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RESEARCH ARTICLE

THE EFFECT OF SEQUENTIAL WASHINGS ON MORPHOLOGICAL PROPERTIES OF COTTON FABRIC SURFACE PROTRUSION

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Abstract. Repeated washings on the textiles have abraded the material surface which contributed to the release of the microfibres into the wastewater. The evaluation on fabric surface is important because the protrusion formed acts as the intermediate state before microfibre release could happen and natural fibres such as cotton have a significant contribution towards such situation. Hence, the main aim of this study is to investigate the protrusion of woven cotton fabric through microscopic image observation with Scanning Electron Microscopy (SEM), which was then analysed with imageJ software. The relationship between the cotton fabric protrusion properties with the number of washing cycle intervals were explored. A sample of 100 % cotton woven fabric has been washed for 25 times with a lab-scale washer, and the protrusion length, void space and protrusion coverage image were investigated for every five washings interval. It was found that the length of the fabric protrusion increased within the 25 washing cycles by total up to 30 %, the void space reduced by 2.31 % whilst the protrusion coverage increased by 3.09 % after the sequential washes which showed that there was an effect on the fabric protrusion due to the washing activities. A thorough study on the fabric protrusion of cotton fabric would provide a clear understanding on one of the root causes of the microfibre release issue and be the reference or the starting point in the creation of an anti-microfibre-release finish based on the fabric protrusion characteristic.

Keywords: Textile washing, protrusion, microfibre release.

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1. INTRODUCTION

Fabric protrusion or fuzz can be defined as a phenomenon when small fibres merging on the textile surface from loose fibre ends which can be created due to fibre weakening and abrasion [1]. Mechanical action during washing could be the cause of the problem and making the merging fibres to peel off. It would create an issue such as the accumulation of the escaped tiny fibres or known as microfibres in the environment which are emitted in the wastewater from the washing activities [2-5]. On a global scale, it is estimated that 0.018 to 0.53 million tonnes per year of tiny particles released into the ocean are micro-sized fibres emitted from textiles during this process [6]. Natural fibre such as cotton is likely to release microfibres when exposed to mechanical forces with the presence of water as it more susceptible to abrasion and damage [7]. Hence, other than synthetic textiles, these natural fibres also have a significant contribution towards the environment pollution [8-9]. This is due to the fact that the fast degradation of natural fibres will make the release of chemical pollutants (e.g., dye stuffs) available to the river or sea sooner to enter the food chain of aquatic lives [10], and implying that any textile fibres need to be studied as the fibres could give bad impacts to the environment.

The morphological analysis is important because the protrusion acts as the intermediate state before microfibre release could happen especially on textile made of short staple yarn like cotton. The type of materials used and the structure are among the factors determining the frequency and length of fibres and yarns protruding from the textiles [11]. The yarn which is protruded from the body of the fabric will critically affect the fabric smoothness, frictional and surface roughness, as well as surface appearance [12]. As to date, very little works have been done in relation to morphological properties for textile protrusions due to textile care activities such as washing and drying. Past studies on image of fabrics after different conditions of washing and drying under Scanning Electron Microscope (SEM) showing the characteristic of the surface changes and damages [13]. However, the progressive change on the fabric surface with relation to microfibre release was seldomly discussed.

The common methods for the evaluation of pilling and protrusion are based on human judgement, which is by comparing the samples with photos, hologram or a written description for grading [14]. This subjective method according to the authors was not so reliable especially when different evaluators would give different judgement on the samples observed due to the varied visual abilities. The micro-sized fibres formation on the textile surface is not easy to be visualised physically, unless clear pills are formed. In the context of microfibre release, visual assessment is not enough to represent the volume of protrusion or pilling. This is because the released fibres volume primarily depends on the protrusion formation step and how fragile the fibres to be broken during washing before generating the pills [6]. In other words, the fibre loss occurs even before the pilling are formed, leaving the strong fibres attached on the fabric surface as the abrasion can occur at any cycle of washings.

Therefore, a morphological investigation is important to give meaningful information on tiny fibres from the fabric surface which cannot be detected with bare eyes. This work is important as it investigates the progressive change of the fabric protrusion surface, which directly influences the microfibre release. This effort helps to discover the protrusion behaviour through washing series to gain the information such as the length of protruded fibres, the void space as well as the area of the fabric covered with the protrusion. Therefore, the main aim of this study is to investigate the protrusion of woven cotton fabric through microscopic image observation with SEM and ultimately provide a clear understanding on one of the root causes of the microfibre release issue which can be considered as a never-ending process.

