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VALORIZATION OF RESIDUAL ALGAL BIOMASS FOR NATURAL COLORANT RECOVERY AND TEXTILE APPLICATIONS

BY

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Abstract. Residual algal biomass generated by coastal accumulations, cultivation systems and industrial processing is a renewable feedstock for sustainable textile coloration. This paper reviews the recovery of chlorophylls, carotenoids and phycobiliproteins and evaluates their potential in dyeing, printing and functional finishing. Solvent selection is governed by pigment polarity: hydroalcoholic media are suitable for lipophilic chlorophylls and carotenoids, whereas buffered aqueous systems protect water-soluble phycobiliproteins. Literature data indicate that ultrasound, freeze-thaw treatment, pulsed electric fields and supercritical carbon dioxide can improve extraction performance while limiting thermal degradation. Reported textile applications include green, yellow, brown, red and blue shades on wool, cotton and silk, together with antioxidant activity and ultraviolet protection. The remaining exhausted biomass may subsequently be converted into biosorbents, biochar, biostimulants, biodegradable composites or biogas. A cascading biorefinery approach therefore supports waste prevention, resource efficiency and the development of lower-impact textile processes and creates a coherent basis for future experimental optimization.

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1. Introduction

The textile sector continues to depend heavily on synthetic colorants and auxiliary chemicals, although their manufacture and use are associated with resource consumption, complex effluents and potential ecological and health effects. Natural colorants are therefore being reconsidered as part of broader strategies for cleaner production, circular material use and safer textile finishing (Negi, 2025). Algae and cyanobacteria are especially attractive because they combine rapid biomass generation with a chemically diverse pigment profile and can be cultivated without competing directly with conventional agricultural land (Mutaf-Kılıç *et al.*, 2023; Reimão *et al.*, 2025; Rocha *et al.*, 2025).

The term residual algal biomass covers several streams: seaweed accumulated or collected from coastal areas, residues generated during cultivation and harvesting, filter cakes or solid fractions from industrial processing, and biomass remaining after the recovery of higher-value compounds. Treating these materials exclusively as waste overlooks their content of chlorophylls, carotenoids, phycobiliproteins, polysaccharides and other bioactive constituents. Their selective recovery can convert a disposal problem into a renewable source of color and functionality, while the exhausted fraction can remain available for secondary applications (Lakshmi *et al.*, 2020; Amir *et al.*, 2025).

Algal colorants are relevant to both dyeing and printing. Chlorophyll-rich fractions can generate green and olive shades, carotenoids provide yellow, orange, red and brown tones, and phycobiliproteins supply blue or red hues that are uncommon among naturally derived dyes. In parallel, alginate obtained from brown algae is an established thickening agent for reactive printing pastes. Consequently, algae may contribute simultaneously as a source of chromophores, functional compounds and bio-based process auxiliaries (Akter *et al.*, 2023; Nuru *et al.*, 2025; Tounsi *et al.*, 2023).

Current market development for bio-based textile colorants is driven by cleaner-production targets, circularity commitments and demand for renewable functional finishes, but industrial adoption remains limited by cost, shade reproducibility, raw-material consistency, extraction efficiency and fastness performance. Recent literature therefore frames market acceptance as dependent not only on natural origin, but also on scalable processing, consistent quality and demonstrable environmental benefit (Reimão *et al.*, 2025; Rocha *et al.*, 2025; Negi, 2025).

Compared with recent reviews focused mainly on microalgal pigments as dye sources or on algae-based textile dyeing and functionalization (Mutaf-Kılıç *et al.*, 2023; Rocha *et al.*, 2025), the present review specifically centers on

residual algal biomass, links pigment recovery to literature-derived laboratory workflows, and extends the analysis to cascading uses of the exhausted fraction. From a technology-readiness perspective, most reported algae-derived textile colorants remain at proof-of-concept or laboratory-validation stage, approximately TRL 3–5, rather than at full industrial deployment; pilot-scale validation, process standardization, supply-chain consistency and economic assessment are therefore still required (Reimão *et al.*, 2025).

