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TEXTILE BIO-COLORING – VEGETAL AND BACTERIAL PIGMENTS FOR A SUSTAINABLE DESIGN

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Abstract. This paper explores sustainable methods of textile dyeing using natural pigments, taken from plant sources (walnut leaves and hibiscus) and pathogenic pigments bacteria. The theoretical section provides an overview of natural dyes, their chromatic and functional potential, and bio-dyeing techniques. The experimental research involved the preparation of textile samples made of cotton, linen, wool, and silk, followed by the application of natural pigments under varying conditions of time, temperature, and pH. Significant differences in pigment absorption were observed depending on the fibre composition, exposure time, and colour modifiers used. Animal-based fibres demonstrated higher colour intensity, while plant-based fibres yielded softer, pastel tones. Solid powdered pigments were also extracted and preserved for potential reuse. Additionally, bacterial dyeing was applied to create spontaneous and organic visual prints with promising applications in artistic and bio-inspired textile design. The results confirm the viability of bio-coloration methods in contemporary textile practices and support the transition to environmentally responsible solutions. Future research directions include testing light and wash fastness, expanding the bacterial pigment palette, and integrating these innovative dyeing methods into functional and smart textiles.

Keywords: *natural pigments, sustainable textiles, bacterial colorants, eco-design, natural fibres.*

Rezumat. Articolul abordează metode sustenabile de colorare a textilelor prin utilizarea pigmenților naturali din surse vegetale (frunze de nuc, hibiscus) și a bacteriilor pigmentogene. Partea teoretică cuprinde o analiză a coloranților naturali, a potențialului cromatic și funcțional al acestora, precum și a tehnicilor de colorare bio a textilelor. Cercetarea experimentală a inclus pregătirea mostrelor textile din bumbac, in, lână și mătase, urmată de aplicarea pigmenților naturali în condiții variate de timp, temperatură și pH. S-au observat diferențe semnificative în absorbția pigmenților în funcție de natura fibrei, durata contactului și modificatorii de culoare utilizați. Fibrele de origine animală au prezentat o intensitate mai ridicată a nuanțelor, în timp ce fibrele vegetale au generat tonuri mai blânde și pastelate. Totodată, s-au obținut pigmenți solizi în formă de pulbere, cu potențial de reutilizare, iar colorarea cu bacterii a permis realizarea unor imprimeuri spontane și organice, cu aplicații în designul artistic inspirat din natură. Rezultatele obținute au confirmat viabilitatea metodelor de biocolorare în practica textilă contemporană și susțin dezvoltarea unor soluții durabile. Direcțiile viitoare de cercetare vizează testarea rezistenței culorii, extinderea paletei pigmentare bacteriene și integrarea acestor metode în textile funcționale și inteligente.

Cuvinte cheie: *pigmenți naturali, textile sustenabile, colorare bacteriană, eco-design, fibre naturale.*

1. Introduction

In the last decade, textile industry is facing an increasing pressure from society, environmental organisations and international politics, referring to radically changing its productions model. The traditional liner model, based on extraction of resources, production, consumption and elimination, demonstrated its limits according to a global ecological crisis, which seriously affects ecosystems and people's health. One of the most criticised stage of the textile fabrication is the colouring process, which involves, in most cases, the intensive application of synthetic chemicals, water and energy, generating a major negative impact on the environment. Wastewaters, resulted from these processes, contain toxic dyes, heavy metals and other dangerous substances which pollute freshwater sources and affects aquatic biodiversity [1-3].

In accordance with United Nations, textile industry is responsible for approximately 20% of global pollution of freshwater, the biggest part of that coming from dyeing process and finishing of fabrics [2-5]. Those alarming data determined the appearing of international initiatives intended to stimulate sustainable practices in fashion field and textile production, as „Fashion Pact", „2030 Agenda for a Sustainable Development", or regulations regarding the circular economy promoted by European Union. In this context, reappraisal of traditional methods of textile dyeing takes a special importance, especially those that use natural pigments, obtained from plants, minerals or microorganisms. Those practices offer not only a less polluting alternative, but also a connection between old techniques and contemporary sustainability challenges [1,6,7].

