

## COMPARATIVE EVALUATION OF BIO-BASED AND CONVENTIONAL FINISHES FOR VARIOUS DIGITALLY PRINTED FABRICS

MUHAMMAD MOHSIN, MUHAMMAD AWAIS, KOMAL IFTIKHAR,  
KHURRAM SHEHZAD AKHTAR and WARDHA ANAM

*Department of Textile Engineering, University of Engineering and Technology, Lahore, 3.5 Km  
Khurrianwala, Makuana bypass Faisalabad, Pakistan*

✉ *Corresponding author: M. Mohsin, muhammad.mohsin@uet.edu.pk*

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This research investigates the conventional application of bio-based and synthetic finishes on digitally printed textiles. While digital inkjet printing was used for coloration, all finishes were applied using traditional padding techniques. The performance of the bio-based finishes including fatty acid (softener), citric acid (crease resistance), diammonium hydrogen phosphate (flame retardant), and stearic acid (oil and water repellent) were compared with synthetic analogues such as silicon softeners, DMDHEU resin, phosphorus-based flame retardants, and fluorinated oil and water repellents. Fabrics studied were cotton, polyester, polyester-cotton blend, and silk. The bio-based finishes provided competitive functional performance on digitally printed textiles. This work highlights a sustainable alternative in textile finishing without compromising key performance parameters.

**Keywords:** digital printing, digital textile finishing, eco-friendly finishing, sustainable processing, bio-finishing

### INTRODUCTION

The global textile industry is undergoing a transformative shift toward sustainability, driven by greater environmental concerns, consumer awareness, and regulatory pressures.<sup>1-6</sup> As one of the most resource-intensive industries, textiles contribute significantly to water pollution, chemical waste, and carbon emissions.<sup>7</sup> In response, researchers and manufacturers alike are increasingly prioritizing eco-conscious innovations that reduce environmental burdens, while maintaining performance and aesthetic quality.<sup>8</sup> Among these efforts, the replacement of petroleum-based synthetic chemicals with bio-based alternatives has gained considerable momentum.<sup>9,10</sup> Bio-based finishes, derived from renewable natural resources, offer a compelling path forward, aligning with global sustainability goals and addressing health and ecological concerns associated with conventional chemical finishes.<sup>11</sup> Parallel to the evolution of sustainable chemistry, textile coloration technologies have also advanced.<sup>12</sup>

Digital inkjet printing, in particular, has emerged as a disruptive innovation in the field of textile coloration. It offers high-resolution image-

ry, reduced water consumption, and minimal waste generation, compared to traditional screen printing and dyeing methods.<sup>13</sup> By allowing precise placement of colorants with minimal excess, inkjet printing is now widely recognized as a sustainable alternative that complements the eco-friendly textile agenda.<sup>14</sup> Padding is one of the most established and versatile methods for applying functional finishes to textile substrates.<sup>15</sup> It involves immersing the fabric in a finishing solution, followed by squeezing through rollers to control wet pick-up and uniform distribution. Textile finishes serve multiple functions beyond aesthetics, including improved brightness, handle, enhancing comfort, durability, safety, and usability of the final product.<sup>16</sup> These functional finishes can broadly be classified as bio-based or synthetic based on their chemical origin.<sup>17</sup> Synthetic finishes are typically petrochemical derivatives engineered for high performance, long-term durability, and broad-spectrum functionality.<sup>17</sup> Typical most commonly used textile synthetic finishes exhibit various toxic effects, for example, resins contain formaldehyde, which is a known human carcinogen. Also, the Pyrovatex flame retardant

contains formaldehyde and halogen, both of which are toxic. Similarly, fluorocarbon-based oil and water repellents are toxic and potentially carcinogenic. Conversely, bio-based finishes are derived from plants or renewable resources and are designed to reduce ecological impact without significantly compromising on functionality.<sup>18</sup>

The increasing scrutiny of synthetic compounds, including their toxicity, biodegradability, and environmental persistence, has pushed the industry to consider bio-based alternatives that offer a more balanced approach to performance and sustainability.<sup>19</sup> The selection of finishing agents is intricately tied to the performance requirements of the end-use fabric. Common performance parameters include softness, crease recovery, flame retardancy, and water or oil repellency. These attributes are especially critical in apparel, home textiles, and technical textiles, where comfort, safety, and functionality must be harmonized. Moreover, the interaction between finishing agents and fabric composition significantly influences the outcome. Cotton and silk, being hydrophilic natural fibers, respond differently to finishes compared to polyester and polyester-cotton blends (PC), which exhibit hydrophobicity and higher thermal stability.<sup>20,21</sup> Therefore, evaluating the efficacy of finishes across multiple fabric types is essential to understanding their practical utility in real-world applications.