This paper reviews the main classes of algal pigments, proposes literature-based extraction workflows and critically summarizes quantitative data reported for pigment recovery and textile application. Particular attention is given to the distinction between published experimental results and the proposed laboratory routes presented here. The final section examines cascading uses of the residual fraction in order to position textile coloration within a wider biorefinery framework.

Review methodology

The present paper follows a targeted narrative-review approach. Peer-reviewed studies were identified in Scopus, Web of Science and ScienceDirect using combinations of the terms algae, microalgae, seaweed, cyanobacteria, pigment, natural colorant, dyeing, printing, extraction, residual biomass and waste valorization. The main publication window was 2018–July 2026, with emphasis on 2023–2026 literature and selected earlier studies retained when they provided benchmark extraction data. Studies were included when they addressed pigment recovery, textile dyeing, printing or functional finishing, or downstream valorization of algal residues and reported sufficiently clear process conditions or quantitative outcomes; unrelated applications, non-peer-reviewed sources and papers lacking relevance to the selected pigment families were excluded. Because moisture basis, extraction ratio, analytical method and process scale differ substantially across studies, numerical results were synthesized comparatively rather than pooled statistically.

Residual algal biomass in textile coloration and printing

The valorization route begins with the identification and conditioning of the biomass. Washing removes salts, sand and adhering impurities, whereas low-temperature drying and milling improve storage stability and increase the surface area available for mass transfer. The subsequent extraction step must be matched to pigment polarity and thermal sensitivity. Separation, mild concentration and protected storage then provide fractions that can be assessed for dyeing, printing or functional finishing. The general sequence is presented in Fig. 1.

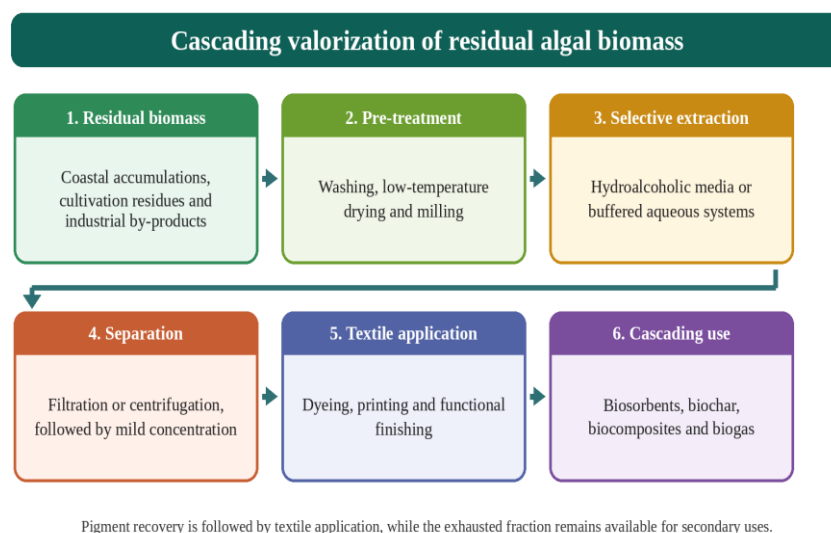


Fig. 1 – General sequence for pigment recovery, textile application and cascading use of residual algal biomass.

2. Dyeing with algal pigments

Published work confirms that algal pigments can be transferred to protein and cellulosic fibres, although performance depends on pigment purity, fibre chemistry, mordanting strategy, temperature and exposure to light or oxygen. Chlorophyll extracted from microalgae has been evaluated on wool, while phycocyanin has produced blue shades on cotton and silk (Baek *et al.*, 2022). Genipin-assisted fixation on silk has also been proposed to improve durability and to retain antioxidant and ultraviolet-protective functions (Jorge *et al.*, 2024; Nair *et al.*, 2025; Wu *et al.*, 2023).

Natural colorants rarely behave as direct substitutes for a standardized synthetic dye. Batch-to-batch variation, sensitivity to pH and temperature, and limited light or washing fastness may require fibre pretreatment, biomordants, crosslinkers or protective formulations. However, these limitations do not invalidate their use; rather, they define the process variables that must be controlled during scale-up. The laboratory appearance of several differently colored extracts and textile swatches is illustrated in Fig. 2.



Fig. 2 – Illustrative laboratory arrangement with algal extracts and dyed textile swatches.

