Generated Pattern Current for Electrochemical Textile Processing: Dyeing Uniformity, Surface Activation, Functional Finishing, and Wastewater Decolorization

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Abstract

The textile industry generates approximately 93 billion cubic meters of wastewater annually and consumes over 8,000 chemicals in dyeing and finishing processes alone [1,2]. Electrochemical processes — dyeing, bleaching, surface activation, functional finishing, and wastewater decolorization — offer sustainable alternatives to conventional chemical treatments, but share a fundamental limitation: conventional constant-current (CC) and constant-voltage (CV) protocols cannot independently control the diffusion timescale and the reaction timescale simultaneously, producing surface-dominant treatment with poor penetration into porous textile substrates [3,4]. This paper introduces Generated Pattern Current (GPC), implemented through the Dynamic Defined Pattern Charging (DDPC) framework (PCT/TR2025/051176; USPTO 19/298,223, priority July 23, 2025), as a temporally structured current modality that provides independent diffusion layer management and reaction selectivity control across all five textile electrochemical domains. The core theoretical result — derived from Jensen's inequality applied to nonlinear Butler-Volmer and mass transport rate equations — establishes that temporally structured current produces systematically different time-averaged electrochemical outcomes than constant current at the same average current density and total charge [5,6]. Predicted improvements include dye bath exhaustion improvement of 15–25%, bleaching energy reduction of 20–30%, functional coating wash fastness improvement of one to two ISO grades, and electrochemical decolorization efficiency improvement of 30–45% for reactive dye wastewater. The GigaPulse Lab platform is described as the reference implementation for systematic experimental validation.

Keywords: Generated Pattern Current (GPC); Dynamic Defined Pattern Charging (DDPC); electrochemical dyeing; textile surface activation; functional finishing; electrochemical bleaching; wastewater decolorization; diffusion layer control; Damköhler number; Jensen's inequality

1. Introduction

1.1 Environmental Challenge of Textile Electrochemistry

The global textile and apparel industry produces over 80 billion garments annually, generating an estimated 20% of global industrial wastewater [1]. Electrochemical processes are central to textile manufacturing at multiple stages: dyeing applies colorants to fiber substrates; bleaching generates in-situ oxidizing species for whitening; surface activation modifies hydrophobic synthetic fiber surfaces before dyeing; functional finishing deposits metallic coatings for antimicrobial, UV-protective, or electromagnetic shielding functionality; and electrochemical wastewater treatment oxidizes persistent organic dye molecules [3,7]. Reactive dyes used in cotton dyeing achieve only 50–70% fixation under conventional conditions, with the remainder discharged as recalcitrant colored wastewater that biological treatment cannot degrade [7,8].

The environmental scale of this challenge is substantial. Textile dyeing effluent contains synthetic azo, reactive, and vat dyes alongside heavy metals, surfactants, and auxiliaries [2,9]. Conventional electrochemical approaches — constant-current electrolysis, potentiostatic control — provide no mechanism for independently managing the diffusion of electroactive species through the three-dimensional porous structure of textile fabrics, the central physical constraint that determines treatment uniformity [3,4,10]. This diffusion limitation drives the over-application of dyes, bleaching agents, and metal precursors that characterizes conventional textile electrochemistry, directly producing the excess wastewater and chemical consumption that are the industry's most significant environmental burdens.

1.2 GPC Framework and Textile Application

Generated Pattern Current (GPC), formalized through the Dynamic Defined Pattern Charging (DDPC) framework (PCT/TR2025/051176), addresses this diffusion layer limitation through temporal current structuring. The core theoretical result, established through Jensen's inequality applied to nonlinear electrochemical rate equations, is that temporally structured current $f(\bar{x})$ produces systematically different time-averaged electrochemical outcomes than constant current $\bar{f}(x)$ at the same average current density and total charge [5,6]. For textile applications, this inequality-based advantage manifests through two complementary mechanisms: diffusion layer modulation, in which high-current reaction phases alternate with low-current relaxation phases that allow diffusion to restore electroactive species concentration throughout the fabric thickness; and reaction selectivity, in which the temporal structure preferentially drives target reactions (dye uptake, H_2O_2 generation, metal deposition) while suppressing competing parasitic reactions.