Textile's dyeing with natural pigments is not a new practice, but one with a millennial history, presented in each world's culture. Antic civilisations, from Egyptians and Greeks to Chinese, Indian and pre-Columbian civilisations, used tectorial plants as indigo, turmeric, mugwort, cochineal or walnut leaves for naturally dyeing furniture. With the development of the petrochemical industry and the advent of synthetic dyes in the 19th century, the use of natural pigments declined, reaching almost complete abandonment in the 20th century, in favour of industrial efficiency, stable colours, and large-scale production [6,7].

Even though, in the last two decades, rediscovery and reinvention of this techniques became part of a global trend of returning to artisanal, sustainable and ethical methods. This renewed interest is supported not only by ecological concerns, but also by changing consumer attitudes, who increasingly value authentic, non-uniform products with cultural and identity value. In a landscape dominated by uniformity and fast- fashion, naturally dyed products offer paramount, texture and an emotional bundle with nature and traditions. Moreover, natural dyeing demonstrated, in numerous studies, beneficial proprieties on human skin, as antibacterial or antioxidant effects, and a superior compatibility with natural fibres, as cotton, linen, hemp or wool, also making it attractive from health perspective and user comfort.

At the same time with the trend of revaluing tradition, contemporary scientific research is exploring new sources of natural pigments, including from the field of biotechnology, such as microalgae, pigmentogenic bacteria or fungi. These living organisms are capable of producing pigments in a controlled, renewable and resource-efficient manner, offering a viable alternative to plant extraction, which depends on seasonality, soil, climate and agricultural areas. Bio-pigments can be cultivated under laboratory or industrial conditions, thus being easy to standardise, and some microbial species allow obtaining rare or unstable colours by traditional methods. These new sources are also being investigated for functional uses, such as UV-protective, antibacterial or antioxidant textiles, which broadens the spectrum of application of natural dyes in the modern textile industry [1,5-9].

Moreover, the integration of natural pigments in contemporary technologies, such as digital printing, high- precision reactive dyeing or intelligent finishing, brings an innovative and versatile dimension, connecting tradition with technology. Thus, the premises are created for a new sustainable aesthetic- one which capitalised organic imperfection, chromatic subtlety and regenerative cycles of nature [1,2,10-13]. At the same time, challenges regarding to colour fixation, wash resistance or stability over time require a complex, multidisciplinary approach that combines traditional knowledge to applicable searches and technological innovation [2].

As a consequence, the transition to natural pigments use, coming from vegetal or biotechnical cultures, does not represent an ecologic demarche, but a cultural, aesthetic and technologic one. This approach offers real opportunities of reducing negative impact of textile industry on environment, of promoting cultural patrimony diversity and stimulating innovation in clothing design. The aim of this work is to investigate actual potential of natural dyeing in textile dye through an analyse of traditional and experimental methods, of advantages and disadvantages of this, as well as the integration of it in contemporary sustainable and creative practices, in the context of an industry in transformation.

2. Materials and Methods

To study the problem, the main sustainable methods of dyeing textiles with natural pigments were analysed, focusing on sources of pigments, technic proceeds, esthetical and cultural characteristics, as well as ecological advantages these technics offer. It will be presented both traditional methods, enhanced from old practices, and modern ones, developed in research laboratories or adopted by contemporary designers interested in sustainability. Simultaneously, will be discussed actual challenges in accordance with efficacy of those methods, stability of colours in time, resources availability and the need for regulation and certification in the context of a more textile „green" targeted market.

The experimental part includes the preparation of natural fibres through washing (silk and wool sample) and boiling (cotton and flax sample), in the aim of removing impurities and optimising pigments absorption. It was obtained natural pigments from walnut and hibiscus leaves through boiling, the coloured solutions being used for dyeing of the textile samples. They were sunk for different times, in the purpose of testing the influence of time on colour intensity. Forwards, it was obtained solid pigments in powder form, using dough and sodium carbonate. As an innovative method, it was tasted the colouring with pathogenic bacteria, through sample's sterilisation, the replacing of bacterial culture, incubation and fixation, being obtained organic prints with great artistic and sustainable potential. The recipes and work steps are described in detail in point 3.3.