2. MATERIALS AND METHODS

2.1 Materials

A 100 % cotton of twill 2/1 fabric was used in this study. Twill 2/1 is the yarn interlacement in which two vertical yarns (warp) being over one horizontal yarn (weft) to create a diagonal pattern. The fabric was a commercial grade which was bought from an online store. The samples were chosen based on the commonly used type of fabric for clothing which needs to be washed regularly, and the fabric was washed sequentially without detergent.

2.2 Washing Procedure

A set of fabric samples of 19 cm x 19 cm size were washed using QuickWash Plus® by SDL Atlas washer which correlates to the International Standard ISO 6330, Textiles – Domestic Washing and Drying Procedures for Textile Testing [15]. All of the four edges of the tested sample were sewn with narrow hem seam, and the stitch size was set at 14 stitches/inch. 1 cm allowance was required for the sewing with 100 % polyester thread. The purpose of the sewing was to prevent fraying and to lock the fraying fibres from escaping the fabric, which would contaminate the fabric surface.

The washing protocol was selected based on the pre-set program in the equipment manual which is in accordance with the Standard ISO 6330 and close to the applications (Program Number 9) as indicated in Table 1. The washing was repeated for 25 times and oven-dried at 85 °C for 45 minutes before SEM image viewing were conducted at every 5 cycles interval. 25 cycles were selected as at least 25 times effect of the washing in the first year of use is possible to give cumulative impact on some textiles [16].

Table 1: Washing settings on Quickwash Plus™ (Program number 9)

Washing Settings	Specification
Fabric type	Woven
Fabric weight	151 – 299 g/m
Wash cycles	1
Agitation time	2 minutes
Rinse cycles	1
Agitation time	45 seconds
Spin time	35 seconds
Water temperature	60 °C
Sample size	19 cm x 19 cm
Water volume	6 litres

2.3 Image Sampling

Six spots for each piece of sample were selected to be observed under SEM. The spots were selected randomly in any way that the same warp and weft yarns would never intersect (refer Figure 1). This is to ensure that different yarns were included in the evaluation. For each of these spots, three images were selected making the number of images captured were 18 in total. The images of the sample surface were then analysed with imageJ. The photographic images of the washed sample surface were taken with Quanta FEG 450 Scanning Electron Microscopy (SEM) at the Faculty of Pharmacy, UiTM Puncak Alam with low vacuum, chamber pressure of 110 Pa and high voltage at 10.0 kV. The images were set at 50x magnification. As a precautionary measure, the working place must be clean from dust to avoid contamination on the samples.

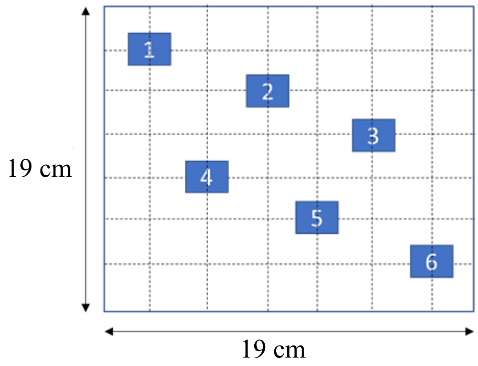

Figure 1: Image capturing layout

2.4 Determination of Protrusion Length

The steps of the measurement of the length of the protrusion are simplified in the illustration in Figure 2. The scale of the image was set prior to the measurement of the protrusion. Free hand tool was selected to track the fibre strand due to the irregular shape of the individual fibre. The reading list in the Region of Interest (ROI) manager was then analysed for the length. The average protrusion length was determined from 360 individual fibre measurements per washing interval, selected only if the entire fibre ends were clearly visible in the image from the pre-determined sampling area.

