Marine Macroalgae in Sustainable Textile Dyeing and Functional Finishing: A Comprehensive Review

Gayathri M[1], Dr. S. Grace Annapoorani[2]
[1]Ph.D. Research Scholar, Department of Textiles and Apparel Design, Bharathiar University, Coimbatore, Tamil Nadu, India

[2] Professor and Head, Department of Textiles and Apparel Design, Bharathiar University, Coimbatore, Tamil Nadu, India
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Abstract

The textile sector is one of the thirstiest and most polluting divisions of global production and a considerable share of that load can be traced back to synthetic dyeing and chemical finishing. Over the last decade, marine macroalgae, commonly known as seaweeds have gone from being a wonder of coastal biochemistry to a serious contender for greener colouration and functional finishing of fabrics. Their tissues are packed with a spectacular array of chlorophylls, carotenoids such as fucoxanthin, and phycobiliproteins, as well as phenolic compounds and sulphated polysaccharides which acts as antioxidant, antimicrobial and UV-shields. This review summarises recent findings on the classification and pigment chemistry of brown, red and green macroalgae, the extraction routes used to recover their colourants (conventional solvent extraction, ultrasound- and microwave-assisted methods, supercritical fluid extraction), the dyeing and mordanting strategies applied to cellulosic, protein and synthetic fibres, and the resulting colour fastness and functional performance, including antimicrobial activity and ultraviolet protection factor. Species-specific case studies are contrasted, and environmental and economic issues examined. The continuing challenges to commercial uptake, i.e. dye output, shade repeatability, wash fastness and biomass supply are detailed combined with proposal for future research. The research presented here implies that macroalgal dyes and finishes are technically viable and ecologically promising, but that consistent process standardisation and larger-scale experiments are still needed before they can consistently compete with synthetic alternatives.

Keywords: Marine macroalgae, seaweed pigments, natural dyes, sustainable textile dyeing, functional finishing, antimicrobial textiles, UV protection, colour fastness, fucoxanthin, phycobiliproteins.

1. Introduction

Textile wet processing, particularly dyeing and finishing, uses large amounts of fresh water and energy and produces effluents that often contain unfixed synthetic dye, heavy metals and non-biodegrade auxiliaries [1,15]. Regulatory pressure, consumer demand for greener fashion, and the sheer enormity of the pollution problem have all combined to rekindle interest in natural colourants which have mostly been supplanted by synthetic azo and reactive dyes over the previous century [15]. The mainstays of this previous history were plants, insects and minerals but they cannot always satisfy the demand for both colour and function at industrial scale today, especially with conflicting land use and seasonal variations [2].

Another proposition is marine macroalgae. Many species grow in coastal waters rather than on arable land, many species propagate rapidly without the input of fertiliser or fresh water and their biomass is already produced at scale for food, hydrocolloid and agricultural applications, meaning that dye and finishing extraction can in principle be integrated into existing value chains rather than competing with food crops [1,4]. The macroalgae are traditionally categorised into three classes based on the dominant photosynthetic pigments: green algae (Chlorophyta), brown algae (Phaeophyceae) and red algae (Rhodophyta) [7,9]. Each group characteristic pigment profile with chlorophylls and lutein in green seaweeds, fucoxanthin ased nd phlorotannins in brown seaweeds, and phycobiliproteins such as phycoerythrin and phycocyanin in red seaweeds, and this variety leads to a relatively wide range of possible shades on fibre [7,9,16].

Many of the same chemicals are bioactive, beside colour. The antioxidant and antimicrobial behaviour of fucoxanthin and related carotenoids has been documented [6], brown seaweeds have antibacterial and anti-inflammatory activity attributed to phlorotannins and sulphated polysaccharides [8], and phenolic-rich extracts from both marine and freshwater algae have been used to impart ultraviolet protection and antifungal properties to cotton when combined with metal or metal-oxide nanoparticles [9,11]. This ability to dye and to functionalise in 0ne treatment step, this dual functionality is what differentiates macroalgal colourants from many other natural dye sources and is the major focus of the present review [1].

