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A critical review of cellulase bio-polishing of yarn-dyed cotton knitted fabrics: mechanistic effects on surface hairiness, pilling kinetics, reactive dye migration, and structural performance

Abstract

This critical narrative review synthesizes the physicochemical and tribological mechanisms governing cellulase bio-polishing of yarn-dyed cotton weft-knitted fabrics, examining the coupled relationships among surface refinement, multi-color stability, and biaxial mechanical integrity. While yarn-dyed cotton weft knits provide multidirectional extensibility, thermo-physiological comfort, and sharp chromatic definition across feeder stripes, checks, and jacquards, their open curvilinear loop geometry and low-twist staple yarn construction render them susceptible to protruding microfibrils (hairiness) and tribological pilling. Cellulase bio-polishing, using synergistic endoglucanases (EC 3.2.1.4), cellobiohydrolases (EC 3.2.1.91), and β-glucosidases (EC 3.2.1.21) coupled with hydrodynamic shear, selectively hydrolyzes β-1,4-glycosidic linkages within sterically accessible amorphous domains, permanently excising surface fuzz. In multicolored yarn-dyed structures, however, wet-finishing optimization is uniquely constrained by aqueous color migration, wherein substantively bound hydrolyzed reactive dyes and enzymatically cleaved dyed cello-oligosaccharides desorb from dark donor courses and redeposit onto adjacent bleached white or pastel loops. Exceeding critical operational thresholds induces secondary cell-wall erosion, excessive mass per unit area (GSM) loss, multidirectional diaphragm bursting-strength reduction, relaxation shrinkage, perceptible shade drift ($\Delta E00$), and white-stripe cross-staining. Finally, we establish constrained multi-response optimization frameworks that integrate Response Surface Methodology (RSM), desirability functions, standardized micro-aperture spectrophotometry, and industrial jet hydrodynamic scale-up for sustainable, right-first-time wet processing.

Keywords: weft-knitted fabric, cellulase bio-polishing, pilling kinetics, reactive dye desorption, cross-staining, multi-response optimization

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Bashir Ahmed,[1] Md Ahshan Habib,[2] Md Asfikur Rahman,[1] Al-Khalid Kheal[1]
1Department of Apparel Manufacture & Technology (AMT), Sonargaon University (SU), Bangladesh
2Department of Fashion Design & Technology (FDT), Sonargaon University (SU), Bangladesh

Correspondence: Md. Ahshan Habib, Department of Fashion Design & Technology (FDT), Sonargaon University (SU), Dhaka, Bangladesh

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Introduction

Industrial significance and tribological vulnerabilities of yarn-dyed knits

The textile and apparel sector serves as a vital macroeconomic pillar across garment-exporting nations such as Bangladesh, driving industrial employment and foreign-exchange earnings.[1,2] Because wet-processing operations consume vast quantities of groundwater, thermal steam, and chemical auxiliaries, engineering right-first-time finishing protocols is an operational and environmental imperative.[1–3] Cotton weft-knitted fabrics dominate global casualwear and activewear markets due to their intermeshed curvilinear loop architecture.[4,5] Unlike orthogonal woven fabrics, interconnected needle and sinker loops slide, bend, and rotate at crossover points under low stress, imparting high biaxial extensibility, three-dimensional formability, air permeability, and soft tactile comfort.[4–6]

Yarn-dyed weft knits occupy a high-margin commercial segment.[7,8] Winding staple-spun cotton onto perforated bobbins for pressurized package dyeing prior to knitting enables sharp horizontal stripes, auto-stripes, checks, and jacquards that piece-dyeing cannot replicate and pigment printing's stiff binder film avoids.[7,8] However, because high-contrast chromatic interfaces are permanently locked into the fabric prior to wet finishing, subsequent aqueous treatments must operate within strict thermodynamic boundaries to prevent cross-contamination.[9–11]

Despite these ergonomic advantages, cotton weft knits are intrinsically vulnerable to surface hairiness and tribological pilling due to open loop geometries and low-twist staple yarns.[12–14] Hairiness denotes protruding fiber ends, arched loops, or wild fibers escaping the yarn core,[15,16] governed by fiber length distribution, short fiber content (SFC), and micronaire;[17] spinning triangle geometry across conventional ring, compact, open-end (OE) rotor, or vortex (MVS) systems;[18,19] yarn linear density and twist;[20,21] and abrasive shear against knitting elements.[22] Crucially, alkaline package scouring, reactive dyeing, and high-speed winding strip native cuticular waxes and elevate friction coefficients, amplifying baseline hairiness before loop formation.[7,23] Optically, protruding microfibrils induce diffuse light scattering ("frosting"), reducing apparent color depth (K/S) and blurring stripe boundaries.[11,16] Mechanically, surface hairs act as the structural precursor to pilling during wear and laundering,[22,24] evolving through fuzz formation, entanglement into neps anchored by bridging fibers, and anchor-fiber fatigue wear-off.[13,24,25] Because knitting yarns employ low twist multipliers ($\alpha e \approx 3.2–3.8$) to prevent single-jersey spirality, radial inter-fiber clamping pressure is reduced, accelerating fuzz generation ($k$form) relative to wear-off ($k$wear).[13,21,26]

Cellulase surface refinement versus reactive dye migration constraints

While thermal singeing causes uneven fiber removal and yellowing on circular knits, and topical softeners wash off progressively and alter shade (ΔE),[27] enzymatic bio-polishing utilizing cellulase complexes

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comprising endoglucanases (EGs, EC 3.2.1.4), cellobiohydrolases (CBHs, EC 3.2.1.91), and β-glucosidases (EC 3.2.1.21) catalyzes the selective hydrolysis of β-1,4-glycosidic bonds in protruding amorphous microfibrils.[28–30] Coupled with hydrodynamic shear, embrittled hairs fracture cleanly, yielding durable pilling resistance and reduced microfiber shedding.[20,29,31,32]