3. Results

3.1. Natural resources for textile bio-colouring

Fabrics dyeing with natural pigments is a technic which dates since old times, being archaeologically attested in the Indus Valley civilization region, around 2600 BC [1-5,9,14]. In those times, plants as indigo (Indigofera tinctoria) and madder (Rubia tinctorum) were used for obtaining intense and durable colours, indicating a high cognition level referring to proprieties of vegetal pigmentation. Over the centuries, natural dyeing was essential in the development of national and aesthetic identity of Asian, European, African and Latin American communities, reflecting not only resources diversity, but also technological cleverness of craftsman [1,5-9].

Natural resources used in bio-colouring includes a variety of plants, insects, minerals and, recently, algae, each of them offering specific pigments, covering a wide range of colours. Those resources, in addition with synthetic dyeing, are biodegradable, safer for health and have a considerably reduced ecological footprint, which is why they are being investigated again in the context of current sustainability [11-15].

Tectorial plants represent the main source of natural dyeing. Roots, leaves, flowers and barks contain pigments as flavonoids, anthocyanins, carotenoids and tannins, each with a different chromatic capacity of fixation and stability. For example, turmeric (*Curcuma longa*) is used to the obtaining of yellow, while the onion peel, walnut leaf or pomegranate peels are valuable for brown or golden tones [3-5,16].

Insects, although less common used nowadays, had an essential role in the history of textile dyeing. The most know is cochineal (*Coccus cacti*), from which is extracted carmine acid- a red pigment that is not only used in textile industry, but also in cosmetology and food field. Animal- based dyes were valuable for their stability and intensity, especially for luxury textiles [1-3,10].

Minerals, as iron oxide and clay, were used traditionally for obtaining of earth tones, from yellow to brown-reddish. Due to their high resistance to extern factors, mineral pigments were frequently used for long-term usage textile, as carpets, curtains or traditional clothes [1-3,13,16,17].

Algae consists a great resource for natural pigments. Those contain compounds as phycocyanin (blue), astaxanthin (red) and chlorophyte (green), which can be extracted and use for the dyeing of textile fibres. In the context of contemporary searches, algae offer a promising solution for bio-colouring, especially due to their capacity to be cultivated sustainably, without competing with food agriculture [16,18].

In this global context, **Republic of Moldova** has significant potential for capitalising on local resources for the production of natural dyes. Ecologic diversity, favourable climate and old craft ship creates an advantageous place for rediscovering and promoting natural dyeing. According to ethnographic and botanical searches, on the territory of Republic of Moldova exists approximately 100 species autochthon of tectorial plants, historically used for wool dyeing, hemp, flax and cotton [6-9,16]. Among the most well-known plants used for this purpose are saffron, dandelion, marigolds, currants, walnut leaves, and onion peel. Table 1 synthesises the main species used, the pigments contained and the colours obtained.

As it can be seen from Table 1, the diversity of local plants offers valuable potential for the development of sustainable textile dyeing practices. Pigments extracted from this plant sources not only allow the production of varied and aesthetic shades, but also contribute to reduce the ecological impact of the dyeing process. The revalorisation of these resources, in combination with traditional techniques and modern innovations previously explained, supports the transition to a more environmentally and culturally responsible textile industry.

Table 1

Plants with tectorial proprieties [6-9,16]

