (24.2%)

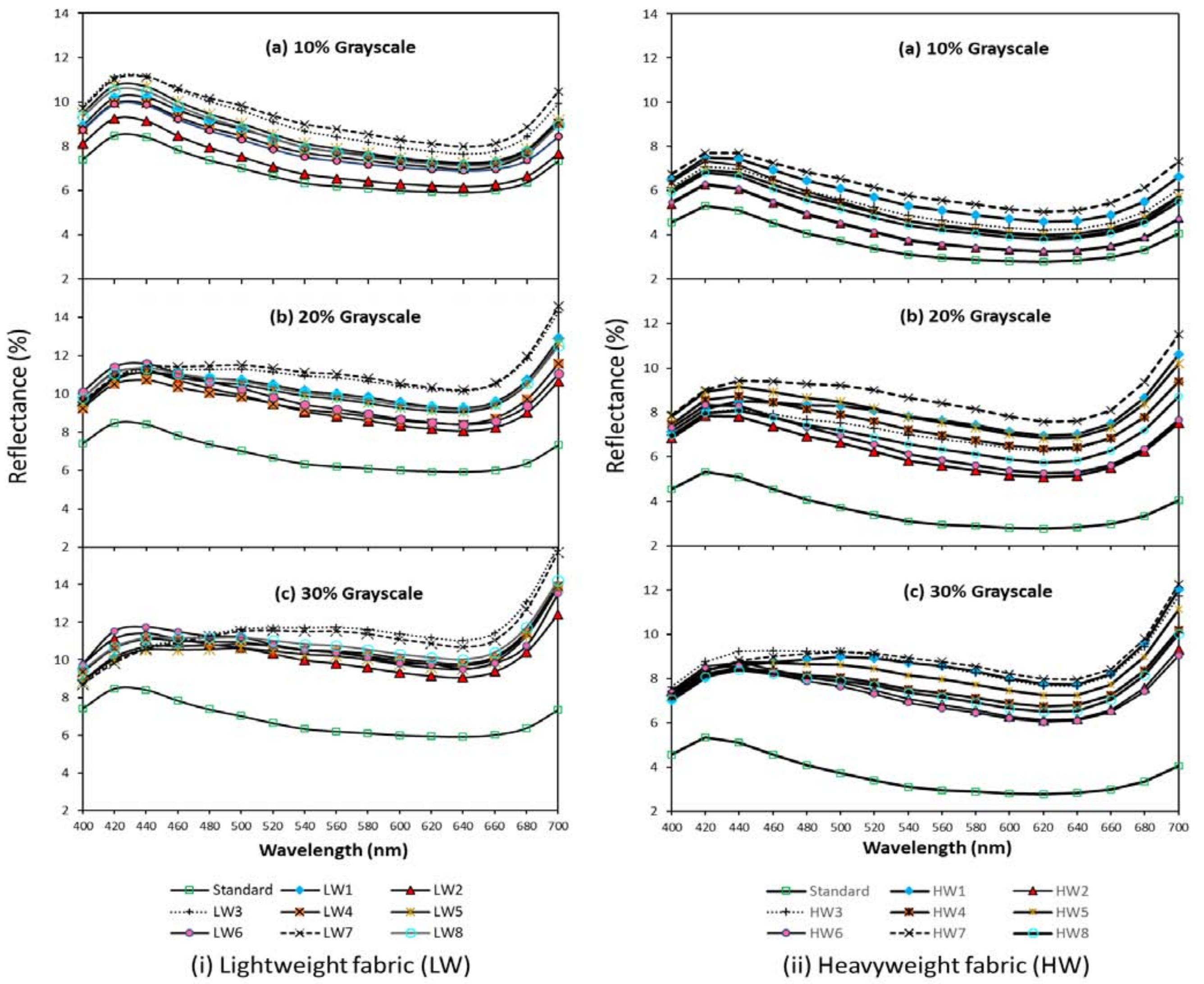

Figure 4: Spectrophotometer – reflectance values for (i) LW and (ii) HW fabrics at 10, 20 and 30% grayscale.

and for 30% GS LW3 (45%) and LW7 (44%). At 10% GS LW6 and 8 had marginal difference from the pristine denim, and at 20 and 30% GS, sample LW2 and 6 had the lowest difference in tensile strength from pristine denim.