However, applying bio-polishing to multicolored yarn-dyed knits introduces acute colorimetric constraints.[9,10,28] Yarn-dyed stripes use anionic monochlorotriazine (MCT), vinylsulfone (VS), or bifunctional (MCT/VS) reactive dyes.[9,10,27] Competing alkaline hydrolysis during package dyeing converts 10–30% of the bath into inactive hydrolyzed dye that remains substantively adsorbed within dense bobbins.[7,9,10] Furthermore, enzymatic cleavage of dyed surface microfibrils liberates soluble dye–cello-oligosaccharide complexes into the shared liquor.[28,29,33] Elevated temperatures (>50 □C), extended dwell times, low liquor ratios, and mechanical shear mobilize these desorbed species to redeposit onto adjacent white loops, causing irreversible cross-staining and shade drift ($\Delta E00$).[9,10,31,32,34] Simultaneously, over-hydrolysis erodes load-bearing secondary walls at loop crowns, causing excessive mass (GSM) loss (>3.5–5.0%), severe bursting-strength reduction (>15–25%), and relaxation shrinkage.[12,33,35–38]

Research gaps and scope of the review

Reviewing literature across hairiness,[17–19,24] pilling,[13,25,26] cellulase kinetics,[12,28,29,35,36] and dye desorption,[9,10,32,35] highlights four gaps:

i. lack of coupled surface-and-coloration studies on striped knits;[9,10,12,35,36]

ii. fragmented comparison of acid, neutral, and bacterial cellulases regarding dye bond scission and shade drift;[26,28,29,33]

iii. metrological confusion in distinguishing in-bath cross-staining from dry storage transfer;[10,11,39,40]

iv. absence of validated multi-response optimization frameworks scaled to industrial jet machinery.[31,33,41]

This review synthesizes these domains across Sections 2.0 to 5.0.

Literature review

Engineering and wet-processing of yarn-dyed cotton knitted fabrics

Knitted textiles are engineered by intermeshing continuous yarn loops longitudinally along wales (warp knitting) or horizontally across courses (weft knitting).[4] Cotton weft-knitted structures encompassing plain single jersey, 1×1 and 2×2 ribs, interlock, pique (Lacoste), and double-jersey jacquards dominate global apparel due to their versatility and thermo-physiological comfort.[4,13,26,41] In plain single jersey, each loop is drawn through the preceding one on a single needle bed, producing a technical face of vertical wales and a technical back of sinker loops.[4,13] Because constituent yarns follow a three-dimensional curvilinear path rather than an orthogonal tensioned trajectory, adjacent loops slide, bend, and rotate at crossover points under stress, imparting high biaxial extensibility, low initial modulus, hemispherical formability, and permeability.[4–6] However, this open architecture exposes a large specific yarn surface area at loop crowns to external contact and friction.[6,13,26] To prevent single-jersey course spirality and preserve softness, knitting yarns utilize lower twist multipliers than weaving yarns, reducing radial inter-fiber clamping pressure and promoting fiber protrusion, relaxation shrinkage, and pilling.[13–15,21]

Unlike piece-dyed knitwear, yarn-dyed knits are fabricated from staple cotton yarns pre-colored via pressurized batch package dyeing.[7] The sequential workflow includes spinning, precision winding onto perforated bobbins, radial-flow package dyeing and wash-off in autoclaves, hydro-extraction, drying, paraffination, circular knitting, and post-knitting wet finishing.[7,23] Minor heterogeneities in package winding density or yarn tension alter local hydraulic permeability under alternating liquor flow, causing radial shade variations that manifest as periodic color barring.[7] Furthermore, alkaline package scouring, bleaching, and reactive dyeing strip natural cuticular waxes and deposit electrolytes and dye molecules, elevating friction coefficients.[23] Hydrodynamic shear inside autoclaves and mechanical drag across extra high-speed winding cycles (soft winding before dyeing and hard-cone back-winding after) disturb surface fibers and elevate baseline hairiness prior to knitting.[7,22,23]

Arranging pre-dyed or color-spun mélange yarns8 across multiple circular knitting feeders enables complex feeder stripes, auto-stripes, checks, and jacquards without the stiff binder film of pigment printing.[7,8] However, maintaining visual quality in high-contrast structures (e.g., deep reactive black, navy, or crimson adjacent to bleached white courses) requires preserving chromatic contrast at zero-separation course boundaries.[9–11,42] As Mirjalili et al.[11] demonstrated through color-difference modeling (ΔE_NS), human visual sensitivity to chromatic shifts is amplified when two colored fields share direct physical contact. Because greige yarn-dyed knits accumulate paraffin wax, needle oils, and take-down strain during knitting, post-knitting wet finishing (scouring, bio-polishing, softening, drying, compaction) is mandatory.[5,6,12,22,23,27,37] Yet, because every shared aqueous bath exposes dark donor courses and white acceptor courses to the liquor, unoptimized finishing triggers reactive dye desorption, white-stripe cross-staining, auxiliary shade drift,[27] or enzymatic strength loss.[36]

Origins and metrology of surface hairiness

Hairiness denotes individual fiber ends, arched loops, or wild fibers projecting outward from the yarn core or fabric plane.[15,26] Quantitative yarn hairiness metrology relies on three primary approaches.

Diffuse Light Scattering (Uster Hairiness Index, H)

Infrared light illuminates yarn moving at 400 m/min, and scattered light from protruding fibers is measured to yield H (total protruding length in cm per 1-cm yarn field).[15,18,21] While rapid, H aggregates short (<2 mm) and long (≥3 mm) hairs into a single scalar.[15,18]

Photoelectric Length-Class Counting (Zweigle S_3 Metric)

Optical sensors count individual protruding fibers at discrete distances (1 to 12 mm) from the yarn edge.[17–19] The S_3 value (cumulative fibers ≥3 mm per 100 m) predicts knitting lint and pilling because long hairs span inter-loop spaces to entangle with adjacent courses.[17,19,21,24]

Relative Hairiness Index and Fabric Profilometry

Huang et al.[15] formulated a Relative Hairiness Index normalizing protruding fiber count against theoretical fiber security. At the fabric level, optical profilometry, laser triangulation, and digital image analysis quantify surface fuzz across finishing stages.[16,21]

Raw *Gossypium* fiber properties govern baseline hairiness.17 Lots with high short fiber content (SFC < 12.7 mm) and low upper-half mean length (UHML) exhibit elevated hairiness because short fibers lack the critical embedding length to wrap securely into the yarn

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core.[17] During twist insertion, longer, finer fibers migrate radially toward the axis, whereas shorter, coarser, high-micronaire fibers with high flexural rigidity are displaced to the periphery, projecting rigid trailing ends outward.[17,21] Pre-spinning combing removes short fibers and neps, yielding lower H and S_3 values than carded equivalents.[13,17,21]