Daily using name (*the scientific name*)	**Obtained colour**	**Observations referring to pigments and using**
Walnut shell (*Juglans regia*)	Dark brown	The shell offers warm tones of brown; the pigment is stable and suitable for natural fibres.
Onion peel (*Allium cepa*)	Yellow, brown	Widely used, it offers chromatic variations depending on concentration.
Dandelion (*Taraxacum officinale*)	Light yellow	Flowers generate a light tone, easily obtained from infusions or boiling.
Marigold (*Calendula officinalis*)	Orange-yellow	The petals offer warm colours, suitable for vegetal fibre dyeing.
Soffran (*Crocus sativus*)	Dark yellow	Crocin is the active compound responsible for the intense hue; the plant is valuable for dyeing fine hair.
Buckthorn (*Hippophae rhamnoides*)	Gold yellow	Fruits offer a shiny yellow, with great stability at light.
Melissa (*Melissa officinalis*)	Yellow-green	The leaves give a pale shade, often used in dyeing delicate threads.
Walnut leaf (*Juglans regia*)	Light green	Through fibres, leaves give green pigments for ecologic dyeing.
Hop (*Humulus lupulus*)	Green	The infusions offer greenish tones.
Hyssop (*Hyssopus officinalis*)	Blue-greenish	Produces a blue or greenish tint, depending on the method and fixatives; used mostly for experiments.
Chicory (*Cichorium intybus*)	Blue or purple	The root generates cold tones, especially in the presence of mordanture.
Currants (*Ribes uva-crispa*)	Red	Red fruits offer an intense colour, frequently applied on wool or cotton.
Raspberry (*Rubus idaeus*)	Red or pink	Fruits produce light colours, with moderate resistance at washing.
Eglantine (*Rosa canina*)	Red	Flowers are natural sources of pigments for textiles, especially in traditional technique.
Hazelnut (*Corylus avellana*)	Brown	Shell and branches provides a large palette of brown tones.
Oak bark (*Quercus robur*)	Brown	The high tannin content allows for a wide range of browns to be obtained, depending on the technology.

The application of natural mordents, such as aluminium salts, tannins or iron, contributes to the stabilisation of colours and the intensification of shades, while the use of traditional techniques ensures aesthetic authenticity and the continuity of the craft heritage [6-9,16].

3.2. Sustainable techniques of textile dyeing with natural pigments: the bundle between tradition and contemporary tradition

In actual context, in which sustainability became an essential criterion in each industrial field, inclusive in the textile one, bio-colouring methods acquiring an increasing relevance. The bio-dyeing process, it is characterised by significantly lower water and energy consumption, the absence of toxic compounds and high biodegradability of residues. In addition, these methods contribute to reducing wastewater pollution and maintaining an ecological balance in the communities where they are applied [1,2].

In opposition, conventional dyeing, although cost-effective and industrially scalable, generates a considerable amount of toxic waste, using aggressive chemicals that can affect the health of workers and consumers. In this sense, the transition to natural alternatives is not just an aesthetic or ethical choice, but a necessity to achieve the global sustainable development goals.

Another important step in promoting bio-dyeing methods is the consumer awareness. Although interest in organic products is growing, many people do not have sufficient information about the direct benefits of using textiles dyed with natural pigments. Educational programs, sustainable marketing campaigns and clear labelling of products with organic certifications can encourage more responsible choices, thus supporting the development of a circular economy in the fashion industry [11-13].

Among the most widespread methods of bio-dyeing are the extraction and use of plants pigment. The methods of application of natural dyes are diverse, from simple techniques, such as immersion, to complex methods like digital printing with natural pigments. The immersion technique involves immersing the textile material in a bath of natural dye, followed by a fixing step, in which natural mordents (tannin, aluminum sulfate, vegetable ash, etc.) are used to stabilise the colour and increase washing resistance. Applying modern alternatives using traditional mordents include, also, the usage of biodegradable enzymes, which, beside technological efficiency, reduce pollution and allows a more harmonious integration into ecological systems [16-19, 20,21].

Digital printing with natural pigments is a particularly promising innovation, as it allows for precise dosing of the dye and reducing the amount of resources used. This method contributes to product customisation, supports the concept of custom production, and allows experimentation with complex designs without generating significant material losses [16].

Similarly with classical dyeing methods, contemporary research is exploring the use of biotechnological sources of pigments, such as microalgae, fungi or pigmentogenic bacteria. These organisms can be cultivated under controlled conditions, providing a renewable source of pigments with remarkable chromatic properties. For example, certain species of microalgae produce carotenoids that can be used to obtain vibrant shades of orange or red, while bacteria can produce indigo or other colour dyes through metabolic processes [22].

At the same time, dyeing textiles with natural pigments is closely linked to the cultural heritage of many cultures. The batik technique, specific to Indonesia, is an eloquent example of the connection between functionality and artistic expression. It consists of applying hot wax to the fabric to protect certain areas of dyeing. After dyeing, the wax is removed by melting, revealing a contrasting and detailed drawing. The use of the tjanting tool, a fine copper container with a beak for drawing, offers the possibility of creating extremely elaborate design compositions [8,13,15].