Printing and the technological role of alginate

In textile printing, algae contribute in two distinct ways. Pigment fractions may be incorporated into coating or printing formulations, while alginate functions as a rheology modifier. Sodium alginate is widely used as a thickener for reactive dyes because it develops the viscosity required for pattern definition and shows limited undesirable reaction with the dye under alkaline fixation conditions. Research on alternative and mixed thickeners further demonstrates that print sharpness, penetration, handle and washing-off behavior are strongly governed by paste rheology (Akter *et al.*, 2023; Nuru *et al.*, 2025).

From a sustainability perspective, the strongest approach is not merely the replacement of one ingredient, but the design of a formulation in which the colorant, thickener and fixation system are selected together. Algal pigments may therefore be most effective when integrated with bio-based thickeners, low-temperature treatment and controlled water use rather than introduced into an otherwise unchanged conventional process (Rocha *et al.*, 2025).

Major classes of algal colorants

Three pigment families dominate the discussion of algae-derived textile colorants: chlorophylls, carotenoids and phycobiliproteins. Their chemical structures determine color, solubility and process stability. Chlorophylls and most

carotenoids are lipophilic and are generally recovered with ethanol, hydroalcoholic mixtures or other solvents of intermediate polarity. Phycobiliproteins are water-soluble protein-pigment complexes and require buffered aqueous extraction under mild conditions. Table 1 summarizes the principal examples and their relevance to textile processing (Mutaf-Kılıç *et al.*, 2023; Tounsi *et al.*, 2023).

Table 1
Major algal pigment classes and their relevance to textiles

Pigment class*	Representative pigments and common sources	Color / solubility	Textile relevance
Chlorophylls	Chlorophyll a in most algae; chlorophyll b in green algae; chlorophyll c in brown algae and marine microalgae	Green to olive; mainly lipophilic	Promising for green shades, but sensitive to light, oxygen, acidic media and prolonged heating.
Carotenoids	β -carotene in <i>Dunaliella</i> ; lutein in <i>Chlorella</i> and <i>Scenedesmus</i> ; astaxanthin in <i>Haematococcus</i> ; fucoxanthin in brown algae	Yellow, orange, red or brown-gold; lipophilic	Useful for warm shades and antioxidant finishing; solvent choice and oxidation control are critical.
Phycobiliproteins	Phycocyanin in <i>Arthrospira/Spirulina</i> ; phycoerythrin and allophycocyanin in red algae and cyanobacteria	Blue, red-pink or blue-green; water-soluble	Rare natural hues with potential for cotton and silk; highly sensitive to heat, light and extreme pH.

*The table is a synthesis based on Mutaf-Kılıç *et al.*, 2023, Tounsi *et al.*, 2023, Reimão *et al.*, 2025 and Rocha *et al.*, 2025.

Chlorophylls

Chlorophylls contain a magnesium-porphyrin chromophore with a hydrophobic phytol chain. Chlorophyll **a** is widely distributed, chlorophyll **b** is characteristic of green algae, and chlorophyll **c** occurs in several brown algae and marine microalgae. Their intense green color is attractive for textile applications, but stability is limited by pheophytinization, photo-oxidation and reactions promoted by acids, heat or oxygen. Extraction and application must therefore be performed rapidly, at low temperature and with protection from light (Kulkarni and Nikolov, 2018; Jorge *et al.*, 2024).

Carotenoids

Carotenoids are conjugated isoprenoid compounds that generate yellow, orange and red coloration and may also provide antioxidant activity. β -Carotene,

lutein, astaxanthin and fucoxanthin are the most relevant examples for algal processing. Their lipophilic nature favors ethanol or other solvents of intermediate polarity, ultrasound-assisted extraction and, for high-value compounds, supercritical carbon dioxide. Because the conjugated structure is vulnerable to oxidation and isomerization, oxygen, light and excessive temperature must be controlled (Molino *et al.*, 2018; Di Sanzo *et al.*, 2018; Oliyaei and Moosavi-Nasab, 2021).