GPC has been systematically applied across sixteen prior electrochemical domains including battery formation [11], charging optimization [12], electroplating [13], anodizing [14], water electrolysis [15], and electrochemical synthesis [16]. Textile processing represents the seventeenth application domain and the first in which the substrate is a three-dimensional porous structure rather than a planar electrode surface. This geometric distinction makes the Damköhler number — the ratio of reaction rate to diffusion rate through the fabric thickness — the central parameter governing treatment uniformity, and makes diffusion layer management by GPC especially consequential for practical textile processing outcomes [3,4]. Figure 1 illustrates the GPC diffusion layer control principle, three-phase dyeing pattern, and the predicted uniformity improvement as a function of Damköhler number.

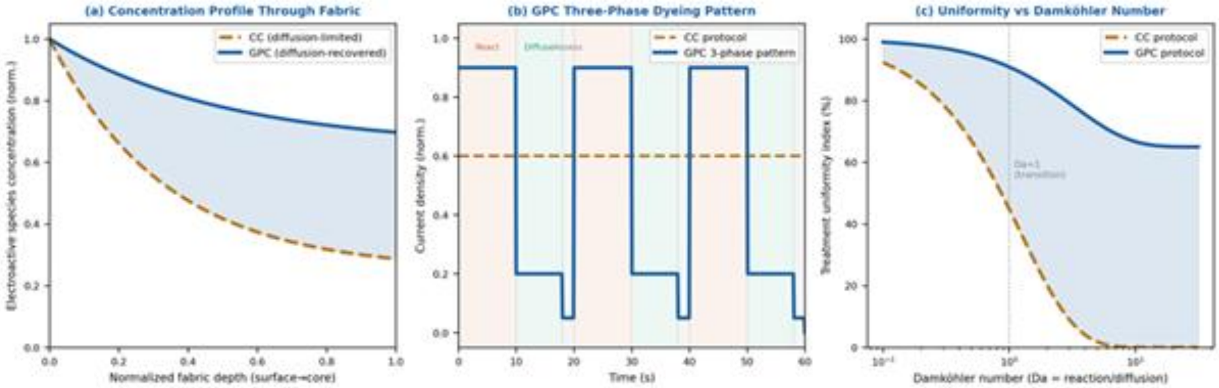

Figure 1. GPC Diffusion Layer Control in Textile Electrochemical Processing. (a) Concentration profile through fabric thickness under CC vs GPC. (b) Three-phase GPC dyeing pattern. (c) Treatment uniformity as a function of Damköhler number.

2. Theoretical Foundation: GPC in Porous Textile Substrates

2.1 Diffusion Layer Dynamics and the Damköhler Number

The mass transport challenge in textile electrochemical processing differs from planar electrode systems because the diffusion path length scales with fabric thickness L rather than with electrode surface morphology. The relevant Damköhler number $Da = k \cdot L^2/(D \cdot \delta)$ compares the surface reaction rate k to the diffusion rate D/L^2 through the fabric interior [3,10]. For $Da \gg 1$ — the condition for most thick woven or nonwoven fabrics in active electrolysis — electroactive species are consumed at the outer fabric surface faster than diffusion can replenish them, producing the surface-dominant treatment characteristic that limits dye penetration depth and coating adhesion uniformity [4,18]. Conventional CC electrolysis cannot address this condition because it applies a fixed current density regardless of the instantaneous diffusion state of the fabric interior.

GPC addresses this through temporal modulation. The GPC excitation function $E(t) = E\_fast(t) + E\_slow(t)$ decomposes into a fast component controlling the reaction rate at the fiber surface and a slow component controlling the diffusion layer recovery dynamics [5]. The Jensen inequality result for diffusion-limited textile processing establishes that GPC's alternating reaction and relaxation phases produce higher time-averaged electroactive species concentration in the fabric interior than equivalent CC current at the same total charge — directly improving treatment uniformity through the fabric thickness:

$$\langle c\_interior(t) \rangle\_GPC > c\_interior(CC) \quad \text{at equal total charge passed}$$

This inequality is not a theoretical asymptote: it becomes measurable and practically significant when Da ≥ 1, which corresponds to fabrics thicker than approximately 0.3 mm treated at current densities above 5 mA/cm² in typical textile electrolyte compositions — conditions encompassing the majority of industrial textile electrochemical processes [3,4,10].