Another artistic method that has become popular in the modern era is eco-printing. This technique involves arranging plants, leaves, flowers or oxidised metal objects on the material, which, through direct contact, release pigments or leave textural traces. The material is rolled tightly, fixed and exposed to the action of heat and humidity, which allows the transfer of pigment into the fibre. The result is a unique, the print reflecting the specifics of the plants used and the method conditions [16,17,19].

Shibori, the Japanese technique of dyeing by folding and binding, produces fluid and abstract patterns that are impossible to reproduce identically. The material is folded into geometric shapes (triangles, squares), tied tightly with string or ribbons, and dipped in dye. The covered areas absorb the pigment, thus forming an uncontrolled, but harmonious, pattern that highlights the beauty of imperfection [12,13].

The dip-dye technique, although simple in execution, has a spectacular visual effect. It involves the gradual immersion of a part of the material in the dye bath, creating delicate chromatic transitions, with shadows effect. It is used in both clothing and decorative industries, offering a modern but sustainable look [17,19,20].

It is important to note that these methods are not recent discovered, but have their origins in the practices of ancient civilizations. The Egyptians used indigo to dye cotton, and the populations of South America obtained intense colours from cochineal – a red pigment extracted from insects. Thus, the colouring of textiles with natural pigments also has an anthropological dimension, illustrating the deep relationship between human, nature and cultural expression.

Based on the information studied, we can state that bio-dyeing practices of textiles combine ancient craftsmanship with modern technologies, offering a viable and sustainable alternative to classic industrial methods of textile dyeing. This synthesis between art, science and ecological responsibility opens new directions for creativity and research, contributing to the development of a more ethical, innovative and sustainable textile industry.

3.3. Practical applications - examples

The dyeing with vegetal bio resources is a traditional method reinterpreted by modern searches, which emphasis sustainability, quality and colour durability, using optimised processes of extraction, mordant and application. The dyeing with natural colorants from vegetal origin constitutes the practical experience, the Romanian people, of capitalising on spontaneous flora, to obtain a diverse range of warm, harmonious, non-reproducible colours, with satisfactory light and wash resistance [14]. Examples of works by researchers in the field highlight the colouring potential of plant pigments (Figures 1-3) [22-24].

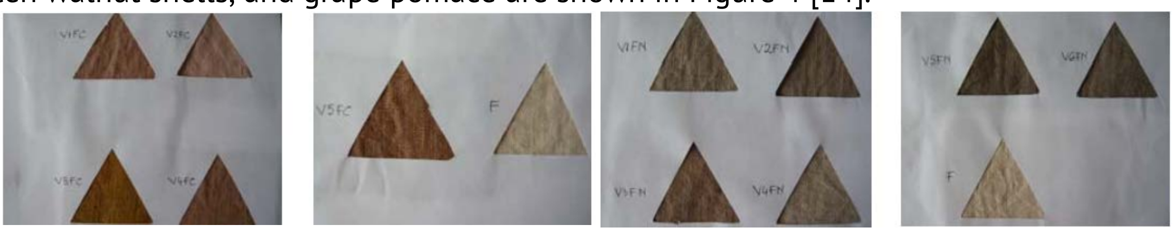
Figure 1. Bio dye results for simmering the textile in the dye bath ½ h, 2 h and overnight [22,23].

Figure 2. Results on color modification applied to different type of textile [22,23].

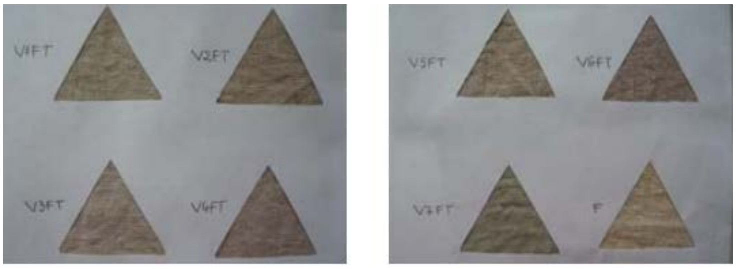
a) b)

Figure 3. Imaging of the color hue generated on cotton (a) and wool fabric after dyeing with *Alnus glutinosa* (b) [24].