Spinning consolidation kinematics establish a clear hairiness hierarchy (Vortex (MVS) < OE Rotor < Compact Ring < Conventional Ring)[12,17–19,21]:

Conventional Ring vs. Compact Spinning

Conventional ring spinning forms a wide spinning triangle where edge fibers escape full core integration.[18] Compact spinning introduces pneumatic/mechanical condensing, virtually eliminating the spinning triangle, suppressing S_3 hairiness, and enhancing tenacity.[17,18,21]

Open-End (OE) Rotor vs.Air-JetVortex (MVS) spinning

OE rotor yarns bind fibers with exterior wrapper fibers, yielding lower optical hairiness (H) than conventional ring yarns.[12,19] In contrast, Murata Vortex Spinning (MVS) utilizes high-velocity compressed air vortices inside a nozzle block to whip open trailing fiber ends tightly around a parallel, twistless core, producing a two-part structure with the lowest hairiness across all length classes and superior pilling resistance.[12,18,43] As detailed by Turşucular,[43] the structural and mechanical performance of MVS yarns is governed by yarn type (100% cellulosic staple, blended, or core-spun configurations), yarn linear density (tex or dtex), and, in hybrid or filament-core systems, the filament number and comparative spinning/texturing technologies such as bulked continuous filament yarn (BCY), air-textured yarn (ATY), and drawn textured yarn (DTY). Because nozzle vortex pressures increase wrapper-fiber ratio and radial packing density as linear density (tex/dtex) and filament integration are optimized, MVS architectures significantly influence key yarn mechanical properties specifically elasticity modulus (E, GPa) and tensile strength (MPa) balancing axial stiffness and breaking tenacity against surface fuzz suppression.[19,43]

Across all spinning systems, coarser yarns (higher tex or dtex / lower Ne) contain a greater number of fibers or filaments in the cross-section and a larger specific perimeter, increasing baseline hairiness and microfiber shedding.[20,21,43] While higher twist multipliers suppress hairiness and pilling,[21,24] weft-knitted yarns use low twist factors ($\alpha_e \approx 3.2–3.8$) to prevent spirality.[13,21] When low-twist packages lose natural waxes during reactive dyeing and undergo high-speed back-winding and circular knitting over creel tubes, tension discs, storage feeders, sinkers, and latch needles, abrasive shear pulls loose loops outward.[22,23] Differential dye and electrolyte loading between dark reactive-dyed yarns and bleached white yarns creates unequal friction across knitting feeders, inducing uneven hairiness, machine fly ("fly-in" defects), optical frosting, and aquatic microfiber release during laundering.[20,22,23,33]

Pilling kinetics and structural determinants

Pilling is a dynamic tribological degradation process wherein tangled spherical fiber bundles remain anchored to the fabric surface.[13,24,25] In Gintis and Mead's mode,[25] pill population reflects a kinetic competition between fuzz formation rate (k_form) and anchor-fiber wear-off rate (k_wear).[13,25] Although 100% cotton fibers exhibit lower tenacity and more brittle fracture than synthetics, cotton weft knits experience severe early-to-mid-life pilling because low-twist yarns and open loop geometry drive rapid fuzz generation (k_form > k_wear).[12–14,24,26] Protruding hairs exceeding a critical inter-loop reach (>1–2 mm) initiate immediate entanglement under low frictional energy.[15,21,24,25]

Macro-structural loop geometry stitch type, loop length (l), and tightness factor ($TF = \sqrt{tex} / l$) strongly regulates pilling.[6,13,26] Tighter structures with shorter loop lengths increase inter-yarn clamping pressure at loop crossovers, restricting fiber pull-out.[13,26] Conversely, incorporating tuck stitches (pique/Lacoste, cardigan) reduces pilling resistance because raised tuck crowns concentrate abrasive contact forces and create adjacent open pores that facilitate fiber withdrawal.[26,41] Across yarn parameters, pilling resistance follows the inverse hairiness hierarchy.[12,13,17,19–21,24] During domestic laundering, radial fiber swelling, surfactant lubrication, and mechanical tumble drying accelerate surface fibrillation and entanglement.[32,34,37] In multicolored yarn-dyed knits, inter-stripe fiber migration generates two-tone contrast pills that stand out starkly against contrasting stripe backgrounds, rendering even low pill densities visually objectionable.[11,24,39]

Biochemical kinetics and process engineering of cellulase bio-polishing

Synergistic mechanism and industrial cellulase classifications: Enzymatic bio-polishing is a controlled biochemical surface modification where cellulases catalyze the hydrolytic cleavage of β-1,4-glycosidic bonds in cotton cellulose.[28–30] Because globular cellulase proteins (20–80 kDa, hydrodynamic diameter 3–7 nm) cannot penetrate dense crystalline Cellulose I micropores, adsorption is topochemically restricted to exposed amorphous chains on protruding microfibrils.[28,29,35] Complete natural cellulase systems (*Trichoderma reesei*, *Humicola insolens*, or bacterial *Bacillus* strains[28–30,36] operate via three synergistic classes[28–30]:

a) Endoglucanases (EGs, EC 3.2.1.4)

b) Randomly cleave internal β-1,4-bonds along amorphous regions, rapidly lowering degree of polymerization (DP).[28–30]

c) Exoglucanases / Cellobiohydrolases (CBHs, EC 3.2.1.91)

d) Act processively from reducing (CBH I) and non-reducing (CBH II) chain ends to liberate cellobiose dimers while eroding crystalline domains.[28–30]

***e) β*-Glucosidases (Cellobiases, EC 3.2.1.21)**

f) Hydrolyze cellobiose and cello-oligosaccharides into β-D-glucose, preventing end-product feedback inhibition.[28–30]

$(C_6H_{10}O_5)_{nEndoglucanase}$ (EG)Exposed Chain EndsCellobiohydrolase (CBH)Cellobiose $(C_{12}H_{22}O_{11})$ $_{\beta\text{-Glucosidase}}2\beta$-D-Glucose $(C_6H_{12}O_6)$ (1)

Coupled with hydrodynamic shear, this catalytic cascade embrittles protruding hairs, fracturing them cleanly from the yarn surface.28,29,35 Commercial cellulases are classified by optimal pH and protein engineering into acid, neutral, and thermotolerant bacterial systems (Table 1).[28–30,36]