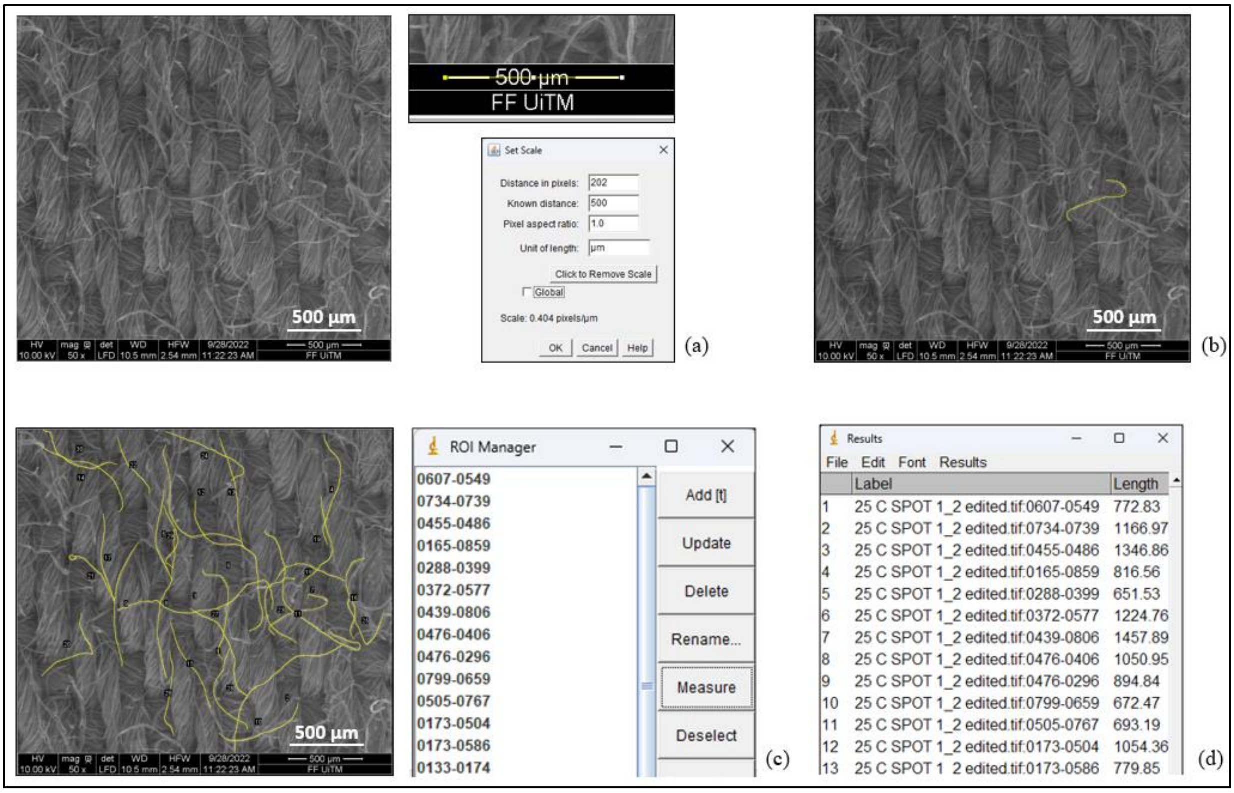

Figure 2: Determination of protrusion length on ImageJ software at 50x magnification. (a) Scale setting, (b) free hand tracking, (c) multiple measurement selection with Region of Interest (ROI) manager and (d) results: length

2.5 Determination of Void Space

In general, some empty areas could present in the image due to the void among the yarns [17]. This gap which is called 'void space', can be segmented by thresholding the grey scale image into black and white or binary form. The presence of protrusion in the image would fill in or interrupt the void space and hence could be analysed as a part of the protrusion evaluation. The segmentation of the images was done by considering the void space as super pixels or set of contours [17]. The dark areas (considered as void space) which share the same label of pixels would be segmented and the void area percentage would be measured.

The void space determination in the current study was adapted from the past work [18], and the step-by-step method is illustrated in Figure 3. 18 images for each washing interval were analysed without image manipulation done prior to the analysis. The images were firstly fully cropped and duplicated to exclude the details bar in the bottom of the image, or else the details bar would be analysed too. The cropped images were then converted to 8-bit of grey scale before doing the thresholding. The thresholding was adjusted manually to distinguish between the void space and the fibres, and the void area percentage was measured. Note that the dark background option is unticked in Figure 3(c) so that the dark area would be segmented and measured.