This review covers recent literature on macroalgal pigments methods of extraction, practice of dyeing and mordanting, colour fastness and functional performance ends with the comparison of the environmental promise of this approach with the practical barriers that still divide laboratory demonstration from industrial adoption.

2. Marine Macroalgae: Classification and Pigment Diversity

Macroalgae are commonly categorised into three groups based on pigmentation, cell wall composition and storage carbohydrates: Chlorophyta (green algae), Phaeophyceae (brown algae) and Rhodophyta (red algae) [7]. Green seaweeds are characterised by the presence of chlorophyll a and b, which are responsible for the green colour, and accessory pigments such as siphonaxanthin modulate the shade in some species [9,11]. The brown seaweeds owe their colour to a mixture of chlorophyll c, beta-carotene and, most distinctively, fucoxanthin, a xanthophyll carotenoid production alone and is particularly concentrated in genera such as Sargassum, Turbinaria and Fucus [6,8]. The red hue of the seaweeds is largely due to phycobiliproteins, water-soluble proteins which are attached to open-chain tetrapyrrole chromophores absorbing light in the 520 to 630 nanometre range and appearing pink, red or purple depending on the ratio of phycoerythrin to phycocyanin present [9,16].

Table 1 provides summary of the major pigment classes, the colours they are likely to give to fabric and the bioactivity most for each algal group commonly documented in the literature examined for each algal group

Algal Group	**Major Pigments**	**Normal Hue on Fabric**	**Bioactivity Reported**
Green macroalgae (Chlorophyta)	Chlorophyll a & b, siphonaxanthin, lutein	Green, yellow-green	Antioxidant, modest antibacterial action
Brown macroalgae (Phaeophyceae)	Fucoxanthin, chlorophyll c, phlorotannins, alginate	Brown, olive, tan, khaki	Antioxidant, antibacterial, UV-absorbing
Red macroalgae (Rhodophyta)	Phycoerythrin, phycocyanin, R-phycobiliproteins	Pink, red, purple	Antioxidant; reported antibacterial and UV-shielding

Table 1. Classes of pigments in the three macroalgal families and their reported importance for textile colouration and functional finishing [1,2,7,9,16].

Bioactive Pigments and Compounds Relevant to Textile Dyeing

2.1 Chlorophylls

The main light- absorbing pigments in green and brown seaweeds are chlorophylls a and b. They are chemically comparable magnesium-centred tetrapyrroles that differ only by a single substituent and this minor structural change causes a modest shift in their absorption, imparting a green to olive tone on fabric for chlorophyll-rich extracts [11]. However, chlorophylls relatively sensitive to light and heat, which is one reason chlorophyll-dyed textiles often need a mordant or protective finish to maintain the colour depth after washing [2,14].

2.2 Carotenoids, with special emphasis on fucoxanthin

Carotenoids are lipid-soluble pigments found in all three categories of algae but are most prevalent in brown seaweeds, in which fucoxanthin constitutes a large proportion of the overall pigment content [6,8]. Besides its colour, fucoxanthin has been shown in bioassay experiments to have antioxidant, antibacterial, anti-obesity and anticancer properties, which is one reason why fucoxanthin and brown-algae extracts general are gaining interest for functional, not just ornamental textile finishing [6].

2.3 Phycobilliproteins

Pink to purple and blue colours can be obtained from red-algal extracts, due to the presence of the main phycobiliproteins of red seaweeds and cyanobacteria, Phycoerythrin and phycocyanin. As proteins, they are more sensitive to heat and pH conditions of standard dye baths than carotenoids, and cold or low temperature dye baths with appropriate mordant, such as tannic acid, which has shown good results in comparative trials, are usually recommended to maintain colour yield [1,16].

2.4 Phenolics, polysaccharides and alginate

Brown seaweeds are also a rich source of phlorotannins and sulphated polysaccharides like fucoidan, substances which have been associated with antibacterial, antiviral, anticoagulant and antioxidant effects in the broader bioactivity literature [8]. Alginate, derived primarily from brown seaweed, is being separately pursed as a biopolymer for regenerated cellulosic-type fibres. Brown macroalgae as a potential dual source of both fibre and dye within a single, largely non-competing biomass stream [4].

