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Natural dyeing of algae fibers: Toward fully bio-based textiles

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Abstract

Conventionally natural fibers are sourced from plant or animals. Additional to these terrestric sources, natural fibers can be also gained from aquatic sources like algae. Filamentous algae species offer the chance for the development of a new type of natural fiber which can be sourced sustainable and without extensive land use. However, the development of a fully sustainable fiber material requires additionally to the fiber also the development of a sustainable coloration. With this background, the scope of the current study is to demonstrate a natural dyeing procedure for coloration of algae fiber materials. For this purpose, the dyeing with logwood extracts in combination with different iron mordanting processes are evaluated. Finally, dark/grey to black coloration are realized on the algae fibers. The wash fastness and light fastness exhibit medium to good grades for natural dye application. These promising results provide a clear prove-of-concept and offer the chance for development of a new type of sustainable fiber materials – colored algae fibers.

Keywords

Aquatic fibers, Non-woven, Dyeing, Natural dye, Logwood, Mordanting procedures, Fastness properties, Sustainability

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1 Introduction

The dyeing of textiles and fiber materials is probable the most mentioned and most prominent textile treatment. For actual industrial processes, conventionally synthetic dyes are used [1-3]. Prominent examples are reactive dyes and direct dyes for cotton, acid dyes for polyamide fibers and disperse dyes for polyester fibers [4-7]. However, the widespread use of synthetic dyes has raised many environmental and health concerns. A significant proportion of these dyes is not fully fixed to the fibers during dyeing and is discharged into wastewater streams, contributing to water pollution [8,9]. Many synthetic dyes and their degradation products are toxic, carcinogenic, or mutagenic, posing risks to aquatic ecosystems and human health [10,11]. In addition, dyeing processes often require large amounts of water, energy, and auxiliary chemicals, which increase their environmental footprint. The persistence and low biodegradability of synthetic dyes can lead to long-term accumulation in natural environments, making their removal from wastewater challenging and costly [12,13]. As alternative for synthetic dyes, natural dyes can be applied. However, their application in industrial processes remains limited at present. One main argument for using of natural dyes is their role in enabling fully bio-based textile materials, with the aim of developing sustainable products in which both fibers and dye are derived from renewable bio-based sources [14,15]. In this context, the selection of an appropriate dyeing system is essential to fully exploit the sustainability potential of these bio-based fibers. Natural dyes offer several advantages, including their generally lower toxicity, biodegradability, and reduced environmental impact compared to synthetic dyes [16]. They are often derived from renewable resources and can contribute to safer working conditions in textile processing. Furthermore, natural dyes may provide functional properties such as antimicrobial and UV-protective effects, depending on their chemical composition, which can add value to the final textile products [17]. Bio-based fibers are currently available from different resources, including plants and animals. The most prominent plant-based fiber is cotton, with other fibers as hemp, jute and regenerated cellulosic fibers having significant relevance [18]. These natural fibers offer several advantages, including renewability, biodegradability, good mechanical performance, and high comfort properties such as breathability and moisture absorption. In addition, their production is generally associated with lower carbon emissions compared to synthetic fibers. However, one main disadvantage of current natural fibers is the significant land use required for their production. This land use can be seen as a significant limit in the production of plant-based natural fibers [19]. For synthetic fibers, land use is not an issue. However, their main disadvantages include a slow biodegradability and generation of microplastic pollution [20]. With this background, a demand for alternative natural based fibers with low land use during production can be stated. A promising solution to satisfy this demand is the use of filamentous algae as innovative aquatic natural fibers [21,22]. In addition to raw algae filaments, regenerated fibers made from alginate can be included into the category of aquatic based fibers [23]. Furthermore, regenerated chitosan fibers produced from shrimp or crab shells can be defined as animal-based aquatic fibers [24]. Specifically, using algae as a fiber source offers several distinct advantages. Algae cultivation does not require arable land or freshwater resources and can be performed in aquatic environments, thereby avoiding competition with food production [25,26]. In addition, algae exhibit faster growth rates and higher biomass productivity compared to terrestrial plants, making them an efficient and renewable raw material [27,28]. Algae-based materials are biodegradable and contribute to carbon capture during cultivation due to high efficiency of CO_2 fixation, further enhancing their environmental sustainability [29,30]. Moreover, the biochemical composition of algae, including polysaccharides, fatty acids, proteins, and bioactive pigments provides functional properties that can be beneficial for many additional applications through biorefinery [25]. Algae materials are naturally

colored. However, it is necessary for textile applications to offer a broader range of stable and controllable colorations for algae fiber- containing materials. Despite the recent growing interest in algae-based textiles, there is still a lack of systematic studies addressing suitable dyeing strategies for such materials, particularly using fully bio-based and sustainable dyeing systems. In particular, the interaction between natural dyes and algae-based fibers, as well as the influence of mordanting processes on color development and fastness properties, remains insufficiently explored. Therefore, the current study aims to develop a natural dyeing process using logwood extract to support a deep black coloration for algae fibers. The experiments are done using a consortium of filamentous wild algae collected during summer 2024 from a lake (Schwetzingen, Germany) and an aquarium in Mönchengladbach, Germany containing mainly *Rhizoclonium* sp. Wet processing and dyeing experiments are performed in two steps. First, pure algae fibers are dyed in fiber form. Based on these initial results, in a second step, nonwoven blends composed off algae and cotton fibers (ratio 1:1) are dyed. This approach opens the pathway for the development and realization of a new class of sustainable textile materials towards colored algae-based fibers.

2 Experimental Section

2.1 Materials

The experiments were done using two types of filamentous wild algae consortia. Algae consortium A was collected in summer 2024 from a lake (castle Schwetzingen) in Southern Germany. The algae consortium B was collected from an aquarium in Mönchengladbach (Germany) containing mainly *Rhizoclonium* sp. The preparation conditions for this algae and further material properties were described in earlier publications in detail [22,31]. The moisture gain of the algae fibers was reported to be around 12 % [22]. This moisture up-take is slightly higher compared to the humidity up-take reported for regenerated cellulosic fibers as e.g. Seacell or Tencel [32]. The biodegradability of the algae fiber is expected to be excellent. For actual investigations, algae fibers were also blended with cotton fibers at 1:1 ratio by weight to be used further in a laboratory scale carding machine (337A, Mesdan S.p.A.). The formed web was then fed in to a sample needle punching machine (Oskar DILO DE) to produce a non-woven fabric. The 1:1 ratio for the nonwoven material was chosen to combine a good mechanical stability with a significant algae fiber content. With higher algae fiber content, the mechanical stability of the nonwoven is expected to decrease, while the hand-feel of the nonwoven is not negatively influenced by a higher algae content. As natural dye, logwood extract (*Lignum Campeche*) was used. The used logwood extract was supplied by Pflanzenfärbershop (Hückelhoven-Baal, Germany) as red/brown colored powder [33]. IR spectroscopic data of this dye extract in comparison to spectroscopic data of other logwood products were recently published [34]. General recommendations for application and dyeing recipes are supported by the supplier [35]. As mordanting agent iron(II)sulfate ($FeSO_4$ $7H_2O$) was used gained from Pflanzenfärbershop (Hückelhoven-Baal, Germany). Following textile chemicals were used for pretreatment and washing of investigated fiber materials – Perizym DBS for the enzymatic pre-treatment of cotton; Perlavin NIC for pre-washing and wetting of fiber materials; Perlavin LMO for the wetting of textile surfaces. These three textile chemicals were supplied by the company Textilchemie Dr. Petry GmbH (Reutlingen, Germany).