A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in the tensile strength (in warp direction for LW fabric) across three levels of laser treatment (pristine denim- LW0, LW3 and LW7 at 30% grayscale). The data were normally distributed determined using a boxplot and Shapiro-Wilk test (p>0.05), respectively. The assumption of sphericity was violated as shown by Mauchly's test of sphericity χ^2 (2) = 6.40, p = 0.041. Therefore, a Greenhouse-Geisser correction was applied (Epsilon, ε = 0.50) [41]. Laser treatment affected the tensile strength in the warp direction and was significantly different between various levels of laser patterning, F (1, 4) = 201.84, p < 0.005, partial η^2 = 0.99, with strength decreasing from 940±51.5 N pristine denim to 510.66±10.21 N for LW3 and 525±8.62 N at LW7. Post hoc analysis with a Bonferroni adjustment revealed a statistically significant decrease in tensile strength was noted from pristine denim to LW3 (429.7 (95% CI, 243 to 616) N, p<0.010), from pristine denim to LW7 (415 (95% CI, 161.5 to 668.5) N, p<0.019, but not between LW3 and LW7 (14.66 (95% CI, 52 to 82) N, p=0.715).

Similarly, repeated-measures ANOVA was conducted to determine whether there were statistically significant differences in the tensile strength (in warp direction for HW fabric) across three levels of laser treatment (pristine denim, HW0, HW3 and HW7 at 30% grayscale). Mauchly's test of sphericity χ^2 (2) = 0.75, p = 0.866 was not violated. Laser treatment affected the tensile strength in the warp direction and was significantly different between various levels of laser patterning, F (2, 4) = 67.06 p < 0.01, with strength decreasing from 1261 ± 65.50 N pristine denim to 928.6 ± 51.73 N HW3 and 907.33 ± 17.67 N at HW7. Post-hoc analysis revealed a statistically significant decrease in tensile strength was noted from pristine denim to HW3 (332.42 (95% CI, 146 to 519) N, p<0.016), from pristine

