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DOPAMINE-DRIVEN COLORATION TECHNOLOGIES: A KNOWLEDGE STRUCTURING BUILT ON CITAVI AND ARTIFICIAL INTELLIGENCE

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Abstract. *The interdisciplinary field of dopamine-mediated coloration, spanning materials science, biomimetics, and sustainable chemistry, has experienced rapid growth, making comprehensive literature synthesis increasingly challenging. This paper presents a novel methodology for transforming the reference management software Citavi into a structured knowledge system, enabling both manual and AI-augmented trend analysis. We curated and annotated over 1,000 publications, with particular focus on dopamine and polydopamine in textile functionalization and coloration. Structuring via custom taxonomies (e.g., substrate type, deposition method, durability metrics) enabled AI-driven synthesis using Qwen3-Max. Key insights include: (1) PDA's role as a universal textile modifier enhancing dye fastness, enabling structural color, and imparting antimicrobial/UV functions; (2) enzymatic (laccase-mediated) DA polymerization as an emerging green alternative; (3) under-explored potential in wool and scalability studies. AI insights were reintegrated into Citavi as "AI Insight Notes," creating a dynamic human-AI collaborative environment. This approach offers a reproducible framework for domain mapping in fast-evolving fields.*

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Introduction

Dopamine, 2-(3,4-dihydroxyphenyl)ethylamine, initially recognized for its pivotal role as a neurotransmitter in the mammalian central nervous system, has undergone a remarkable scientific transformation from a biological signaling molecule to a cornerstone of modern materials chemistry. This evolution began in earnest with the landmark 2007 study by Lee et al. [1], who demonstrated that polydopamine (PDA), a synthetic polymer inspired by the adhesive proteins of marine mussels, could form robust, conformal coatings on virtually any material surface under mild aqueous conditions. This discovery unlocked a new paradigm in surface engineering, positioning PDA as a universal platform for functionalization of various materials.

In the decade that followed, research expanded rapidly beyond adhesion. Scientists revealed that PDA's chemical versatility rooted in catechol and amine functionalities enabled applications in biomedicine (e.g., drug delivery, antifouling coatings), environmental remediation (e.g., heavy metal adsorption [2-4]), energy storage (e.g., battery electrodes [5, 6]), and catalysis [7-9]. Seminal reviews [10, 11] systematized the chemistry of PDA formation and highlighted its role as a "molecular glue" for hybrid material design. Studies by Kohri and colleagues (2025-2021), for example [12-14] illuminated PDA's melanin-like optical properties, drawing parallels between synthetic polydopamine and natural pigments responsible for coloration in skin, hair, and feathers.

This optical dimension gradually catalyzed interest in color generation. Unlike conventional dyes that rely on molecular absorption, PDA-based systems began to be explored for their ability to produce structural color, a phenomenon where hue arises from nanoscale architecture rather than chemistry. Early demonstrations included PDA nanoparticles for non-iridescent coatings and PDA-assisted assembly of photonic crystals on textiles and polymers. Several works [15, 16], and [14] established that PDA not only serves as a scaffold but also enhances color purity by absorbing stray light, mimicking the function of natural melanin in biological structural color.

As the field matured, dopamine-mediated coloration emerged at the intersection of sustainable chemistry, biomimetics, and advanced functional textiles. Researchers began to explore green alternatives, such as laccase-catalyzed dopamine polymerization ([17, 18]), and multifunctional finishes that combine color with UV protection, antimicrobial activity, or environmental responsiveness. Yet, this rapid expansion has led to fragmentation: contributions now span chemistry, materials science, textile engineering, photonics, and sustainability, making comprehensive synthesis increasingly difficult.

Traditional review methodologies struggle to map such a dynamic, interdisciplinary landscape. There is thus a pressing need, not for another application-focused study, but for a novel knowledge-mapping framework capable of revealing cross-cutting trends, methodological shifts, and underexplored opportunities. This paper responds to that need by introducing a structured knowledge system built in Citavi and augmented by AI-driven trend analysis. Rather than presenting new experimental data, we offer a methodological innovation for navigating complex scientific domains using dopamine-mediated coloration as a representative case study.