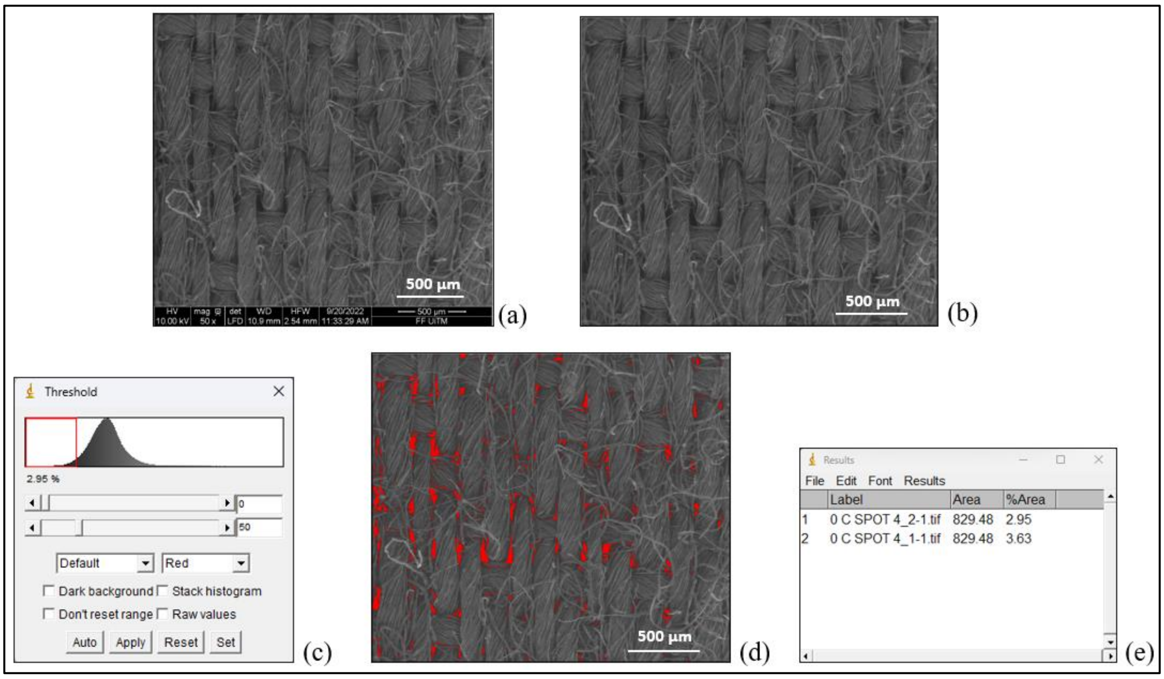

Figure 3: Determination of fabric void space on ImageJ Software at 50x magnification. (a) Original image, (b) fully cropped and duplicated image, (c) manual thresholding, (d) thresholding with red highlighting the dark empty space and (e) results: red highlighted area percentage

2.6 Determination of Fabric Protrusion Coverage

Figure 4 shows determination of protrusion coverage on ImageJ software. The protrusion coverage determination method was the opposite of the void space image analysis. Note that the dark background option is ticked in Figure 4(c) so that the light area (protrusion) would be segmented and measured. The fibres which were coming out from the fabric would be closer to the SEM lens (source of light) as compared to the fibres which were bound tightly in the yarns. Hence, the fibres would appear lighter than the background fibres, and the thresholding highlighted these fibres before being measured for the area coverage percentage.

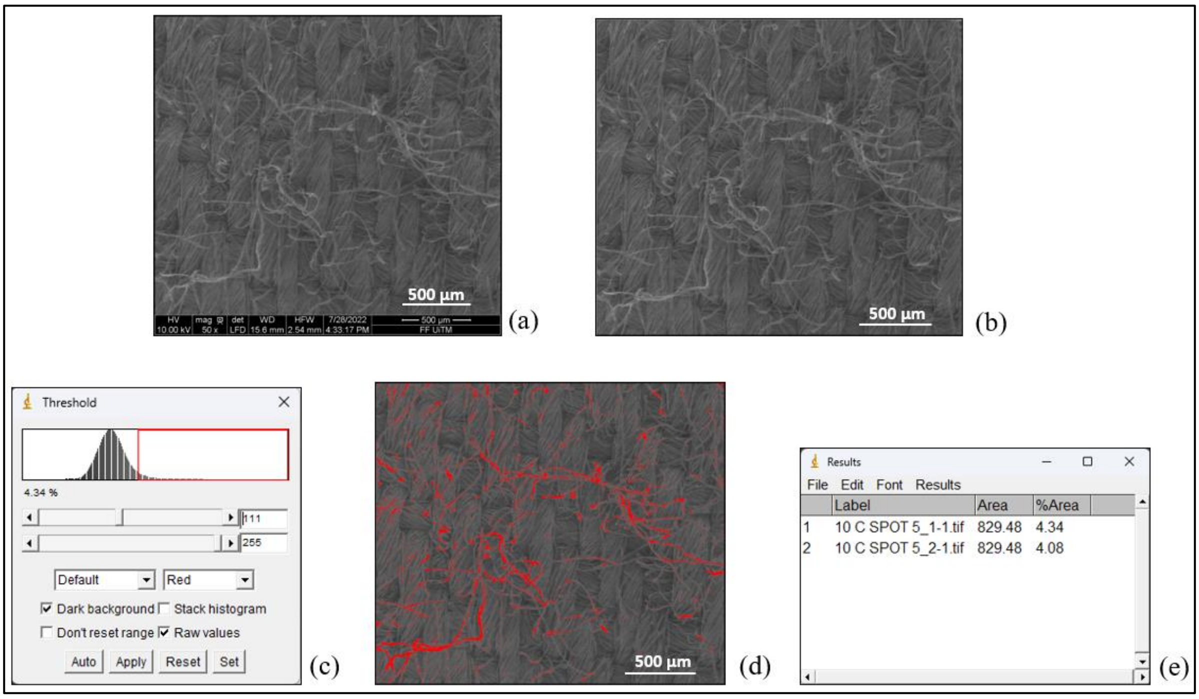

Figure 4: Determination of protrusion coverage on ImageJ software at 50x magnification. (a) Original image, (b) Fully cropped and duplicated image, (c) Manual thresholding, (d) Thresholding with red highlighting the light protruding fibres and (e) Results: red highlighted area percentage

3. RESULTS AND DISCUSSION

3.1 Basic Physical Properties

Table 2 shows the weight, density and thickness of the tested fabric. It is found that the fabric falls under medium weight category with 112.40 gm^{-2}. Hence, this category of fabric is commonly used for a wide range of applications especially clothing which requires frequent washings.