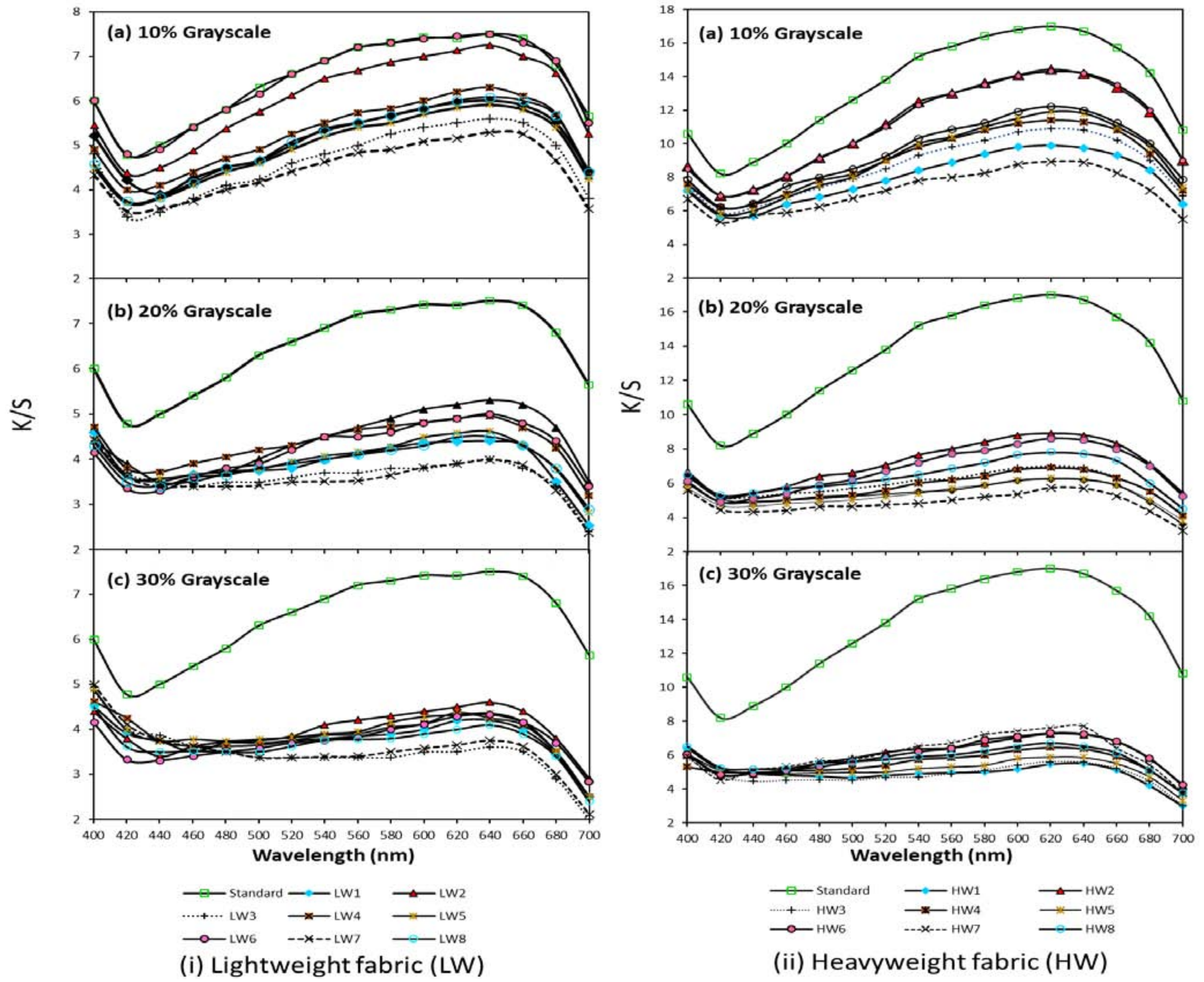

Figure 5: Spectrophotometer – colour yield (K/S) for LW and HW fabrics – 10, 20 and 30% grayscale.

denim to HW7 (353.75 (95% CI, 54 to 654) N, p<0.036, but not between HW3 and HW7 (21.33 (95% CI, 264 to 306.5) N, p = 1.0). It can be inferred that there is a statistically significant difference in tensile strength of fabrics in warp direction at 30% GS for both LW3, LW7 when compared with pristine denim. The above trend applies to HW3 and HW7 denim samples.

Repeated measures ANOVA was also conducted to determine whether there were statistically significant differences in the tensile strength (in warp direction for HW fabric) across three levels of laser treatment (pristine denim - HW0, HW2 and HW6 at 30% grayscale). Laser treatment did not affect the tensile strength in the warp direction, and there was no significant difference between various levels of laser patterning, $F(2, 4) = 2.64$ $p > 0.18$, with strength decreasing from 1261 ± 65.50 N pristine denim to 1253 ± 12.74 N for HW2 sample and 1176 ± 38.43 N at HW6. However, laser treatment did affect the tensile strength in the warp direction and was significantly different between various levels of laser patterning (pristine denim - LW0, LW2 and LW6 at 30% grayscale), $F(2, 4) = 15.23$, $p = 0.018$ with strength decreasing from 940.39 ± 51.5 N pristine denim to 826.33 ± 9.29 N for LW2 sample and 814.3 ± 15.82 N at LW6. Post-hoc analysis revealed no significant difference between samples LW0, LW2 and LW6.

In the case of LW fabric, the thickness variation is marginal. 30% GS has a more pronounced surface fibre loss than 10 and 20% GS. This trend was similar across all the samples (Figure 11). On the other hand, LW4 - 8 had a lower thickness compared to other samples and were different from standard fabric thickness (0.66mm). For HW fabric, except HW1, all other samples have more or less similar variation, with 30% GS showing more surface fibre loss and volatilization of indigo dyes resulting in a marginal difference in the thickness compared to other HW samples and standard HW fabric thickness (1.10mm). Overall, it could be noted that the difference in surface thickness for lightweight fabric is slightly more than heavyweight fabric when compared to untreated or standard fabric thickness. This could be attributed to a higher density of fibers in the heavyweight fabric, which contributes to lower loss of surface fibers and increased tensile strength, as noted in Figure 10.