Methods

Building a Structured Knowledge System in Citavi

Source Collection and Import

We collected over 1,000 publications (2007–2025) from Scopus, Web of Science, Google Scholar, and eLIBRARY.ru. Sources included:

- peer-reviewed journal articles,
- review papers,
- conference proceedings,
- theses and technical reports.

All items were imported into Citavi 6 (Windows) [19], with metadata (title, authors, year, abstract, DOI) auto-extracted where possible. PDFs were attached and full-text indexed for search.

Knowledge Structuring via Taxonomy and Metadata

We designed a domain-specific annotation schema using Citavi's native features:

Hierarchical Keywords (Thematic Organization)

- Dopamine Form
  - Dopamine (monomer)
  - Polydopamine (polymer)
- Material Substrate
  - Natural Fibers: Cotton, Silk, Wool
  - Synthetic Polymers: PET, Nylon
  - Inorganics: TiO_2, SiO_2
- Coloration Mechanism
  - Oxidative Self-Polymerization
  - Metal-Ion Coordination (Fe^{3+}, Cu^{2+})
  - Structural Color
- Application Area
  - Textile Dyeing
  - Smart Sensors
  - Anticounterfeiting
  - Biomedical Coatings
- Deposition Method
  - Dip-Coating
  - Spray Coating
  - Electrochemical
  - Vapor-Phase

Custom Fields (Structured Data Capture)

Field	Type	Example Value
pH of Reaction	Number	8.5
Dopamine Concentration	Number	2 mg/mL
Color (CIE L*a*b*)	Text	L*:60, a*:20, b*:30
Wash Stability (cycles)	Number	50
Country of Study	Text	China, Russia, USA
Temporal Phase	Text	Foundational (2007–2015)

Annotation and Synthesis

Each entry received:

- Quotations: Key methodological or result sentences.
- Comments: 2–3 sentence summary of contribution.

- Idea Notes: Cross-paper synthesis (e.g., "Contradiction: optimal pH reported as 8.5 vs. 9.0—needs meta-study").
- Tasks: "Compare with Zhang 2023," "Check scalability claim."

Native Citavi Analytics

We used Citavi's built-in tools for preliminary trend spotting:

- Statistics → Publications per Year: Growth curve of field.
- Statistics → Keywords: Frequency of themes (e.g., "Biomedical Coatings" rose 300% post-2020).
- Filters: "Show all 2020–2025 papers on Silk + pH-responsive."

AI-Augmented Trend Analysis with Qwen3-Max

About Qwen3-Max:

Qwen3-Max is the most capable variant in the Qwen3 series of large language models, developed by Alibaba's Tongyi Lab (2025) [20]. It features:

- Strong multilingual (EN/RU) and scientific reasoning
- 32,768-token context window—ideal for aggregated bibliographic datasets
- Instruction-following fine-tuning for analytical tasks
- We selected Qwen3-Max for its ability to perform thematic clustering, temporal trend detection, gap analysis, and synthesis over structured metadata.

Workflow: Citavi → AI → Citavi

- Export: Citavi project exported as structured CSV (Title, Year, Keywords, Custom Fields, Notes).
- Preprocess: Formatted into prompt-ready blocks.
- Prompting: Key prompts included:
  - "Cluster these 1000+ entries by Material + Application + Year. Identify top 5 thematic clusters and their evolution."
  - "What material-application combinations are under-researched? Suggest 3 high-potential opportunities."
  - "Detect contradictions in optimal pH or concentration across studies."
- Validation: AI outputs cross-checked against manual review and domain knowledge.
- Reintegration: AI insights added back into Citavi as "AI Insight Notes" attached to relevant keywords or papers.

Results and Discussion

Key Trends Identified by AI Synthesis

Our AI-augmented analysis of the Citavi knowledge base reveals that dopamine-mediated coloration has evolved from a biomimetic curiosity into a multifunctional platform for sustainable materials engineering. Central to this evolution is the systematic structuring of literature via domain-specific metadata, exemplified by the annotation schema in Table 1. This schema transforms Citavi from a passive bibliography into an active knowledge discovery system. Each custom field encodes critical experimental and performance parameters:

- pH of Reaction and Dopamine Concentration capture synthesis conditions that dictate coating morphology and adhesion;
- Color (CIE L*a*b*) provides objective, quantitative color data essential for comparing structural vs. pigment-based hues;
- Wash Stability and the newly added Light Fastness fields directly address industrial durability requirements;
- Substrate and Deposition Method enable cross-material comparisons (e.g., cotton vs. PET) and green chemistry assessments (e.g., enzymatic vs. chemical oxidation).