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Table 1 Comparative characteristics of industrial cellulase systems used in cotton bio-polishing (Synthesized from published literature[28–30,33,35,36])

Characteristic	Acid cellulases	Neutral cellulases	Alkaline / Thermotolerant bacterial cellulases
Typical Microbial Source	Fungal (Trichoderma reesei)[28–30]	Fungal (Humicola insolens)[28–30]	Bacterial (Bacillus amyloliquefaciens)[28,36]
Optimal pH Window	pH 4.5–5.5[28–30]	pH 6.0–7.0[28–30]	pH 7.0–9.0[28,36]
Optimal Temp. Range	45–55 ∘C[28–30]	50–60 ∘C[28–30]	50–70 ∘C[36]
Catalytic Rate & Dwell	High rate; short dwell (20–45 min)[28,29]	Moderate rate; longer dwell (30–60 min)[28,29]	Variable; high thermal and pH tolerance[36]
Mass & Strength Risk	High GSM loss (>3–5%) and strength drop if over-run[28,29,33]	Lower strength loss; broader safe operating window[28,29,33]	Low-to-moderate fiber damage depending on EG specificity[36]
Back-Staining Tendency	High dye back-staining on white cotton due to acidic protein-cellulose affinity[28,29,33]	Low back-staining; preserves white stripe contrast[28,29,33]	Low back-staining; compatible with neutral/ alkaline baths[28,36]
Deactivation Requirement	Alkaline shift (pH 9–10) and/or thermal shock (75–80 ∘C)[28,29]	High temperature (>75 ∘C) or alkaline shift (pH >9.0)[28,29]	Thermal shock (>80 ∘C) or oxidative shift[36]

Whole acid cellulases (*T. reesei*, pH 4.5–5.5) exhibit high CBH content with cellulose-binding domains (CBDs) that bind crystalline cellulose tightly, accelerating core attack, strength loss, and dye back-staining.[28,29,33] Neutral cellulases (*H. insolens*, pH 6.0–7.0) and bacterial cellulases (*B. amyloliquefaciens* M7[36]) inflict substantially less strength degradation and minimize dye back-staining on adjacent white courses.[28,29,33,36]

Multi-variable process kinetics and mechanical synergy: Heterogeneous cellulase catalysis is co-regulated by six interdependent variables[28,29,31,33,36]:

a) Enzyme Concentration: Following Michaelis-Menten kinetics, increasing dosage accelerates initial hydrolysis until surface sites saturate; excess enzyme diffuses into yarn capillaries, escalating GSM and bursting-strength loss.[29,33,35,36,38]

b) Temperature: Balances catalytic activation against protein denaturation.[28,29,36] Activity peaks at 45–55 ∘C and drops sharply above 65 ∘C.[28,33,35,36] Temperatures >50–55 ∘C exponentially accelerate desorption of hydrolyzed reactive dyes.[10,32]

c) Dwell Time: Fuzz is cleaved within 20–45 min, plateauing at pilling Grade 4–4.5.[29,33,35,36,38] Extended times (>60 min) erode structural loop crowns, causing linear weight loss and severe strength reduction.[29,33,35,38]

d) pH Profile: Regulates active-site ionization.[28,29,36] Scouring alkali causes upward drift unless buffered.[28,35,36] Because vinylsulfone ester dyes hydrolyze at high alkali (pH >9–10), neutral thermal deactivation is preferable in yarn-dyed finishing.[9,10,27–29]

e) Liquor Ratio (M:L): Lower ratios (1:6 to 1:8) elevate enzyme molarity and inter-fabric friction, accelerating defuzzing.[29,31] However, ultra-low ratios concentrate desorbed dye, accelerating white-stripe cross-staining.[9,10,31]

f) Mechanical Action: Hydrodynamic shear, nozzle flow, and tumbling are essential to fracture embrittled microfibrils and desorb bound enzymes for catalytic turnover.[28,29,31,34,35]

Physical, dimensional, and bursting-strength impacts: Controlled bio-polishing improves Martindale pilling ratings (most dramatically on ring-spun knits, rising from Grade 1–2 to 4–4.5).[12,25,35,36,38] An enzymatic dry mass loss of 1.5–3.5% yields optimal defuzzing, softer handle, and drape.[12,28,29,33,35,37,38] Wet agitation and drum drying release knitting strains, requiring tensionless drying to maintain shrinkage within ≤3–5% per ISO 6330.[6,37,40,44] Because endoglucanases nick amorphous regions at loop crossovers, multidirectional diaphragm bursting strength (ISO 13938-145) decreases monotonically with dosage, time, and weight loss.[12,28,29,33,35,36,38] While a 5–10% strength loss accompanies normal weight loss, over-polishing (>5% weight loss) induces catastrophic strength drops exceeding 20–30%.[28,29,33,35]

Thermodynamics and kinetics of color migration in yarn-dyed bio-polishing

Color migration proceeds via a three-step pathway governed by chemical potential gradients between dark donor courses and white acceptor courses[9,10,31,34,42]:

(i) Endothermic desorption across the hydrodynamic boundary layer,

(ii) Convective/diffusive transport through liquor, and

(iii) Re-adsorption onto white fibers via van der Waals and hydrogen bonding[9,10,34]:

$$D_{\text{donor fiber}} \underset{k_{des,1}}{\overset{k_{ads,1}}{\rightleftharpoons}} D_{\text{aqueous bath}} \underset{k_{ads,2}}{\overset{k_{des,2}}{\rightleftharpoons}} D_{\text{acceptor (white) fiber}} \quad (2)$$

Although monochlorotriazine (MCT) and vinylsulfone (VS) reactive dyes form covalent ester/ether bonds with cellulosate anions (Cell-O−), yarn-dyed shades remain vulnerable to bleeding via three mechanisms[7,9,10,27,28,29,33]:

(i) Residual unfixed hydrolyzed dye (10–30% from package dyeing) trapped within dense dark bobbins leaching into warm baths[7,9,10];

(ii) Covalent bond scission via alkaline β-elimination or acid hydrolysis;[9,10]

(iii) Enzymatic release of dyed cello-oligosaccharides and colored particulates driving back-staining.[28,29,33]