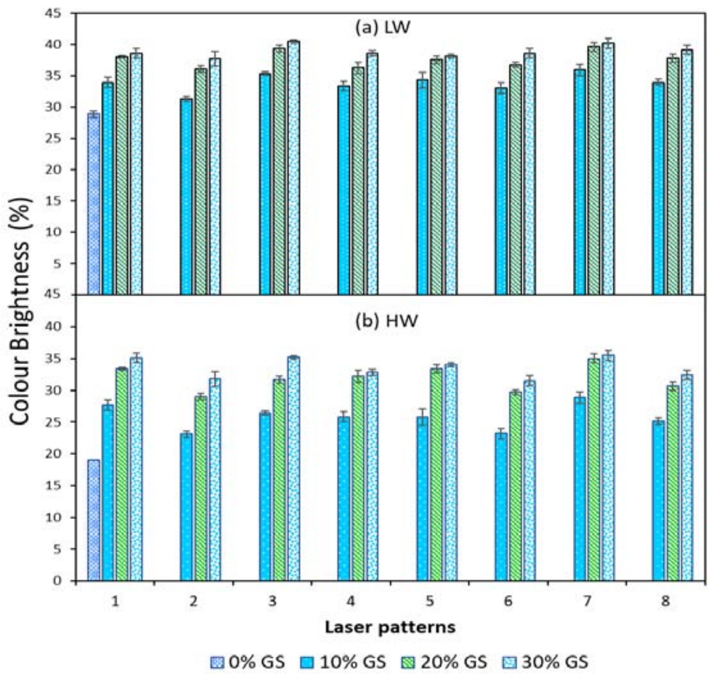

Figure 6: Colour Brightness (B) – (a) LW fabric and (b) HW fabric.

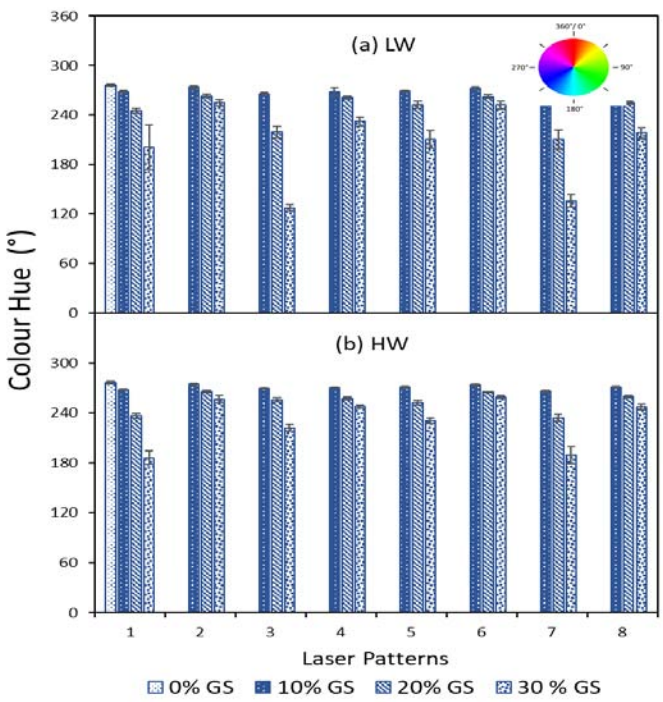

Figure 7: Colour Hue (H) – (a) LW fabric and (b) HW fabric.

From the above analysis, it can be revealed that lower power (30%) and higher speed (100%) produces lower damage to the surface fibers of the denim, and it applies to LW/HW - 2 and 6 samples, especially at 10-20% GS, where fabric strength variation from the pristine denim is lower than the lasered samples. Hence, laser patterning (faded or distressed effect) can be obtained without compromising the fabric strength. However, higher laser power 40%, lower laser speed 80% (at 400/300PPI) - applies to LW/HW 3 and 7 samples, which affects the fibre structure, resulting in lower tensile strength, especially at 30% GS and distinct colour contrast.