Bio-based finishing agents are increasingly being investigated as sustainable alternatives to traditional chemicals. Fatty acids, derived from natural oils, function effectively as softeners by lubricating fiber surfaces and improving handle.<sup>22</sup> Citric acid, a tricarboxylic acid sourced from citrus fruits, has shown promise as a crease recovery agent due to its crosslinking ability with cellulosic fibers.<sup>23,24</sup> Diammonium hydrogen phosphate, while traditionally used in fertilizers, has emerged as a potential flame retardant with relatively low toxicity.<sup>25,26</sup> Stearic acid, a saturated fatty acid found in plant and animal fats, contributes to hydrophobicity and water repellency.<sup>27,28</sup> These compounds offer a favourable environmental profile, being biodegradable, renewable, and often non-toxic. However, their industrial use remains limited by variability in performance, less optimization, as compared to their synthetic analogues, and challenges in large-scale processing.

While bio-based agents offer promise, their comparative performance against synthetic agents

when applied via conventional methods to digitally printed fabrics has not been thoroughly investigated. Existing literature often separates studies on finishing and printing, leaving a research void in understanding how these two aspects interact. Moreover, most sustainability-oriented finishing studies are conducted on grey or traditionally dyed fabrics, not on digitally printed ones where ink chemistry and surface interaction may influence the outcome. Further, limited comparative data exists across fabric types especially when assessing how bio-based finishes perform differently on hydrophilic and hydrophobic substrates. Therefore, a systematic evaluation of both finish types across multiple substrates is necessary to assess real-world feasibility.

This study aims to evaluate the conventional application of bio-based and synthetic finishing agents on digitally printed textile fabrics. Digital inkjet printing was used for coloration of four fabric substrates: cotton, polyester, polyester-cotton blend (PC), and silk. All finishing agents both bio-based and synthetic were applied using conventional padding techniques to maintain methodological consistency and industrial relevance. The selected functional properties under investigation include softness, crease recovery, flame retardancy, and oil and water repellency. Bio-based agents used include fatty acids (softener), citric acid (crease recovery), diammonium hydrogen phosphate (flame retardant), and stearic acid (oil and water repellent). Their synthetic counterparts include silicon-based softeners, DMDHEU, phosphorus-based flame retardants, and fluorinated repellents.

## EXPERIMENTAL

### Materials

Four commercially relevant textile substrates were used. Plain weave 100% cotton (150 g/m<sup>2</sup>) and a polyester-cotton blend (65/35%, 160 g/m<sup>2</sup>) were obtained from Kamal Textile (Faisalabad, Pakistan). Plain weave 100% polyester (140 g/m<sup>2</sup>) and 100% silk fabric (120 g/m<sup>2</sup>) were obtained from Sapphire Textile Mills (Lahore, Pakistan). All fabric lots arrived with certificates of analysis, indicating fibre composition, fabric count, and greige finish status.

Analytical-grade reagents for bio-based finishes: fatty acid, citric acid, diammonium hydrogen phosphate, maleic acid, stearic acid, and sodium hypophosphite (SHP) were purchased from Sigma-Aldrich. Silicone softener, DMDHEU (dimethylol dihydroxyethylene urea), the phosphorus-based flame

retardant, and the fluorine-based oil-and-water repellent were obtained from Archroma Ltd.

### Methodology

Digital printing was conducted using an EPSON Head 1390 in a textile inkjet printing machine. Digital textile printing was performed using commercially available Epson textile pigment printing four color process inks, including cyan, magenta, yellow, black. The same ink type and printing conditions were used for all fabric substrates to establish a uniform printing baseline prior to finishing.

The objective of this study was to investigate the effect of bio-based and synthetic finishing agents applied on digitally printed fabrics. Therefore, all printed samples were treated identically and considered equivalent before the application of finishing treatments. Conventional finishing was performed on a pneumatic padder. Thermal curing was subsequently carried out in a laboratory stenter frame capable of maintaining temperatures between 100 °C and 250 °C. Bath formulation and monitoring were conducted using a calibrated pH meter with an accuracy of  $\pm 0.01$  pH units and an analytical balance with a precision of  $\pm 0.001$  g.

The fabrics were pre-bleached and all of them were digitally printed prior to finishing. The same recipe and process was used to enable comparison. The same pattern was printed digitally on the surface of the fabrics and then the finishing formulations were prepared in two distinct series: bio-based and synthetic, each tailored for four functional finishes: softening, crease recovery, flame retardancy, and oil-water repellency. All baths were formulated at room temperature under gentle magnetic stirring. The detailed compositions of the bio-based and synthetic finishing baths are

summarized in Table 1. In the bio-based series, softener finishes included 3% fatty acid, while bio-based crease recovery recipe include 5% citric acid and 3% sodium hypophosphite (SHP). The bio-based flame-retardant recipe incorporated 20% diammonium hydrogen phosphate, 5% citric acid and 2% sodium hypophosphite. The bio-based oil and water repellent finish included 5% stearic acid, 3% SHP. In the case of synthetic finishes, the softener formulation contained 3% silicone softener. Synthetic crease recovery finishes used formaldehyde based 5% DMDHEU and 1% magnesium chloride. The flame-retardant formulation featured 20% phosphorus-based chemical (Pyrovatex CP New). Lastly, the synthetic oil and water repellent bath contained 5% fluorine-based agent.

