

Original Research

Purple Non-Sulfur Bacteria Biomass as a Chromophoric Particulate System for Textile Printing: A Material-Driven Review Toward Sustainable Printing

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Abstract

The textile industry remains one of the most resource-intensive manufacturing sectors, and textile printing still relies heavily on synthetic colorants, auxiliary chemicals, and solvent- or energy-intensive processing. Purple non-sulfur bacteria (PNSB) have attracted interest as a bio-based platform for sustainable biomanufacturing because they can convert light and low-value organic substrates into pigment-rich biomass. This review examines a concept that has received little attention in textile research: the use of intact PNSB biomass, rather than extracted pigments, as a chromophoric particulate phase for textile printing. From a materials-oriented perspective, the review considers how the micrometer-scale dimensions of PNSB cells, the intracellular organization of carotenoids and bacteriochlorophylls, and the resulting optical response may support pigment-style surface coloration. Key issues relevant to translation into printing systems are discussed, including biomass production and preparation, dispersion stability, matrix and binder interactions, rheological requirements, fixation pathways, and expected durability. The potential sustainability advantages of this concept include avoidance of extraction-intensive pigment processing, reduced chemical complexity, and compatibility with waste-derived cultivation routes. At the same time, important challenges remain, particularly biomass standardization, batch-to-batch optical variability, preservation of pigment-protein organization during downstream processing, and validation of print performance. Overall, the review reframes intact PNSB biomass as a candidate particulate color phase for textile printing and identifies

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the main research questions that must be addressed before this concept can be evaluated experimentally and technologically.

Keywords: purple non-sulfur bacteria (PNSB), textile printing paste, bio-based printing materials, bacterial pigments, eco-printing, sustainable printing

Introduction

The textile industry is widely recognized as one of the most resource-intensive manufacturing sectors, with coloration processes contributing substantially to water consumption, chemical use, and environmental pollution [1, 2]. Although textile printing is generally more water-efficient than exhaust dyeing, it still depends heavily on synthetic dyes and pigments derived from petrochemical feedstocks. Their production involves complex chemical synthesis, solvent-intensive processing, and the use of auxiliary chemicals that generate contaminated effluents and persistent environmental burdens [2, 3]. Even pigment printing, often viewed as a comparatively sustainable coloration route, still relies on resource-intensive pigment manufacture, dispersion, and binder-assisted fixation [4]. For this reason, alternative color systems that reduce chemical inputs and fit circular-material strategies remain a major research priority [3, 5].

Biological colorants from plants, fungi, algae, and microorganisms have therefore attracted growing attention as potential alternatives to conventional synthetic colorants [6, 7]. Most studies on microbial colorants for textile applications have focused on extraction, purification, and subsequent application of isolated pigment molecules [6, 7]. That strategy offers advantages for chemical characterization and formulation control, but it also introduces additional processing, solvent demand, and potential loss of native pigment organization. Among microbial colorants, the most extensively studied are single-chromophore systems such as violacein, produced mainly by *Janthinobacterium lividum* and *Chromobacterium violaceum*, and prodigiosin, produced by *Serratia* spp. and certain cold-adapted *J. lividum* strains. Both pigments offer well-characterized extraction and purification protocols and documented antimicrobial and antioxidant activities; however, their industrial application is constrained by the opportunistic pathogenicity of their native producers and, in many cases, by cultivation temperatures below 20°C [8, 9]. Bacterial melanins provide a robust and photostable black pigment but suffer from poor water solubility and underdeveloped large-scale extraction processes [8].

Within this broader landscape, purple non-sulfur bacteria (PNSB) are especially interesting because they combine resource-efficient cultivation with the biosynthesis of complex pigment systems, mainly carotenoids and bacteriochlorophylls, that produce characteristic yellow-orange, red, purple, and brown tonalities [10, 11]. PNSB are also of established interest in environmental biotechnology, including wastewater

treatment, resource recovery, and biomass generation from low-value substrates [12, 13]. Unlike the microbial pigments described above, PNSB differ fundamentally because their coloration originates not from a single discrete chromophore but from the membrane-organized assembly of bacteriochlorophylls and carotenoids embedded within intracellular photosynthetic membranes. Furthermore, the pigment content of intact PNSB cells can be monitored directly using non-destructive spectroscopic techniques, enabling efficient assessment of pigment-rich biomass during cultivation without extraction [14]. This unique combination of biosafety, substrate flexibility, membrane-organized multi-pigment structure, and compatibility with non-destructive process monitoring provides the principal rationale for considering intact PNSB biomass as a potential textile colorant.

By contrast, the direct use of intact microbial biomass as a coloring material remains largely unexplored in textile printing. In the case of PNSB, this gap is especially significant because their pigments are not freely dispersed molecules; rather, they are organized within intracellular membrane systems that determine both absorption behavior and visible color expression.

This review therefore considers intact PNSB biomass not as a source of extracted pigments, but as a possible chromophoric particulate phase for textile printing. The focus is conceptual and material-driven. Instead of assuming a single fixation mechanism or an already validated industrial process, the review examines whether the physical dimensions of PNSB cells, their hierarchical pigment organization, and their optical behavior are compatible with pigment-style printing concepts based on surface deposition and matrix-assisted immobilization. Particular attention is given to biomass structure, optical response, formulation requirements, and the major technical questions that would need to be resolved before experimental translation.

Materials and Methods

This review was based on a comprehensive literature search of Web of Science, Scopus, PubMed, and Google Scholar using keywords related to purple non-sulfur bacteria (PNSB), microbial pigments, textile printing, pigment-based coloration, and bio-based colorants. Peer-reviewed articles, authoritative books, book chapters, and recent publications were prioritized, while seminal studies on PNSB physiology and photosynthetic pigment systems provided the scientific foundation. Publications lacking scientific relevance or

methodological rigor were excluded, ensuring a robust and up-to-date evidence base for this materials-oriented review. The selected literature was systematically categorized into thematic sections covering biomass characteristics, optical properties, printing paste formulation, printing technologies, fixation mechanisms, durability, sustainability, and future perspectives. Literature identification and selection were guided by the general principles of the PRISMA framework to enhance transparency and reproducibility. Owing to the conceptual and interdisciplinary nature of the available evidence, a formal quantitative meta-analysis was not appropriate. Instead, a materials-oriented narrative synthesis was employed to integrate quantitative findings and qualitative evidence, critically evaluate current knowledge, and identify research gaps and future directions for the development of PNSB biomass as a chromophoric particulate system for sustainable textile printing.

Results and Discussion

PNSB Biomass as a Candidate Chromophoric Particulate Material

Purple non-sulfur bacteria are a diverse group of anoxygenic phototrophic microorganisms capable of photosynthesis without oxygen evolution. They are metabolically versatile, growing photoheterotrophically under anaerobic or microaerophilic conditions and, in many cases, chemoheterotrophically in the dark. This physiological flexibility helps explain their broad environmental distribution and the sustained interest in their environmental and biotechnological applications (Table 1) [15, 16].