Colourfastness after washing

In the case of LW fabric, the colourfastness after washing for

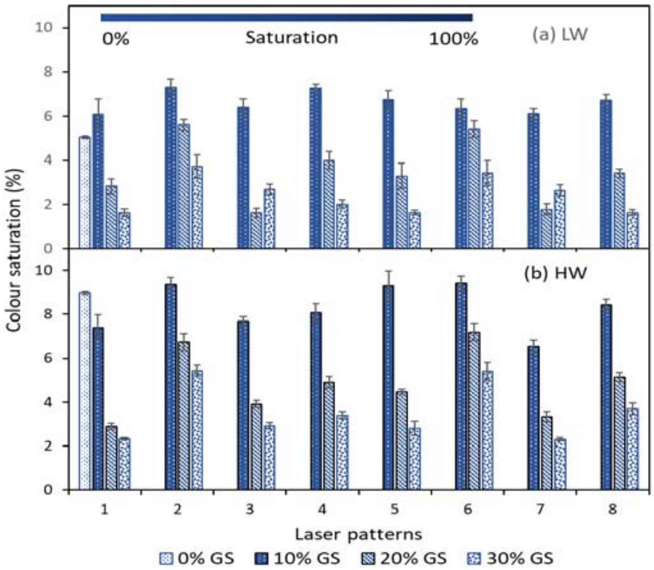

Figure 8: Colour Saturation (S) – (a) LW fabric and (b) HW fabric.

Table 3: Colour fastness to washing LW and HW fabric.

ID	Gray scale	Change in colour		Colour fastness to staining							
				Acetate		Cotton		Polyamide		Polyester/Acrylic/Wool	
		LW	HW	LW	HW	LW	HW	LW	HW	LW	HW
1	10%	4*	4*	5	5	5	5	4/5	4/5	5	5
	20%	3*	3*	5	5	5	5	4/5	4/5	5	5
	30%	3*	3*	5	5	5	5	4/5	4/5	5	5
2	10%	4*	4/5*	5	5	5	5	4/5	4/5	5	5
	20%	4*	4*	5	5	5	5	4/5	4/5	5	5
	30%	3*	3*	5	5	5	5	4/5	4/5	5	5
3	10%	4*	4*	5	5	5	5	4/5	4/5	5	5
	20%	3*	3*	5	5	5	5	4/5	4/5	5	5
	30%	2*	3*	5	5	5	5	4	4/5	5	5
4	10%	5	4*	5	5	5	5	4/5	4/5	5	5
	20%	3*	3*	5	5	5	5	4/5	4/5	5	5
	30%	2*	3*	5	5	5	5	4/5	4/5	5	5
5	10%	4*	4/5*	5	5	5	5	4/5	4/5	5	5
	20%	3*	3*	5	5	5	5	4/5	4/5	5	5
	30%	2/3*	3*	5	5	5	5	4/5	4/5	5	5
6	10%	4/5	5	5	5	5	5	4/5	4/5	5	5
	20%	4*	4*	5	5	5	5	4/5	4/5	5	5
	30%	3*	4*	5	5	5	5	4	4/5	5	5
7	10%	4*	4*	5	4/5	5	5	4/5	4/5	5	5
	20%	3*	3*	5	4/5	5	5	4/5	4/5	5	5
	30%	2*	3*	4/5	4/5	5	5	4/5	4/5	5	5
8	10%	4*	4*	5	4/5	5	5	4/5	4/5	5	5
	20%	3*	3*	5	4/5	5	5	4/5	4/5	5	5
	30%	3*	3*	5	4/5	5	5	4/5	4/5	5	5

Interpretation of grayscale rating for change in colour: 4-5: no significant loss in colour; 3: loss in depth and change in hue; 1-2; significant loss in depth and greatest contrast; *fabrics after wash had marginally darker colour hue due to removal of charred surface fibers and back staining.