Colorants of vegetal origin are ecologic and offers satisfactory dyeing of natural textile fibres in pale tones and warm shades. Examples of dyeing hemp fabric with onion leaves, rotten walnut shells, and grape pomace are shown in Figure 4 [14].



a) b)



c)

Figure 4. Technological options of dyeing hemp fabric with onion leaves (a), rotten walnut shells (b) and grape pomace (c) [14].

The dyeing process mentioned in specialised literature includes steps of textile sample, colorant preparation, dyeing, treating with mordents and colour fixative for coloured sample [8,9,14,25].

Preparation of natural fibres for bio-colouring is a mandatory step for ensuring the quality of dyeing process with organic pigments. This preliminary procedure contributes to the elimination of impurities, at the open of fibres texture and at the creation of a suitable surface for the fixation of dye [25].

Depending on the origin of the fibres – animal or vegetable – the cleaning methods differ, in order to protect the specific structure of each type of material and optimise the absorption of colouring substances.

Animal fibres, such as wool or silk, are sensitive and require gentle intervention. They are washed in warm water, using a neutral pH detergent, without strong friction, to prevent the fabric from breaking. It is necessary to maintain a constant temperature throughout the entire process, as sudden variations can negatively affect the integrity of the fibre, causing shrinkage or damage. After washing, the material must be rinsed thoroughly to remove any traces of detergent, which could, otherwise, influence the fixation of the pigment [23,25].

In the case of vegetable fibres – such as cotton, linen or hemp – a more aggressive treatment is necessary to remove natural waxes, oils and other residues that could affect the process. These materials are boiled for about an hour in a solution of water with baking soda or soda ash (in proportion of two tablespoons to four litres of water). Boiling allows the pores to open and the fibres to be thoroughly cleaned. The procedure can be repeated for optimal results. Alternatively, the fibres can be washed at high temperatures in the washing machine, but this method is not as effective as traditional boiling [22-25].

The preparation stage is not only functional, but also directly influences the aesthetic quality and durability of dyed textiles. Clean fibres allow the uniform pigment distribution and deeper fixation, resulting in uniform and long-lasting shades. Without proper preparation, dyeing can be compromised, resulting in stains, colour variations, or poor pigmentation. Therefore, careful treatment of materials before dyeing is an essential condition for fully exploiting the potential of bio-dyeing.

Every detail of this process must be approached with precision to ensures not only efficient dyeing, but also extend lifespan of textile products. Thus, bio-dyeing becomes not only an ecological alternative, but also an expression of quality and responsibility in contemporary textile design.

The steps and methods applied in this work for the preparation of textile samples are presented in Table 2, which details the specific procedures depending on the type of fibre used.

Table 2

The textile preparation for dyeing

Sample type	Description of the preparation
Unbleached cotton, linen	The textile material is subjected to a heat treatment by boiling for approximately one hour in a solution obtained from four litres of water and two tablespoons of baking soda. To ensure complete cleaning and effective opening of the fibre structure, it is recommended to repeat this procedure twice.
Wool, silk	Clean using warm water and a sufficient amount of neutral pH soap. It is important to wash carefully, without rubbing vigorously, as wool may be deformed or damaged, and silk may become more sensitive and prone to breakage. At the same time, it is necessary to avoid sudden variations in water temperature, as these can negatively affect the structure of the fibres, causing shrinkage or loss of the integrity of the material.

For the experimental stage in this work, walnut leaves and hibiscus tea were used as natural sources of pigments for dyeing textile samples. These natural colorants were chosen due to their accessibility, diverse chromatic potential and ecologic character. The colorants were tested on different types of fibres support: unbleached cotton, linen, silk and wool, each reacting differently, depending on the chemical composition of the fibre and the natural pigment used. Walnut leaves offered shades from golden brown to deep brown, due to their high tannin content, while hibiscus tea generated various tones, from pale pink to burgundy, influenced by the pH of the solution and the infusion time. The dyeing process includes the following steps:

1. We added walnut/ hibiscus leaves to boiling water.
2. After 10 min, the previously prepared textile samples were immersed.