In this study, the term 'bio-based' refers to formulations in which the primary or one functional component (such as fatty acids, stearic acid derivatives and citric acid) is bio-based in each finish. However, some auxiliary or other chemicals used to promote crosslinking or char formation, such as sodium hypophosphite (SHP) and diammonium hydrogen phosphate (DAP), are not bio-derived. These auxiliaries were included only to ensure proper curing or flame-retardant performance.

Conventional finishing trials were conducted on four different fabric substrates on a padder and stenter. After a 5 min equilibration at ambient temperature, specimens were cured in the laboratory stenter according to the finish type: for softener, at 100 °C for 2 minutes, while all the other finishes at 170 °C for 3 min. Finally, all specimens were equilibrated in standard testing atmosphere (25 °C, 65% RH) for 48 h prior to performance evaluations.<sup>29,30</sup>

Table 1  
Types and details of synthetic and bio-based finishes

Finish function	Bio-based finish	Synthetic finish
Softening	Fatty acid	Silicone softener
Crease recovery	Citric acid, sodium hypophosphite (SHP)	DMDHEU, magnesium chloride
Flame retardancy	Diammonium hydrogen phosphate, citric acid, SHP	Phosphorus-based agent (Pyrovatex CP New)
Oil-water repellency	Stearic acid, SHP	Fluorine-based agent

### Characterization

#### Crease recovery angle

ISO 2313-1 2021 was used to determine the crease recovery angle of textile fabrics by first conditioning 40 mm × 15 mm specimens for at least 24 h at  $21 \pm 1$  °C and  $65 \pm 2\%$  RH under ISO 139, then folding them horizontally and pressing under a  $10 \text{ N} \pm 0.5 \text{ N}$  load for 5 min. The load was removed within 1 s to minimise sudden spring-back, and specimens were allowed to recover for 15 s (rapid recovery) and again for 5 min (delay recovery) before the angle between the two limbs

was read to the nearest degree on a circular scale accurate to  $\pm 0.5^\circ$ , with the mean of at least five specimens in both warp and weft directions calculated and rounded to one decimal place.

#### Air permeability

GB/T 5453-1997 was used to determine the air permeability of textile fabrics by first conditioning circular specimens (test area  $\approx 20 \text{ cm}^2$ ) for at least 24 h at  $21 \pm 1$  °C and  $65 \pm 2\%$  RH under GB/T 6529, then clamping them in an HY0461D/E automatic air-

permeability tester, fitted with the appropriate test head and applying a constant pressure differential of 100 Pa. The instrument measured the steady-state volumetric airflow per minute through the specimen, converted this to the equivalent water-column change, reported the result in mm/min, and the mean of at least five specimens in both warp and weft directions was calculated and rounded to one decimal place.

**Flame resistance of textiles (vertical test)**

ASTM D6413 was used to determine the char length and char width of textile fabrics by first conditioning 76 mm × 300 mm specimens for at least 24 h at 21 ± 1 °C and 65 ± 2% RH under ASTM D1776, then mounting each specimen vertically with its lower edge 19 mm above a propane flame and exposing it for 12 ± 0.2 s, while observing any melting or dripping. Upon flame removal, after-flame and after-glow times were recorded to the nearest 0.2 s, the char length was measured from the undamaged edge to the furthest point of visible damage along the fabric with a ruler to the nearest 3 mm, and char width was determined by drawing a line perpendicular to the fabric's length at the maximum char point and measuring the width of the charred zone with calipers to the nearest 3 mm. Five specimens in both the warp and weft directions were tested, and the mean char length and width were calculated and rounded to one decimal place to ensure reproducibility.

**Water repellency spray test**

The AATCC 118 spray test was used to determine the water repellency of textile fabrics by first conditioning each specimen for at least 24 h at 21 ± 1 °C and 65 ± 2% RH under ASTM D1776, then mounting the specimen on a 152 mm diameter hoop and placing it at a 45° angle beneath the nozzle of an HY0813 Spray Rating Tester. A volume of 250 mL of distilled water at 27 ± 1 °C was poured through the tester's funnel, allowing the water to spray uniformly over the fabric surface within 25-30 seconds. After spraying, the specimen was gently tapped to remove excess water, and the wetted pattern was visually compared to the AATCC spray test rating chart. A rating from 0 (complete wetting) to 100 (no wetting) was assigned based on the extent of surface wetting, with higher ratings indicating better water repellency. Five samples were tested to ensure reproducibility.

**Oil repellency hydrocarbon resistance test**

AATCC 118 oil repellency hydrocarbon resistance test was employed to quantitatively assess the oil repellency of textile fabrics by evaluating their resistance to wetting by a graded series of hydrocarbon liquids. Specimens were conditioned for a minimum of 4 hours at 21 ± 1 °C and 65 ± 2% relative humidity in accordance with ASTM D1776 to ensure consistent moisture content. The test was conducted by placing fabric samples flat on blotting paper, then carefully

applying droplets (approximately 5 mm in diameter) of standardized test liquids using silicone-free apparatus to prevent surface contamination. Each droplet was observed for 30 ± 2 seconds at a 45° angle to detect any visible signs of wetting, wicking, or loss of surface tension. The evaluation proceeded sequentially from the lowest-numbered liquid until wetting occurred, and the oil repellency rating was assigned as the highest-numbered liquid that did not cause visible fabric wetting. Five samples were tested to ensure reproducibility. This method provided a precise and reproducible means to evaluate the efficacy of oil-repellent finishes on textiles.