From a production standpoint, pigment-rich PNSB biomass can be generated using waste-derived substrates or wastewater streams, which strengthens its relevance for circular bioeconomy concepts [15, 17]. In integrated treatment schemes, clarified waste streams may serve

as feed to photobioreactors in which PNSB proliferate, while residual solids and side streams can be further valorized through downstream treatment. For the present review, the key point is not the exact bioprocess configuration, but the fact that PNSB biomass can, in principle, be produced through resource-recovery-oriented routes rather than through conventional pigment-manufacturing pathways, as illustrated in Fig. 1 [17].

A central reason to consider intact PNSB biomass as a possible printing material is its size regime. Individual cells typically fall within a micrometer-scale range of approximately 0.5–2.0 μm , depending on species and cultivation conditions [18]. This overlaps with the dimensional scale of many particulate colorants used in textile coloration, making PNSB geometrically compatible with pigment-style surface deposition. On size alone, intact cells can therefore be discussed as pigment-like particles rather than as molecular colorants. However, PNSB are not inert particles. Their pigmentation arises from a highly organized intracellular photosynthetic membrane system, generally described as the intracytoplasmic membrane (ICM) and, in many species, as chromatophores [19, 20]. These membrane systems house the light-harvesting machinery required for phototrophic growth, and bacteriochlorophyll autofluorescence is commonly used to visualize their spatial distribution within the cell [20]. At the molecular level, the pigments are assembled in defined pigment–protein complexes rather than dispersed freely in the cytosol. The canonical organization includes peripheral antenna complexes (LH2, when present), core antenna complexes (LH1), the reaction center (RC), and associated cofactors [21–23]. Fig. 2 illustrates the hierarchical structural organization of PNSB chromophoric membranes, from the cellular level to the vesicular chromatophore level. Within these small membrane vesicles, LH2, LH1, and RC complexes are packed closely together, providing the structural basis for efficient light harvesting and excitation-energy transfer. Both bacteriochlorophylls and carotenoids are

Table 1. Major genera and representative species of PNSB and selected application areas.

Major Genera and Species	Representative Application / Relevance	Reference(s)
<i>Rhodopseudomonas</i> spp.	Often considered among the most versatile PNSB; <i>Rhodopseudomonas palustris</i> is widely discussed for biofertilization and bioremediation.	[15, 16]
<i>Rhodobacter</i> spp.	Includes <i>Rhodobacter sphaeroides</i> (also reported as <i>Cereibacter sphaeroides</i>) and <i>Rhodobacter capsulatus</i> ; frequently studied in wastewater treatment and aquaculture-related applications.	[15, 16]
<i>Rhodospirillum</i> spp.	Includes <i>Rhodospirillum rubrum</i> , a well-studied model species used in metabolism and photosynthesis research.	[15, 16]
<i>Rhodovulum</i> spp.	Relatively salt-tolerant taxa relevant to marine or brackish environments.	[15, 16]
<i>Rhodoplanes</i> spp.	Reported as common members of rice paddy ecosystems.	[15, 16]
<i>Rhodobium</i> spp.	Associated with marine environments and aquaculture systems.	[15, 16]
<i>Blastochloris</i> spp.	Includes thermotolerant representatives such as <i>Blastochloris tepida</i> .	[15, 16]

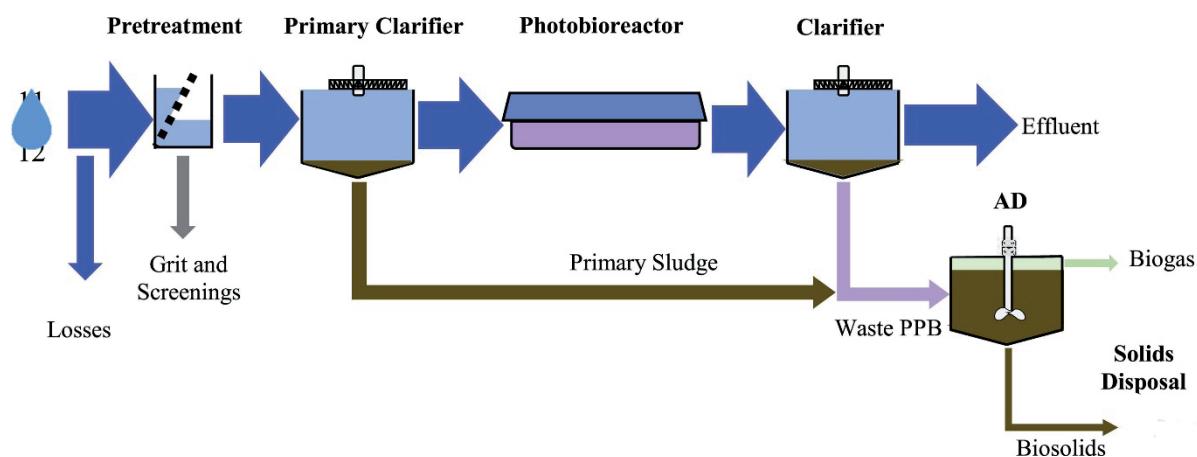


Fig. 1. Process stages of the photobioreactor system [17].

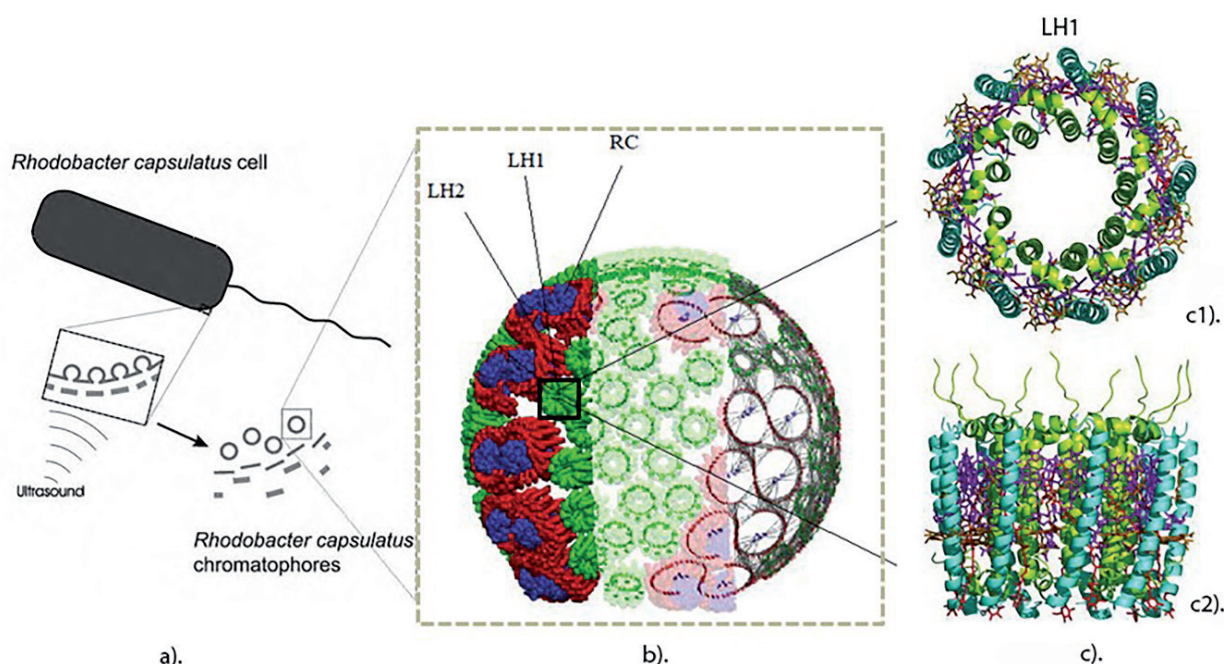


Fig. 2. Structural organization of purple non-sulfur bacteria (PNSB) and their chromophoric membrane systems [21-23].

noncovalently bound to integral membrane proteins embedded in the ICM. As a result, the optical properties of PNSB biomass emerge from membrane-integrated supramolecular assemblies rather than from discrete, chemically isolated pigment grains.