2.2 Dyeing experiments

2.2.1 Dyeing of pure algae fibers

Before dyeing a pre-treatment of algae fibers was performed to remove residues and substance from fiber surface and to enhance subsequent dye up-take. For this pre-treatment, an aqueous solution of Perizym DBS (6g/L) and Perlavin NIC (3g/L) was used and applied to the algae fibers at 60 °C for 30 minutes. This was followed by treatment with soft water at 90 °C for 5 minutes and 60 °C for 5 minutes. The pretreatment and dyeing processes were done in a Zeltex high temperature using process temperature profile as shown in Figure1.

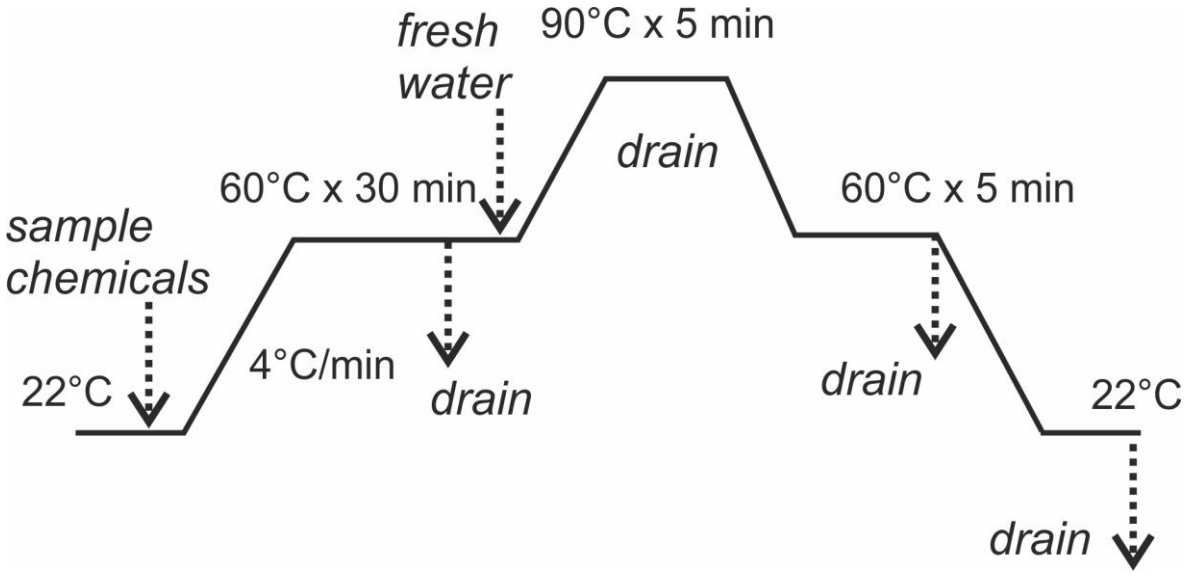

Figure 1. *Profile of process temperature for the scouring of algae fiber material.*

The following described dyeing recipes and procedures were previously developed and improved for the dyeing of cotton, wool and Lyocell fiber materials [33,36,37]. The application of logwood extract on textiles requires mordanting to improve the color depth and fastness properties [31,36,37]. Therefore, a pre-mordanting using iron (II) sulfate was applied. Dyeing was done at process temperatures of 60˚C or 80˚C. Further, two different fixation methods, namely air fixation and sodium chloride fixation NaCl were separately applied. A material-to-liquor ratio 1:10 is maintained throughout all wet processes. After pre-treatment, algae fibers were treated with iron (II) sulfate mordant solution (6% owf) for 10 minutes in the sample dyeing machine. The fibers were then equally divided by weight into two portions before starting the dyeing process. For identification, the samples were named as MH1, MH2, MH3 and MH4 following varied dyeing temperature and fixation methods as shown in Table 1. The dyeing duration was set to 45 minutes, where an aqueous solution of logwood extract with a concentration of 20% owf was used. Dyeing temperature and process duration were chosen to gain a sufficient dye up-take by the fiber material. After dyeing, the samples MH1 and MH3 were dipped in 2% owf NaCl solution for 15 minutes. Samples MH2 and MH4 were removed from the dyeing vessel and exposed to ambient air for 15 minutes to allow oxidation. This oxidation step was needed to convert the remaining hematoxylin into the color component hematein [38]. Finally, the samples were rinsed three times with cold soft water to remove excess dye. The first two rinsing steps were performed for 15 minutes each, while the final rinsing step was done for 10 minutes. The rinsing of in total 25 minutes is comparable time consuming and should be optimized to shorter duration in case of scale-up the process to industrial dyeing. Final drying of the fiber samples was done at 120 °C for 15 minutes.

Table 1

Overview of dyed algae samples showing the corresponding process temperature and fixation method.

Sample name	*Process temperature (°C)*	*Method of fixation*
MH1	60	NaCl (aq)
MH2	60	Oxidation in air
MH3	80	NaCl (aq)
MH4	80	Oxidation in air

2.2.2 Dyeing of algae/cotton non-woven

The dyeing of non-woven materials was evaluated for different mordanting conditions, as pre-mordanting, meta-mordanting and post-mordanting. For this, three fabric samples of equal weight were prepared and wetted with 2 g/L Perlavin LMO® solution for 10 minutes in the sample dyeing machine. For following applications of mordanting agents, a material to liquor ratio (MLR) of 1:10 was maintained. All aqueous solutions of iron (II) sulfate were prepared before each experiment to avoid Fe^{2+} air oxidation to Fe^{3+}. An overview on used mordanting procedure with mordant and logwood extract concentration is given in Table 2.

Table 2

Overview of dyed algae/cotton non-woven samples showing the used mordanting procedure with the corresponding concentrations of iron mordant and logwood extract.