Table 2: Fabric samples physical properties

Fibre	Fabric weight (gm^{-2})	Yarn type	Fabric Density		Thickness (mm)
			Warp/cm	Weft/cm	
100 % Cotton	112.40	Staple	51	26	0.291

3.2 Protrusion Length

The number of washing cycles have influenced the length of protruding fibres on the fabric surface when a one-way ANOVA test ($F(5,102) = 37.289$, $p < 0.001$) reveals a significant difference across washing intervals (refer Table 3). There is a total increase of up to 30 % in the length of fabric protrusion over the sequential washing cycles. When the cotton fabric was washed repeatedly, more extensive friction was subjected on the textile. Hence, fabric protrusion and fibrillation were created intensely due to the abrasion on the fabric surface in wet condition. A twisted ribbon-like structure has given cotton uneven convoluted surface which increases the inter-fibre friction [19]. The weakened fibres would break when the fibres had been pulled apart leaving the fibrillated fibre bundles while the rough surface inside the machine contributes to the physical forces that cause the fibrils to simply separate when the fibre is wet. This claim was supported when 34.107 mg of fibre fragments with the length ranging between 814 – 1,173 µm were collected from the wastewater during the sequential washes of 25 g of cotton fabric. There is possibility that the fibre rupture occurs from deep inside of the yarn, which creates longer fibre fragments than the protrusion which is assessed from the fabric surface.

Table 3: Length of protrusion for cotton. Values with different superscripts in a column differed significantly (ANOVA, $p < 0.001$)

Washing cycle	Length of Protrusion (µm)
0	512.47^{a}
5	553.47^{b}
10	580.19^{bc}
15	608.48^{cd}
20	636.21^{de}
25	666.41^{e}

3.3 Void Space and Protrusion Coverage

The results obtained in Table 4 shows that the void space of the tested cotton fabric is different significantly across the sequential washes (Kruskal-Wallis, $\chi^2(5) = 92.136$, $p < 0.001$). The protrusion coverage and the thickness of the tested cotton are also revealed to be different significantly across the washing series (Kruskal-Wallis, $\chi^2(5) = 75.234$, $p < 0.001$) and ($\chi^2(5) = 48.902$, $p < 0.001$) respectively. The void space for the unwashed sample is 3.13 % and reduced to 0.82 %, a reduction of 2.31 % after being washed for 25 times, whilst no change in the void space after 20 cycles of washing was observed. The protrusion coverage is 2.61 % at zero wash, and increased by 3.09 % up to 5.70 % at 25 washing cycles, and there is no significant change in the protrusion coverage observed at wash cycle 11-15 with 4.85 %. The increment of the protrusion coverage is supported by the fabric thickness which increased by 50.86 % after the washes. This is due to the entanglement of fibres on the fabric surface which made the structure to be bulkier, and hence adding to the fabric thickness.

Table 4: Void space, protrusion coverage and fabric thickness. Values with different superscripts in a column differed significantly (Kruskal-Wallis, $p < 0.001$)

Washing cycle	Void space (%)	Protrusion coverage (%)	Fabric thickness (mm)
0	3.13^{a}	2.61^{a}	0.291^{a}
5	2.09^{b}	4.11^{b}	0.429^{b}
10	1.56^{c}	4.53^{c}	0.431^{b}
15	1.32^{d}	4.85^{c}	0.441^{c}
20	0.87^{e}	5.26^{d}	0.442^{c}
25	0.82^{e}	5.70^{e}	0.439^{bc}

Figure 5 shows the SEM images of the cotton sample for the void space area determination. The red highlight in Figure 5(b) which have been segmented represents the void area. Note that there is more highlighted area on the image of the unwashed sample as compared to samples which were washed for 20 and 25 times. The reduction of the void space is caused by the close distance due to the movement of yarns after several washes.