PNSB biomass also shows substantial morphological diversity. Depending on species and growth conditions, cells may be rod-shaped, ovoid, or spiral [18, 24]. In particulate coating systems, particle geometry influences packing density, interparticle void structure, surface roughness, and light scattering [25]. By analogy, differences in PNSB cell shape are likely to influence biomass arrangement after surface deposition and may therefore affect film uniformity and visual appearance.

This structural complexity is accompanied by structural sensitivity. During harvesting, concentration,

centrifugation, washing, or mild drying, the integrity of the cell envelope, the organization of the ICM, and the stability of pigment–protein complexes may change [13]. Such changes may alter aggregation behavior, surface chemistry, mechanical stiffness, and optical response. Accordingly, the main material advantage of intact PNSB biomass – its integrated, pigment-bearing biological architecture – is inseparable from a potential vulnerability: the same organization that generates color may be modified by downstream processing. This dual character is fundamental to assessing PNSB as a candidate chromophoric particulate material. The main structural characteristics of PNSB biomass relevant to textile-printing concepts are summarized in Table 2.

Table 2. Structural characteristics of PNSB biomass relevant to textile-printing concepts.

Parameter	Typical Range / Feature	Relevance to Printing Applications	Reference(s)
Cell size	0.5-2.0 μm	Comparable to many conventional particulate colorants.	[13]
Cell morphology	Rods, spirals, ovoid forms	May influence packing, roughness, and film uniformity.	[13]
Major pigments	Carotenoids, bacteriochlorophylls	Provide broad visible and near-infrared absorption.	[13]
Pigment localization	Intracytoplasmic membrane systems	Provides natural encapsulation and biologically organized color generation.	[13]
Absorption maxima	Approx. 450-550 nm and 800-890 nm	Associated with deep, often matte color development.	[13]
Photostability	Potentially moderate to high, but condition-dependent	Relevant to fading resistance and color durability.	[13]
Need for pigment extraction	Potentially avoidable	Supports simplified, lower-impact processing routes.	[13]

Optical Properties and Color Development of Chromophoric PNSB Biomass

The optical properties of intact PNSB biomass arise from both pigment composition and hierarchical pigment organization. Unlike extracted dyes or many synthetic pigments, whose behavior is often interpreted primarily at the molecular or crystalline level, intact PNSB cells derive their color from pigment-protein assemblies embedded within photosynthetic membranes [21]. Consequently, visible appearance depends not only on which pigments are present, but also on how those pigments are spatially organized within the cell. The main pigments responsible for optical activity are bacteriochlorophylls – predominantly bacteriochlorophyll *a* – and carotenoids [21-23]. Bacteriochlorophylls are arranged in ordered arrays within light-harvesting complexes (Fig. 2c). In LH2, two spectroscopically distinct absorption bands are typically observed, designated B800 and B850 according to their absorption maxima. In LH1, bacteriochlorophylls are more strongly coupled and absorb farther into the red and near-infrared region, often around 870-890 nm [21-23].

Carotenoids occupy defined positions within the membrane protein scaffold, where they interact with both bacteriochlorophylls and surrounding proteins [21-23]. They broaden visible-light absorption, transfer excitation energy to bacteriochlorophylls, and contribute photoprotective functions by quenching reactive excited states. Importantly, carotenoids also contribute to structural stabilization of the photosynthetic complexes. In *Rhodobacter sphaeroides*, for example, the absence of colored carotenoids has been associated with unstable LH2 assembly, indicating that pigment presence and membrane architecture are closely linked [26].

The optical behavior of intact PNSB biomass is inseparable from the spatial organization of pigments within chromatophore membranes. For the present

discussion, these structural details matter because they show that the chromophoric behavior of PNSB biomass is inseparable from its membrane architecture. Intact biomass is therefore better understood as a biologically structured optical material than as a simple carrier of pigments. The absorption spectrum of BChl *a*-containing purple bacteria typically combines broad carotenoid absorption in the visible region (420-550 nm), a bacteriochlorophyll Q_x band near 590 nm, and strong near-infrared bands associated with antenna and core complexes around 800, 850, and 870-890 nm, depending on species and physiology (Fig. 3) [27]. These combined spectral features produce the macroscopic colors associated with PNSB biomass, including orange-brown, red-brown, deep red-violet, and purple-brown tonalities (Table 3) [10, 11]. The typical visual appearance and optical characteristics of PNSB biomass are summarized in Table 3 [28, 29].

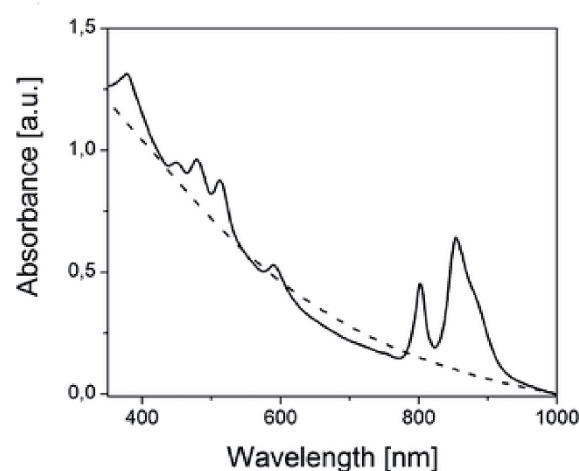


Fig. 3. Absorption spectra of *Rb. sphaeroides* 2.4.1 suspensions cultured photosynthetically (in the presence of light and absence of oxygen, solid line) and heterotrophically (in the presence of oxygen and absence of light, dashed line) [27].

Table 3. Generalized visual appearance and optical tendencies of PNSB biomass.

PNSB Biomass Visual Color	Dominant Pigment System	Approximate CIELab Tendency	Optical Characteristics	Grayscale Appearance	Reference(s)
Yellow–orange	Carotenoids with low BChl contribution	Higher L*, higher b*	Strong absorption in blue region	Light gray	[10, 11]
Orange–brown	Moderate carotenoid content	Medium to high L*, moderate a* and b*	Broad visible absorption; warm tone	Medium-light gray	[10, 11]
Red–brown	Carotenoids + bacteriochlorophyll	Medium L*, higher a*	Enhanced visible-region absorption	Medium gray	[10, 11]
Deep red–violet	Bacteriochlorophyll-dominant	Lower L*, very high a*	High optical density with NIR absorption	Dark gray	[10, 11]
Purple–brown to violet-black	High total pigment density	Low L*, negative or neutral b*	Broad-band absorption across visible and NIR	Very dark gray to near black	[10, 11]

Importantly, these optical properties are not fixed. Light intensity, oxygen availability, nutrient supply, carbon source, and growth phase influence both pigment composition and the extent of intracytoplasmic membrane development [10, 30]. Photosynthetically grown cultures typically display stronger near-infrared absorption bands associated with well-developed antenna systems, whereas heterotrophically grown cultures (grown in the absence of light) show diminished NIR features because the photosynthetic membrane system is less developed (Fig. 3 – dashed line). As a result, color and spectral response may vary between biomass batches. Any attempt to use intact PNSB biomass as a reproducible coloring material would therefore require controlled cultivation and standardized post-harvest handling.