Sample name	*Mordanting procedure*	*Iron mordant (owf%)*	*Logwood extract (owf%)*
NW1	Pre-mordanting	3	20
NW2	Meta-mordanting	6	20
NW3	Post-mordanting	6	20

The pre-mordanting procedure was performed as follows: The pre-wetted fabric sample was soaked and agitated iron (II) sulfate solution for 25 minutes at 22˚C in the sample dyeing machine. The bath was then drained and the dyeing process is carried out at 60˚C for 45 minutes. Subsequently, the sample was allowed to fix for 10 minutes in ambient air, then rinsed three times with cold soft water, following by drying the fabric sample at 140˚C. For meta-mordanting procedure, the pre-wetted fabric sample was placed in the dyeing vessel and both dye liquor and iron (II) sulfate solutions were added simultaneously. The dyeing machine was the operated at 60˚C for 45 minutes. Process temperature and duration were chosen to gain a sufficient dye up-take by the fiber material. The subsequent fixation, rinsing and drying steps followed the same procedure as the pre-mordanting. For post-mordanting, the pre-wetted fabric sample was first dyed at 60˚C for 45 minutes and then drained. The dyeing vessel was filled with iron (II) sulphate solution and the machine was run for 15 minutes. Fixation, rinsing and drying processes followed the same procedure as in pre-mordanting.

2.3 Analytics

The color properties of the prepared samples were determined using a Datacolor 400 Spectrometer (Datacolor GmbH, Marl, Germany). By using the Datacolor 400 device the CIE L* a* b* indices, the chroma C* and the hue h were measured under two different types of illumination. Scanning electron

microscopy (SEM) was performed to determine the surface topography of prepared samples using a tabletop scanning electron microscope TM 4000Plus (Hitachi, Japan). The microscope equipped with an EDS unit Quantax (electron dispersive spectroscopy) from Bruker enabled the determination of surface elemental composition and distribution. Wash fastness of the colored samples was tested according to DIN EN ISO 105-C06 (at 40˚C) using an Ahiba Polymat dyer (Datacolor GmbH, Marl, Germany). Light fastness of the dyed samples was determined using a Xenotest according to DIN EN ISO 105-B02 with an Atlas Xenotest Alpha LM instrument (Atlas Material Testing Technology GmbH, Linsengericht- Altenhaßlau, Germany).

3 Results and Discussion

3.1 Dyeing of algae fibers

Color properties and dyeing behavior are initially investigated using algae fibers without further textile structuring or processing. The original filamentous algae material shows light green coloration due to the presence of chlorophyll (Figure 2a) [39]. It is noteworthy to mention that the original dark green color was naturally bleached over incubation due to chlorophyll sensitivity to solar radiation [40,41]. The light green coloration turns to darker green after scouring procedure (Figure 2). This bleaching and the following turn to darker green by scouring are of course influencing the final coloration results after the following dyeing procedures. With a totally bleached white fabric other coloration results can be expected in comparison of dyeing a naturally green fiber material. The used scouring procedure is an enzymatic treatment of fibers aims to remove waxes and other surface residues from fibers in order to improve dye accessibility in the subsequent dyeing process. After dyeing with logwood extract, the initial green-colored algae samples are converted to a black coloration (Figure 2c). No significant color differences are noticed between the four samples (MH1 to MH4) by visual inspection under day-light illumination, which are further checked as described below.

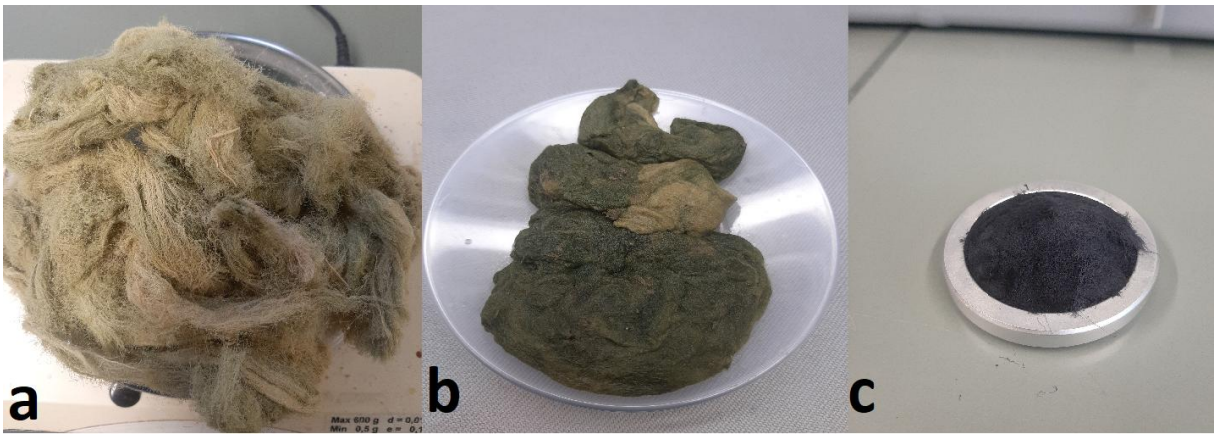

Figure 2. *Photographs showing the original algae fibers – a: before scouring; b: after scouring; c: after dyeing with logwood extract.*

For the four dyed algae fiber samples (MH1 to MH4), color properties are quantified using the color indices L*, a* and b* determined with two different light sources. Further determined are the chroma C* and the hue h (Table 3). All samples show similar values, indicating homogeneous dye uptake and comparable color strength. The index L* is 14 for all samples, standing for dark coloration. Only, for sample MH2 a slightly lower value for Chroma C* is observed. According to these indices, the color of the dyed algae fibers can be described as a dark blue-grey to black appearance.

Table 3

Color indices of the dyed algae fibers. The indices are recorded with two different light sources.

Light source	*Sample*	*Index L**	*Index a**	*Index b**	*Chroma C**	*Hue h*
D65 10°	MH1	14	-0.2	-4.1	4.1	267
	MH2	14	-0.6	-2.4	2.5	255
	MH3	14	-0.3	-3.4	3.5	265
	MH4	14	-0.3	-4.3	4.3	266
A 10°	MH1	14	-1.3	-4.5	4.6	254
	MH2	14	-1.2	-2.8	3.1	246
	MH3	14	-1.2	-3.8	4.0	253
	MH4	14	-1.4	-4.7	4.9	263

All four dyed algae samples (MH1 to MH4) are additionally tested for wash fastness (Table 4). Under the applied washing conditions (at 40 °C), all samples show good washing fastness with values of 4 to 4-5. Staining performance on adjacent multifabric is also good with values in the range of 4 to 5 (Table 4). However, the staining on adjacent cotton fabric is weaker with grades of 3-4.

Table 4

Washing fastness and staining performance of differently dyed algae samples.