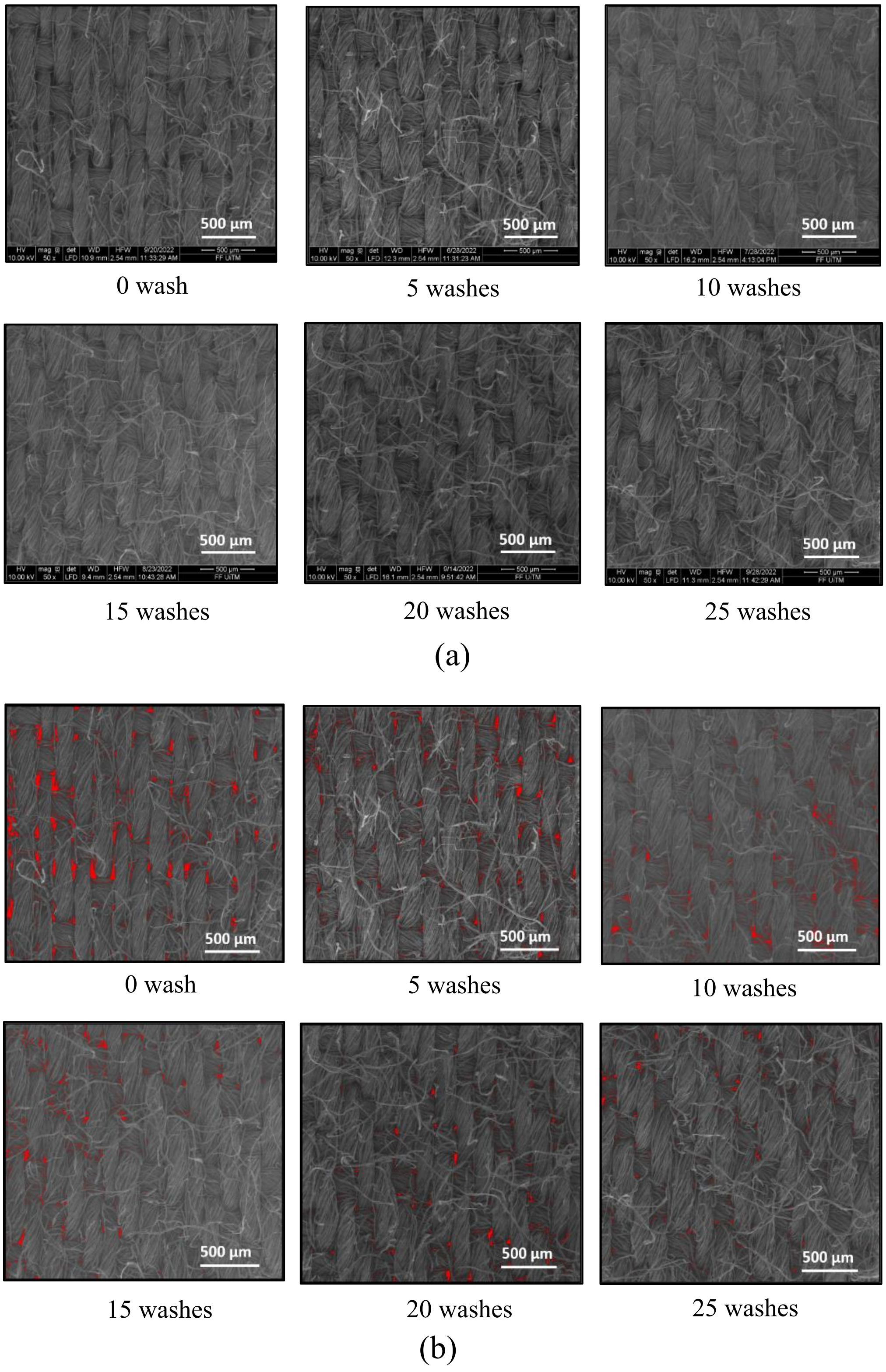

Figure 5: The void space on SEM image of cotton sample (a) Before segmentation and (b) After segmentation

It is observed in Figure 6 that there are 13 warp yarns (vertical direction) and six weft yarns (horizontal direction) in the SEM image before washing, and 14 warps and seven wefts are observed after 25 washings. The yarns are prominently shifted during the first five washes as indicated by the fabric density in Table 5. Subsequently, the swelling and loosening of the yarn structure increased the yarn width, thus reducing the inter-yarn void space. This compaction forces the newly formed protrusion fibres to accumulate and entangle on the fabric surface, which is supported by the increase in protrusion coverage.