Formulation of PNSB-based Printing Paste

If intact PNSB biomass is treated conceptually as a chromophoric particulate phase, formulation must be approached from the perspective of particulate printing systems rather than soluble dye systems. In such systems, performance is governed primarily by dispersion stability, particle–matrix interactions, rheology, film formation, and fixation behavior [31–33]. The following sections therefore address formulation requirements in terms of biomass preparation, optical consequences of surface deposition, paste composition, binder interactions, and printability.

Biomass Harvesting and Preparation

Biomass harvesting and preparation are upstream steps with direct consequences for both physical handling and color performance. Cultivation conditions such as light intensity, oxygen level, carbon source, nutrient availability, and growth phase affect biomass productivity, cell morphology, pigment composition, and intracytoplasmic membrane development [10, 34, 35]. Under reported favorable conditions – typically around 28–32°C, pH 6.8–7.5, and low dissolved oxygen – PNSB can achieve substantial biomass and pigment yields,

especially under infrared illumination with suitable organic carbon sources such as acetate [12, 36]. These relationships are summarized in Table 4.

For printing applications, the practical implication is straightforward: cultivation becomes part of color design. Because biomass color depends on the physiological state of the cells, uncontrolled growth conditions are likely to translate into batch-to-batch variation in hue, optical density, and material behavior. Reproducible printing would therefore require tighter biological standardization than is necessary for many conventional pigment systems.

Following cultivation, biomass is typically recovered by centrifugation, sedimentation, or membrane-based separation [35, 37]. Subsequent operations may include washing, concentration, and mild dehydration to obtain solids contents appropriate for paste preparation. These steps must be managed carefully. Excessive thermal or chemical treatment may disrupt pigment-bearing membrane systems and degrade sensitive chromophores, while aggressive mechanical processing may alter aggregation state or cell integrity. From a formulation standpoint, minimally disruptive downstream processing is preferable, even though it may increase challenges related to moisture control, microbial stability, and storage.

Conceptual Optical Considerations for Textile Printing

In pigment-style textile printing, color development is governed primarily by surface coverage and light-matter interactions rather than by diffusion of soluble chromophores into the fiber [38, 39]. Applied to intact PNSB biomass, this means that the visible outcome would be expected to depend on how pigment-bearing cells are distributed, packed, and immobilized at the textile surface. Biomass concentration would influence color strength and opacity, while particle arrangement and local aggregation would influence scattering, matte appearance, and spatial color uniformity.

A further distinction from conventional pigments is that the optical response of PNSB biomass may remain

Table 4. Reported cultivation conditions relevant to pigment-rich PNSB biomass production.

Parameter	Reported Favorable Range / Setting	Expected effect on growth or pigment formation	Reference(s)
Light	Approx. 3,000-5,000 lux; IR-rich illumination; often 12 h light / 12 h dark	Drives photoheterotrophic growth; excessive light may cause photoinhibition.	[12, 36]
Temperature	28-32°C	Supports growth and pigment formation.	[12, 36]
pH	6.8-7.5	Helps maintain stable physiological conditions for pigment synthesis.	[12, 36]
Carbon Source	Acetate 2-5 g L ⁻¹ (also lactate/malate reported)	Can enhance biomass and carotenoid accumulation.	[12, 36]
Nitrogen Source	Limited NH ₄ Cl or related nitrogen supply	May influence pigment accumulation and growth balance.	[12, 36]
Oxygen Level	Microaerobic / low dissolved oxygen	Favors bacteriochlorophyll formation.	[10, 34, 35]
Mixing	Approx. 100-250 rpm; low shear	Improves illumination and mass transfer while limiting damage.	[10, 34, 35]
Typical output	Approx. 0.8-1.2 g L ⁻¹ day ⁻¹ biomass; 20-30 mg pigment g ⁻¹ biomass	Illustrates reported productivity under favorable conditions.	[10, 34, 35]

partly shaped by the biological matrix surrounding the pigments. Because carotenoids and bacteriochlorophylls are embedded within lipid-protein membrane structures, the local environment may affect pigment packing, photophysical behavior, and stability [29, 40]. Whether these native effects are preserved, altered, or lost after deposition on textile surfaces remains unknown. This is one of the central research questions for translating PNSB biomass from a biological material into a functional color phase.

Paste Composition Principles

Textile printing pastes are multicomponent systems composed of a chromophoric phase, a continuous matrix, and additives that control viscosity, stability, wetting, and fixation [31, 32]. In a PNSB-based system, the biomass would function as the chromophoric particulate phase, while the matrix would be designed to maintain homogeneous dispersion, enable controlled transfer through the printing process, and immobilize the biomass after deposition.

Because intact PNSB biomass is particulate rather than soluble, sedimentation control and dispersion homogeneity would be essential. Uneven dispersion would be expected to cause local variation in optical density, poor print definition, and color non-uniformity. Suitable formulation approaches may therefore include polymeric binders, thickened aqueous matrices, crosslinked hydrogel-type systems, or hybrid designs combining several stabilization mechanisms [33, 41].

At this stage, no single formulation route can be considered established. Instead, the relevant principle is that the matrix should preserve sufficient chromophoric exposure while providing adequate cohesion, deposition control, and mechanical stability. Too much matrix coverage may shield the biomass optically and reduce apparent color strength; too little matrix cohesion

may compromise adhesion and wash resistance. The formulation problem is therefore one of balance rather than simple inclusion of biomass in a conventional paste.

Binder and Matrix Interactions

In pigment-based textile printing systems, interactions between pigment particles and the surrounding binder or matrix play a critical role in determining dispersion stability, fixation behavior, and overall print durability [31, 42]. At the interfacial level, pigment surface properties – such as charge, hydrophilicity, and the presence of residual extracellular polymers – can influence compatibility with binders and thickeners [42, 43]. Excessive matrix coverage may reduce chromophoric exposure and consequently decrease apparent color intensity, whereas insufficient matrix cohesion may compromise abrasion and washing durability. Consequently, formulation design generally requires careful balancing of chromophoric visibility and mechanical stability [32, 44].

Within this conceptual framework, interactions between PNSB biomass and the surrounding matrix would likely be central to both print quality and durability. When polymeric binders are employed, fixation in particulate systems typically occurs through physical immobilization of pigment particles within the binder film formed during drying or curing [31, 42]. Alternatively, thickened or crosslinked matrices may provide mechanical entrapment of chromophoric particles without relying exclusively on film-forming binders [41, 42].

Rheology and Printability Requirements

Rheological control is a critical factor in textile printing pastes, as flow behavior directly influences paste

transfer, pattern definition, and overall print quality [31, 45]. Accordingly, printing pastes are generally designed to exhibit shear-thinning behavior during application, followed by rapid viscosity recovery to maintain pattern definition after deposition [45]. Within this general framework, similar rheological requirements would be expected for PNSB-based printing pastes.