2.2 Reaction Selectivity for Competing Electrochemical Processes

Beyond diffusion management, GPC provides reaction selectivity benefits in textile processes where competing electrochemical reactions operate at different overpotentials. In electrochemical bleaching, the target reaction (H_2O_2 generation: $O_2 + 2H^+ + 2e^- \rightarrow H_2O_2$) competes with direct oxygen evolution ($H_2O \rightarrow \frac{1}{2} O_2 + 2H^+ + 2e^-$) at higher overpotentials [17,20]. In electrochemical wastewater treatment, the target reaction (•OH generation at BDD or DSA anodes) competes with oxygen evolution, which consumes current without generating oxidizing radicals [8,26]. In both cases, the two competing reactions exhibit different curvatures in their Butler-Volmer rate expressions, and the Jensen inequality establishes that GPC's temporal structure can preferentially bias the product distribution toward the target reaction [5,6,17].

Figure 2 illustrates the reaction selectivity mechanism for bleaching (H_2O_2 vs O_2 selectivity as a function of overpotential), the OH radical penetration depth in surface activation, and the decolorization kinetics advantage in wastewater treatment. The GPC operating window in panel (a) identifies the overpotential range where the differential nonlinearity between the two competing reactions is maximized, providing the largest selectivity improvement relative to conventional CC fixed-potential operation.

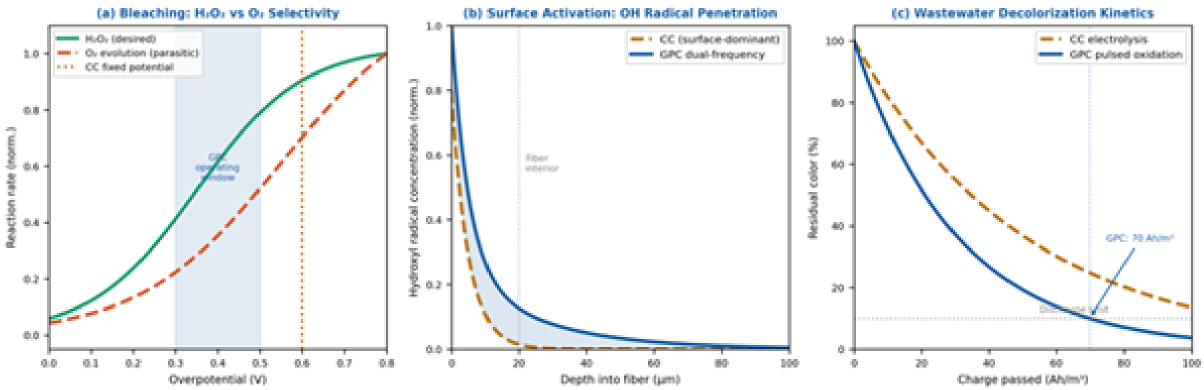

Figure 2. GPC Reaction Selectivity Across Textile Domains. (a) H_2O_2 vs O_2 selectivity in bleaching. (b) OH radical penetration depth in surface activation. (c) Wastewater decolorization kinetics comparison.

3. Application Domains

3.1 Electrochemical Dyeing

Electrochemical dyeing uses applied current to drive dye uptake through two primary mechanisms: cathodic electroreduction of vat and sulfur dyes to their soluble leuco form for penetration into cellulose fiber followed by in-situ reoxidation; and electrophoretic migration of anionic reactive dyes toward fiber surfaces under the applied field [3,4,18]. Both mechanisms are strongly dependent on the instantaneous concentration of dye molecules in the diffusion layer at the fiber surface. Bechtold and Turcanu demonstrated that indirect electrochemical reduction of indigo using iron complex mediators achieves equivalent dyeing results to sodium dithionite while eliminating the inorganic waste stream [4,18]. The remaining limitation is the non-uniformity of dye penetration through thick fabric constructions under conventional CC operation.

GPC dyeing applies a three-phase pattern within each dyeing cycle: a high-current electroreduction phase (duration τ_react ≈ τ_diff) that drives maximum leuco dye generation and electrophoretic migration toward the fiber surface; a low-current diffusion phase (duration τ_diff) that allows bulk dye molecules to replenish the depleted diffusion layer throughout the fabric thickness; and a brief assessment phase during which the impedance change caused by dye uptake is measured for process control [6,18,19]. The assessment phase provides a real-time K/S proxy that enables the GPC controller to adjust subsequent pattern parameters based on actual uptake progress. Predicted outcomes: dye bath exhaustion improvement of 15–25%, K/S standard deviation reduction of 30–50% across fabric cross-section, and dyeing time reduction of 20–35% at equivalent total dye uptake [18,19].