Table 1. Citavi Annotation Schema — Custom Fields (Enhanced for Textiles)

Field	Type	Example Value	Description
pH of Reaction	Number	8.5	Optimal for PDA formation
Dopamine Concentration	Number	2 mg/mL	For uniform coating
Color (CIE L*a*b*)	Text	L*:60, a*:20, b*:30	Measured color metrics
Wash Stability (cycles)	Number	50	Post-wash color retention
Light Fastness (scale)	Number	4–5 (ISO 105-B02)	UV resistance rating
Substrate	Text	Cotton, Silk, PET	Fiber type
Deposition Method	Text	Dip-Coating, Enzymatic	Application technique
Temporal Phase	Text	Foundational (2007–2015)	Historical context

This structured approach not only supports native Citavi analytics but also enables precise AI prompting, such as “Compare light fastness of PDA-ZnO coatings on silk vs. cotton”, thereby turning fragmented literature into a queryable, evolving knowledge map.

The dominant material in this domain remains polydopamine (PDA), synthesized via oxidative self-polymerization of dopamine. Its unique combination of strong adhesion, high refractive index, and tunable optical properties makes it ideal for surface functionalization. Closely related are melanin-like nanoparticles, which leverage broad UV-visible absorption for high-contrast, non-fading coloration.

Three primary coloration mechanisms emerged from the analysis:

1. Structural colors generated via light interaction with nanostructures – offering eco-friendly, high-saturation alternatives to dyes;
2. Interference and scattering effects, enhanced by PDA’s high refractive index;
3. Non-iridescent colors, a recent research focus aimed at achieving angle-independent, high-visibility hues for practical applications.

Surface coating and functionalization strategies further demonstrate PDA’s versatility. Coatings are consistently reported as durable, wash-fast, and fade-resistant, while functionalization with graphene, metal nanoparticles, or metal oxides imparts antimicrobial, UV-protective, or conductive properties-transforming passive textiles into active, responsive materials.

Application of Dopamine and Polydopamine in Textile Coloration

The application of PDA in textiles spans surface modification, durability enhancement, and structural color fabrication. Critically, these advances are tracked and contextualized through the trends identified in Table 2, which highlights the most dynamic research trajectories in the field.

PDA-templated antimicrobials (e.g., ZnO/Ag on cotton) represent a mature yet rapidly growing area (+150% since 2018), directly enabled by PDA's role as a nucleation platform. This trend aligns with industrial demands for multifunctional finishes. Similarly, structural color on silk/cotton has surged (+220% since 2020), driven by the need for non-toxic, non-fading alternatives to synthetic dyes. Notably, PDA coatings significantly improve the light fastness of natural dyes on silk [21]. Ran's group further showed that PDA-ZnO hybrid coatings on cotton not only enhance UV blocking but also impart photocatalytic self-cleaning properties without compromising color stability [22]. This concept has been extended to other photocatalytic nanocomposites: for instance, Ag-TiO_2 nanoparticles immobilized on polyester fabric (without PDA) demonstrated enhanced solar-driven self-cleaning and antibacterial activity, with the anatase phase content critically dependent on the Ag^+/Ti^{4+} ratio [23]. Similarly, mechanically activated TiO_2-pillared montmorillonite exhibited high photocatalytic efficiency in dye degradation due to increased surface area and defect-mediated active sites [24]. The enhanced activity of TiO_2 in the anatase phase suggests that PDA-based templating could further improve the dispersion and adhesion of such advanced photocatalysts on textiles.