**Bending length**

The cantilever standard, as specified in ASTM D1388, was used to measure bending length by placing a conditioned fabric strip on a smooth horizontal platform and advancing it at a constant rate until its free end sagged under its own weight to 41.5° below the horizontal at that precise angle, the overhanging length was recorded as the bending length. Five strips, cut to standardized dimensions and tested in both warp and weft directions, were measured, and their lengths were averaged to yield a representative value.

**RESULTS AND DISCUSSION**

**Crease recovery**

The results of crease recovery (easy-care) finishes are demonstrated in Figure 1. In this study, the conventional (synthetic) easy-care finish refers to the formaldehyde-based DMDHEU, while the bio-based easy-care finish is formulated with citric acid as a cross-linking agent. In cotton fabrics, the conventional easy-care finish achieves a crease recovery angle of 91.55 degrees. When utilizing the bio-based easy-care finish, this value increases to 96.3 degrees, representing a 5.1% improvement. The bio-based finish forms ester covalent bonds with the fabric via carboxylic acid groups. For PC fabrics, the conventional easy-care finish results in a crease recovery angle of 113.1 degrees and it is mainly due to the toxic DMDHEU leading to ether bond with the fabric. Polyester is more crystalline as compared to cotton, subsequently it exhibited superior crease recovery angle to that of cotton. However, the bio-based version yields a crease recovery angle of 104.4 degrees, indicating only 7.7% decrease as compared to the synthetic alternative. 100% polyester fabrics treated with the conventional easy-care finish show a crease recovery angle of 135.35 degrees. The application of the bio-based easy-care finish further enhances this to 139.2 degrees, marking a 3.0% improvement. Silk fabrics with easy-care finish, both conventional and bio-based, achieve a crease

recovery angle of 135.35 degrees. These results indicate that the easy-care finish, particularly the bio-based variant for cotton and 100% polyester, can substantially improve crease recovery angles.

Research indicates that easy-care finishes function by forming cross-links with textile fabric.<sup>31</sup> The bio-based agents, such as polycarboxylic acids, provide an eco-friendly alternative to traditional chemical agents. They are expected to play a key role in sustainable ways of making textiles. Still, the success of bio-based finishes depends on both the fabric type and the types of materials used. The use of bio-based agents in cotton could result in cross-linking with the cellulose molecules. All things considered, the easy-care finish does an excellent job in helping fabric recover from creases. When it comes to fabric, bio-based options have other benefits and

meet the industry's goals for environmental care. So, they could have a great future impact on the textile industry. Using citric acid as zero formaldehyde easy-care finish, for 100% cotton, showed better performance with an increase in shade depth from 12.42 to 13.56 and maintained excellent fastness values of dry rubbing 5, wet rubbing 5, fading 5, staining 5. For 100% polyester, it also performed well with a shade depth increase from 5.54 to 8.02 and good fastness ratings of dry rubbing 5, wet rubbing 5, fading 4/5, staining 5. Silk fabric also exhibited good increase with shade depth from 4 to 6.46, while maintaining high fastness values.

The detailed color properties (shade depth and fastness) of all fabrics treated with the bio-based easy-care finish are summarized in Table 2.

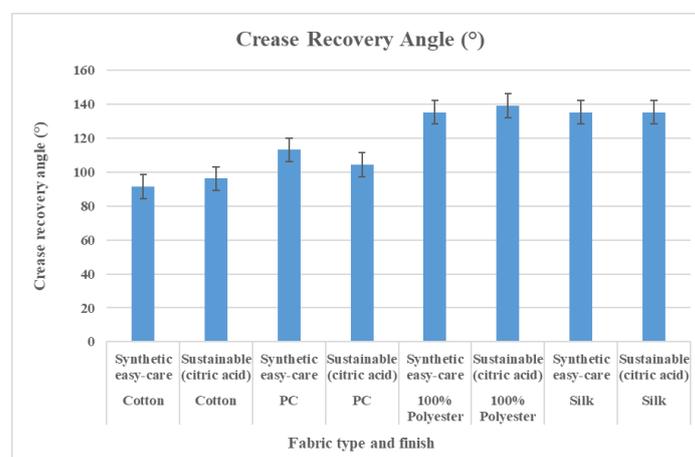


Figure 1: Crease recovery angle of digitally printed finished fabrics with bio (sustainable) and commercial finishing (synthetic) recipes

Table 2  
Color properties of printed and finished samples by using bio easy-care finish

Sr No	Substrate	Shade depth before finishing	Shade depth after finishing	Crocking fastness		Washing fastness	
				Dry rubbing fastness	Wet rubbing fastness	Fading	Staining
1	100% Cotton	12.42	13.56	5	5	5	5
2	100% Polyester	5.54	8.02	5	5	4/5	5
3	Silk	4	6.46	5	4/5	5	5
4	Polyester/cotton	3.86	5.022	5	5	5	5

### Fire retardancy

The fire-retardant finish demonstrates varying degrees of fire resistance across different fabric types, as shown in Figure 2. In cotton fabrics, conventional fire-retardant finish results in a char

width of 1.305 cm and a char length of 2.175 cm. However, the conventional fire-retardant finish, Pyrovatex CP New contains toxic and carcinogenic formaldehyde and halogen. In contrast, DAP along with the bio-based fire-retardant finish yields a

char width of 1.465 cm and the same char length of 2.175 cm. Compared to the conventional finish, the bio-based finish increases the char width by 12.26%, suggesting slightly inferior fire resistance.