Desorption kinetics escalate exponentially above 50 ∘C due to pore swelling and hydrogen-bond disruption.[10,32] Mitigating cross-staining on high-contrast stripes requires pairing neutral EG-enriched cellulases (pH 6.0–7.0)[28,29,33] with non-ionic surfactants and polymeric dye-transfer inhibitors (DTIs like PVP/PVNO) to complex free dye ions and disperse colored fibrils, alongside careful post-finishing softener selection to avoid shade drift (ΔE).[10,27,29,42]

Furthermore, morphological analyses and standardized color fastness evaluations of cellulosic-based natural yarns undergoing reactive dyeing (including hybrid reactive applications with natural

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dyestuffs) confirm that alkaline and thermal processing conditions alter surface cuticular morphology, directly governing wash, water, and rubbing fastness ratings prior to enzymatic finishing.[46]

Methodology

Mechanistic narrative review framework

This study adopts a critical mechanistic narrative review framework to synthesize cross-disciplinary physical, biochemical, and thermodynamic principles rather than a pooled quantitative meta-analysis. Because yarn-dyed cotton knitwear wet processing spans disparate scales from spinning kinematics and package-dyeing hydrodynamics to heterogeneous Michaelis-Menten catalysis and coloration metrology primary studies utilize widely varying architectures and testing standards. A mechanistic narrative synthesis provides the optimal framework to integrate chemical-physical rate laws, reconcile literature contradictions, and evaluate multi-response engineering trade-offs.

Literature search strategy and eligibility criteria

Bibliographic searches were conducted across Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar, alongside official ISO and AATCC standards. Boolean queries utilized domain-specific combinations: ("cellulase" OR "bio-polishing") AND ("cotton knitted fabric" OR "yarn-dyed") AND ("hairiness" OR "pilling" OR "color migration" OR "cross-staining"). The primary literature window spanned 2000 to 2026 to reflect modern compact and vortex spinning, recombinant thermotolerant cellulases, and micro-aperture CIEDE2000 spectrophotometry, while retaining foundational works (e.g., Gintis-Mead 1959 pilling model; Cavaco-Paulo 1998 synergy framework).

Screening enforced strict criteria

Inclusion Criteria:

Peer-reviewed articles, conference proceedings, monographs, and active ISO/AATCC standards providing quantitative insights into yarn hairiness, weft-knit geometry, pilling, cellulase kinetics, reactive dye desorption, anti-backstaining agents, or statistical optimization.

Exclusion Criteria:

Unrefereed websites, preprints lacking peer review, unvalidated patents, and studies investigating non-textile biofuel saccharification or synthetic-only dyeing.

Results and discussion

Multi-response parameter interactions and antagonistic trade-offs

Wet-processing variables exert opposing effects on surface refinement, mechanical integrity, shrinkage, and color fastness in yarn-dyed cotton knits.[9,10,12,28–32,35–37] Table 2 integrates these mechanistic vectors across eight primary operational parameters.

Table 2 Synthesis of literature-based tendencies of bio-polishing, washing, and drying variables on cotton knitted fabric properties[9,10,12,28–30, 31, 32, 35–37]

Process variable	Surface hairiness reduction	Pilling resistance (ISO 12945 [47])	Mass loss (GSM reduction)	Bursting strength (ISO 13938 [45])	Dimensional stability / shrinkage (ISO 6330 [44])	Color migration / Cross-staining risk & shade shift (ΔE)
Enzyme Concentration (↑ dosage)	↑ Increases rapidly at low-to-moderate dosage; plateaus at saturation.[35,36,33]	↑ Improves by 1.0–2.5 grades up to saturation; over-dosing may roughen core.[12,35,36]	↑ Progressive mass loss (1–6%) as dosage increases.[35,36,33]	↓ Progressive strength loss; severe drop (>15–25%) at high dosage.[12,35,33,38]	Moderate effect; structural loosening at high dosage increases relaxation shrinkage.[33,38]	↑ Releases more dyed cellulose oligomers into bath, increasing back-staining risk.[28,29,33]
Bath Temperature (↑ up to 45–55 ∘C, then >60 ∘C)	↑ Peaks in optimal 45–55 ∘C range; ↓ drops sharply above 65 ∘C via denaturation.[28,35,36]	↑ Maximized within optimal thermal window of the enzyme strain.[35,36]	↑ Peaks at enzyme optimum temperature[35,36,33]	↓ Greatest strength loss occurs at peak catalytic temperature if time/dosage are high.[35,33]	↑ Higher temperatures increase loop relaxation and thermal shrinkage.[32,37]	↑↑ Critical driver: Desorption and diffusion of hydrolyzed reactive dye increase exponentially above 50 ∘C.[32,9,10]
Treatment Dwell Time (↑ duration)	↑ Most hairiness cleaved in first 20–45 min; plateaus thereafter.[29,35,33]	↑ Reaches plateau (4–4.5) at moderate time; extended time yields diminishing returns.[29,35,33]	↑ Increases almost linearly with prolonged dwell time[29,35,33]	↓↓ Continuous depolymerization of load-bearing yarn core over extended time.[29,35,33,38]	↑ Extended wet tumbling increases length/width relaxation shrinkage.[32,37]	↑ Prolonged contact time allows slow-diffusing dye to leach and stain white stripes.[32,10]
pH Profile & Enzyme Class (Acid pH 4.5–5.5 vs. Neutral pH 6.0–7.0)	Acid cellulases act faster; neutral cellulases achieve comparable smoothness with controlled dosing.[28,29,30]	Both systems achieve high pilling resistance when operated at their respective optimal pH.[28,29,30]	Acid cellulases cause higher mass loss than neutral cellulases for equivalent depilling.[28,29,33]	Neutral cellulases preserve significantly higher bursting strength than whole acid cellulases.[28,29,33]	Indirect effect via swelling and fiber damage.[28,29]	Neutral pH (6.0–7.0) minimizes back-staining; strongly alkaline deactivation (pH >9) triggers reactive dye bleeding.[28,29,9,10]
Liquor Ratio (↓ lower M:L ratio)	↑ Higher enzyme molarity and higher inter-fabric friction accelerate defuzzing.[29,31]	↑ Enhanced mechanical shear at low M:L improves pill removal.[29,31]	↑ Slightly higher weight loss due to enhanced mechanical abrasion.[29,31]	↓ Higher mechanical shear at ultra-low M:L can increase strength loss.[29,31]	↑ Higher mechanical compaction/friction at low M:L can increase shrinkage.[31]	↑↑ High risk at low M:L: Concentrated bath liquor promotes rapid redeposition of bled dye onto white yarns.[31,9,10]

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Table 2 Continued...