Phycobiliproteins

Phycobiliproteins are fluorescent, water-soluble complexes in which an open-chain tetrapyrrole chromophore is covalently linked to a protein. Phycocyanin produces blue shades, phycoerythrin gives red-pink coloration, and allophycocyanin appears blue-green. Their aqueous solubility is advantageous for lower-impact processing, but the protein component makes them sensitive to denaturation. Neutral pH, cold conditions and limited processing time are therefore essential (Tounsi *et al.*, 2023; Dehn *et al.*, 2026; Le Guillard *et al.*, 2023).

Proposed extraction routes and laboratory workflow

The procedures in this section are proposed laboratory workflows derived from the reviewed literature; they do not represent original experimental results. Their purpose is to provide a coherent starting point for future trials using residual algal biomass. The three routes share preliminary washing, controlled drying or cold handling, size reduction and protected storage, but they differ substantially in solvent system and cell-disruption strategy (Fig. 3).

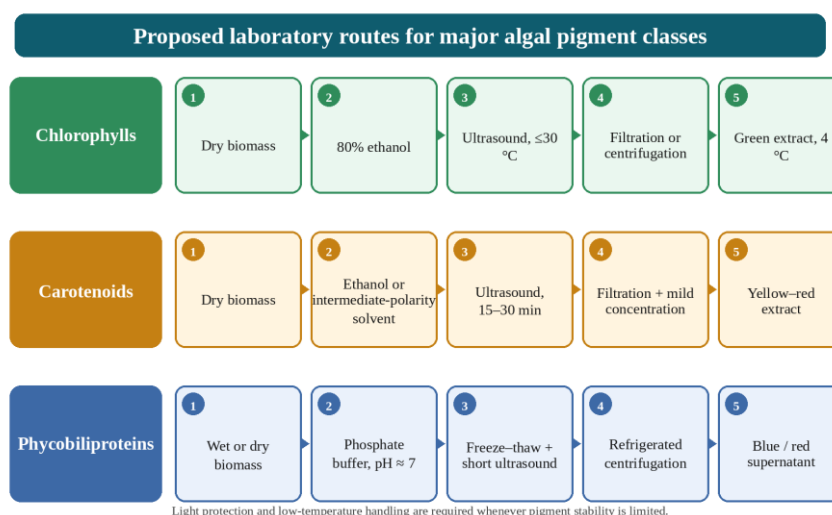


Fig. 3 – Proposed laboratory routes for chlorophylls, carotenoids and phycobiliproteins. The scheme is based on the reviewed extraction literature.

Proposed chlorophyll extraction

A practical chlorophyll route starts with washed biomass dried at low temperature and ground to a fine powder. Approximately 1.00 g of dry biomass may be contacted with 20–30 mL of 80% ethanol. Ultrasound treatment for 20–30 min at a temperature not exceeding 30 °C can support cell disruption and mass transfer. Filtration or centrifugation separates the green liquid fraction, which should be stored in amber containers at 4°C until spectrophotometric characterization or preliminary textile application. A sequential extraction may improve recovery and selectivity (Kulkarni and Nikolov, 2018).

Proposed carotenoid extraction

For carotenoids, 1.00 g of dried and milled biomass may be extracted with 20–30 mL of ethanol or another solvent selected according to the target pigment. Ultrasound treatment for 15–30 min can be followed by filtration and mild solvent removal under reduced pressure. The expected fraction may range from yellow for lutein to orange for β -carotene, red for astaxanthin or brown-gold for fucoxanthin. Where equipment is available, supercritical carbon dioxide can reduce solvent residues and provide selective recovery, although pressure, cost and energy demand must be considered (Di Sanzo *et al.*, 2018; Oliyai and Moosavi-Nasab, 2021).

Proposed phycobiliprotein extraction

Phycobiliprotein recovery should use a buffered aqueous medium near neutral pH. A solid-to-liquid ratio close to 1:20 can be combined with three to five freeze-thaw cycles, short homogenization or ultrasound treatment and refrigerated centrifugation. The colored supernatant is then collected and stored in darkness at low temperature. Pulsed electric fields may further improve phycoerythrin release from macroalgae, while extended ultrasound-assisted enzymatic hydrolysis has also been investigated. Process severity must remain low enough to avoid protein denaturation (Dehn *et al.*, 2026; Le Guillard *et al.*, 2023).