The presence of micrometer-scale biomass particles introduces additional complexity, as particle size, shape, and concentration may influence yield stress and overall flow behavior of the paste.

Thickeners and structuring agents can be employed to tailor paste rheology while maintaining stable dispersion of particulate components [31, 45]. The optimal rheological window depends on the intended printing technique, particularly screen and direct printing methods, where viscosity directly affects paste penetration, edge sharpness, and surface coverage [31, 45].

Processing conditions should also be carefully controlled, as excessive shear may influence dispersion stability and could potentially affect biomass integrity in particulate biological systems [46].

Substrate Considerations

In textile printing systems, the properties of the textile substrate play a critical role in determining print performance, durability, and the interaction between the printed layer and the fabric surface [47]. Accordingly, in conceptual PNSB-based chromophoric systems, the choice of substrate would also be expected to influence the performance of the deposited particulate layer.

At a conceptual level, initial investigations could reasonably focus on widely used reference fabrics (e.g., cotton, polyester, and cotton/polyester blends) that represent standard substrates in pigment printing and enable systematic comparison of surface chemistry, porosity, and binder-substrate adhesion. Substrate structure (woven vs. knitted), surface roughness, and absorbency may influence paste add-on, layer uniformity, handle, and durability of the printed layer.

Substrate properties can also be modified through pre-treatment or controlled oxidation processes to tailor surface chemistry, wettability, and interfacial interactions, thereby providing additional opportunities for optimizing matrix anchoring and print performance [48, 49]. Beyond interfacial and mechanical considerations, surface modification of textile substrates can introduce additional functional properties, such as antimicrobial activity, as demonstrated for chitosan-modified cotton systems [50].

When considering the integration of biologically derived chromophoric materials such as PNSB biomass into textile structures, such functional surface modifications could potentially provide complementary benefits, supporting both matrix anchoring and overall material functionality.

Because surface-applied layers may influence fabric stiffness, drape behavior, and thermophysiological

comfort, evaluation frameworks used for bio-based garments may provide relevant benchmarks for assessing potential print-induced changes in wearer experience [51].

Textile Printing Techniques Potentially Compatible with PNSB-Based Paste Systems

Textile printing techniques differ in their ability to process particulate chromophoric systems, depending on factors such as paste viscosity, particle size tolerance, and deposition mechanism. Methods traditionally used for pigment printing are generally more compatible with particulate colorants because they rely on surface deposition rather than fiber-level diffusion [52-54]. Within this conceptual framework, the following section discusses printing techniques that could potentially accommodate PNSB-based chromophoric pastes.

Screen Printing

Screen printing is widely recognized as one of the most versatile techniques for textile pigment printing, particularly due to its tolerance for high-viscosity, particle-containing pastes and its ability to deposit relatively thick and well-defined print layers [52, 55]. For this reason, screen printing can be considered conceptually compatible with PNSB-based pastes, which would behave as particulate chromophoric systems.

The mesh-controlled transfer mechanism of screen printing enables controlled deposition of particulate chromophoric materials onto textile substrates while limiting excessive penetration into the fiber structure, thereby favoring surface coloration governed primarily by light absorption and scattering rather than fiber diffusion [55, 56].

From a formulation standpoint, screen printing typically requires pastes exhibiting shear-thinning behavior and rapid viscosity recovery, rheological properties commonly associated with systems containing micrometer-scale particulate phases [55, 57]. In addition, screen printing allows precise control of paste add-on, layer thickness, and pattern definition, parameters that are particularly important in particulate chromophoric systems where color intensity is strongly influenced by surface coverage.

Accordingly, screen printing may be regarded as a suitable conceptual platform for exploring PNSB-based chromophoric systems, as it allows deposition of particulate biomass without relying on solubility-driven or diffusion-controlled coloration mechanisms.

Block and Direct Printing Techniques

Block printing and other direct-contact textile printing methods are traditionally used for transferring viscous pastes onto fabric surfaces through mechanical contact, making them generally tolerant of coarse and highly viscous formulations [58]. Within this

framework, such techniques could be considered conceptually compatible with PNSB-based printing pastes, which would behave as particulate chromophoric systems. These methods rely on the mechanical transfer of paste from a solid printing tool to the textile surface, emphasizing localized pressure and surface deposition rather than deep penetration into the fiber structure. As a result, they align well with particulate chromophoric systems in which color formation occurs primarily at or near the textile surface.

However, compared with screen printing, block and other direct-contact printing techniques generally provide more limited control over paste uniformity and deposited layer thickness [58, 59]. Variations in applied pressure, tool geometry, and paste loading may lead to spatial variability in biomass distribution and optical appearance. While such characteristics may restrict reproducibility in industrial-scale production, they could also enable distinctive visual and textural effects, suggesting potential relevance for artisanal, small-scale, or design-oriented explorations of PNSB-based textile printing concepts.

Limitations of Digital Printing Technologies for Biomass-Based Chromophoric Systems

Digital textile printing technologies, particularly inkjet printing, are generally designed for low-viscosity formulations containing very fine and well-dispersed colorants, which imposes strict requirements on particle size, dispersion stability, and rheological behavior [58, 60]. For this reason, such technologies are typically less compatible with particulate biomass-based paste systems, including those conceptually derived from PNSB.

Inkjet printing systems typically require particle diameters well below one micrometer to ensure reliable nozzle operation and stable droplet formation [58, 60]. Given that intact PNSB cells generally exhibit micrometer-scale dimensions, direct inkjet deposition of whole-cell biomass would therefore be considered impractical without substantial size reduction, fractionation, or encapsulation strategies.

Moreover, digital textile printing relies on low-viscosity inks and highly controlled droplet generation, conditions that are not readily compatible with dense particulate suspensions [60]. Although future advances in nozzle design, ink formulation, or biomass processing could potentially enable alternative digital approaches, current digital textile printing technologies remain largely unsuitable for the direct deposition of intact microbial biomass.

Sensitivity to Process Parameters

Printing processes are generally sensitive to operational parameters such as paste viscosity, printing speed, applied pressure, and drying or curing conditions, all of which can significantly influence print quality

and layer stability [55, 57]. Within this general framework, PNSB-based printing pastes would also be expected to exhibit sensitivity to such process parameters.

Excessive shear forces or applied pressure could potentially affect biomass integrity and pigment organization, while insufficient fixation may lead to reduced durability or limited surface stability of the printed layer. Consequently, optimization of printing parameters would likely need to be approached holistically, taking into account both chromophoric performance and the mechanical stability of the deposited particulate layer.

Conceptual Fixation, Durability, and Print Performance of PNSB-Based Textile Prints

The practical relevance of any textile printing system is largely determined by its fixation efficiency, durability under use conditions, and resulting print performance [61, 62]. When PNSB biomass is considered conceptually as a chromophoric particulate system, these properties would primarily depend on the ability of the printing matrix to retain pigment-containing biomass at the textile surface and maintain structural integrity under mechanical and environmental stresses. In such systems, fixation and durability would likely be governed mainly by matrix composition, curing conditions, and interfacial adhesion within the printed layer rather than by fiber–colorant interactions typical of molecular dye systems.