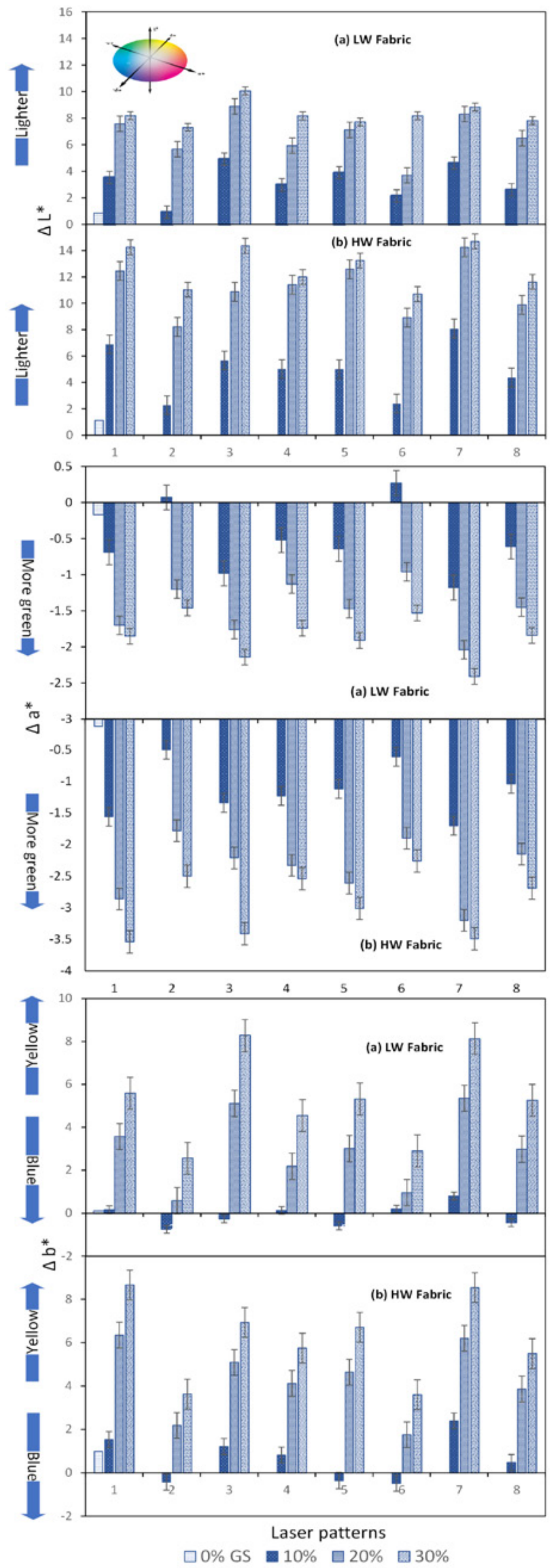

Figure 9: Colour space CIE ΔL* Δa* Δb*.

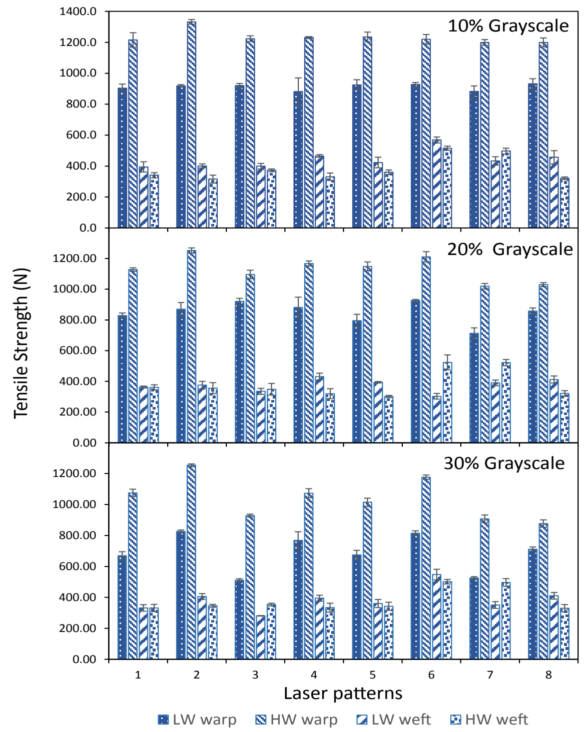

Figure 10: Tensile strength (N) - 10, 20 and 30% grayscale.