The laboratory configuration required for such preliminary work is relatively simple: conditioned biomass, extraction vessels, an ultrasonic bath or homogenizer, filtration or centrifugation equipment, amber storage vials and textile swatches for screening. Fig. 4 presents an illustrative arrangement. Quantitative characterization should subsequently include UV-Vis spectra, pigment concentration, colorimetric coordinates and standardized fastness testing.



Fig. 4 – Illustrative laboratory setup for conditioning residual algae, extracting pigments and collecting colored fractions.

Experimental data reported in the literature

Quantitative data from the literature demonstrate the strong dependence of pigment recovery on biological source and process conditions. Direct comparison must be made cautiously because studies use different moisture bases, extraction ratios, solvents and analytical procedures. Nevertheless, the values summarized in Table 2 identify useful ranges for designing future experiments and confirm that assisted or sequential methods can substantially improve recovery.

Table 2
Selected experimental data for algal pigment extraction

Pigment / source	Extraction conditions	Reported literature result*	Reference
Chlorophylls and lutein / <i>Chlorella vulgaris</i>	Selective three-stage Kulkarni ethanol extraction	15.4 mg chlorophylls / g dry biomass and 5.4 mg lutein / g	Kulkarni and Nikolov, 2018
Phycocyanin / oxygenic photogranules	Freeze-thaw, phosphate buffer and 15 min ultrasound	104.69±3.8 mg / g	Nair <i>et al.</i> , 2025
Astaxanthin and lutein / <i>Haematococcus pluvialis</i>	Supercritical CO ₂ , 50°C, 550 bar, 3.62 g / min	19.72 mg / g astaxanthin and 4.03 mg / g lutein	Di Sanzo <i>et al.</i> , 2018

Pigment / source	Extraction conditions	Reported literature result*	Reference
Astaxanthin / <i>Haematococcus pluvialis</i>	GRAS-solvent extraction after mechanical pretreatment	Approximately 87% maximum recovery	Molino <i>et al.</i> , 2018
Fucoxanthin / <i>Sargassum angustifolium</i>	Acetone, 15 min ultrasound-assisted extraction	0.79 ± 0.03 mg/g	Oliyai and Moosavi-Nasab, 2021
R-phycoerythrin / <i>Palmaria palmata</i>	PBS 0.02 M, 1:20 solid-liquid ratio; pulsed electric field pretreatment	2.05 ± 0.07 mg/g dry matter conventionally and 7.39 mg/g after PEF	Dehn <i>et al.</i> , 2026
R-phycoerythrin / <i>Grateloupia turuturu</i>	Ultrasound-assisted enzymatic hydrolysis; plateau at 180 min	4.28 ± 0.09 mg/g dry weight	Le Guillard <i>et al.</i> , 2023

*Values are reproduced as reported by the cited studies and should not be interpreted as directly comparable without considering differences in analytical basis and process scale.

For quantitative comparison, results expressed as pigment mass per unit dry biomass provide the most useful common basis where available. In the reviewed studies, dry-biomass-normalized values span markedly different ranges across pigment classes, while percentage recovery is sometimes the only reported metric. These values should therefore be compared within equivalent pigment and analytical categories rather than ranked directly across all studies. Future work should preferentially report mg pigment/g dry biomass together with extraction yield, solvent-to-solid ratio and recovery definition to improve cross-study comparability.

Textile application and functional performance

The literature also shows that algal fractions may provide more than visible coloration. Chlorophyll uptake on wool, phycocyanin adsorption on cotton and silk, ultraviolet protection and antioxidant activity have all been reported. The numerical data in Table 3 are particularly useful because they link colorant fixation to functional performance and washing behavior.