Fixation Mechanisms in PNSB-Based Prints

Fixation in pigment-based textile printing is typically achieved through the formation of a continuous or semi-continuous matrix that anchors chromophoric particles to the textile surface after drying or curing [61, 63]. When considered conceptually in the context of PNSB-based systems, similar matrix-assisted principles would be expected to govern fixation behavior.

Polymeric binders, when employed, may physically entrap biomass particles within a film network that adheres to the textile substrate. Alternatively, thickened or cross-linked matrices can immobilize chromophoric entities through mechanical confinement without relying exclusively on film formation [59, 64, 65].

The effectiveness of fixation generally depends on matrix composition, curing conditions, and interfacial compatibility between the chromophoric particles and the surrounding matrix [63, 66]. Excessive matrix coverage may shield chromophoric particles and reduce apparent color intensity, whereas insufficient immobilization may result in limited resistance to mechanical or wet treatments. Accordingly, fixation strategies should be considered a balance between chromophoric exposure and mechanical anchoring in order to achieve acceptable print stability.

Washing, Light, and Abrasion Durability

Durability under washing, light exposure, and mechanical abrasion represents a critical performance criterion for printed textiles [61, 67]. In particulate-based printing systems, resistance to washing is primarily governed by the strength of particle immobilization and the integrity of the fixation matrix rather than by chemical bonding to the fiber. Accordingly, when considered conceptually, PNSB-based systems would be expected to exhibit durability trends analogous to those of conventional pigment prints, provided that appropriate matrix-assisted fixation is achieved. In general, textile products are expected to withstand at least 25 laundering cycles while maintaining acceptable functional and aesthetic properties [68].

Lightfastness is another important consideration for chromophoric systems derived from biological pigments. Carotenoids and bacteriochlorophylls are known to exhibit sensitivity to photoinduced degradation under certain conditions [69, 70]. In intact PNSB biomass, pigments are embedded within membrane-associated pigment-protein complexes, where the surrounding protein-lipid environment can influence pigment stability and susceptibility to photooxidative degradation. While systematic lightfastness studies on surface-deposited PNSB biomass in textile contexts are currently lacking, insights from photosynthetic biology suggest that pigment-protein assemblies may exhibit intrinsic stabilization features that could be relevant for surface coloration systems.

Abrasion resistance in PNSB-based prints would be expected to depend strongly on matrix cohesion, film flexibility, and particle-matrix adhesion. As observed in conventional pigment-printing systems, brittle or insufficiently elastic matrices may crack or flake under repeated mechanical stress, leading to particle loss and color fading [64]. Consequently, optimization of matrix elasticity and curing conditions would be an important consideration for achieving acceptable abrasion performance in conceptual PNSB-based printing systems.

Print Performance and Optical Uniformity

Beyond durability, overall print performance encompasses color strength, uniformity, surface appearance, and handle [54, 60, 66]. When considered conceptually, print performance in PNSB-based systems would be expected to depend strongly on the spatial distribution, packing density, and layer uniformity of biomass particles within the printed layer. Homogeneous dispersion and controlled layer thickness are therefore critical to minimize mottling, uneven color development, and excessive surface roughness in particulate chromophoric systems [61, 67].

From an optical standpoint, uniform surface coverage and consistent particle distribution generally govern

color strength and visual homogeneity in particulate printing systems [61, 62]. In PNSB-based systems, the particulate nature of the biomass may additionally influence surface topology and tactile properties of the printed layer. In addition to visual and tactile attributes, the deposition of particulate chromophoric layers may influence fabric drape and bending behavior, which are important aspects of overall print performance. Smartphone-based digital image processing approaches have been demonstrated as effective, non-destructive tools for quantifying drape-related changes induced by textile surface modification [71].

Performance Limitations and Optimization Considerations

Despite the conceptual viability of PNSB-based fixation strategies, several limitations warrant careful consideration. Variability in biomass composition, sensitivity to moisture, and the potential for biological or physicochemical degradation may influence long-term performance and batch-to-batch reproducibility. In addition, regulatory, hygienic, and consumer safety considerations may impose constraints on permissible biomass loadings or necessitate post-treatment steps when such systems are envisaged for consumer textile applications.

In textile printing systems, performance optimization generally requires the integration of controlled material preparation, appropriate matrix and binder design, and systematic adjustment of processing parameters [55, 58, 61]. Accordingly, future development of PNSB-based printing concepts would likely rely on similar integrated formulation and process-engineering strategies. These efforts should be guided by established testing methodologies used for pigment-printed textiles, including standardized assessments of washing durability, lightfastness, and abrasion resistance [62, 67], while allowing for appropriate adaptation to account for the specific characteristics of biomass-based chromophoric systems.

Environmental Impact and Circular Bioeconomy Perspective

The growing environmental burden associated with conventional textile printing has intensified interest in alternative material concepts aimed at reducing chemical consumption, energy demand, and waste generation. Within this broader context, bio-based and naturally derived color systems have been increasingly discussed from life-cycle assessment and circular bioeconomy perspectives as potential pathways toward more sustainable textile printing technology [5, 72]. Against this background, the conceptual consideration of PNSB biomass as a chromophoric particulate system may offer potential environmental advantages. Unlike conventional pigment systems derived from

petrochemical synthesis, PNSB-based chromophoric materials originate from biological growth processes that may be compatible with resource recovery and waste valorization strategies.

Reduced Chemical and Solvent Use

One of the potential environmental advantages associated with PNSB-based printing concepts lies in the possible reduction of chemical and solvent usage. Conventional pigment production typically involves multi-step synthesis, purification, and surface modification processes that consume significant quantities of solvents, dispersants, and stabilizing agents [6]. In contrast, when PNSB biomass is considered as a chromophoric particulate material, the direct utilization of intact cells could, in principle, avoid solvent-intensive pigment extraction and purification steps while preserving the native organization of photosynthetic pigments within the cellular structure. By maintaining pigments within their native biological matrix, such approaches could potentially reduce reliance on additional stabilizers or encapsulation agents that are often required to protect extracted natural pigments from degradation. Beyond possible reductions in chemical processing, the biological origin of chromophoric biomass may conceptually align with circular bioeconomy principles, particularly in scenarios where PNSB biomass could be produced using waste-derived substrates or integrated within resource recovery value chains, potentially contributing to lower material complexity, reduced energy demand, and decreased emissions.

Waste-to-Color Concept

The valorization of organic waste streams through microbial biotechnology is increasingly explored as a strategy for converting low-value residues into functional biomaterials and industrial feedstocks within circular bioeconomy frameworks [12, 13]. PNSB are well recognized for their metabolic versatility and ability to grow on diverse organic substrates, including waste-derived carbon sources [12]. This characteristic enables the conceptual integration of PNSB biomass production with wastewater treatment and organic waste management systems. In such frameworks, waste streams are not merely treated for disposal but are transformed into resources for producing functional chromophoric biomass.

The resulting “waste-to-color” concept aligns closely with circular bioeconomy principles, wherein waste-derived inputs are converted into value-added materials for industrial applications. When coupled with textile printing, this approach conceptually links environmental remediation with sustainable manufacturing, offering dual environmental benefits: pollution mitigation and reduced reliance on virgin raw materials.