Sample	*Wash fastness*	*Staining performance against adjacent test fabrics*					
		wool	*acrylic*	*polyester*	*polyamide*	*cotton*	*acetate*
MH1	4-5	4	4-5	4-5	4-5	4	4-5
MH2	4-5	4-5	4-5	4-5	4-5	3-4	5
MH3	4-5	4	4-5	4-5	4	3-4	4-5
MH4	4	4-5	4-5	4-5	4	4	5

In addition to the grey scale evaluation, color indices, Chroma and hue of washed samples are determined (Table 5). For the samples MH1, MH2 and MH4, a slight decrease of index L* is determined, standing for a slightly darker coloration after washing. Only sample MH3 shows increase of index L* to 18 and lower Chroma value, indicating brighter sample and thus partial dye loss during washing. Overall, these results confirm that the applied logwood-based coloration provides generally good washing stability an algae fiber, with only minor sample-dependent variations.

Table 5

Color indices determined of dyed algae fibers after washing. The indices are recorded with two different light sources.

Light source	*Sample*	*Index L**	*Index a**	*Index b**	*Chroma C**	*Hue h*
D65 10°	MH1	13	-0.5	-3.0	3.0	261
	MH2	13	-0.4	-1.9	1.9	258
	MH3	18	-0.4	-3.2	3.2	262
	MH4	13	-0.5	-2.8	2.8	260
A 10°	MH1	12	-1.2	-3.3	3.5	250
	MH2	13	-0.9	-2.1	2.3	248
	MH3	18	-1.2	-3.6	3.7	252
	MH4	12	-1.2	-3.1	3.3	250

3.2 Dyeing of algae/cotton nonwoven

The nonwoven materials composed of algae and cotton fibers exhibits a white to slightly green appearance (Figure 3a). Apart from some larger algae fibers, the green algae fibers are mostly regularly distributed in the nonwoven material. After dyeing with logwood extract, the nonwoven materials exhibit a dark grey coloration in all tested procedures (Figure 3c-d). The darkest color shade was achieved in the pre-mordanting procedure, as indicated by the lowest L* value of 28 (Table 6). Meta- and post-mordanting resulted in slightly higher L* values, corresponding to lighter shades. For all samples, slightly positive a* values and clearly negative b* values were obtained. Accordingly, the dyed samples can be described as blue-shaded grey.

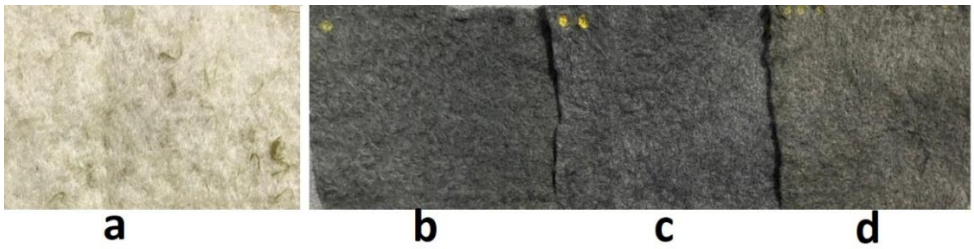

Figure 3. *Photographs of algae/cotton nonwoven samples - a: undyed; b: sample NW1 / dyed with pre-mordanting procedure; c: sample NW2 / dyed with meta-mordanting procedure; d: sample NW3 / dyed with post-mordanting procedure.*

Table 6

Color indices of dyed algae/cotton nonwoven materials. The indices are recorded with two different light sources.

Light source	*Sample*	*Index L**	*Index a**	*Index b**	*Chroma C**	*Hue h*
D65 10°	NW1	28	1.3	-2.7	3.0	296
	NW2	31	0.5	-4.3	4.3	277
	NW3	30	0.9	-3.4	3.5	285
A 10°	NW1	28	1.0	-2.5	2.7	292
	NW2	31	-0.5	-4.5	4.5	264
	NW3	29	0.2	-3.4	3.5	274

3.3 Fastness properties of dyed algae/cotton nonwoven

The color fastness of dyed algae/cotton nonwoven is tested against washing and light (Table 7). The wash fastness for all samples is quite similar and in a medium to good range (grade 3-4 to 4). However, differences are observed for the staining properties. While samples NW2 and NW3 show excellent staining values of 4-5, the performance of sample NW1 is weaker. For NW1, low staining ratings of 2 to 2-3 are observed for wool and cotton, indicating a noticeable transfer of dye onto adjacent fabrics during washing. However, the staining grades for polyester and polyamide adjacent test fabrics are better compared to cotton and wool, probable because the dye does not have a good affinity to these types of synthetic fibers. In general, it can be concluded that meta- and post-mordanting procedures are for the current application probable better. However, for further product development these samples should be also evaluated under repeating industrial laundering cycles for investigation of the stability under long-term use.

Table 7

Wash fastness of dyed algae/cotton nonwoven materials. Shown is the color change of the wash non-woven and the staining on adjacent test fabrics. The numbers are given in the grey scale with the range from 1 to 5 (lowest to highest fastness property).

Fastness properties	*Nonwoven samples*		
	NW1	*NW2*	*NW3*
Wash fastness	*3-4*	*4*	*3-4*
Staining properties on adjacent test fabric			
Wool	2	4-5	4-5
Acrylic	4	4-5	4-5
Polyester	4	4-5	4-5
Polyamide	3	4-5	4-5
Cotton	2-3	4-5	4-5
Acetate	2-3	4-5	4-5

The light fastness of dyed nonwoven samples was further evaluated using Xenotest for illumination durations of 100 and 200 h (Fig. 4). Results were determined by comparison with a simultaneously exposed blue standard.

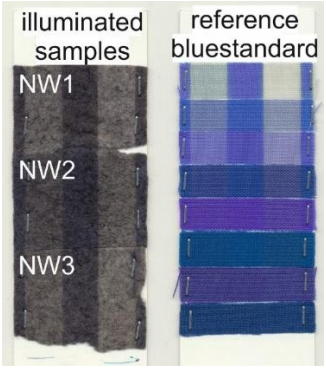

Figure 4. *Photographs of algae/cotton nonwoven after illumination in the Xenotest. For comparison a simultaneously illuminated blue standard reference is shown. The middle area of the samples is not illuminated. The left area is illuminated for 100 hours while the right area is illuminated for 200 hours.*

According to light fastness, the sample NW2 exhibits the best performance with a medium light fastness grade 3 / 3-4 (Table 8). However, samples NW1 and NW3 prepared with pre- or post-mordanting procedures exhibit lower performance (Table 8). For the investigated system, meta-mordanting procedure is advantageous when improved light fastness is required. Such a better light fastness in case of meta-mordanting for the dyeing combination logwood/iron was earlier reported for dyeing of wool fabrics [36]. This result might be explained by a better complex formation between dye molecule and iron ions in contrast to the pre- or post-mordanting procedures [42,43]. In the actual investigation with meta-mordanting procedure, also superior washing and staining performance is reached. However, this comes at the expense of slightly lower color depth compared to the other methods. Further improvements in lightfastness could be reached in future optimization by combination with organic UV absorbers [44]. By view on the aim of a fully bio-based material, here UV stabilizers based on gallic acid or tannic acid might be valuable additives for combination with the actually presented dyeing recipe [45,46].