Mechanical Action (↑ agitation / jet shear)	↑↑ Essential synergy to break off enzymatically weakened surface fibrils.[28,29,35]	↑↑ Required for effective depilling; poor pilling grades occur in static baths.[28,29]	↑ Accelerates detachment of hydrolyzed cellulose fibrils.[29,35]	↓ Excessive agitation causes fibrillar damage and accelerates strength loss.[29,33]	↑ High hydrodynamic tension and tumbling increase loop distortion and shrinkage.[31,34]	↑ Thins diffusion boundary layer and accelerates mechanical dye loss and fibril cross-transfer.[31,34]
Post-Washing Intensity (↑ temp/ alkalinity)	Removes detached lint and terminates enzymatic hydrolysis.[28,29,33]	Stabilizes final pilling performance by halting over-hydrolysis.[28,29]	Removes loose microfibrillar debris.[32]	Prevents post-process residual enzyme strength degradation.[28,29]	Additional wet agitation contributes to cumulative relaxation shrinkage.[32]	Harsh hot/alkaline wash stops enzyme but risks stripping dye from dark stripes; DTI polymer aids required.[32,9,10,42]
Drying Conditions (Drum tumble vs. Relaxed drying)	High-temperature drum tumbling can re-raise surface fuzz if over-dried.[37]	Tumble drying can accelerate initial surface fibrillation if uncontrolled.[37]	Apparent GSM increases as fabric shrinks in length and width.[37,40]	Over-drying at excessive temperatures causes brittle fiber damage.[37]	↑↑ Drum drying significantly increases dimensional shrinkage compared to relaxed conveyor drying.[37,40]	High heat on damp, insufficiently rinsed fabric can induce thermal contact migration across stripes.[37,10]

Four fundamental antagonistic trade-offs govern process engineering in yarn-dyed cotton knitwear:

Surface defuzzing versus wall erosion

Because glycosidic bond hydrolysis is non-selective once cellulases penetrate past protruding hairs, surface smoothness and internal structural damage follow diverging kinetic trajectories.[28,29,33] EGs and CBHs initially cleave protruding microfibrils; however, once fuzz is excised, enzymes adsorb onto the outer yarn perimeter, attacking primary walls, winding layers, and load-bearing secondary walls at loop crowns.[12,28,29,33,35,36] Thus, surface improvement saturates rapidly (20–45 min), whereas internal structural damage accumulates linearly.[29,35,33]

Hairiness reduction versus contractual GSM tolerances

Excising protruding microfibrils permanently reduces dry cellulose mass.[12,28,35,38] Commercial apparel contracts enforce strict mass per unit area (GSM) tolerances (±3–5%); attempting to eliminate all surface fuzz on coarse carded ring-spun knits via high enzyme dosages induces 4–6% mass loss, pushing fabrics below specification.[12,13,33,35] Parameters must constrain weight loss within 1.5–3.0% to selectively remove pill-forming hairs (>2–3 mm).[28,29,35]

Pilling resistance versus diaphragm bursting-strength reduction

Cellulase bio-polishing enhances pilling resistance (ISO 12945[47]) by excising existing hairs and hydrolytically weakening residual surface fibers so nascent pills fracture rapidly during wear (accelerating *k*wear in Gintis-Mead[25]).25,28,29 However, this hydrolytic weakening degrades biaxial loop tenacity, depressing diaphragm bursting strength (ISO 13938[45]).[12,29,38,41,48] As Pamuk demonstrated in Lacoste knits,[41] minimizing pill density inherently depresses bursting strength, which represents a critical bottleneck in lightweight single jersey (140–180 g/m^2) where dropping below commercial minimums (220–250 kPa) causes seam rupture.[26,41,48]

Cleaning efficiency versus color migration

Proess adjustments maximizing enzymatic defuzzing (temperatures 55–60 ∘C, extended dwell times, low liquor ratios, intense jet shear, and hot alkaline deactivation) exponentially accelerate reactive dye desorption and white-stripe cross-staining.[9,10,27,28,29,31,32,34] Conversely, operating at 35 ∘C for 15 min preserves stripe contrast but leaves unhydrolyzed fuzz.[28,29,35,36] Decoupling this antagonism requires pairing neutral endoglucanases at moderate temperatures (45–50 ∘C, pH 6.0–6.8, M:L 1:8–1:10) with polymeric dye-transfer inhibitors (PVP/PVNO).[10,28,29,33,42]

Critical evaluation of colorimetric and fastness assessment protocols

A pervasive methodological flaw in technical literature is the conflation of test protocols designed for in-bath aqueous cross-staining, domestic laundering fastness, and dry storage dye transfer.[10,11] Table 3 synthesizes standard colorimetric and fastness test methods.

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Table 3 Critical comparison of colorimetric, color fastness, and dye-migration evaluation standards relevant to yarn-dyed cotton knitted fabrics