Table 3
Selected experimental data for textile application of algal pigments

Pigment / substrate	Process or measured parameter	Reported literature results*	Reference
Chlorophyll / wool	Initial uptake on mordanted and unmordanted wool	Approximately 70%; total uptake reached 87% after two cycles	Jorge <i>et al.</i> , 2024
Chlorophyll / wool process effluent	Copper recovery in a proposed circular process	Approximately 98% Cu ²⁺ recovery	Jorge <i>et al.</i> , 2024
Phycocyanin / cotton	Double mordanting and cold dyeing	55.5 ± 2.8 mg/g adsorption; 64.97% color retention after five washes	Nair <i>et al.</i> , 2025
Phycocyanin / silk	Double mordanting and cold dyeing	31.32 ± 1.09 mg/g adsorption; 44.43% color retention after five washes	Nair <i>et al.</i> , 2025
Phycocyanin / cotton and silk	Antioxidant activity after coloration	64.78 ± 3.06% for cotton and 93.93 ± 1.76% for silk	Nair <i>et al.</i> , 2025
Phycocyanin / cotton and silk	Ultraviolet protection factor	UPF >200 for cotton and approximately 35 for silk	Nair <i>et al.</i> , 2025
Phycocyanin + genipin / silk	10% o.w.f phycocyanin, 1 g/L genipin, 70°C, 3 h	UPF up to 39 and radical scavenging above 70% in 60 min	Wu <i>et al.</i> , 2023

*The table contains published results only. Differences in fibre pretreatment, concentration and test method must be considered when interpreting the values.

Comparative assessment of extraction technologies and pigment stability

The reviewed extraction routes differ not only in pigment selectivity but also in equipment demand, energy intensity and scale-up complexity. Table 4 summarizes the main strengths, limitations and indicative technological maturity of the principal approaches. The maturity levels are interpretative estimates derived from the scale and type of studies reviewed and do not represent formal technology certification.

Table 4
Comparative assessment of principal algal pigment extraction technologies

Technology	Main advantages	Main limitations	Indicative maturity
Hydroalcoholic / conventional solvent extraction	Simple equipment; adaptable to chlorophylls and carotenoids; low initial capital demand.	Solvent consumption and recovery; oxidation risk; selectivity depends strongly on solvent composition and biomass pretreatment.	TRL 4–6
Ultrasound-assisted extraction (UAE)	Shorter extraction time; enhanced mass transfer; can operate at comparatively mild temperature.	Scale-up requires uniform acoustic energy distribution; energy demand and possible pigment degradation must be controlled.	TRL 4–5
Freeze–thaw / buffered aqueous extraction	Compatible with water-soluble phycobiliproteins; avoids organic solvent use; mild chemical environment.	Time-consuming cycles; cooling/freezing demand; protein stability remains sensitive to temperature, light and pH.	TRL 3–4
Pulsed electric field (PEF) pretreatment	Nonthermal cell disruption; can improve intracellular pigment release while limiting heat damage.	Specialized equipment; optimization depends on biomass conductivity and structure; limited textile-scale demonstrations.	TRL 3–4
Supercritical CO ₂ extraction	High selectivity for lipophilic compounds; low solvent residue; tunable process conditions.	High-pressure equipment, capital cost and energy demand; less suitable for water-soluble pigments.	TRL 4–5
Ultrasound-assisted enzymatic hydrolysis	Mild processing; useful for difficult macroalgal matrices; can improve selective release.	Enzyme cost, long treatment time and process-control complexity can limit scale-up.	TRL 3–4

**Indicative maturity is a qualitative interpretation based on the reviewed literature (Kulkarni and Nikolov, 2018; Di Sanzo et al., 2018; Le Guillard et al., 2023; Dehn et al., 2026) and is not a formal TRL certification.*

Qualitative stability of major algal pigment classes during processing

Pigment class	Light exposure	Heat	Extreme pH	Oxygen
Chlorophylls	High	High	High	High
Carotenoids	High	Moderate	Moderate	High
Phycobiliproteins	High	High	High	Moderate

High = greater sensitivity and stronger need for protective processing; qualitative synthesis, not a numerical scale.

Fig. 5 – Qualitative comparison of the sensitivity of the major algal pigment classes to processing stresses, synthesized from the reviewed literature. High sensitivity indicates a stronger need for protective processing conditions.

Critical interpretation

The extraction results show a clear polarity-based division: ethanol and supercritical systems are effective for lipophilic pigments, whereas buffered water, freeze-thaw treatment and nonthermal cell disruption are preferred for phycobiliproteins. The textile results confirm that fibre type and fixation method are equally important. Cotton displayed higher phycocyanin adsorption and color retention than silk in one study, while silk displayed greater antioxidant activity. This contrast illustrates why color depth, fastness and functionality must be optimized simultaneously rather than evaluated in isolation (Nair *et al.*, 2025).