3. Extraction Techniques for Macroalgal Colourants

Conventional solvent extraction, maceration or Soxhlet extraction in water, ethanol, methanol or acetone, remains the most widely reported method for recovering algal pigments, and the choice of solvent has a marked effect on both dye yield and hue: aqueous extracts of brown seaweeds tend to give brown tones, whereas organic solvents from the same biomass can yield green, yellowish-green or greenish-yellow extracts because different solvents mobilise different pigment fractions [1]. Alkaline extraction, for example with potassium hydroxide, has also been used to improve colorant recovery from some brown and red species [5].

More recent work has turned to intensified extraction technologies that reduce solvent use, time and energy input. Ultrasound-assisted extraction disrupts algal cell walls through cavitation, improving pigment release, and has been reported to raise extraction efficiency markedly over conventional decoction for various natural-dye sources, with comparable benefits demonstrated for freshwater green algae such as Cladophora glomerata [14,20]. Microwave-assisted extraction and supercritical fluid extraction, the latter often using carbon dioxide with an ethanol co-solvent, have likewise been benchmarked against Soxhlet extraction for chlorophyll and carotenoid recovery from green algae, generally outperforming the conventional method in yield and processing time while avoiding some of the solvent load associated with older techniques [14]. Enzymatic pre-treatment of algal biomass, though less extensively documented for macroalgae specifically, follows the same green-chemistry logic already established for other natural dye and finishing sources [18].

4. Dyeing Methodologies and Mordanting Strategies

Macroalgal extracts have been applied to cellulosic (cotton), protein (wool, silk) and blended fabrics predominantly by the exhaust method, with dye-bath temperature, pH, liquor ratio and extract concentration all reported as significant process variables [2,23]. Because many algal pigments, phycobiliproteins especially, are heat- and pH-sensitive, dyeing protocols are often adapted toward cold or moderate-temperature conditions rather than the near-boiling baths typical of many synthetic dyes [1].

Mordanting remains central to achieving usable colour depth and fastness with natural dyes generally, and macroalgal dyes are no exception. Metallic mordants such as iron sulphate and aluminium salts (alum, potassium aluminium sulphate) have produced darker, more fixed shades than unmordanted fabric in several brown-algae dyeing studies, while bio-mordants such as tannic acid have performed particularly well with phycocyanin and fucoxanthin extracts under cold dyeing conditions [1]. Chitosan pre-treatment of cotton has also been compared favourably with alum mordanting for algae-extract dyeing, giving washing and perspiration fastness ratings in the good-to-excellent range [2]. Meta-mordanting, in which the mordant is applied simultaneously with the dye rather than before or after, has likewise been used successfully with methanol-based Sargassum extracts on cotton and silk [1].

5. Colour Characteristics and Fastness Properties

Colour outcomes are typically quantified using CIE L*a*b* coordinates and K/S (colour strength) values derived from reflectance spectroscopy, allowing objective comparison across species, solvents and mordants [2,23]. Reported hues span brown and khaki from brown-algal aqueous extracts, green and yellow-green from organic-solvent extracts of the same biomass, and pink to green tones from phycobiliprotein-rich extracts of red and blue-green algae depending on species and post-treatment [1,23].

Fastness performance, resistance to fading under washing, rubbing (crocking), perspiration and light exposure, is the property most often flagged as the weak point of natural dyes generally, and macroalgal dyes show a similar pattern: unmordanted fabrics often achieve acceptable washing and rubbing fastness (ratings of 4 to 5 on the standard grey-scale) but comparatively variable light fastness (as low as 3), which mordanting reliably improves [1]. Wash fastness assessed separately in cold water, hot water and soap-water conditions has shown that aqueous extracts tend to hold colour better under cold-water washing than under hot or soap-water conditions, reinforcing the case for gentler, energy-saving care regimes for macroalgae-dyed textiles [1].