For polyester-cotton (PC) fabric, the conventional fire-retardant finish produces a char width of 1.155 cm and a char length of 2.175 cm. The bio-based finish maintains the same char width, but slightly increases the char length to 2.280 cm – a 4.83% rise, indicating a marginal decline in fire resistance. In 100% polyester fabrics, the conventional fire-retardant finish results in a char width of 1.056 cm and a char length of 2.005 cm. However, the bio-based finish achieves a char width of 0.890 cm and a char length of 1.740 cm, representing a significant 15.72% decrease in char width and a 13.22% decrease in char length, thus markedly improving fire resistance. For silk fabrics, conventional fire-retardant finish leads to a char width of 1.670 cm and a char length of 2.440 cm. The bio-based finish reduces these to 1.590 cm and 2.175 cm, respectively, a 4.79% decrease in char width and a 10.86% decrease in char length, enhancing fire resistance.

This indicates that the bio-based fire-retardant finish performs quite well on 100% polyester fabrics, significantly reducing char width and length. On cotton and silk fabrics, it also shows some improvement in fire resistance compared to conventional finishes, while on PC fabrics, it slightly underperforms conventional finishes. Research indicates that fire retardant finishes primarily function by forming a protective layer on the fabric surface to prevent flame spread and inhibit combustion.<sup>32</sup> The performance of bio-

based fire-retardant agents varies across different fabric types due to differences in fiber composition and structure, as well as the compatibility between bio-based agents and fibers. For instance, in 100% polyester fabrics, DAP along with the bio-based agent can form a stable protective layer on the polyester fiber surface, effectively inhibiting combustion. In cotton and silk fabrics, DAP along with the bio-based agent may be more compatible with the fibers, enabling the formation of a more effective protective layer and improving fire resistance. However, in PC fabrics, the interaction between DAP along with the bio-based agents and the cotton-polyester fibers produces a protective layer on the fabric surface, but it may be less efficient than in the case of the 100% cotton because of the presence of the hydrophobic polyester portion in the blend, thus exhibiting a slightly lower fire resistance compared to the fire retardant finished 100% cotton fabric.<sup>33,34</sup>

Overall, the fire-retardant finish, particularly the bio-based variant, shows significant potential in enhancing the fire resistance of various fabric types, aligning with the trend of eco-friendly development in the textile industry. The shade depth of the fire retardant finished digitally printed fabric demonstrated improvement in shade depth for cotton, polyester, polyester-cotton and silk treated fabrics (Table 3). In addition, there was slight improvement in fastness properties of the finished fabrics as well.

**Air permeability**

The air permeability data presented in Figure 3 reveal how different fabric finishes impact breathability.

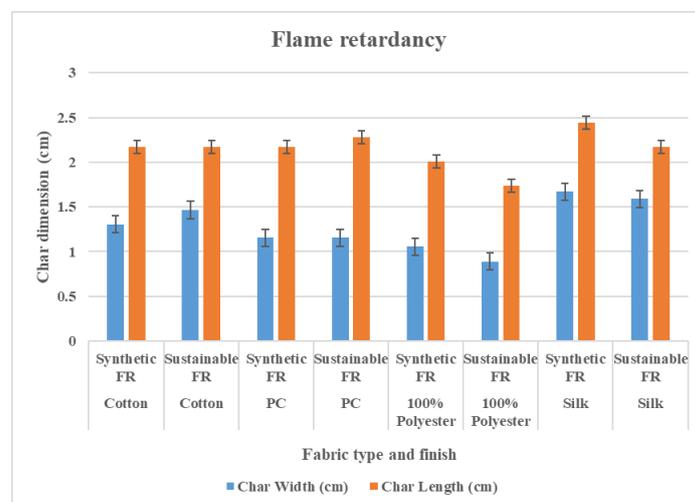


Figure 2: Char length and char width of digitally printed finished fabric samples

Table 3  
Color properties of printed and finished samples by using bio-fire-retardant finish

Sr No	Substrate	Shade depth before finishing	Shade depth after finishing	Crocking fastness		Washing fastness	
				Dry rubbing fastness	Wet rubbing fastness	Fading	Staining
1	100% Cotton	12.42	12.96	5	5	4/5	4/5
2	100% Polyester	5.54	5.98	5	4/5	5	4
3	Silk	4	6.08	5	4/5	5	4
4	Polyester/cotton	3.86	4.87	4/5	4/5	4/5	4/5

For cotton fabrics with easy-care finish, the conventional air permeability is 26.1 mm/min, while the bio-based version increases this to 30.55 mm/min – a 17.05% improvement. The softener finish on cotton enables a conventional air permeability of 30.45 mm/min, with the bio-based version rising to 33.06 mm/min, with an 8.57% increase. The cotton treated with the fire retardant finish has a conventional air permeability of 17.2 mm/min, but the bio-based version drops to 13.05 mm/min, with a 24.13% decrease. The cotton samples treated with oil and water repellent finish sees a conventional air permeability of 21.75 mm/min, while the bio-based version also decreases it to 13.05 mm/min, with a 39.98% reduction.