The evidence base remains heterogeneous. Several studies investigate purified or purpose-grown microalgae rather than true post-industrial residues, and relatively few report complete mass balances, wastewater quality or life-cycle indicators. Future work should therefore compare residual and cultivated biomass under the same extraction and dyeing protocol, quantify solvent and energy demand, and test color fastness according to recognized standards.

From an industrial perspective, process intensification should be evaluated together with economic and environmental performance. Future scale-up studies should therefore combine Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) to quantify biomass logistics, solvent recovery, water and energy demand, pigment yield, waste management and capital requirements, and to compare algae-based routes with conventional synthetic dyeing on an equivalent coloration and functional-performance basis. Supercritical CO₂ can reduce solvent residues but requires high-pressure equipment, whereas aqueous and ultrasound-assisted routes may reduce chemical burden while still carrying energy requirements for drying, cooling, concentration or cell disruption.

Commercialization also requires regulatory and quality-assurance pathways. Natural origin does not automatically guarantee safety because algal biomass may accumulate metals, salts or other contaminants depending on its

source; extracts therefore require compositional characterization, contaminant control, toxicological suitability and batch-to-batch consistency. Textile performance should be verified using recognized standardized methods for washing, light and rubbing fastness, such as the ISO 105 series or equivalent AATCC procedures, together with color-strength and CIELab measurements. Functional claims, including ultraviolet protection or antioxidant activity, should likewise be supported by validated test protocols and durability testing after laundering.

Compared with conventional natural dyes obtained from plants, insects or fungi, algal colorants offer rapid biomass generation, reduced competition with agricultural land and access to distinctive blue, blue-green and red phycobiliprotein hues. Their present disadvantages include pigment instability, variability of residual feedstocks, lower process standardization and less mature industrial supply chains. Priority research should therefore focus on standardized residual-biomass characterization, stabilization and fixation chemistry, pilot-scale continuous extraction, solvent and water recycling, long-term fastness, contaminant management, integrated TEA/LCA and demonstrations on industrial textile machinery.

Cascading valorization beyond the textile application

Pigment extraction should be viewed as the first stage of a cascade rather than the final use of the biomass. The remaining solid fraction can retain polysaccharides, minerals, proteins and carbonaceous material. Depending on composition and contamination, it may be converted into a biosorbent, biochar, agricultural input, biodegradable composite filler or anaerobic digestion feedstock. Such secondary routes distribute processing impacts across several products and reduce the fraction requiring disposal (Amir *et al.*, 2025; Lakshmi *et al.*, 2020).

Table 5

Examples of cascading uses for residual algal biomass

Valorization route*	Residual biomass and process	Reported performance	Reference
Biosorbent for dye-containing water	Fresh and dried <i>Ulva fasciata</i> and <i>Pterocladia capillacea</i>	Dried biomass achieved 98.88–99.56% removal for some reactive dyes and 100% under selected conditions	El-Agawany <i>et al.</i> , 2023
Biochar for wastewater treatment	Marine algal biomass carbonized at 400 °C and ball-milled	Maximum methylene blue adsorption capacity of 500 mg/g	Soares Dias <i>et al.</i> , 2025

Valorization route*	Residual biomass and process	Reported performance	Reference
Recovery of bioactive compounds	Residue of <i>Gracilaria tenuistipitata</i> after agar extraction	95.27 mg gallic acid equivalents/g phenolics and $93.10 \pm 1.19\%$ DPPH activity	Akter <i>et al.</i> , 2026
Agricultural biostimulant	Stranded seaweed fermented biologically	15–25% anaerobic-sludge fermentation products supported plant growth; yeast-fermented material increased soil water retention by up to 27%	Yoruklu <i>et al.</i> , 2022
Biodegradable composite filler	Acetylated algal residual biomass in PLA/PBAT	Relative crystallinity increased from 12.77% to 32.30%; material cost decreased by 14.13% at 25% loading	Yang <i>et al.</i> , 2025
Anaerobic co-digestion	<i>Ulva lactuca</i> mixed with cow manure	Maximum methane yield of 325.75 mL CH ₄ / g VS at a 2:1 ratio	Farobie <i>et al.</i> , 2025

*These routes are complementary to textile use and illustrate the progressive recovery of value from the same biological resource.