6. Functional Finishing Properties

6.1 Antimicrobial activity

A recurring finding across the literature is that macroalgal and algal extracts confer antimicrobial activity on treated fabric independent of, or in addition to, their role as colourants [2,9,19]. Extracts combined with biosynthesised metal or metal-oxide nanoparticles have shown particularly strong effects: cotton functionalised with copper oxide nanoparticles synthesised using Azolla nilotica algae extract achieved a substantial zone of inhibition against Candida albicans in one optimisation study, while related work on the same system reported synergistic antibacterial and UV-protective performance when phenolic compounds from the same extract were combined with the nanoparticles [9,11]. Silver nanoparticles reduced and stabilised using seaweed extract have similarly been used to functionalise cotton, with the coated fabric outperforming both untreated cotton and seaweed-extract-only cotton in antibacterial testing [12].

6.2 Ultraviolet protection

Because many algal pigments, fucoxanthin and phlorotannins among them, absorb strongly in the ultraviolet range as part of the alga's own photoprotective strategy, extracts rich in these compounds translate that property directly onto treated fabric [6,8]. Ultraviolet protection factor (UPF) values exceeding 90 have been reported for cotton finished with a combined algae-extract and copper oxide nanoparticle treatment, and silver-nanoparticle-coated cotton produced using seaweed extract has likewise shown higher UPF than uncoated or extract-only fabric [9,12]. These results position macroalgal extracts as a plausible bio-based alternative to synthetic UV absorbers in sun-protective clothing.

6.3 Antioxidant and other functional properties

Antioxidant activity, commonly measured by DPPH radical-scavenging assays, is another property that travels from the raw extract onto the finished fabric; water-based extracts of the microalgae Arthrospira platensis and Porphyridium cruentum, for example, retained antioxidant activity above sixty percent when characterised alongside their dyeing performance on cotton, a pattern consistent with reports for macroalgal phenolics [2,8]. Emerging work also points toward additional functions such as flame-retardant behaviour, improved water-vapour and air permeability, wound-healing support and even carbon-dioxide capture associated with algae-based textile finishes, though these applications remain at an earlier stage of investigation than dyeing, antimicrobial and UV-protective functions [1].

7. Species-Specific Case Studies

Table 2 collects representative species-level studies discussed in the literature reviewed here, summarising the extraction or mordanting approach used, the fabric treated and the principal reported outcome. Read together, these examples illustrate both the breadth of species already investigated and the still-fragmented, largely lab-scale nature of the evidence base.

Species (Algal Group)	Extraction / Mordant	Fabric	Reported Outcome
Stoechospermum marginatum (brown)	Aqueous extract; $FeSO_4$ / alum mordants	Cotton	Darker shades with $FeSO_4$; wash, crocking and light fastness ratings 3.5–5 [1]

Sargassum sp. (brown)	Methanol maceration; FeSO4, alum-potassium sulphate, vinegar (meta-mordant)	Cotton, silk	Unmordanted fastness 4–5 for washing/rubbing; light fastness 3–5, improved by mordanting [1]
Turbinaria ornata, Padina tetrastromatica, Sargassum tenerrimum (brown)	Water, acetone, ethanol, methanol extracts	Cotton thread	Brown shade from aqueous extract; green/yellow-green shades from organic solvents; cold-wash fastness 4–5 [1]
Iyengaria stellata, Sargassum muticum, Colpomenia sinuosa (brown); Laurencia obtusa (red)	KOH (4%) and 80% acetone extraction	Cotton	L. obtusa gave the highest colorant yield among the species tested [5]
Turbinaria conoides (brown), Halymenia dilatata (red)	Pigment-targeted extraction (fucoxanthin, phycoerythrin); tannic acid, alum, mango kernel, lemon juice, aloe vera mordants	Cotton	Tannic-acid mordant gave the best colour uptake for both pigments [1]
Cladophora glomerata (green)	Soxhlet, ultrasound-, microwave-assisted and supercritical fluid extraction	Cellulosic fabric	Ultrasound- and microwave-assisted methods improved chlorophyll/carotenoid recovery over Soxhlet extraction [14]
Azolla nilotica (green, freshwater)	Methanolic extract combined with biosynthesized CuO nanoparticles	Cotton	UPF of 90.3 and a 20.5 mm inhibition zone against Candida albicans [9,11]
Mixed seaweed extract	Extract used as reducing/capping agent for silver nanoparticles	Cotton	AgNP-coated fabric achieved higher UPF than seaweed-extract-only or untreated cotton [12]

Table 2. Representative macroalgal dyeing and finishing case studies reported in recent literature.