In order to establish the optimal duration of the dyeing process, the samples were removed from the solution after different periods of time: ½ h boiling, 2 h boiling and 12 h. The results obtained are presented in figure 5 and 6. It can be observed that the final appearance of the colour depends significantly on the type of fibre, as well as on the duration of the dyeing process.

Figure 5. Textile sample dyed with hibiscus.
Source: sample dyed with hibiscus - realised by the authors.

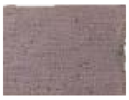
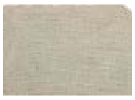
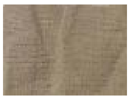
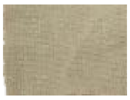
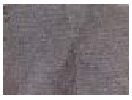
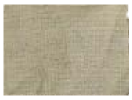
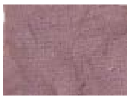
Figure 6. Textile sample dyed with walnut leaves.
Source: sample dyed with walnut leaves - realised by the authors.

In Figures 5 and 6, the samples resulted from the dyeing process are presented in the following sequence: silk, linen, cotton, wool; after ½ h, 2 h and 12 h of dyeing. It is observed that the final appearance of the colour depends significantly on the type of fibre, as well as on the duration of the dyeing process: animal fibres (silk and wool samples) acquire a more intense colour, and those of animal origin – pastel colours.

The natural silk samples, initially dyed, were treated with colour-modifying solutions: vinegar, sodium bicarbonate, iron liquor, and citric acid (Table 3).

Table 3

Colour change

Colour modifying solution	**Result**	
	Samples dyed with hibiscus	**Samples dyed with walnut leaves**
150 mL of vinegar + 300 mL of water		
25 g of sodium bicarbonate + 300 mL of water		
10 g of iron powder + 300 mL of water		
10 g of citric acid + 300 mL of water		

To obtain the pigments, 300 mL of dye, alum and sodium carbonate were used in proportion of 2: 1. The process of pigments' obtaining includes the following steps:

1. The alum is dissolved in a small amount of hot water.
2. It is added the sodium carbonate.
3. The solution obtained is poured into the pigment jar.
4. After the "volcano" effect, the mixture is filtered through a coffee filter.
5. The foam obtained is left to dry, thus obtaining the powdered pigment.

Figure 7 shows sequences from the process of obtaining hibiscus and walnut pigment.

Figure 7. Pigments obtaining.

Source: pigments - realised by the authors.

The pigments obtained is stored in dry containers and can be used to obtain inks (Figure 8).

In the process of ink acquire, for a 100 mL of dye we used water and ethanol (96%) in proportion of 1:2.

Figure 8. Inks obtained from coloured pigments.
Source: inks and pigments - realised by the authors.

Another method of dyeing textiles is bacterial dyeing – an innovative method used to obtain unique prints on textile surfaces. The example made for this work is shown in figure 9. The process includes:

1. Binding of textile materials.
2. Sterilise the textile samples into a container intent for this purpose.
3. The textile sample is placed in a sterile Petri dish.
4. Put a little bacterial culture on the sterilised textile sample.
5. It is "fed" the bacterial culture on the textile surface.
6. Badge the Petri dish with parafilm tape.
7. Leave to incubate for 2 days.
8. The sample removed from incubation is sterilized and treated with alum fixative solution (alum can be replaced with another mordant).

Figure 9. Sequences from the process of dyeing the textiles with bacteria.
Source: dyeing with bacteria - realised by the authors.

4. Discussion

The experimental results obtained following the application of natural dyes and the bacterial bio-colouring method clearly highlight the influence of fibre type, pigment source, contact duration and subsequent treatment on the quality and intensity of textile coloration.

In the case of dyeing with walnut leaves and hibiscus tea, differentiations can be noted between the behaviour of animal fibres (silk, wool) and plant fibres (cotton, flax). Silk and wool samples showed a better absorption capacity, resulting in deeper and more saturated shades, which can be explained by the protein structure of these fibres, which facilitates the interaction with the phenolic and acidic compounds of natural dyes. In contrast, cellulosic fibres offered paler tones, even after pre-treatment, suggesting a weaker incorporation and a reduced chemical affinity towards pigments.