Comparison with Conventional Pigment Printing

When considered conceptually, bio-based and particulate chromophoric systems have been discussed in the literature as alternatives to conventional pigment printing, particularly in relation to material origin, processing pathways, and potential environmental implications [5, 6]. Compared with conventional textile printing, bioprinting approaches have the potential to provide several sustainability-related advantages. The use of biologically derived colorants or chromophoric biomass may reduce water consumption by minimizing extraction, purification, and repeated washing steps typically associated with conventional pigment production. Likewise, replacing synthetic colorants with biological materials may reduce dependence on hazardous chemicals, including heavy metals and certain fixation auxiliaries. In addition to coloration, many biological materials possess intrinsic functional properties, such as antimicrobial activity and ultraviolet (UV) protection, potentially reducing the need for additional functional finishing treatments.

Against this broader background, PNSB-based textile printing represents one potential bioprinting strategy and would be expected to differ from conventional pigment printing primarily in terms of raw material sourcing and upstream processing intensity. While both approaches rely on particulate chromophoric systems and surface deposition mechanisms, conventional pigments are predominantly synthetic and typically require energy-intensive production routes, whereas PNSB biomass originates from biological growth processes and may be regarded as a potentially renewable chromophoric resource. Furthermore, although both systems depend on matrix-assisted fixation and surface deposition mechanisms, differences may arise with respect to moisture management, biomass standardization, and variability associated with biological production. From a sustainability perspective, PNSB-based approaches could conceptually align more closely with circular bioeconomy strategies, particularly when integrated with waste-derived substrates or resource recovery processes.

Sustainability Advantages and Limitations

The sustainability implications of emerging chromophoric materials must be evaluated in relation to both their potential environmental benefits and the practical constraints associated with their production and application [39, 72]. From a sustainability perspective, PNSB-based chromophoric systems could offer potential advantages related to renewable sourcing, reduced chemical complexity, and conceptual compatibility with circular bioeconomy frameworks. However, these potential benefits must be considered alongside practical challenges, including the energy demand associated with biomass cultivation, process scalability, batch-to-batch consistency, and regulatory acceptance.

Life-cycle assessments specifically addressing PNSB-based textile printing systems are currently lacking, and future studies will therefore be required to quantitatively evaluate their environmental performance relative to established pigment printing technologies. Nevertheless, the conceptual alignment of PNSB biomass with sustainable manufacturing principles suggests that further systematic investigation of this approach may be justified.

Circular Bioeconomy Integration Model

Circular bioeconomy approaches increasingly emphasize the conversion of waste-derived resources into value-added biomaterials through integrated biological and industrial processes, supporting closed-loop material cycles and more sustainable manufacturing systems [12, 15, 72].

Fig. 4 illustrates a conceptual circular bioeconomy model integrating PNSB biomass production with textile printing. In this framework, waste-derived substrates are converted into chromophoric biomass through biological cultivation, formulated into aqueous printing pastes, applied via textile printing processes, and ultimately reintegrated into bioresource recovery loops. Such integration emphasizes closed material cycles and highlights the role of biotechnology in enabling environmentally responsible textile coloration.

Potential Applications

From a conceptual standpoint, such surface-dominated chromophoric systems are relevant across a broad spectrum of textile contexts, ranging from technical and functional textiles – where surface activity and limited penetration are desirable – to commercial pigment-printed fabrics and fashion applications, where visual appearance, texture, and sustainability narratives play a dominant role. In fashion and design-driven contexts, where aesthetics and sustainability narratives co-evolve, minimal-waste garment design approaches

provide a relevant framework for positioning novel bio-derived coloration concepts [73].

Importantly, even in cases where chromophoric stability is limited, such behavior does not necessarily represent a drawback. In fashion and design-driven contexts, controlled color instability or gradual color evolution may be deliberately exploited to create dynamic, time-responsive, or conceptually expressive textiles that change appearance during use or aging [63].

By contrast, for commercial and technical textile applications, formulation strategies, substrate modification, and matrix-assisted fixation can be tailored to prioritize chromophoric retention, durability, and performance stability. In this sense, intact PNSB biomass enables a versatile surface-coloration concept that can be positioned across technical, commercial, and design-oriented textile frameworks without relying on fiber-level diffusion mechanisms.

Challenges and Future Perspectives

Despite the strong conceptual rationale for considering PNSB biomass as a chromophoric particulate system for textile printing, several scientific, technological, and translational challenges remain to be addressed before such concepts can advance toward practical or industrial relevance. These challenges are primarily associated with biomass standardization, optical reproducibility, formulation and process engineering, durability under use conditions, sustainability validation, and regulatory acceptance.

Biomass Standardization and Process Scale-Up

The use of biologically derived materials in industrial processes is often associated with intrinsic variability, which can complicate efforts to achieve consistent material properties and reproducible manufacturing performance [6]. A fundamental challenge in conceptual PNSB-based chromophoric systems therefore lies in the intrinsic variability of biological materials.

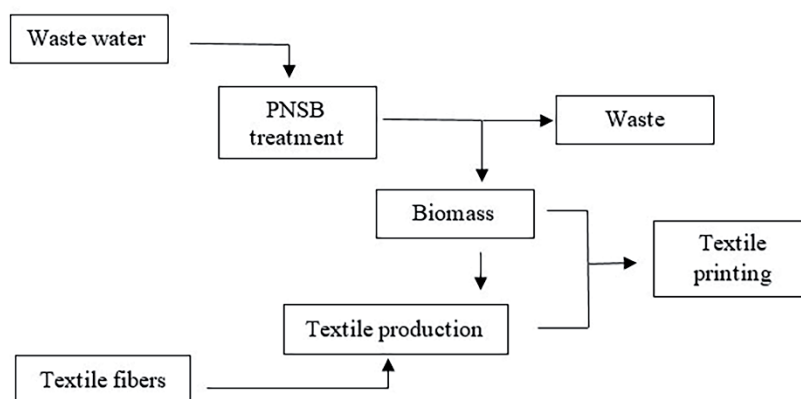


Fig. 4. Waste-to-color concept showing the transformation of wastewater into PNSB-driven chromophoric biomass for sustainable textile printing.

In general, the composition and structural characteristics of microbial biomass can be strongly influenced by cultivation conditions such as light intensity, nutrient availability, carbon source, and growth phase. For PNSB specifically, pigment composition, intracellular pigment density, and cell morphology may vary under different cultivation regimes. Although this biological tunability could potentially offer opportunities for adjusting optical properties, it may simultaneously complicate batch-to-batch reproducibility, which is an essential requirement for textile printing applications. This challenge becomes particularly significant when intact PNSB biomass is conceptually considered as a pigment-like feedstock rather than as an extracted molecular dye.

While PNSB cultivation has been demonstrated at pilot scale in areas such as wastewater treatment and resource recovery [12, 17], the controlled production of chromophoric biomass for potential textile applications would likely require optimized photobioreactor configurations, precise process control, and carefully designed downstream handling strategies. Data-driven process modeling and machine-learning-assisted optimization have increasingly been applied to biological and biotechnological systems to improve process control, reproducibility, and scalability [30]. Future studies could explore the application of such modeling approaches to PNSB cultivation and biomass production systems in order to support more consistent and scalable generation of chromophoric biomass.