For PC with easy-care finish, the conventional air permeability is 139.2 mm/min, and the bio-based version decreases it to 104.4 mm/min, with a 24.99% drop. PC with softener finish has a conventional air permeability of 180.3 mm/min, with the bio-based version reducing it to 147.9 mm/min – a 17.97% decrease. PC with fire

retardant finish shows a conventional air permeability of 56.6 mm/min and the bio-based treatment gave 52.2 mm/min, with a 7.77% reduction. PC with oil and water repellent finish has the conventional air permeability of 79.5 mm/min, while the bio-based version decreases it to 74.45 mm/min, with a 6.35% drop.

For 100% polyester with easy-care finish, the conventional air permeability is 69.6 mm/min, but the bio-based version surges it to 190.4 mm/min, with a remarkable 173.61% increase. The softener finish on 100% polyester leads to a conventional air permeability of 82.8 mm/min, and the bio-based version also increases it to 190.4 mm/min, with a 130.00% improvement. The fire retardant finish on this fabric type shows a conventional air permeability of 18.92 mm/min and the bio-based version – 122.2 mm/min, with a massive 540.54% increase. The oil and water repellent finish on 100% polyester leads to a conventional air permeability of 34.8 mm/min, while the bio-based version decreases it to 39.15 mm/min, with a 12.46% increase.

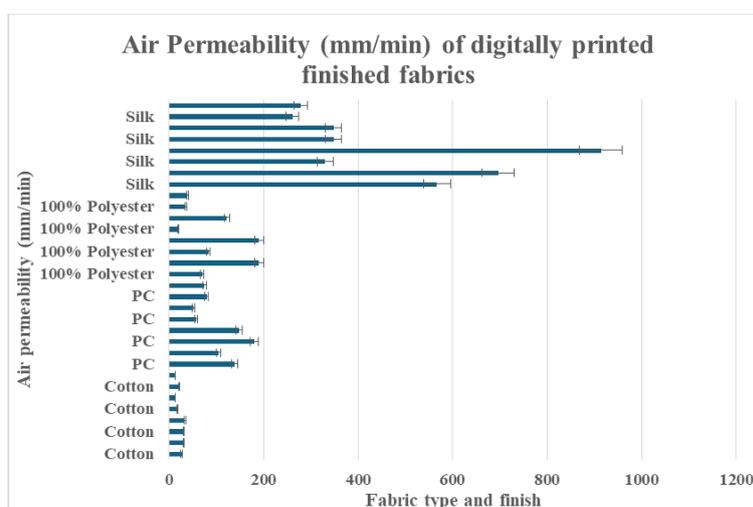


Figure 3: Air permeability of digitally printed finished fabric samples

Silk treated with easy-care finish has a conventional air permeability of 567 mm/min, and the bio-based version doubles it to 696 mm/min – a 22.75% improvement. Silk with softener finish shows a conventional air permeability of 330.6 mm/min, with the bio-based version soaring to 913.5 mm/min, with a 176.35% increase. The fire retardant finish on silk has a conventional air permeability of 348 mm/min, and the bio-based version maintains the same value. Lastly, the oil and water repellent finish on silk leads to a conventional air permeability of 261 mm/min, while the bio-based version increases it to 278.4 mm/min, with a 6.67% improvement.

Overall, the bio-based finish significantly enhances air permeability on 100% polyester and silk fabrics, particularly in the easy-care, softener, and fire retardant finishes, while showing mixed results on cotton and PC fabrics. This could be due to differences in fiber composition and the compatibility of bio-based agents with different fabrics. For instance, the chemical structure of bio-based agents might align better with polyester and silk fibers, enhancing breathability. In contrast, cotton and PC fabrics might not interact as effectively with bio-based agents, leading to varied outcomes. These findings provide valuable insights for textile manufacturers aiming to improve fabric breathability through sustainable treatments.

**Oil and water repellency**

The water and oil repellency data revealed different levels of performance across various fabric types and finishes, as shown in Table 4. For conventional finishes, cotton and PC with oil and water repellent finishes both achieved a water repellency of 70 and an oil repellency of 3.48. In contrast, 100 percent polyester and silk with conventional oil and water repellent finishes showed lower water repellency values of 60.6, but

slightly better oil repellency values of 2.64 for polyester and 3.48 for silk. It is important to note that fluorocarbon based synthetic oil and water repellent finish is toxic and subject to increasing regulatory restrictions onto textiles.