Obtained results in this study are consistent with observations in specialised literature, where it was highlighted that protein fibres (wool, silk) absorb and fix natural pigments more intensely due to chemical bonds with phenolic compounds, while cellulosic fibres (cotton, linen) present lighter and pastel colours [23,25].

As well, studies show that pigments from walnut leaves offer a superior resistance at light and washing, with a decrease in intensity below 10% after multiple washing cycles, while hibiscus dyes have vivid colours, but with lower resistance to rubbing, which may require the use of additional fixation treatments [10,14,25].

Furthermore, recent literature also highlights the functional potential of natural dyes, including the antibacterial activity demonstrated for some plant extracts, such as saffron, which may add additional functionalities to naturally dyed textiles [12,24].

The application of colour modifiers (vinegar, sodium bicarbonate, iron liquor, citric acid) on silk samples, led to the achievement of various shades, demonstrating the sensitivity of natural pigments to pH and the presence of metal ions. This result highlights a high potential for the development of a rich chromatic palette using a single natural pigment, which is relevant for a sustainable and economical approach in textile design.

Obtaining of dried pigment from hibiscus and walnut represents an additional step in valorising the plant sources, allowing its conservation and reuse in the form of powder or natural ink. This strategy extends the applicability of plant pigments beyond textile colouring, allowing them to be integrated into ecological printing techniques or textile graphic design.

Experimental dyeing with bacteria has offered promising results, especially from an aesthetic and unique perspective. The prints obtained on sterile textile samples showed an organic, unexpected character, but also recognisable in the bacterial texture. Although the colour intensity is lower compared to traditional dyeing methods, this method opens innovative perspectives for bio-integrated design and textile customisation through natural processes. The technical limitations related to shape control and colour fixation are counterbalanced by the sustainable nature and artistic potential of the method.

5. Conclusions

This study highlights the potential of natural dyes, obtained from plants and bacterial sources, in the context of developing sustainable textile dyeing methods. The introduction part and the analysis of the specialised literature provides an important theoretical basis, demonstrating that bio-dyeing is not only an ecological alternative to conventional dyeing, but also a strategic direction for the future of responsible textile design.

The experimental part of the work highlights the importance of adequate preparation of the fibres, adapted according to their origin – vegetable or animal – to ensure an efficient and uniform fixation of the pigments. The results obtained from dyeing with walnut and hibiscus leaf extracts demonstrated the achievement of chromatic variations, influenced by the type of fibre, duration of contact with the dye and the post-dyeing treatments with pH modifiers or metal salts. Protein fibres, such as silk and wool, demonstrated an increased affinity towards natural pigments, reflected by the intensity and durability of the colours obtained.

A remarkable aspect of the research is the obtaining of pigments in dry form, which can be subsequently used as ink or for other dyeing processes. This stage brings added sustainability and economic efficiency, allowing the full exploitation of natural resources. At the same time, the application of innovative method of colouring with pigmentogenic bacteria illustrates a great aesthetic potential, by creating unique, natural visual patterns, impossible to reproduce mechanically. Although the control of shape and fixation of colour in this context remain a technical challenge, the benefits of this method – both ecological and expressive – justify the increasing attention in future research.

The results obtained confirm that textile bio-colouring is not only an alternative to conventional chemical methods, but can become a vector of artistic and ecological innovation in clothing design. The integration of these methods into educational, artistic or industrial practice can contribute to the development of a culture of sustainability, reducing environmental impact and reconnecting the creative process with natural resources.

Based on observations made, several research directions emerged can help at deepen and expand the topic of textile bio-colouring: study of the stability over time of colours obtained by natural methods, under various lighting, washing and wear conditions, to evaluate real durability in everyday use; investigation of the effects of pH and different natural and synthetic mordents on the intensity and resistance of colours, especially in the case of cellulose fibres; development of standardised protocols for staining with bacteria, allowing the reproduction of patterns or the direction of bacterial growth in an artistically controlled way; expansion of the range of bacterial and vegetable pigments studied, with an emphasis on indigenous plants and microorganisms, easily accessible in the local context; transdisciplinary collaboration between designers, biologists, chemists and engineers for the development of bio-functional textile products, including in the field of medical or environmental clothing.

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