Table 2. Top 5 Research Trends in Textile Applications (AI-Identified)

Trend	Description	Key Papers	Year	Growth
Structural Color on Silk/Cotton	Rapid, durable, angle-independent color	Zhu et al. 2020, 2021 [15]; [25]	2020	220%
Enzymatic (Laccase) Deposition	Eco-friendly, metal-free functionalization	Nong et al. 2020; Jia et al. 2017 [18]; [17]	2017	180%
PDA-Templated Antimicrobials	ZnO/Ag on cotton for durable protection	Ran et al. 2018; Tania et al. 2021 [22]; [26]	2018	150%
Smart Responsive Textiles	pH/temp-triggered color for sensing	He et al. 2014; Wang et al. 2022 [16]; [27]	2014	130%
Scalability Gap	Lack of industrial-scale process studies	AI-flagged gap	—	—

The one-step, rapid fabrication of angle-independent hues, often using PDA-melanin films, addresses both aesthetic and durability requirements.

Emerging green chemistry approaches are captured in the enzymatic (laccase) deposition trend (+180% since 2017), which avoids toxic oxidants and enables metal-free functionalization. This pathway complements conventional chemical methods and reflects the field's shift toward sustainability.

Meanwhile, smart responsive textiles (+130% since 2018) leverage PDA's stimuli-responsive chemistry for pH- or temperature-triggered color shifts, enabling applications in sensing and adaptive camouflage.

Notably, Table 2 also exposes a critical gap: the scalability gap, flagged by AI as a complete absence of studies on industrial-scale PDA coating processes. This insight, reintegrated into

Citavi as an "AI Insight Note", has already spurred new research tasks, such as "Collaborate with textile mills to pilot continuous PDA coating lines."

Together, Tables 1 and 2 form a complementary framework: Table 1 provides the structured data foundation, while Table 2 reveals the emergent knowledge patterns. This human-AI collaborative loop—structured data → AI synthesis → enriched annotations → deeper queries—enables continuous refinement of the knowledge base and targeted identification of research opportunities.

Research Gaps and Emerging Opportunities

The trends identified in Table 2 not only map the current frontiers of dopamine-mediated textile functionalization but also expose critical imbalances in the research landscape. While structural color on silk and cotton has surged by 220% since 2020, driven by demand for eco-friendly, non-fading alternatives to synthetic dyes, this progress remains concentrated on a narrow set of substrates. Similarly, PDA-templated antimicrobials (e.g., ZnO/Ag on cotton) reflect a mature yet still expanding trajectory (+150% since 2018), demonstrating PDA's utility as a universal nucleation platform for durable, multifunctional finishes.

However, Table 2 also reveals a stark asymmetry: despite the rise of "green chemistry" approaches like enzymatic (laccase) deposition (+180% since 2017), these innovations remain confined to lab-scale demonstrations on silk or model surfaces. More critically, the "Scalability Gap", flagged by AI as a complete absence of studies on industrial-scale PDA coating processes, represents a systemic blind spot. No publication in our knowledge base addresses continuous dip-coating, roll-to-roll spray systems, or compatibility with existing textile finishing lines. This disconnect between academic innovation and industrial applicability threatens to limit real-world impact.

Furthermore, certain high-potential materials remain neglected. Wool, for instance, appears in fewer than 10 studies, despite its protein-rich surface being highly compatible with catechol-based adhesion and its relevance to sustainable fashion. This underrepresentation suggests a significant opportunity for research that bridges biomimetic chemistry with natural fiber valorization.

Human-AI Collaboration: Closing the Loop Between Insight and Action

The true power of our methodology lies not in AI's ability to detect trends, but in the feedback loop it enables between machine-generated insight and human expertise. As illustrated in Table 2, AI does not merely list topics, it contextualizes them: identifying "enzymatic deposition" not just as a keyword, but as an emerging green alternative with standardization potential; framing the "scalability gap" not as a void, but as a high-impact opportunity for industry-academia partnership.

This synergy is operationalized through reintegration: AI outputs are transformed into actionable Citavi annotations – "Idea Notes," "Tasks," and "AI Insight Notes" – that directly shape research strategy. For example:

- When AI flagged enzymatic deposition as rising, a human expert linked it to laccase-catalyzed grafting on silk [18, 17], recognizing its alignment with metal-free, low-energy textile processing.

- When AI noted the absence of scalability studies, the team created a concrete task: "Collaborate with textile mills to pilot continuous PDA coating lines", turning a bibliometric gap into an R&D agenda.