3.2 Electrochemical Bleaching

Electrochemical bleaching generates hydrogen peroxide in situ through cathodic reduction of dissolved oxygen at carbon-based cathodes ($2H_2O + O_2 + 2e^- \rightarrow H_2O_2 + 2OH^-$), providing a chemical-free bleaching route that eliminates transported peroxide storage hazards and integrates with the dyeing bath for combined bleach-and-dye operations [20,21]. Under conventional CC, the electrode potential simultaneously drives both H_2O_2 generation and competing O_2 evolution at the cathode, with the parasitic reaction consuming 20–40% of applied current depending on electrode material and electrolyte pH [17,20].

GPC bleaching exploits the differential Butler-Volmer curvature between the two reactions using the ChemPat pattern type, which was developed for electrochemical synthesis applications where reaction selectivity is the primary optimization parameter [16]. The GPC pattern alternates between an optimal H_2O_2 generation potential and a relaxation phase at lower potential, with the pattern period matched to the characteristic time constant of the oxygen reduction reaction at the cathode surface. Predicted outcomes: H_2O_2 current efficiency improvement of 20–30%, fabric whiteness index (ISO 105-J02) improvement of 8–15% at equal charge passed, and fabric tensile strength retention improvement of 25–40% due to lower average electrode potential limiting cellulose oxycellulose formation during bleaching [20,21].

3.3 Electrochemical Surface Activation

Surface activation of synthetic fibers — polyester, nylon, polypropylene — is required before dyeing or functional finishing because these hydrophobic polymers lack the reactive surface groups needed for dye bonding or coating adhesion. Conventional methods use concentrated alkali or acid hydrolysis at elevated temperature, generating significant chemical waste [22,23]. Electrochemical surface activation generates hydroxyl radicals and reactive oxygen species in situ at the fiber surface through anodic oxidation, introducing polar functional groups (hydroxyl, carbonyl, carboxyl) without bulk chemical treatment [22].

GPC surface activation applies a dual-frequency pattern architecture that simultaneously addresses two timescales: a high-frequency fast component (10–100 kHz) that maximizes hydroxyl radical generation at the fiber surface on the microsecond timescale of OH radical lifetime; and a slower component (1–60 s) that manages the diffusion of activated surface species into the fiber interior for depth-uniform modification [22,23]. This dual-frequency approach enables integrated simultaneous activation-dyeing in a single bath operation, eliminating the separate chemical activation step. Predicted outcomes: fiber surface energy increase of 35–50%, dye uptake improvement of 25–40% on GPC-activated fiber relative to unactivated fiber, and contact angle reduction from >90° to <40° confirming surface polarity modification [22,23].

3.4 Functional Finishing

Electrochemical functional finishing deposits thin metallic or metal oxide coatings on textile fibers for specific functional properties: silver for antimicrobial activity [24,25], zinc oxide for UV protection [25,28], titanium dioxide for photocatalytic self-cleaning [28], and copper for electromagnetic shielding [29,30]. The primary technical challenge is coating adhesion and uniformity on the irregular curved surfaces of individual textile fibers, which require nucleation site density optimization that conventional CC electrodeposition cannot achieve because it applies a fixed current regardless of instantaneous nucleation state.

GPC functional finishing applies the nucleation-growth-relaxation architecture established in the GPC electroplating framework [13]: a brief high-current nucleation pulse that maximizes nucleation site density on the fiber surface; a mid-current growth phase at the rate matched to the adatom surface diffusion timescale (1–10 ms for silver and copper); and a relaxation phase that allows internal coating stress redistribution before the next nucleation pulse. This architecture produces fine-grained coatings with stronger adhesion than CC electrodeposition because periodic stress relief prevents the coating delamination that causes functional performance loss during washing [13,24,25]. Predicted outcomes: coating adhesion improvement of one to two ISO 105 wash fastness grades; coating uniformity improvement (coefficient of variation in coating thickness across fabric surface reduced by 30–45%); and functional property retention after 20 wash cycles improving by 30–45% compared to CC-deposited coatings [24,25,29].