Table 8

Light fastness of dyed algae/cotton nonwoven materials after two different duration of illumination (100 and 200 hours) by comparison with blue standard reference. The numbers are given in the blue scale with the range from 1 to 8 (lowest to highest fastness property).

Nonwoven sample	*Light fastness*	
	For illumination with 100 hours	*For illumination with 200 hours*
NW1	2	3
NW2	3	3-4
NW3	2-3	3

3.4 Microscopic investigations of undyed and dyed algae/cotton nonwoven

Microscopic evaluation of sample topography is carried out using scanning electron microscopy (SEM). Initially, the undyed nonwoven is examined. Two representative areas are investigated and shown with increasing microscopic magnification (Figure 5), one with regularly distributed smaller algae fibers and

another containing larger algae fiber fragments. In the SEM images, algae fibers can be easily distinguished from cotton fibers by fiber shape and recorded brightness. In addition to the recorded sample topography, SEM also supports a certain information on the chemical composition of the investigated sample surface area. Areas containing chemical elements of higher atomic weight, appear brighter in recorded SEM images [47]. Accordingly, algae fibers contain obviously differences in composition compared to cotton, indicating the presence of additional (heavier) chemical elements as carbon and oxygen.

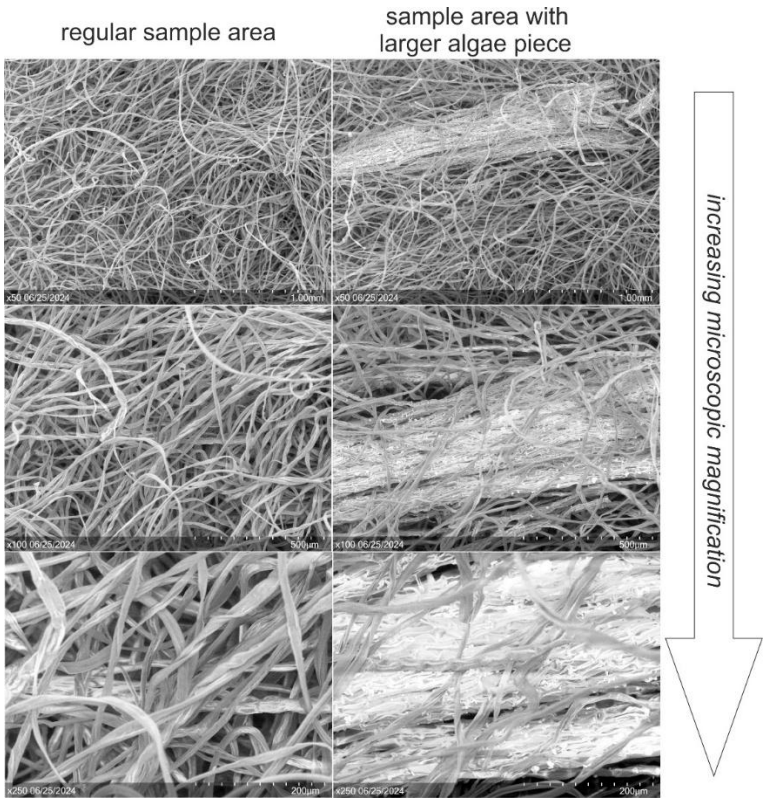

Figure 5. *SEM images of the undyed algae/cotton nonwoven with increasing microscopic magnification. The images are taken from different sample areas – left: sample area with regular distribution of algae and cotton fibers; right: sample area with larger algae piece.*

SEM images recorded form the different dyed nonwoven samples are presented in Figure 6. Their surface topography is mainly similar to the undyed nonwoven material presented in Figure 5.

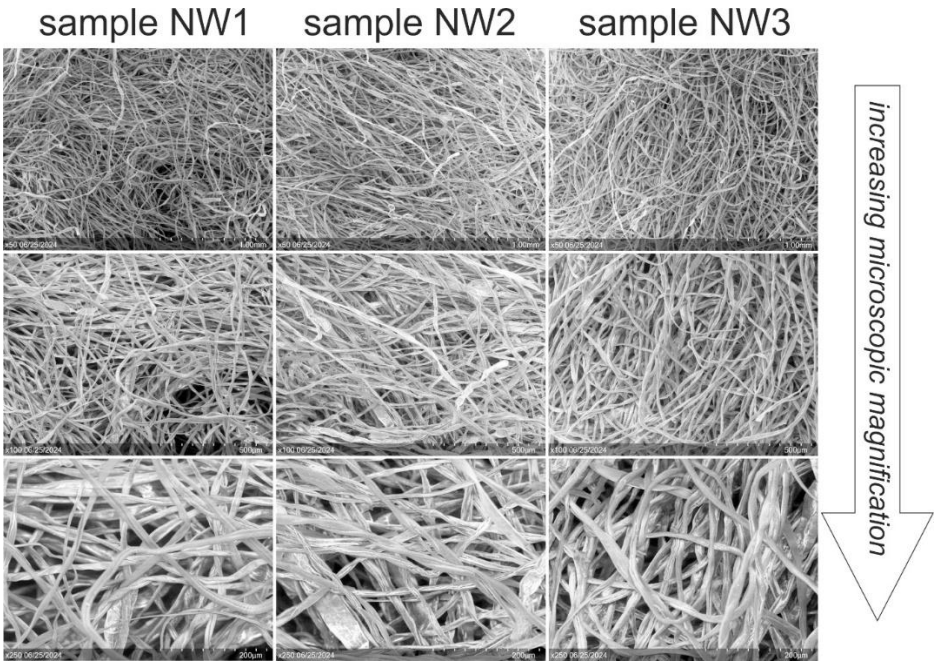

Figure 6. *SEM images taken from the different dyed algae/cotton nonwoven samples with increasing microscopic magnification.*

Finally, the composition of chemical elements on the surface of the nonwoven samples is analyzed by electron dispersive spectroscopy EDS (Figure 7). For the undyed nonwoven, carbon and oxygen are the dominant elements as expected from the organic nature of the fibers. The chemical element hydrogen cannot be determined by EDS method [47]. Minor amounts of additional elements can be attributed to the algae fiber content. The detected sulfur can be attributed to the proteins containing sulfur-bearing amino acids such as cysteine. Sodium, potassium and calcium are likely present as naturally occurring ions in the algae fibers. After dyeing, the elemental composition changed significantly. Sodium and potassium were no longer detected, which can be attributed to their removal during pretreatment and dyeing. In contrast, iron was clearly detected on the fiber surface, confirming the presence of the applied mordant. The sulfur content slightly increases, which can be attributed to sulfate ions from the iron(II) sulfate mordant. Such a removal of sodium and potassium cations form the algae fibers during pre-treatment decrease the number of positively charged cations on the fiber surface. Such a decrease in cationization might influence a further dye up-take. However, in the actually used dyeing procedure such an influence is not expected, because of the relevant concentration of Fe^{2+} ions in the applied mordanting agent.