Standard / method	Official title & scope	Physical mechanism evaluated	Metric output	Applicability to yarn-dyed bio-polishing
ISO 105-A02[49] & ISO 105-A03	Textiles Tests for colour fastness Part A02/A03: Grey scale for assessing change & staining	Visual comparison of tested specimen against standard matte grey chip pairs under D65 lighting.[11,49]	Discrete visual grades (1–5) in half-grade steps.[11,49]	Essential visual benchmark for grading dark stripe shade shift (A02) and white stripe cross-staining (A03).[11,49]
ISO 105-J01 & ISO 105-J03	Measurement of surface colour & Calculation of colour differences (ΔE*ab, ΔE00)	Reflectance spectrophotometry measuring CIELAB coordinates (L∗,a∗,b∗) using small apertures.[27,11]	Continuous numerical values (ΔE00) and Whiteness Index change.[27,11]	Gold standard for objective quantification of dark yarn shade drift and trace white stripe cross-staining.[27,11]
ISO 105-C06[50] (or AATCC TM61)	Colour fastness to domestic and commercial laundering	Aqueous desorption and staining during accelerated mechanical washing (40–95 ∘C) with steel balls.[32,10,50]	ISO 105-A02/ A03 grades against adjacent multifiber fabric.32,10,50	Evaluates whether bio-polished fabrics will bleed or cross-stain during subsequent wet laundering.[32,10,50]
ISO 105-E01 & ISO 105-E04	Colour fastness to water (E01) & Perspiration (E04)	Wet contact migration under static pressure (12.5 kPa at 37 ∘C for 4 h).[10]	ISO 105-A02/A03 grades (1–5).[10]	Simulates dye bleeding when wet or damp yarn-dyed fabric sits folded in a pile or during wear.[10]
ISO 105-X12 (or AATCC TM8)	Colour fastness to rubbing (crocking)	Dry and wet mechanical friction transfer onto white cotton rubbing lawn.[12,9,33]	ISO 105-A03 staining grade (1–5).[12,9,33]	Indicator of surface cleanliness: effective bio-polishing improves rubbing fastness by removing loose dyed fuzz.[12,9,33]
AATCC TM163[51]	Colorfastness: Dye Transfer in Storage; Fabric-to-Fabric	Long-term ambient/elevated temperature storage transfer between compressed fabric layers.[51]	AATCC Grey Scale for Staining (1–5).[51]	Limited to post-finishing storage: Evaluates packed garment dye transfer; not a valid substitute for aqueous bio-polishing bleeding.[51]

Critical analysis exposes three errors:

(i) Misapplying storage-transfer standards (AATCC TM163[51]) to convective aqueous bleeding;

(ii) Relying solely on external multifiber strips during post-finishing wash tests (ISO 105-C06[50]) without quantifying dye migration onto internal white stripes during the bath

(iii) Mixing visual Grey Scale ratings with improperly sampled spectrophotometric readings where apertures straddle narrow stripe boundaries.[10,11,49–51]

To ensure validity, investigations must implement a three-tier colorimetric protocol using an ultra-small area view (USAV) spectrophotometer under D65/10□ conditions[11,27]:

1) Pre- vs. post-treatment white-stripe staining quantified via CIEDE2000 (Δ*E*00,white), Whiteness Index shift (Δ*WI*CIE), and ISO 105-A03 ratings;

2) Dark-stripe shade drift (Δ*E*00,dark and Δ(*K*/*S*)) to separate true dye stripping from optical shade deepening

3) UV-Vis spectrophotometric Beer-Lambert quantification of desorbed reactive dye in spent bath liquor.[9,11,27]

Constrained multi-response statistical optimization framework

Because hairiness reduction, pilling resistance, GSM retention, bursting strength, dimensional shrinkage, dark-stripe shade stability (Δ*E*00,dark), and white-stripe cross-staining resistance (Δ*E*00,white) respond in opposing directions to wet-processing variables, single-response optimization is fundamentally unsuitable for industrial yarn-dyed knitwear.[33,41,52] Pamuk[41] applied Response Surface Methodology (RSM) coupled with Derringer and Suich's desirability function to balance bursting strength against pill density in Lacoste knits, while Mondal and Khan,[33] Fouda et al.,[36] and Rejali et al.[52] utilized statistical designs and ANN-Pareto models for enzymatic washing and pilling optimization.

However, a unified RSM framework integrating colorimetric cross-staining (Δ*E*stain) and shade drift (Δ*E*shade) alongside hairiness (*H* or *S*3), pilling resistance (ISO 12945[47]), GSM change, shrinkage (ISO 6330[44]), and bursting strength (ISO 13938[45]) on high-contrast yarn-dyed knits has yet to be fully realized.[33,36,41,44,45,47,52] To account for curvilinearity and second-order parameter interactions (*XiXj*), process optimization must fit empirical second-order polynomial regression models verified via Analysis of Variance (ANOVA)[33,41,52]:

$$Y_k = \beta_0 + \sum_{i=1}^{m} \beta_i X_i + \sum_{i=1}^{m} \beta_{ii} X_i^2 + \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \beta_{ij} X_i X_j + \varepsilon \quad (3)$$

where *Yk* denotes each measured fabric response, *Xi*,*Xj* represent coded process variables, β denotes regression coefficients, and ε is experimental error.[33,41] Each predicted response *Y^k* is transformed onto a dimensionless individual desirability scale *di*□[0,1] bounded by strict industrial pass/fail thresholds (e.g., setting *d*burst=0 if bursting strength drops below 220–250 kPa, or *d*stain=0 if white-stripe staining falls below ISO Grade 4–4.5), and combined via the weighted geometric mean[33,41,52]:

$$MaximizeD = \left(\prod_{i=1}^{k} d_i^{wi} \right)^{\frac{1}{\Sigma W_i}} \quad (4)$$

where *D* is composite desirability and w_i represents the relative importance weight assigned to each quality criterion.[41,52]

Unresolved substrate complexities, scale-up validation, and sustainability roadmap

Comparing the surface-mechanics track[12,13,21,24,35,36,38] and dye-desorption track[9,10,32,34] exposes critical substrate, hydrodynamic scale-up, and environmental bottlenecks requiring empirical validation (Table 4):

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Table 4 Summary of established knowledge versus unresolved research gaps in the bio-polishing of yarn-dyed cotton knitted fabrics