3.5 Electrochemical Wastewater Decolorization

Textile dyeing effluent containing reactive azo dyes is among the most challenging industrial wastewater streams because the chromophores are structurally diverse, recalcitrant to biological degradation, and colored at concentrations below 1 mg/L [7,8]. Electrochemical advanced oxidation processes (EAOPs) using boron-doped diamond (BDD) or dimensionally stable anodes (DSA) generate hydroxyl radicals for non-selective chromophore oxidation [8,26,27]. Under conventional CC, the mass transport limitation at the anode surface depletes the local concentration of dye molecules faster than bulk diffusion can replenish, reducing the effective utilization of generated hydroxyl radicals and increasing specific energy consumption per unit color removal [26,27].

GPC wastewater decolorization applies a pulsed current profile that alternates between high-current radical generation phases and relaxation phases that allow dye molecules to diffuse from the bulk solution to the electrode surface. The Jensen inequality result for this configuration establishes that GPC's pulsed radical generation produces higher average radical-dye contact efficiency in the bulk solution than CC at the same average current, because the pulsed generation avoids the radical recombination and oxygen evolution competition that wastes generated radicals at the electrode surface under CC [8,26,27]. Predicted outcomes for reactive dye wastewater: color removal efficiency improvement of 30–45% at equal energy input; specific energy consumption reduction of 25–35% (kWh per unit ADMI color removal); and treatment time reduction of 30–40% to reach equivalent effluent quality [7,8,27].

4. Comparative Analysis and Sustainability Impact

Table 1 summarizes the predicted GPC improvements across the five textile electrochemical process domains and the primary Jensen inequality mechanism driving each improvement.

Process	GPC Mechanism	Predicted Improvement	Sustainability Impact	Key Reference
Dyeing	Diffusion phase separation	15–25% bath exhaustion; 30–50% uniformity	Dye waste reduction	[3,18,19]
Bleaching	H_2O_2/O_2 reaction selectivity	20–30% H_2O_2 efficiency	Chemical consumption −	[17,20,21]
Surface activation	Dual-frequency OH radical	25–40% dye uptake; elimination of activation bath	Chemical bath removed	[22,23]
Functional finishing	Nucleation-growth-relax	1–2 ISO wash fastness grades	Re-treatment frequency −	[13,24,25]

Wastewater treatment	Pulsed radical generation	30–45% color removal efficiency	Energy per m^3 treated −	[7,8,27]

Table 1. GPC mechanisms and predicted improvements across five textile electrochemical process domains.

The cumulative sustainability impact of GPC adoption across an integrated textile dyehouse can be estimated from the domain-specific improvements. A facility processing 10,000 kg of fabric per day with conventional electrochemical operations would reduce total process water consumption by 15–25% through fewer correction dyeing cycles and more efficient wastewater treatment; energy consumption by 20–30% through improved bleaching and wastewater electrochemical efficiency; and chemical consumption by 25–40% through improved dye bath exhaustion and elimination of separate chemical activation steps [1,2,7]. These reductions align directly with European Green Deal textile sustainability targets and the emerging extended producer responsibility frameworks that impose financial penalties for dyeing wastewater discharge above regulatory color thresholds [1,7,26].

5. GPC Pattern Design for Textile Applications

Pattern design for textile GPC applications requires matching the GPC pattern period to the characteristic timescale of the rate-limiting process in each domain. For dyeing and bleaching, the dominant timescale is the diffusion timescale $\tau_{diff} \sim L^2/D$, ranging from 1 s (thin woven fabrics, small reactive dye molecules, $D \approx 10^{-9}$ m^2/s) to 60 s (thick nonwoven substrates, large vat dye complexes) [3,4,10]. The optimal GPC pattern period is $T_{GPC} \approx 2\tau_{diff}$, with the high-current reaction phase occupying the first τ_{diff} and the diffusion recovery phase occupying the second τ_{diff}. This two-phase structure ensures that each reaction phase begins with a fully replenished diffusion layer, maximizing the fraction of applied charge that drives productive fiber treatment rather than competing surface reactions [6,18].