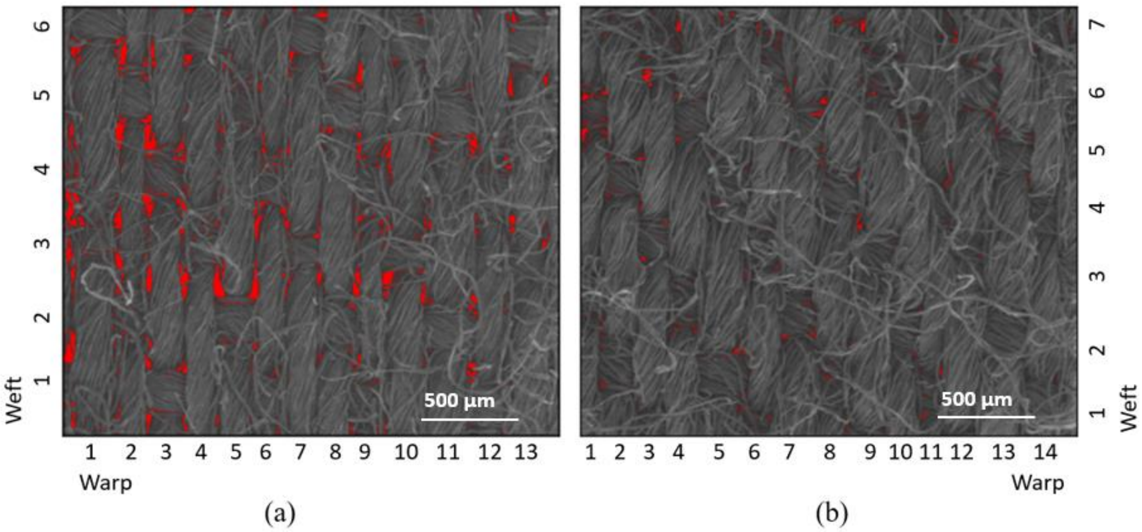

Figure 6: Warp and weft yarns in cotton. (a) Zero washing and (b) 25 washings

Table 5: Fabric density

Washing cycle	Fabric density	
	Warp/cm	Weft/cm
0	51	26
5	54	30
10	54	31
15	54	31
20	54	32
25	54	32

The SEM images of the cotton sample for the protrusion coverage determination before and after segmentation are displayed in Figure 7. The red highlight in Figure 7(b) shows the protrusion that covers the fabric surface. The yarn surface which is loosened and the fibres which are coming out from the fabric would appear lighter in the image and are segmented. High coverage of fabric protrusion is observed in the image of the cotton fabric which was washed for 25 times as compared to zero washed fabric.

The protrusion coverage increases accordingly with the increase of the protrusion length results in Sub-section 3.2. It is presumed that the longer protrusion would cause fibre entanglement on the fabric with the increase in the washing cycle number. Some part of the protrusion also shows a dense fibre accumulation which creates higher chance of fibre removal if further washed (Figure 8). This is due to the fact that protruding fibre ends can be easily fibrillated under the mechanical action and wet conditions of washing, leaving small fibre fibrils prone to breakage and detachment [20].