When examining bio-based finishes, cotton showed reduced water repellency of 61.1 and oil repellency of 1.74. PC maintains water repellency at 70, but sees a significant drop in oil repellency to 0.87. 100% Polyester with bio-based finish improves water repellency to 79.5, but reduces oil repellency to 1.74. Silk with bio-based finish also enhances water repellency to 69.6, but decreases oil repellency to 0.87. Overall, conventional finishes generally outperform bio-based ones in oil repellency across all fabric types. In terms of water repellency, bio-based finishes show mixed results: they perform lower on cotton, but better on 100% polyester and silk. This indicates that the effectiveness of bio-based finishes varies depending on the fabric type and specific finish applied.

The superior performance of synthetic finishes in oil repellency is attributed to the toxic fluorocarbon. However, the improved water repellency on certain fabrics suggests that bio-based agents may have better affinity or interaction with specific fiber types, enhancing water resistance. These findings highlight the need for further optimization of bio-based formulations to achieve a balance between water and oil repellency ,while maintaining environmental benefits.

Bio oil and water repellent finish for 100% cotton fabric showed a modest improvement in shade depth and maintained excellent fastness values of dry rubbing 5, wet rubbing 5, fading 5, staining 5 (Table 5). For 100% polyester, it also showed a slight improvement in shade depth and good fastness values of dry rubbing 5, wet rubbing 4/5, fading 5, staining 5.

Table 4  
Color properties of printed and finished samples by using bio-oil and water repellent finish

Sr No	Substrate	Shade depth before finishing	Shade depth after finishing	Crocking fastness		Washing fastness	
				Dry rubbing fastness	Wet rubbing fastness	Fadin g	Staining
1	100% Cotton	12.42	12.71	5	5	5	5
2	100% Polyester	5.54	6.86	5	4/5	5	5
3	Silk	4	6.15	5	4/5	5	5
4	Polyester/cotton	3.86	4.21	5	5	5	5

Table 5  
Oil and water repellency of digitally printed finished fabric samples

Finish type	Fabric	Oil repellency	Water repellency
Conventional oil and water repellent	Cotton	3.5	70
	PC	3.5	70
	100% Polyester	2.5	60
	Silk	3.5	60
Bio-based oil and water repellent	Cotton	1.5	60
	PC	1.0	70
	100% Polyester	1.5	80
	Silk	1.0	70

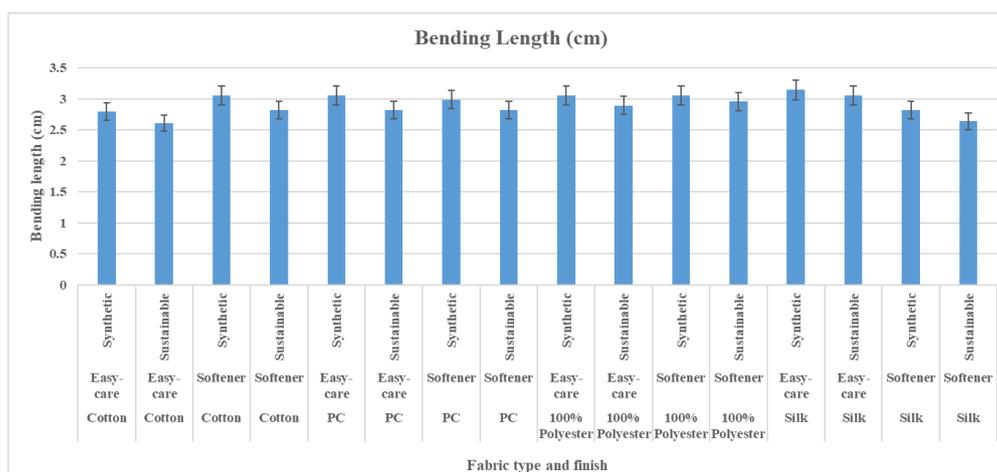


Figure 4: Bending length of digitally printed finished fabric samples

Silk fabric had a slight increase in shade depth and maintained high fastness values of dry rubbing 5, wet rubbing 4/5, fading 5, staining 5. Polyester/cotton fabric also showed a slight improvement and high fastness values of dry rubbing 5, wet rubbing 5, fading 5 and staining 5.

### Softness

Bending length analysis demonstrates how different fabric finishes modulate the stiffness of the fabrics (Fig. 4). For cotton fabric with easy-care finish, the conventional bending length was 2.8 cm, while the bio-based version reduced it to 2.61 cm, which was a 6.79% decrease. Cotton with softener finish had a conventional bending length of 3.055 cm and the bio-based version reduced it to 2.816 cm, which was a 7.82 percent decrease. For PC fabric with easy-care finish, the conventional bending length was 3.055 cm and the bio-based version reduced it to 2.816 cm, showing a 7.82 percent drop. The PC softener finish showed a bending length of 2.99 cm after the conventional treatment and 2.816 cm after the bio-based one, which was a 5.82 percent decrease. In the case of 100 percent polyester with easy-care finish, the

conventional bending length was 3.055 cm and the bio-based version reduced it to 2.895 cm, which was a 5.24 percent reduction. The softener finish on 100 percent polyester led to a bending length of 3.055 cm for the conventional treatment and 2.958 cm for the bio-based one, which was a 3.18 percent decrease. Silk with easy-care finish showed a bending length of 3.144 cm for the conventional treatment and 3.055 cm for the bio-based version, which was a 2.83 percent decrease. Silk with softener finish had a conventional bending length of 2.816 cm and the bio-based version reduced it to 2.64 cm, showing a 6.25 percent drop.