8. Environmental and Economic Sustainability Considerations

The environmental case for macroalgal dyes rests on several pillars: seaweed cultivation does not require arable land, fresh water or synthetic fertiliser, extraction can often be performed in water or dilute aqueous-organic mixtures rather than the harsher solvents used for some synthetic dye intermediates, and the resulting effluent is, in principle, more biodegradable than conventional dye-house wastewater [1,4]. Intensified extraction methods such as ultrasound- and microwave-assisted extraction additionally cut processing time and energy demand relative to conventional decoction or Soxhlet methods, which is a meaningful consideration at industrial scale [14,20].

Economic viability is less settled. Macroalgal biomass supply is regionally uneven and subject to seasonal and environmental variability, pigment concentrations differ considerably between species and even between harvests of the same species, and the additional processing steps needed to stabilise pigments such as phycobiliproteins add cost relative to synthetic dyes with well-established supply chains [1,2]. A recent industry-facing report on algae in textiles concluded that, while pilot-scale trials show real promise for both dyeing and fibre applications, further work is still needed to identify the best-performing species, optimise dyeing protocols and demonstrate that colour fastness can consistently meet commercial specification [4].

9. Challenges and Limitations

Several obstacles recur across the literature reviewed here. Light fastness is consistently the weakest fastness parameter for macroalgal dyes, even when washing and rubbing fastness are acceptable, and mordanting, while effective, reintroduces a chemical step that partly offsets the eco-friendly rationale for using natural dyes unless bio-mordants are used [1]. Shade reproducibility is complicated by natural variation in pigment content between algal batches, and heat-sensitive pigments such as phycobiliproteins constrain dye-bath conditions, which can limit compatibility with existing high-temperature dyeing infrastructure [1,16]. Standardised, large-scale extraction and dyeing protocols are still relatively scarce, and most published work remains at laboratory or pilot scale rather than industrial demonstration [2,4]. Finally, life-cycle data comparing macroalgal dyeing directly against both synthetic dyeing and other natural-dye sources on a like-for-like basis are still limited, making it difficult to quantify the net environmental benefit with confidence [1].

10. Future Perspectives

Closing the gap between laboratory promise and industrial practice will likely depend on several parallel efforts: breeding or selecting algal strains with higher and more stable pigment content, refining green extraction technologies such as ultrasound-, microwave- and supercritical-fluid-assisted extraction to improve yield while further reducing solvent and energy use, and developing bio-based mordants and fixing agents that preserve the sustainability advantage of the dye itself [1,14,20]. Combining algal extracts with green-synthesised nanoparticles has already shown that dyeing and multifunctional finishing (antimicrobial, UV-protective) can be achieved in a single treatment step, and this integrated approach seems a particularly promising direction for further optimisation and scale-up [9,11,12]. Wider adoption will also benefit from closer integration with existing seaweed industries, food, hydrocolloid and agricultural biostimulant production, so that dye and finishing extraction can be positioned as a value-added co-product rather than a stand-alone, higher-cost process [4,7].

11. Conclusion

Marine macroalgae bring together, in a single renewable biomass, the pigment diversity needed for textile colouration and the bioactivity needed for functional finishing, a combination that few other natural dye sources offer as completely. The evidence reviewed here shows workable dyeing protocols across brown, red and green seaweed species, encouraging antimicrobial and ultraviolet-protective performance, particularly when extracts are paired with green-synthesised nanoparticles, and extraction technologies that are steadily becoming more efficient and less resource-intensive. At the same time, light fastness, batch-to-batch pigment variability, and the absence of large-scale, standardised processing routes remain real barriers to commercial deployment. With continued research into strain selection, extraction optimisation and bio-based mordanting, marine macroalgae are well positioned to become a genuine, scalable contributor to sustainable textile dyeing and functional finishing rather than a niche, laboratory-only alternative.

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