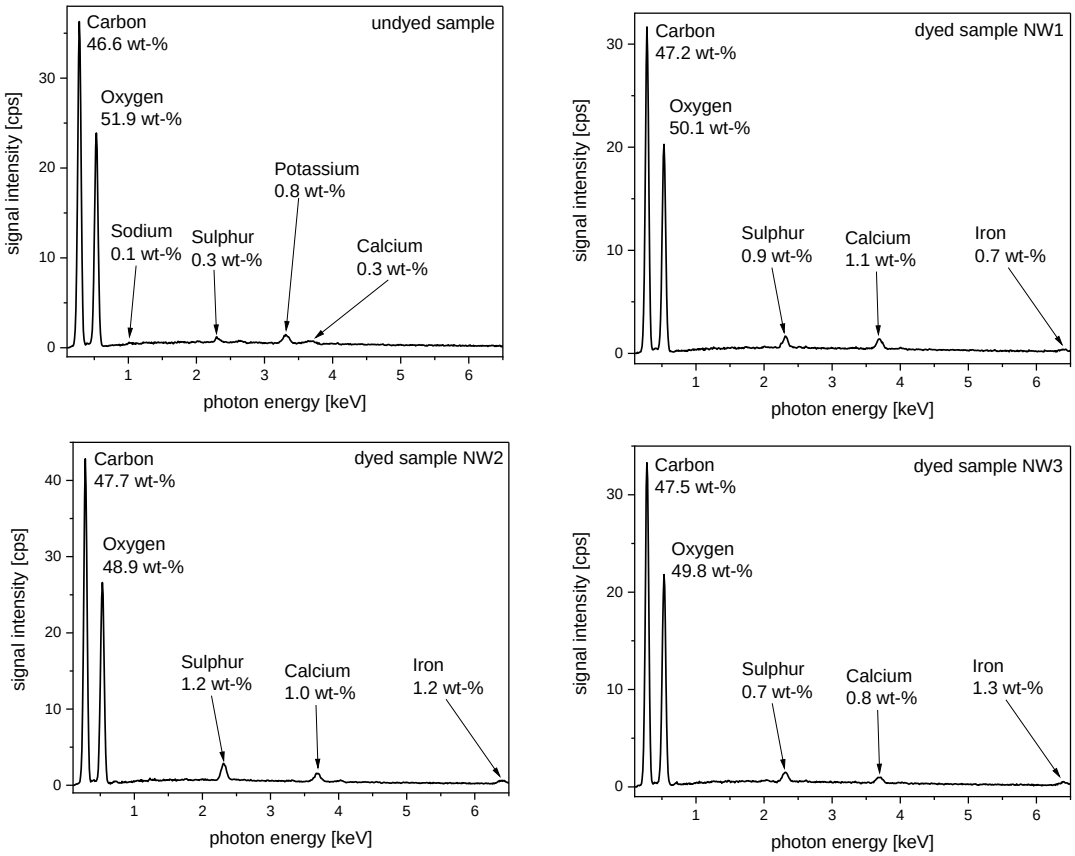

Figure 7. *EDS spectra recorded from the undyed and the different dyed algae/cotton nonwoven samples.*

4 Conclusions

Algae fibers and algae-based fiber materials are successfully dyed to grey/black color shades using logwood extract as a natural dye and iron(II)sulfate as a mordant. Results demonstrates that effective coloration of algae-derived fibers can be achieved using fully bio-based dyeing components, supporting the development of sustainable textile materials. Among the investigated dyeing strategies, pre-mordanting resulted in the highest color depth, whereas meta-mordanting provided a more balanced performance in terms of wash and light fastness. In particular, meta-mordanting exhibited improved resistance to dye bleeding and better overall fastness properties, although with slightly reduced color intensity compared to pre-mordanting. The dyed algae fibers showed good washing fastness, indicating stable dye fixation, while the algae/cotton nonwoven materials exhibited medium to good fastness properties depending on the mordanting method applied. Microscopic and elemental analyses confirmed that the dyeing process does not significantly alter the fiber morphology, while the presence of iron and sulfate on the fiber surface verified the successful incorporation of the mordant. Finally, the presented results are a fine proof-of-concept for natural dyeing of algae fiber materials and for this a good starting point for the fiber development on this innovative fiber materials.

Author Contributions

All authors have read and agreed to the published version of the manuscript. The authors contribute as followed to the manuscript – M.H. Arachchige: dyeing experiments and testing of fastness properties; L. Blanckart: production of fibers & fabric materials, conceptualization and methodology; C. Heil & K.

Ratovo: production of fibers & fabric materials; A. Abomohra: development of algae materials and manuscript writing; E. Bendt: supervision & funding; B. Mahltig: original draft preparation, writing, visualization, microscopy and EDS measurements.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. The presented research is realized under the funding of the research project IBÖM-08: AlgaTex-"Green algae as fiber material of the future?"—Feasibility phase for the use of filamentous freshwater algae as a potential raw material for the textile industry, funding code: 031B1358A, funded by the German Federal Ministry of Education and Research. The authors are highly grateful for this funding.