In general, the bio-based finishes reduced the bending length for all fabric types, which showed that the fabrics became softer.<sup>35</sup> The bio-based finishes exhibited better softness due to the physical modification of the fabric surface and the lubricating nature of natural-derived compounds. This results in a cleaner, smoother fabric that avoids the waxy or greasy feel sometimes associated with conventional synthetic softeners.

The softening effect was more noticeable in cotton and PC fabrics with softener finish. This showed that bio-based agents worked better for

these fabrics. The results also showed that bio-based finishes helped keep or improve softness, while being more environment-friendly. These findings would be helpful for textile makers, who are interested in finding better and greener ways to make soft fabrics. Softener finished fabric of 100%

cotton showed a slight increase in shade depth and maintained good fastness values of dry rubbing 4/5, wet rubbing 4/5, fading 4/5, staining 4/5 (Table 6). Similarly, 100% polyester fabric also exhibited a slight increase in shade depth, but maintained good fastness values.

Table 6  
Color properties of printed and finished samples by using bio-silicone softener

Sr No	Substrate	Shade depth before finishing	Shade depth after finishing	Crocking fastness		Washing fastness	
				Dry rubbing fastness	Wet rubbing fastness	Fading	Staining
1	100% Cotton	12.42	13.15	4/5	4/5	4/5	4/5
2	100% Polyester	5.54	6.81	4/5	4/5	4/5	5
3	Silk	4	4.37	4/5	4	4/5	4
4	Polyester/cotton	3.86	4.56	4/5	4/5	4/5	4/5

**CONCLUSION**

This study examined the application of both bio-based and synthetic textile finishing agents onto digitally printed fabrics using conventional finishing methods, bridging the gap between modern coloration techniques and traditional finishing processes. While digital printing has revolutionized textile coloration by enabling high-resolution, customized patterns with reduced environmental impact, the subsequent functionalization of these digitally printed substrates has largely remained tied to conventional, resource-intensive practices. This research sought to evaluate how different finishing chemistries perform when applied through traditional means on digitally printed cotton, polyester-cotton blends, polyester, and silk fabrics. The selected finishing functions included crease resistance, softness, flame retardancy, and oil and water repellency.

In terms of wrinkle resistance, bio-based finishes demonstrated substantial improvements in crease recovery, particularly in cotton (5.1%) and polyester (3.0%) substrates, indicating that citric acid effectively formed ester based crosslinked networks with both cellulosic and synthetic fibers. Air permeability results showed better improvement with bio-based softener treated polyester fabrics. These results suggest that the molecular size and affinity of fatty acids may facilitate better pore accessibility, causing less surface blockage than bulkier synthetic softeners.

Flame retardancy tests revealed superior performance of bio-based finishes in polyester, as evidenced by reduced char length (13.22%) and width (15.72%). This indicates that diammonium

hydrogen phosphate along with bio citric acid has a synergistic effect with synthetic fibers when applied through conventional methods, reinforcing its potential as a sustainable alternative to formaldehyde and phosphorus-based synthetic retardants.

In terms of tactile properties, bending length measurements consistently showed lower values for bio-based finishes across all fabric types, signifying softer hand feel, without the need for silicone-based agents. Color properties of all four fabrics for the four finishes exhibited better shade depth as compared to non-finished fabric. In addition, there was improvement in fastness properties of the finished fabric as well. These results underscore the compatibility of bio-based chemistry with conventional application techniques, even when used on modern, digitally printed substrates. However, oil repellency remained a limitation for bio-based finishes, particularly in cotton and polyester-cotton fabrics, where performance dropped significantly compared to toxic fluorinated synthetic finishes. This underperformance is chemically expected, given the absence of fluorine or similar low-surface-energy groups in bio-based molecules. In contrast, water repellency showed promising improvements on polyester and silk, suggesting the potential for fabric-specific strategies that leverage fiber finish interactions more effectively.

Overall, this study validates that bio-based finishes, even when applied through traditional methods, can provide competitive functional performance on digitally printed textiles. Importantly, these findings reinforce the feasibility of combining digital coloration with sustainable

finishing practices, even within the constraints of conventional application infrastructure. From a practical standpoint, the study underscores the viability of integrating bio-based finishing technologies into existing production pipelines that already utilize digital printing, allowing manufacturers to pursue incremental yet impactful sustainability goals. By demonstrating that many bio-based formulations can perform on par with, or even exceed, synthetic ones under standard finishing conditions, this research advocates for a broader rethinking of functional finishing strategies toward a more sustainable, fiber-specific, and technologically cohesive textile manufacturing paradigm.

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