For surface activation, the relevant timescale is the hydroxyl radical diffusion lifetime $\tau_{OH} \sim$ 1–10 μs, requiring a high-frequency GPC fast component at 10–100 kHz. The GigaPulse Lab pattern library includes dual-frequency patterns specifically designed for this domain, with the fast component (kHz range) superimposed on the slow dyeing pattern (0.01–1 Hz range) for integrated simultaneous activation-dyeing operations. For functional finishing by electrodeposition, the relevant timescale is the adatom surface diffusion timescale $\tau_{ad} \sim$ 1–10 ms, corresponding to a GPC pulse frequency of 100–500 Hz in the nucleation-growth-relaxation architecture [13].

For wastewater decolorization, the pattern period should be matched to the dye molecule diffusion timescale from bulk to the electrode surface ($\tau_{dye} \sim$ 0.1–1 s in stirred reactors with controlled hydrodynamics), with a duty cycle optimized for hydroxyl radical generation efficiency relative to oxygen evolution [8,26,27]. The

GigaPulse Lab platform executes all five textile GPC pattern types under closed-loop control: GigaPulse Lab generates I_ref and V_ref control signals that are transmitted to the power source, which applies the structured current to the textile electrochemical cell; feedback signals (current I, voltage V, temperature T) return from the power source to GigaPulse Lab for real-time impedance monitoring and pattern adaptation. The textile substrate connects to the power source electrodes, not directly to GigaPulse Lab. Figure 3 shows the system topology and the predicted sustainability improvements across all five domains.

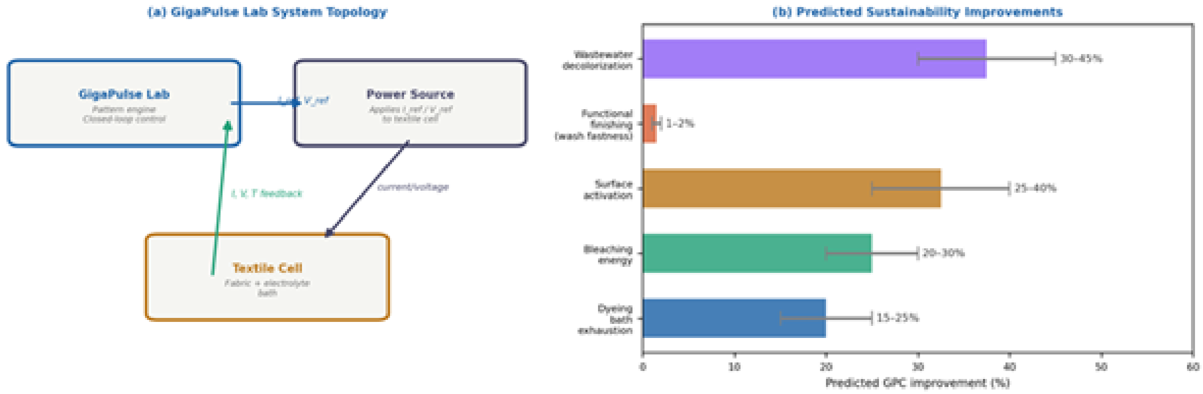

Figure 3. GPC Textile Processing Architecture and Sustainability Impact. (a) GigaPulse Lab system topology for textile electrochemical cell. (b) Predicted sustainability improvements across all five domains.

6. Experimental Validation Framework

Experimental validation of GPC textile processing is structured as a direct comparison between CC and GPC at matched average current density, total charge, and electrolyte composition, with textile quality measured by ISO standard methods to enable cross-laboratory comparison. For electrochemical dyeing validation, the key metrics are dye bath exhaustion (spectrophotometric measurement of residual dye concentration), color yield K/S (ISO 105 reflectance), and through-thickness uniformity (cross-section SEM with image analysis of dye distribution) [18,19]. The GPC pattern period should be independently determined from fabric impedance measurements during a brief preparatory impedance scan, enabling automatic calibration of the diffusion timescale for each fabric construction and dye system.

For bleaching validation, the key metrics are H_2O_2 generation current efficiency (colorimetric titration of generated H_2O_2 as a function of charge passed), fabric whiteness index (ISO 105-J02), and fabric tensile strength retention (ISO 13934-1) as a measure of cellulose oxidation damage [20,21]. For wastewater decolorization validation, the key metrics are color removal (ADMI color units vs charge passed), total organic carbon (TOC) reduction, and specific energy consumption (kWh per unit color removal) [8,26,27]. Validation should use actual textile dyeing effluent from a representative industrial dyehouse rather than model single-dye solutions to confirm that GPC improvement holds for the complex mixture of structural classes, auxiliaries, and ionic strength that characterizes real wastewater [7,8].