References

[1] Slama, H. B.; Chenari Bouket, A.; Pourhassan, Z.; Alenezi, F. N.; Silini, A.; Cherif-Silini, H.; Oszako, T.; Luptakova, L.; Golinska, P.; Belbahri, L. Diversity of synthetic dyes from textile industries, discharge impacts and treatment methods. *Applied Sciences* **2021**, *11* (14), 6255. DOI: 10.3390/app11146255

[2] Fobiri, G. K. Synthetic dye application in textiles: A review on the efficacies and toxicities involved. *Textile & Leather Review* **2022**, *5*, 180–198. DOI: 10.31881/TLR.2022.22

[3] Islam, M.T.; Islam, T.; Islam, T.; Repon, M. R. Synthetic dyes for textile colouration: Process, factors and environmental impact. *Textile and Leather Review* **2022**, *5*, 327–373. DOI: 10.31881/TLR.2022.27

[4] Khatri, A.; Peerzada, M.H.; Mohsin, M.; White, M. A review on developments in dyeing cotton fabrics with reactive dyes for reducing effluent pollution. *Journal of Cleaner Production* **2015**, *87*, 50–57. DOI: 10.1016/j.jclepro.2014.09.017

[5] Hoque, M.T.; Benrui, T.; Grethe, T.; Mahltig, B. Evaluation of chitosan based pretreatment for cotton and linen dyeing with direct dyes and reactive dyes. *Communications in Development and Assembling of Textile Products – CDATP* **2023**, *4(2)*, 187–200. DOI: 10.25367/cdatp.2023.4.p187-200

[6] Koh, J.; Sim, G.; Kim, J. pH control in the dyeing of polyamide with acid dyes. *Coloration Technology* **2001**, *117(3)*, 156–160. DOI: 10.1111/j.1478-4408.2001.tb00055.x

[7] Aspland, J.R. Disperse dyes and their application to polyester. *Textile Chemist and Colorist* **1992**, *24(12)*, 18–23.

[8] Yaseen, D.A.; Scholz, M. Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review. International *Journal of Environmental Science & Technology* **2019**, *16(2)*, 1193–1226. DOI: 10.1007/s13762-018-2130-z

[9] Slama, H.B.; Chenari Bouket, A.; Pourhassan, Z.; Alenezi, F.N.; Silini, A.; Cherif-Silini, H.; Oszako, T.; Luptakova, L.; Golinska, P.; Belbahri, L. Diversity of synthetic dyes from textile industries, discharge impacts and treatment methods. *Applied Sciences* **2021**, *11(14)*, 6255. DOI: 10.3390/app11146255

[10] Ismail, M.; Akhtar, K.; Khan, M.I.; Kamal, T.; Khan, M.A. M Asiri, A.; Seo, J.; Khan, S.B. Pollution, toxicity and carcinogenicity of organic dyes and their catalytic bio-remediation. *Current Pharmaceutical Design* **2019**, *25(34)*, 3645–3663. DOI: 10.2174/1381612825666191021142026

[11] Gita, S.; Hussan, A.; Choudhury, T.G. Impact of textile dyes waste on aquatic environments and its treatment. *Environment & Ecology* **2017**, *35(3C)*, 2349–2353.

[12] Ali, H. Biodegradation of synthetic dyes—a review. *Water, Air, & Soil Pollution* **2010**, *213(1)*, 251–273. DOI: 10.1007/s11270-010-0382-4

[13] Negi, A. Environmental impact of textile materials: challenges in fiber–dye chemistry and implication of microbial biodegradation. *Polymers* **2025**, *17(7),* 871. DOI: 10.3390/polym17070871

[14] Mabuza, L.; Sonnenberg, N.; Marx-Pienaar, N. Natural versus synthetic dyes: Consumers' understanding of apparel coloration and their willingness to adopt sustainable alternatives. *Resources, Conservation & Recycling Advances* **2023**, *18*, 200146. DOI: 10.1016/j.rcradv.2023.200146

[15] Pizzicato, B.; Pacifico, S.; Cayuela, D.; Mijas, G.; Riba-Moliner, M. Advancements in sustainable natural dyes for textile applications: a review. *Molecules* **2023**, *28(16),* 5954. DOI: 10.3390/molecules28165954

[16] Negi, A. Natural dyes and pigments: Sustainable applications and future scope. *Sustainable Chemistry* **2025**, *6(3)*, 23. DOI: 10.3390/suschem6030023

[17] Santiago, D.; Cunha, J.; Cabral, I. Chromatic and medicinal properties of six natural textile dyes: a review of eucalyptus, weld, madder, annatto, indigo and woad. *Heliyon* **2023**, *9*, e22013. DOI: 10.1016/j.heliyon.2023.e22013

[18] Schenek, A. *Naturfaser Lexikon*; Deutscher Fachverlag GmbH: Frankfurt am Main, Germany, 2000.

[19] Chen, F.; Ji, X.; Chu, J.; Xu, P.; Wang, L. A review: life cycle assessment of cotton textiles. *Industria Textila* **2021**, *72(1)*, 19–29.

[20] Zhang, Y.Q.; Lykaki, M.; Alrajoula, M.T.; Markiewicz, M.; Kraas, C.; Kolbe, S.; Klinkhammer, K.; Rabe, M.; Klauer, R.; Stolte, S. Microplastics from textile origin – emission and reduction measures. *Green Chemistry* **2021**, *23(15)*, 5247–5271. DOI: 10.1039/D1GC01589C

[21] Blanckart, L.; Ratovo, K.; Mahltig, B.; Bendt, E. Aquatic natural fibers as a new raw material with potential for the textile industry. *Melliand International* **2023**, *28(4)*, 20–22.

[22] Rahaman, A.; Blanckart, L.; Hanelt, D.; Poller, M.J.; Heil, C.; Prova, S.M.; Ratovo, K.; Bendt, E.; Mahltig, B.; Abomohra, A. Unraveling filamentous algae as a renewable bioresource for advanced moisture-absorbent innovative aquatic fibers. *Bioresources and Bioprocessing* **2026**, *13*, 33. DOI: 10.1186/s40643-026-01028-1

[23] Sun, J.; Tan, H. Alginate-based biomaterials for regenerative medicine applications. *Materials* **2013**, *6(4),* 1285–1309. DOI: 10.3390/ma6041285

[24] Ma, B.; Hou, X.; He, C. Preparation of chitosan fibers using aqueous ionic liquid as the solvent. *Fibers and Polymers* **2015**, *16(12),* 2704–2708. DOI: 10.1007/s12221-015-5638-6

[25] Rahaman, A.; Hanelt, D.; von Schwartzenberg, K.; Abomohra, A. Unveiling the potential of freshwater filamentous algae as a promising alternative source of essential fatty acids and bioactive carotenoids. *Algal Research* **2025**, *89*, 104100. DOI: 10.1016/j.algal.2025.104100

[26] Adaschewski, E.; Poller, M.J.; Hanelt, D.; Abomohra, A. Enhanced micro-and nanoplastic (MNP) removal by easy-harvestable filamentous algae with indications of plastic surface transformation. *Journal of Environmental Chemical Engineering* **2026**, *14(2),* 121660. DOI: 10.1016/j.jece.2026.121660

[27] Abomohra, A.E.F.; Jin, W.; Tu, R.; Han, S.F.; Eid, M.; Eladel, H. Microalgal biomass production as a sustainable feedstock for biodiesel: current status and perspectives. *Renewable and Sustainable Energy Reviews* **2016**, *64*, 596–606. DOI: 10.1016/j.rser.2016.06.056