10% grayscale all the samples LW1- 8 had a minor colour change compared to pristine denim. It could be noted that a * superscript is given to some of the ratings, indicating that washed denim was relatively darker, but the change in the shade was noticeable compared to pristine denim. This is because, during washing, the charred fibers (that produced a yellow/green tone) from the fabric could be removed due to mechanical agitation, and possible back staining of dyes could have occurred, which is relatively common in denim fabrics to lose some amount of dyes during first few washes. Such back staining was also noted in a previous study [27]. For 20-30% grayscale, LW2 and LW6 fastness ratings were 4* and 3*; which meant that the change in the shade was noticeable but not significant. But in the case of LW3 and LW7, fastness ratings for 20 and 30% grayscale were 2* and 3* shows a significant colour change compared with pristine denim. This can also be noticed from ΔL* assessments that the fabric was lighter for LW 3 and 7; Δa* showed that fabric had green shade, and Δb* indicated that the samples were yellowish compared to standard untreated denim. For LW4 and 5, colour fastness ratings were in 3* and 2/3*, again indicating the change in colour depth.

For heavyweight fabric, the change in the shade was not pronounced as lightweight fabric. However, at 10% grayscale, the fabric had a mild shade change; but more so for 20-30% grayscale, where the fastness ratings were 3* for most samples (except HW6), indicating a clear and distinct contrast change from the pristine denim. Hence, it could be inferred that colour change is more pronounced for 20 and 30% grayscale samples for both LW and HW fabrics. Colour change after washing has a rating scale of 2-3, indicating a significant loss of depth of hue. This was due to the laser treatment, removing dyes from the surface. This can be noticed for samples LW3, LW4 and LW5 and HW3, HW4 and HW5 fabrics at 30% grayscale from Table

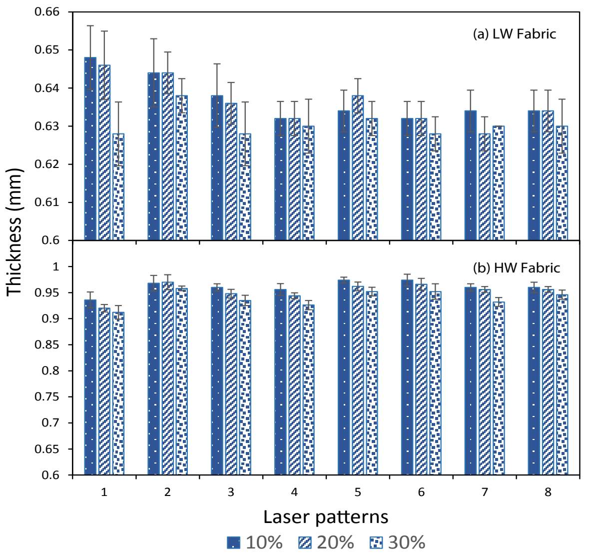

Figure 11: Fabric thickness.

3. This could be attributed to higher grayscale, higher laser power and pulses per inch during laser treatment removing the surface fibers with dyes and being prominent after washing. Ideally, it is not acceptable for any other dark colour fabrics to lose shade after wash. However, it has been a trend to wear distressed or faded effect denim fabrics with denim garments. Hence, it suits the trend of wearing faded denim. Denim samples were also assessed for colour staining by sewing together a multi-fibre strip and determining its fastness using grayscale rating (5-1), where 5 indicates no staining and 1 indicates heavy staining. It could be observed from Table 3, that a colour stain of 4 or 4/5 (mild stain) was observed for polyamide fibers and a 4/5 rating for acetate. This could be because some indigo dyes along with charred fibers of fabric could remain on the polyamide part of the multi-fibre strip resulting in moderate stain compared to pristine denim. No change in staining from grayscale across the multi-fibre strip also indicated that fabric did not bleed colour and is safe to wash with other clothes, especially after treatment with laser for both LW and HW fabric.