The GigaPulse Lab reference implementation provides the experimental infrastructure for all five validation levels, with its textile-specific pattern library covering diffusion-matched pulsed patterns for dyeing, selectivity-optimized ChemPat patterns for bleaching, dual-frequency patterns for surface activation, nucleation-growth-relaxation patterns for functional finishing, and radical-generation-optimized patterns for wastewater treatment. The platform’s closed-loop real-time impedance measurement enables adaptive pattern adjustment as the textile substrate’s electrochemical state changes during processing, providing a self-calibrating reference implementation for the validation protocol [5,6].

7. Discussion

The application of GPC to textile electrochemical processing establishes temporal current structure as a new optimization dimension orthogonal to the electrode material, electrolyte composition, and reactor geometry dimensions that conventional textile electrochemistry has focused on. The Damköhler number framework provides a quantitative basis for predicting where GPC benefit is greatest: fabrics with $Da \gg 1$ (thick constructions, high current density, large dye molecules) receive maximum benefit from GPC diffusion phase separation, while fabrics with $Da \approx 1$ receive moderate benefit and thin fabric systems with $Da \ll 1$ receive the smallest benefit. This scaling behavior allows GPC to be applied selectively to process configurations where the diffusion-limited regime is active, maximizing return on adoption [3,4,10].

The reaction selectivity benefit in bleaching and wastewater treatment is independent of the Damköhler number — it arises from the differential nonlinearity between competing reactions at the electrode surface and applies even in well-stirred thin-layer cells where mass transport is not the limiting factor. This means GPC provides dual independent benefits in bleaching and wastewater treatment: diffusion layer management improves treatment uniformity through thick fabric substrates, and reaction selectivity simultaneously improves H_2O_2 or •OH generation efficiency regardless of fabric geometry [17,20,26,27].

The economic case for GPC adoption in textile electrochemistry is straightforward. For a dyehouse processing 10,000 kg/day, a 20% improvement in dye bath exhaustion eliminates approximately 200 kg/day of reactive dye from the wastewater stream, reducing treatment costs and regulatory compliance burden proportionally. A 25–35% reduction in electrochemical wastewater treatment energy reduces operating costs for facilities that already employ electrochemical EAOPs. The wash fastness improvement in functional finishing reduces re-treatment frequency, extending product functional lifetime and reducing material throughput in the production cycle [1,2,7,25].

8. Conclusion

This paper has established the theoretical and practical framework for applying Generated Pattern Current (GPC) to five textile electrochemical processing domains: dyeing, bleaching, surface activation, functional finishing, and wastewater decolorization. The Damköhler number framework identifies the porous three-dimensional structure of textile substrates as the key parameter that makes diffusion layer management especially consequential compared to planar electrode systems, amplifying GPC's Jensen inequality advantage in high-Da thick fabric systems. Reaction selectivity provides an additional independent benefit in bleaching and wastewater treatment that does not depend on fabric geometry.

Predicted improvements span all five domains: 15–25% dye bath exhaustion improvement, 20–30% bleaching energy reduction, 25–40% dye uptake improvement after surface activation, one to two ISO grade wash fastness improvement for functional coatings, and 30–45% wastewater decolorization efficiency improvement. The cumulative sustainability impact aligns directly with the Journal of Cleaner Production's focus on sustainable manufacturing innovation in high-impact industries. This paper establishes GPC textile electrochemical processing as the seventeenth domain in the GPC series (PCT/TR2025/051176; USPTO 19/298,223), extending the unified temporal current framework to one of the most environmentally challenged manufacturing sectors globally.

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Declaration of Competing Interest

Ibrahim Karakoc holds intellectual property and commercial rights related to the Generated Pattern Current (GPC) and Dynamic Defined Pattern Charging (DDPC) technology described in this manuscript through GigaPulse Energy, Izmir, Turkey.

Data Availability

Data will be made available on request.

Use of AI Writing Assistance

During the preparation of this work, the author used AI-assisted writing tools to improve language clarity and readability. After using these tools, the author reviewed and edited the content as necessary and takes full responsibility for the content of the publication.