[28] Abomohra, A.E.F.; El-Sheekh, M.; Hanelt, D. Pilot cultivation of the chlorophyte microalga *Scenedesmus obliquus* as a promising feedstock for biofuel. *Biomass and Bioenergy* **2014**, *64*, 237–244. DOI: 10.1016/j.biombioe.2014.03.049

[29] D'Souza, A.B.; Rahaman, A.; Ahmed, K.A.; Adaschewski, E.; Hanelt, D.; Abomohra, A. Progressive adaptation of microalgae consortium to elevated carbon dioxide coupled with enhanced production of essential fatty acids. *Carbon Resources Conversion* **2025**, *8(4)*, 100330. DOI: 10.1016/j.crcon.2025.100330

[30] Barati, B.; Fazeli Zafar, F.; Amani Babadi, A.; Hao, C.; Qian, L.; Wang, S.; El-Fatah Abomohra, A. Microalgae as a natural CO_2 sequester: a study on effect of tobacco smoke on two microalgae biochemical responses. *Frontiers in Energy Research* **2022**, *10*, 881758. DOI: 10.3389/fenrg.2022.881758

[31] Blanckart, L.; Munasinghe, E. A.; Bendt, E.; Rahaman, A.; Abomohra, A.; Mahltig, B. Algae-based coatings for fully bio-based and colored textile products. *Textiles* **2025**, *5*, 3. DOI: 10.3390/textiles5010003

[32] Flesner, J.; Mahltig, B. Fibers from Natural Resources. In: *Handbook of Composites from Renewable Materials, Volume 4 - Functionalization*; Thakur, V.K.; Thakur, M.K.; Kessler, M.R. (Eds.), Scrivener Publishing Wiley, Hoboken, New Jersey, USA, 2017; pp. 287–310.

[33] Mai, T.H.; Grethe, T.; Mahltig, B. Wood extracts for dyeing of cotton fabrics—special view on mordanting procedures. *Textiles* **2024**, *4*, 138–164. DOI: 10.3390/textiles4020010

[34] Mahltig, B. Overview on natural dyes and their IR-spectra – Part III: Natural dyes based on wooden materials. *Communications in Development and Assembling of Textile Products – CDATP* **2024**, *5*, 81–101. DOI: 10.25367/cdatp.2024.5.p81-101

[35] Pflanzenfärbershop (Hückelhoven-Baal, Germany), web page with dyeing recipes for logwood extract on wool. https://shop.pflanzenfaerber.eu/farberapporte/280-farberapport-blauholzextrakt-kostenlos-.html (accessed 2026-05-07).

[36] Mahltig, B.; Bhakhar, P.C. Dyeing of Natural Fibers with Extracts from Wood – A Strategy for Fully Bio-Based and Sustainable Textiles. In: Advances in the Textile and Clothing Research, Volume 2: Sustainability, Chemistry and Finishing; Kyosev, Y.; Cherif, C.; Kyzymchuk, O.; Hesse, K.; Penzel, P. (Eds.), Springer Nature, Cham, Switzerland, 2026; pp. 14–37. DOI: 10.1007/978-3-032-20865-1_2

[37] Ostheim, A.; Ratovo, K.; Klinkhammer, K.; Fischer, M.; Bendt, E.; Mahltig, B. Comparison of natural dyes for wool, cotton and Lyocell fabrics under special consideration of titanium dioxalate as mordant. *Journal of Engineered Fibers and Fabrics* **2026**, *21,* 15589250261451076. DOI: 10.1177/15589250261451076

[38] Chablé-Vega, M.A.; García-Hernández, E.; Martínez-Heredia, J.E.; Villalpando-Aguilar, J.L.; Arreola-Enríquez, J.; López-Rosas, I.; Alatorre-Cobos, F. The return of natural dyes: the case of logwood tree (*Haematoxylum campechianum* L.). *Biotechnic & Histochemistry* **2024**, *99(5),* 269–277. DOI: 10.1080/10520295.2024.2367535

[39] Simon, D.; Helliwell, S. Extraction and quantification of chlorophyll a from freshwater green algae. *Water Research* **1998**, *32(7)*, 2220–2223. DOI: 10.1016/S0043-1354(97)00452-1

[40] Lesser, M.P.; Farrell, J.H. Exposure to solar radiation increases damage to both host tissues and algal symbionts of corals during thermal stress. *Coral Reefs* **2004**, *23(3)*, 367–377. DOI: 10.1007/s00338-004-0392-z

[41] Ambarsari, I.; Brown, B.E.; Barlow, R.G.; Britton, G.; Cummings, D. Fluctuations in algal chlorophyll and carotenoid pigments during solar bleaching in the coral *Goniastrea aspera* at Phuket, Thailand. Marine Ecology Progress Series **1997**, *159*, 303–307. DOI: 10.3354/meps159303

[42] Puchtler, H.; Meloan, S.N.; Waldrop, F.S. Application of current chemical concepts to metal-hematein and -brazliein stains. *Histochemistry* **1986**, *85*, 353–364. DOI: 10.1007/bf00982665

[43] Hadi, A.G.; Humedy, E.H.; Saddam, N.S.; Abd-alameer, F.S. Spectrophotometric Study of complex formation between Hematoxylin and Al^{3+} and Fe^{3+} ions. *International Journal of PharmTech Research* **2016**, *9*, 292–298.

[44] Mahltig, B.; Leisegang, T.; Jakubik, M.; Haufe, H. Hybrid sol-gel materials for realization of radiation protective coatings—A review with emphasis on UV protective materials. *Journal of Sol-Gel Science and Technology* **2023**, *107*, 20–31. DOI: 10.1007/s10971-021-05558-2

[45] Quiles-Carrillo, L.; Montava-Jordà, S.; Boronat, T.; Sammon, C.; Balart, R.; Torres-Giner, S. On the use of gallic acid as a potential natural antioxidant and ultraviolet light stabilizer in cast-extruded bio-based high-density polyethylene films. *Polymers* **2019**, *12*, 31. DOI: 10.3390/polym12010031

[46] Sesia, R.; Cardone, A. G.; Ferraris, S.; Spriano, S.; Sangermano, M. Exploitation of tannic acid as additive for the adhesion enhancement of UV-curable bio-based coating. *Progress in Organic Coatings* **2024**, *189*, 108311. DOI: 10.1016/j.porgcoat.2024.108311

[47] Mahltig, B.; Grethe, T. High-performance and functional fiber materials—a review of properties, scanning electron microscopy SEM and electron dispersive spectroscopy EDS. *Textiles* **2022**, *2(2)*, 209–251. DOI: 10.3390/textiles2020012

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