Color Reproducibility and Optical Control

Achieving consistent and predictable color performance is a common challenge in textile coloration systems, where optical appearance depends on chromophore composition, material distribution, and light-matter interactions within the printed layer [38, 44]. In the context of biomass-based textile printing concepts, including those involving PNSB biomass, this challenge may become particularly pronounced. Variations in the carotenoid-to-bacteriochlorophyll ratio may lead to perceptible shifts in CIELab color coordinates, hue, and chroma, thereby complicating color matching and quality control.

In PNSB-based chromophoric systems, intact bacterial cells would behave as particulate chromophoric entities. As a result, the optical appearance of printed layers would likely be governed by both absorption and scattering effects, which depend on particle packing, surface coverage, and layer morphology.

More generally, the presence of particulate biological structures can influence surface topology and optical uniformity in deposited coatings. In PNSB-based systems specifically, bacterial cells introduce a distinct particle microstructure that may affect surface roughness, porosity, and light-scattering behavior, potentially enabling visual effects that differ from those produced by conventional pigment systems.

While such structure–optics interactions have not yet been systematically investigated for PNSB-based textile prints, they represent a potentially valuable research direction from a materials engineering perspective.

Another general consideration in pigment systems derived from photosynthetic organisms is the photochemical sensitivity of pigments under light and oxidative stress [69]. For PNSB-derived chromophoric systems, this sensitivity could represent an additional challenge, even though the native membrane environment of intact cells may provide partial stabilization of pigment-protein complexes.

Reflectance-based colorimetric characterization combined with predictive modeling has increasingly been explored as a strategy for understanding and controlling the optical behavior of complex chromophoric systems and functional materials [30]. Future research could therefore apply such integrated analytical and modeling approaches to relate cultivation parameters and formulation design to optical outcomes, thereby enabling improved control of chromophoric performance.

Formulation Engineering: Binder, Thickener, and Crosslinker Integration

Formulation engineering plays a central role in particulate-based textile printing systems, where binders, thickeners, and crosslinking agents are used to control dispersion stability, rheology, fixation, and durability of the chromophoric phase [31, 45]. Within this general framework, the incorporation of intact PNSB biomass into textile printing pastes introduces formulation challenges that differ from those associated with molecular dyes or conventional pigments.

As a particulate chromophoric phase, PNSB biomass would need to be stably dispersed within complex paste matrices while maintaining cellular integrity, chromophoric exposure, and suitable rheological behavior for printing. In such systems, matrix-assisted immobilization strategies analogous to pigment printing – based on polymeric binders, thickened aqueous systems, or hybrid crosslinked networks – could play a central role in fixation and durability.

At the same time, there is growing interest in the use of bio-based auxiliaries and low-impact thickeners that align with sustainability objectives [5, 31]. Accordingly, future research could explore the development of hybrid formulations that balance chromophoric visibility with mechanical anchoring, highlighting the need for formulation strategies that reconcile optical performance with long-term durability.

Durability, Stability, and Performance Limitations

Durability, stability, and resistance to mechanical and environmental stress are key performance criteria for textiles and are commonly evaluated using standardized textile testing protocols [74, 75]. In the context of

potential PNSB-based textile printing systems, printed materials would need to exhibit durability comparable to that of established pigment-printed textiles in order to be practically relevant.

Durability under laundering and mechanical action is typically assessed through standardized testing procedures that evaluate changes in surface appearance, structural integrity, and functional performance after repeated washing cycles [74, 75]. In particulate-based printing systems, resistance to washing and abrasion generally depends on matrix cohesion and particle–matrix adhesion [61, 62]. Lightfastness is primarily governed by pigment stability and the protective role of the surrounding matrix.

However, systematic durability studies employing standardized textile testing protocols remain scarce for intact biomass-based chromophoric systems, representing an important knowledge gap.

Future optimization efforts could therefore explore the combined effects of matrix elasticity, controlled curing conditions, and mechanistic degradation analysis in order to identify dominant failure modes and guide formulation refinement. Such investigations would be essential for establishing reliable performance benchmarks relative to conventional pigment-printing technologies.

Industrial Readiness and Regulatory Considerations

The introduction of biologically derived materials into consumer textile products raises important regulatory, safety, and quality-control considerations that must be addressed during early stages of technological development [33, 52]. In the case of PNSB-based chromophoric systems, the use of intact microbial biomass may therefore require careful evaluation of factors such as bioburden control, potential allergenicity, and overall product safety. Although purple non-sulfur bacteria are widely studied in environmental biotechnology and are generally regarded as non-pathogenic, their incorporation into finished textile products would likely require additional verification to ensure compliance with regulatory frameworks.

Accordingly, matrix-assisted immobilization strategies and post-print inactivation approaches could potentially be considered in order to meet regulatory requirements while preserving chromophoric performance.

From an industrial perspective, PNSB-based chromophoric printing remains at an exploratory and pre-competitive stage. Progress toward practical application would likely require interdisciplinary collaboration between microbiologists, materials scientists, and textile engineers in order to bridge the gap between biological production systems and textile manufacturing requirements.

Conclusions

This review has examined purple non-sulfur bacteria (PNSB) biomass from a material-driven perspective as a potential chromophoric particulate system for textile printing, framing intact bacterial cells not merely as biological pigment sources but as functional, pigment-scale color carriers. By integrating insights from microbiology, materials science, and textile engineering, the review highlights how the intrinsic pigmentation, micrometer-scale particle dimensions, and biologically organized pigment structures of PNSB fundamentally differentiate them from both molecular dyes and conventional synthetic pigments.

This conceptual analysis indicates that, at a theoretical level, PNSB biomass exhibits several attributes compatible with pigment-style textile printing, including broad visible-light absorption, particulate behavior suitable for surface deposition, and compatibility with matrix-assisted fixation strategies. Unlike extracted natural pigments, the direct use of intact biomass preserves the native supramolecular organization of chromophores, potentially offering advantages in optical performance while reducing the need for solvent-intensive processing. These characteristics support the consideration of PNSB biomass as a distinct class of bio-derived chromophoric materials, rather than as a modification of existing dye systems.

From a formulation and processing standpoint, the review underscores the flexibility of PNSB-based printing concepts, which could accommodate diverse matrix systems, rheological designs, and printing techniques, particularly those traditionally employed for pigment-based coloration. However, this flexibility is accompanied by challenges related to biomass variability, color reproducibility, fixation efficiency, and durability, all of which would require systematic investigation. At present, no standardized industrial or laboratory-scale textile printing systems based on intact PNSB biomass have been established, and experimental validation therefore remains a key objective for future research. The absence of established implementations further emphasizes the exploratory nature of this field and the need for systematic experimental studies.

Environmental and circular bioeconomy considerations provide additional motivation for investigating PNSB-based chromophoric systems. The potential integration of biomass production with waste-derived substrates and resource recovery processes suggests a pathway toward reduced chemical usage, simplified processing chains, and enhanced sustainability of textile coloration. Nevertheless, quantitative life-cycle assessments, regulatory evaluations, and techno-economic analyses remain essential to determine whether these conceptual advantages can be translated into scalable and compliant industrial solutions.

AI Usage Disclosure Statement

During the preparation of this manuscript, the authors used OpenAI ChatGPT (GPT-5.5) solely to improve the English language, grammar, and readability of the text. After using this tool, the authors reviewed, revised, and verified the manuscript as needed and accept full responsibility for the accuracy, originality, and scientific integrity of the published work.

Conflict of Interest

The authors declare no conflict of interest.

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