Thus, Table 2 is more than a summary of trends, it is a living roadmap, dynamically updated through the Citavi → AI → Citavi cycle. This human-AI collaborative framework ensures that literature synthesis is not a static endpoint, but a catalyst for targeted, forward-looking research.

Guiding Future Research Through Structured Knowledge Mapping: Evaluating Thematic Impact with AI-Augmented Citavi

A targeted assessment of the research group led by one of co-authors of current paper, Ran J., reveals a highly focused and application-driven body of work that not only aligns with current trends in dopamine-mediated coloration but also provides a strategic foundation for future research directions.

The research group has consistently demonstrated that polydopamine (PDA) serves as a robust, scalable platform for multifunctional cotton finishing, particularly through the *in situ* growth of ZnO and Ag nanoparticles. Their landmark 2018 study [22] established a mild, aqueous-phase protocol yielding fabrics with simultaneous UV resistance, photocatalytic self-cleaning, antimicrobial activity, and enhanced dyeability, a combination directly responsive to industrial demands for durable, eco-friendly textile functionalization. Critically, these methods avoid high temperatures, organic solvents, or complex equipment, positioning them as near-term translatable solutions.

This work intersects with three high-growth trends identified in Table 2:

- PDA-templated antimicrobials (+150% since 2018), where Ran's ZnO/Ag systems offer empirical validation of PDA's nucleation efficacy;

- Light fastness enhancement, as PDA-ZnO coatings significantly improve UV shielding without compromising color stability;

- Scalability-oriented processing, since their solution-based dip-coating is compatible with existing textile finishing lines.

More importantly, Ran's research trajectory anticipates and enables key future directions:

- Hybrid Functional Systems: By integrating PDA with metal oxides, her work lays the groundwork for multimodal textiles (e.g., UV-protective + antimicrobial + conductive), a frontier highlighted by AI as high-potential.

- Sustainable Process Optimization: While her group uses chemical oxidation, the mild conditions they employ create a natural bridge to enzymatic (laccase-mediated) routes, the fastest-growing green chemistry trend (+180% since 2017). Future work could hybridize Ran's templating strategy with enzymatic polymerization for fully metal-free, low-energy finishing.

- Industrial Translation: The absence of scalability studies in the broader literature (the "Scalability Gap" in Table 2) makes Ran's industrially compatible protocols especially valuable. Her methods provide a ready-to-pilot framework for collaboration with textile mills, precisely the action item generated by AI-human collaboration in Section 4.4.

Notably, Ran's research does not overlap with structural color or wool functionalization, two other emerging frontiers. This strategic focus is a strength: it establishes her group as a reference point for cotton-based, nanoparticle-enhanced PDA finishing, while leaving room for complementary work on other substrates or optical effects.

In summary, Ran's contributions exemplify how targeted, application-oriented research can both validate current trends and scaffold future innovation. Her portfolio not only reinforces the manuscript's core thesis that PDA is a practical, scalable platform for sustainable textile engineering, but also offers a concrete pathway to address the field's most critical gap: industrial translation. As such, her work serves as both an anchor for present understanding and a springboard for next-generation research in dopamine-mediated functionalization.

Conclusion

The application of dopamine and polydopamine in coloration has evolved from biomimetic curiosity into a platform for multifunctional, responsive, and industrially relevant textile engineering. PDA serves as a universal modifier, enhancing dye fastness, enabling durable structural color, and imparting antimicrobial, UV-protective, and conductive properties. Critically, our AI-augmented knowledge system not only maps these advances but also identifies actionable pathways for future innovation, such as the underexplored potential of wool functionalization or the urgent need for scalable PDA coating processes.

The case of Ran's research group exemplifies how targeted, application-driven work, validated and contextualized through our framework, can serve as a springboard for industrial translation. Their scalable, aqueous-phase protocols for cotton functionalization directly address the "scalability gap" flagged by AI, demonstrating how structured knowledge mapping can align academic output with real-world needs.

The Citavi → AI → Citavi methodology thus transcends traditional literature review: it is a reproducible, domain-agnostic framework for strategic research planning in fast-evolving interdisciplinary fields. By transforming fragmented publications into a dynamic, human-AI collaborative knowledge environment, it empowers researchers not just to understand the present, but to shape the future.

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