A practical cascade may begin with the recovery of a pigment fraction for textile trials, continue with the use of the exhausted solid as an adsorbent or material component, and end with energy recovery from the final biodegradable fraction. The sequence shown in Fig. 6 is conditional: food, cosmetic or agricultural applications require strict control of contaminants and traceability, while biomass collected from polluted coastal areas may be more appropriate for materials or energy routes.

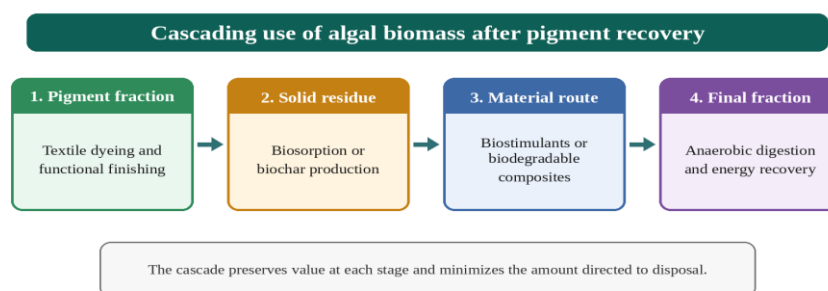


Fig. 6 – Conceptual cascade for using the solid fraction remaining after algal pigment recovery.

3. Conclusions

Residual algal biomass is a technically credible feedstock for natural colorant recovery because it contains chemically distinct pigment classes that cover green, yellow, orange, red, brown and blue shades. Chlorophylls and carotenoids require solvent systems suited to lipophilic compounds, whereas phycobiliproteins are recovered in buffered aqueous media under cold and light-protected conditions. The reviewed data demonstrate that ultrasound, freeze-thaw cycles, pulsed electric fields and supercritical carbon dioxide can improve extraction, although their sustainability must be evaluated through complete mass and energy balances.

Textile studies report successful coloration of wool, cotton and silk and show that algal pigments may also provide antioxidant and ultraviolet-protective properties. At the same time, sensitivity to heat, oxygen, pH and washing confirms the need for controlled fixation strategies, standardized testing and careful formulation. Future experimental work should compare residual biomass sources, characterize pigment composition before application and evaluate color strength, CIELab coordinates and fastness under identical conditions.

The greatest environmental benefit is expected when textile coloration is integrated into a cascading biorefinery. Pigments are recovered first, while the remaining biomass is directed toward biosorption, biochar, agricultural inputs, biodegradable composites or biogas. This sequence supports waste prevention and resource efficiency and provides a scientifically grounded framework for developing lower-impact textile processes.

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VALORIFICAREA BIOMASEI ALGALE
REZIDUALE PENTRU RECUPERAREA COLORANȚILOR
NATURALI ȘI APLICAȚII TEXTILE

(Rezumat)

Biomasa algală reziduală rezultată din depunerile de alge de pe litoral, din sisteme de cultivare sau din procese industriale poate constitui o materie primă regenerabilă pentru colorarea sustenabilă a materialelor textile. Lucrarea analizează recuperarea clorofilelor, carotenoidelor și ficobiliproteinelor, precum și aplicarea lor în vopsire, imprimare și finisare funcțională. Alegerea solventului este determinată de polaritatea pigmentului: mediile hidroalcoolice sunt adecvate clorofilelor și carotenoidelor liposolubile, iar sistemele apoase tamponate protejează ficobiliproteinele hidrosolubile. Datele din literatura de specialitate arată că ultrasunetele, ciclurile de înghețare-dezghețare, câmpurile electrice pulsatorii și dioxidul de carbon supercritic pot îmbunătăți extracția, limitând degradarea termică. Au fost raportate nuanțe verzi, galbene, brune, roșii și albastre pe lână, bumbac și mătase, împreună cu activitate antioxidantă și protecție ultravioletă. După recuperarea pigmentilor, reziduul poate fi valorificat sub formă de biosorbent, biochar, biostimulant, componentă pentru materiale biodegradabile sau substrat pentru producerea biogazului. O abordare în cascadă susține prevenirea deșeurilor și eficiența resurselor.