Conclusions

The CO_2 laser is currently available to produce a surface effect as an environmentally friendly and sustainable method [19,42] compared to conventional mechanical finishing classified as a cleaner production process [17]. In this research, it had been demonstrated that while developing shade change or patterns on dark shaded denim fabric, various laser combinations (laser power, speed, PPI, grayscale) and fabric properties (thickness/area density) had to be carefully considered, and quality of the fabric is not compromised. The CO_2 laser produces changes in colour hue/brightness/saturation by varying the laser parameters in indigo-dyed denim fabrics (lightweight and heavyweight). This was also noted in spectrophotometer assessments of colour reflectance and colour yield (K/S) and during colourfastness after wash. In addition, the durability of denim (tensile strength and thickness) was also affected when exposed to varying laser parameters. The reflectance values for heavyweight fabrics were lower compared to lightweight fabrics, and reflectance values for 20% and 30% grayscale were distinctly different from standard fabric, showing that denim fabric had a pale shade. Colour yield (K/S) also decreased when grayscale was increased from 10-30%, showing a distinct shade change from pristine fabric. In the case of colour hue, the treated sample (LW3 and LW7) had a low hue and green in the shade due to oxidation of cellulose at 30% grayscale. For HW fabrics, as the grayscale increased from 10 to 30%, fabrics had a lower colour hue (190°) compared to pristine fabric, revealing a green/cyan shade. Colour brightness was higher for lightweight fabric than heavyweight fabric, especially at 20-30% grayscale. This was also observed in colour saturation assessments, as indigo dyes were removed from the fabric surface at 20-30% GS, revealing the lighter weft yarns resulting in pale shade compared to pristine denim. Colour shade variation was noted in colourfastness to washing, where shade change rating scale was more pronounced in 20-30% grayscale for LW and HW fabrics, and no staining was observed, which allows consumers to wash their laser-treated and dark shaded denim along with other dark shaded apparel.

The durability of the denim fabrics was affected generally. Tensile strength in the warp direction was higher than the weft direction. As the laser light falls on warp yarns floating in the twill weave structure, tensile strength in the warp direction decreased when grayscale was increased from 20-30% for both LW and HW fabrics. Marginal differences were observed in the weft direction for both the fabrics across varying laser parameters and grayscale. This also confirms that laser treatment did not penetrate the warp yarns that float on the twill weave of denim fabric without affecting the weft yarns of the fabric structure. This resulted in a minor variation in tensile strength in the weft direction. For lightweight fabrics, at 20% GS, the loss of tensile strength was in the range of 12-25% difference compared to pristine fabric. However, at 30% GS, the difference in tensile strength from pristine fabric was 45%. But, for HW fabric, the tensile strength difference was more pronounced at 30% GS, and the loss of tensile strength was comparatively lower than LW fabrics. This can also be noted from thickness measurements, where LW fabrics had an increased loss of surface thickness when compared to heavyweight fabrics.

It could also be noted that a laser combination of 40% laser power; 400 or 300 PPI; 80% laser speed (as seen for LW/HW 3 and 7 samples) had a higher influence on fabric properties - significant differences in tensile strength (warp direction) were noted, in addition, thickness, colour change and colourfastness were also affected. Such a laser combination could be preferred for creating distinct patterns on the dark dyed denim fabric that has a higher area density (≥400 gsm) and thickness (≥1.0 mm). On the other hand, a laser range - 30% laser power; 400 or 300 PPI; 100% laser speed produced a lower effect on fabric colour and durability - as noted for LW/HW 2/6 samples. This could be useful for producing a milder pattern on denim fabric, especially for LW fabrics with lower area density (≥300 gsm) and thickness (≤0.70 mm). Finally, for creating a faded effect using LW fabrics, 20% GS is ideal, whilst 30% GS is suitable for HW fabrics. This research recommends a combination of laser settings and process parameters along with desired fabric properties for various fabric weights and thicknesses where consistent desired patterns can be achieved on denim fabric. Outcomes from this work inform the technologists, designers, and practitioners to use this to develop consistent patterns on indigo dyed denim fabrics, which help improve the fabric properties and the overall quality that is environmentally friendly, economically sustainable.

Declaration

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