Technical domain	Established knowledge in published literature	Unresolved research gaps & future validation needs
Hairiness & Pilling Origins	Fiber length/fineness,[17] spinning system (vortex<rotor<compact<ring),[12,18,19] yarn twist,[21,24] package dyeing friction,[7,23] and knit tightness/tuck geometry[13,26] govern baseline fuzz and pill formation.	Quantifying how package dyeing under varying reactive dye/electrolyte loads differentially alters yarn hairiness and knitting friction between dark and white yarns within the same course.[7,22,23]
Cellulase Bio-Polishing Kinetics	Synergistic action of EGs, CBHs, and β-glucosidases cleaves accessible amorphous microfibrils; mechanical shear breaks weakened hairs.[28–30,35] Neutral cellulases cause less strength loss and back-staining than acid cellulases.[28,29,36,33]	Determining whether bulky reactive dye molecules covalently bound to dark cotton yarns sterically hinder cellulase CBD adsorption compared to adjacent undyed white cotton stripes.[28,29,9]
Reactive Dye Migration & Cross-Staining	Unfixed/hydrolyzed reactive dyes desorb endothermically at elevated temperatures (>50 ∘C), extended times, and high mechanical shear, adsorbing onto white cellulose via van der Waals and H-bonding forces.[32,9,10,34]	Quantifying the relative contribution of free dissolved reactive dye molecules versus enzymatically cleaved dyed cello-oligosaccharides to white-stripe cross-staining during bio-polishing.[28,29,9,10,33]
Metrology & Standard Testing	Optical yarn hairiness (H,S3).[15–19] pilling protocols (ISO 12945-2[47]), bursting strength (ISO 13938-1[45]), shrinkage (ISO 6330[44]), and laundering/water fastness (ISO 105-C06/E01[50]) are well established.	Developing a standardized micro-aperture spectrophotometric protocol (ΔE00, ΔWICIE) and psychophysical grading scale (ΔENS) for in-bath stripe cross-staining and two-tone contrast pilling.[11,39,40]
Process Optimization & Scale-Up	Multi-response statistical tools (RSM, Derringer's desirability, ANN) effectively balance pilling against bursting strength on monochromatic knits and denim.[36,33,41,52]	Executing statistically validated RSM/desirability experiments on high-contrast yarn-dyed knits, followed by hydrodynamic scale-up validation from lab dyepots to industrial soft-flow/airflow jet machines.[29,31,41]

Steric hindrance and differential friction across stripes

In high-contrast striped knits, dark yarns contain high concentrations (4–8% owf) of bulky poly-functional reactive chromophores covalently bound to C2, C3, and C6 hydroxyls.[7,9] These bulky substituents sterically hinder the binding of the enzyme's cellulose-binding domain (CBD) and obstruct chain threading into catalytic clefts.[28,29] Furthermore, differential alkali and electrolyte exposure during package dyeing alters baseline yarn friction and hairiness between dark and white yarns prior to knitting,[7,23] while inter-stripe fiber migration generates two-tone contrast pills that amplify human visual rejection (Δ*E*NS11) compared to monochromatic standards.[39,47]

Hydrodynamic and tribological scale-up validation

Most academic studies utilize sealed laboratory dyepots (100–500 mL) processing 5–30 g tensionless swatches.[29,31] Industrial soft-flow or airflow jet vessels processing 150–800 kg of tubular fabric subject the substrate to driven winch reel longitudinal tension, high-velocity Venturi nozzle hydrodynamic shear, and J-box hydrostatic sliding.[29,31] Consequently, microfibril fracture rates (*k*mech), convective dye mass transfer, and relaxation shrinkage are substantially higher in industrial jets than in laboratory beakers, necessitating pilot-scale dimensionless calibration.[29,31,34,37]

Resource sustainability and microfiber mitigation

Wet processing in major hubs like Bangladesh consumes 80–150 L/kg of groundwater due to multi-stage rinsing and re-processing.[1–3] Deploying neutral or thermotolerant bacterial endoglucanases[28,36] alongside biodegradable non-ionic surfactants and polymeric DTIs (PVP/PVNO [10, 42]) at 45–50 ∘C (pH 6.5–7.0) enables single-bath bio-cleaning and bio-polishing, eliminating separate acid-neutralization and alkaline shock rinses.[1–3,10,28,36] Moreover, excising weakly anchored surface hairs inside the finishing mill curtails aquatic cellulosic microfiber shedding during consumer laundering,[20,32] while emerging magnetic-nanoparticle or stimuli-responsive polymer enzyme immobilization promises catalyst recovery and surface-confined hydrolysis.[28,29]

Conclusion

Cellulase bio-polishing represents an established biochemical finishing technology for enhancing the surface aesthetics, tactile handle, and functional performance of cotton weft-knitted fabrics.[12,28–30,36] By deploying multi-component hydrolytic enzyme complexes comprising endoglucanases, exoglucanases, and β-glucosidases published studies indicate that bio-polishing selectively hydrolyzes and cleaves loose microfibrils and protruding surface hairs extending from the yarn core.[28–30] When coupled with appropriate hydrodynamic shear and mechanical agitation, this enzymatic-mechanical synergy permanently removes surface fuzz, leading to a marked reduction in yarn hairiness indices and a substantial enhancement in fabric pilling resistance.[12,25,28,29,35,36,38]

However, published evidence consistently demonstrates that bio-polishing is governed by strict processing boundaries.[28,29,33,36] Elevated treatment intensity driven by excessive enzyme concentrations, bath temperatures exceeding optimal thermal windows, prolonged dwell times, or overly aggressive mechanical agitation induces severe structural trade-offs.[12,29,33,35,36,38] Over-hydrolysis compromises the load-bearing secondary wall of cotton fibers, resulting in excessive mass loss (GSM reduction), multidirectional bursting-strength degradation, altered dimensional stability (shrinkage), perceptible shade shifts (Δ*E*), and accelerated dye desorption.[12,28,29,33,35–38,40]

These antagonistic trade-offs become uniquely acute in multicolored yarn-dyed knitted fabrics.[9,10,42] Because high-contrast striped structures place reactive-dyed dark yarns directly adjacent to bleached white or pastel yarns, finishing protocols must balance surface refinement against the risk of aqueous dye migration and cross-staining.[9–11,42] Unfixed or hydrolyzed reactive dye species leached during warm aqueous treatments can redeposit onto adjacent light-colored loops, compromising pattern definition and visual

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quality.[9,10,32] Consequently, processing yarn-dyed knits requires the simultaneous control of both enzymatic defuzzing kinetics and dye-transfer thermodynamics.[9,10,28,29,33]

Future experimental research must address existing methodological gaps by integrating surface quality and color stability within comprehensive multi-response optimization frameworks, such as response-surface methodology and desirability-function analysis.[33,41,52] Furthermore, investigations should adopt rigorous, standardized metrological protocols for evaluating hairiness, pilling, bursting strength, dimensional change, and in-bath cross-staining, supported by actual physical replication, precise instrumental colorimetry, and hydrodynamic validation at industrial scale.[11,29,31,41,44,45,47,48] Emphasizing resource efficiency and chemical sustainability, balancing biochemical surface refinement with stringent color and structural preservation remains vital for advancing high-performance wet processing in the global knitwear manufacturing sector.[1–3,28,36]

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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