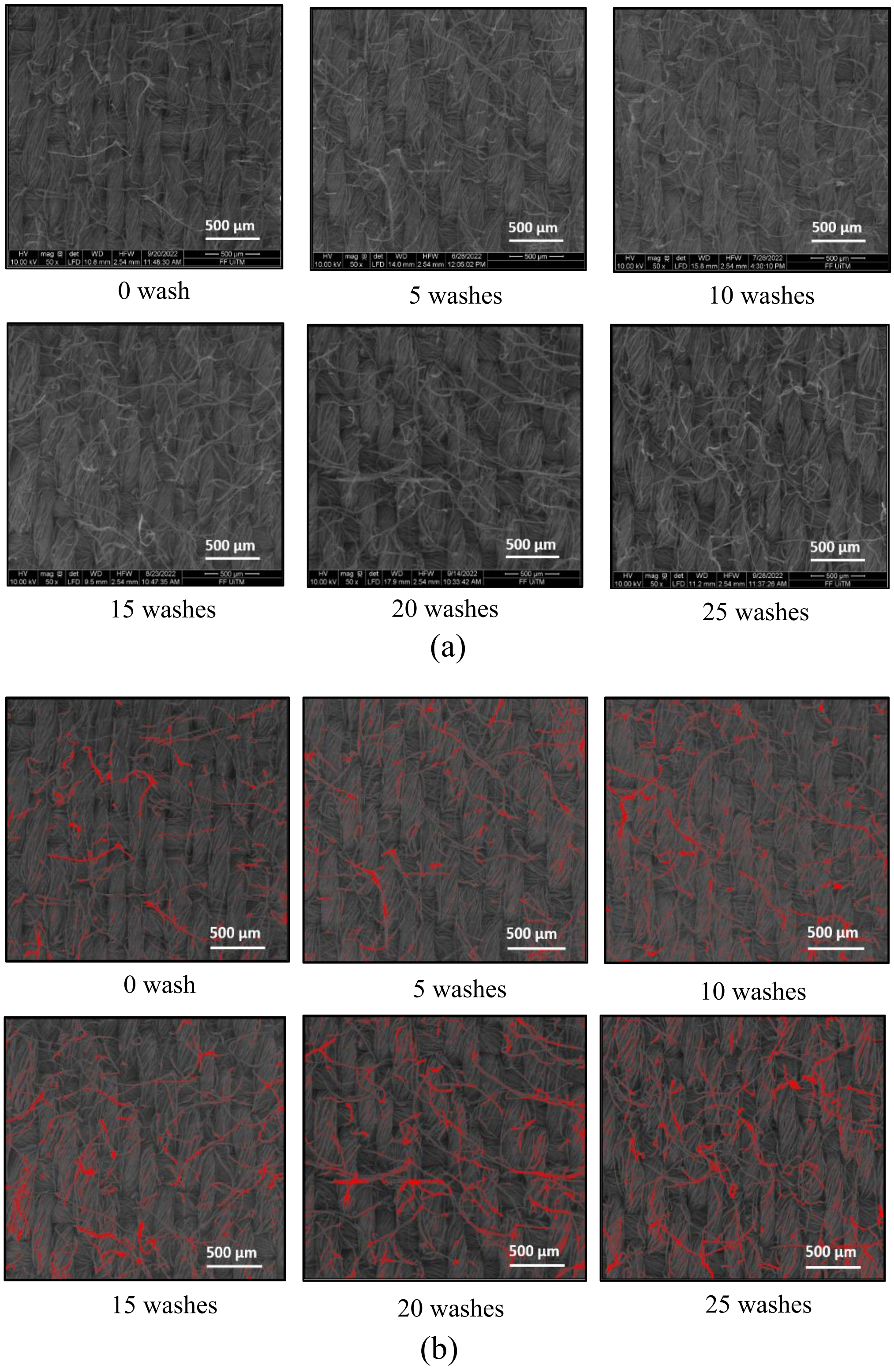

Figure 7: The protrusion coverage on SEM image of cotton sample (a) Before segmentation and (b) After segmentation

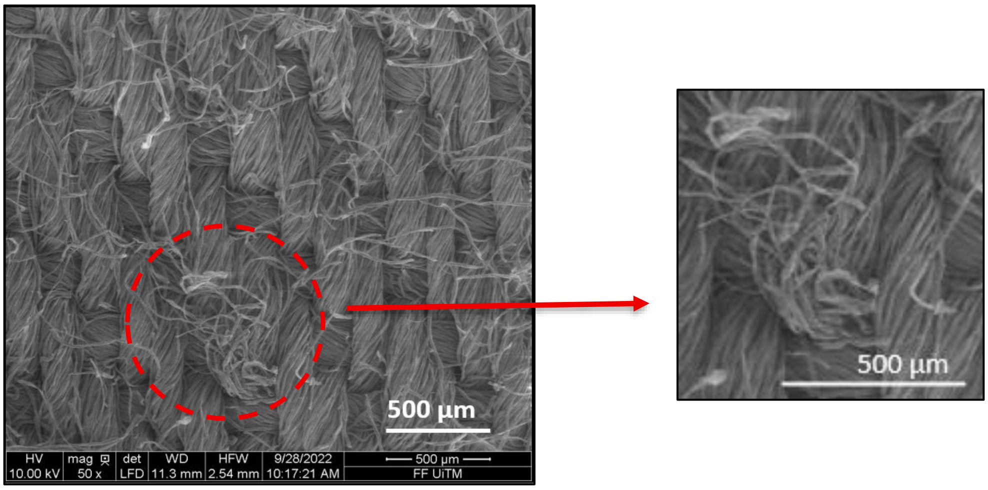

Figure 8: Dense fibre accumulation after 25 washings

4. CONCLUSIONS

In conclusion, washing activities do really affect the protrusion formation on the tested woven cotton fabric. The length of the fabric protrusion increased significantly within the 25 washing cycles by total up to 30 %, the void space reduced by 2.31 % whilst the protrusion coverage increased by 3.09 % after the sequential washes. Hence, it is confirmed that there are fibres which are left protruding on the fabric despite the fibre breakage which contributes to the microfibre release into the aquatic environment. The formation of the protrusion has made zero microfibre release is difficult to achieve as the fibres may re-emerge and repeat the shedding cycle. Simply eliminating these protrusions through singeing or biopolishing is not a sustainable solution and therefore, targeted mitigation strategies at the textile finishing stage (such as applying superficial coatings) is recommended to offer a more effective approach to control the issue. The finishing can help to minimise the surface protrusion formation and potentially lead to a substantial reduction or even elimination of microfibre release, offering a promising direction for sustainable textile manufacturing.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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