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Citation for published version:
https://doi.org/10.1080/00405000.2020.1810474

Digital Object Identifier (DOI):
10.1080/00405000.2020.1810474

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
Journal of The Textile Institute

Publisher Rights Statement:
This is an Accepted Manuscript of an article published by Taylor & Francis in The Journal of The Textile Institute on 27/8/2020, available online: http://www.tandfonline.com/10.1080/00405000.2020.1810474

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Sustainable plant-based bioactive materials for functional printed textiles

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Abstract

The evidence coupled with awareness towards carcinogenic effects of synthetic textiles dyes to the wearer, exhausting fossil fuels, ecological balance distortion, and increased pollutants from the textile industry harming the environment, is on the rise. In this context, the paper provides a significant overview of ancient biomaterial engineering with herbal colorants to refute the modern ecological crisis. The medicinal properties of natural dyes have the potential to create functional textiles, cogently their ability to combat UV radiation and microorganisms are discussed in depth. Cohesively, the subtle and the vital role of plant phytochemicals is comprised.

The paper reveals that it is noteworthy that not only the biomaterial is eco-friendly but also the ancient print process with herbs is relatively rudimentary, less complex, and eco-friendly. This would further propel the textile industry towards slow technology and slow fashion in a big way. Thus, it motivates us to view more in less for radical change. The review analysis identifies the remarkable scope of research and development required to be worked upon with natural dyes, namely digital printing with natural dyes, electrical conductivity, and fluorescence properties of natural dyes that await to be explored further. For the future, the review paper highlight’s on multi-disciplinary research approach at global, institutional, and individual levels of research to meet the anticipated holistic outcomes.

Keywords

Sustainable textiles, anti-microbial textiles, herbal colors, biomaterials, therapeutic textiles, phytochemicals
1. **Introduction**

To circumvent the top global environment crisis efficiently, we ought to comply and copiously support the declared climate emergency [1]. Concurrently, earnestly cohort binoculars on the existing dermatological, respiratory and ecological ill effects of fossil-based textiles [2], for example, 75% of synthetic PET microfibers detected in the fish gut [3], titanium dioxide, and aniline indigo scrutinized as carcinogens and so forth [4]. Thus, there is paradigm shift worldwide to focus on alternative materials and methods to achieve the standards set by U.S. Environmental protection agency (EPA) and “Registration, Evaluation, Authorization & Restriction Of Chemicals” (REACH) [5] and “Sustainable Development Goals” (SDG) set by UN in 2015 for future ethics and responsibility towards environment and humans [6]. These government agencies promulgate the use of eco-friendly natural dyes in the textile dyeing and printing sector. The textile dye industry is the second chief polluter of the biosphere, after big oil. The research and development in the textile dye industry are thus concentrated in renewing natural dye interests for a sustainable future. Likewise, it is anticipated that the global market share of natural dyes will increase the revenue generation by $ 5 + billion by 2024. The compound annual growth rate would be 11% from 2018-2025 [5].

However, the current challenge encountered by the textile dye sector is to produce zero waste and zero carbon footprint in processing. There is a pressing need to shift to alternative materials and encourage interdisciplinary research to circumvent global problems. Thus, integrating textile technology, chemistry, and medicine to produce eco-friendly and sustainable products would provide significant environmental, social, and economic benefits. However, as the critique says the “ECO” concept should not be an illusionary temporary change. For permanent “ECO” lifestyle a radical shift of change in attitude and awareness is essential [7]. Moreover, the scientific research investigations accomplished on natural colors from plants indicate no possible health treat or toxicity to humans and animals [8].
Countries such as China & India being mammoth manufactures of textiles are in a major river water crisis. The textile dye houses are exhausting the water resources and coloring the rivers in magenta and green from the toxic synthetic chemical dye units. If the dyes and additives were of natural origins river pollution would not exist. This is where the giants in the field namely Archroma, Huntsman, and DyStar are cohering their lens on. The Switzerland based company Archroma has expanded into a range of earth colors of plant origin for the textile dye and print industry. Thanks to the Greenpeace alert given in 2011 by releasing colored rivers photos world-wide. The aftermath of green peace detox fashion resulted in the formation of zero discharge of hazardous chemicals (ZDHC) program. It helps the companies towards detox treatment [9] and propels the movement towards low water and energy demand for the sustainable future of the textile industry.

Globally it is evident, that the ancient Gods and Goddesses, Saints, and Monks were accustomed to wearing naturally dyed clothing colored with plant origin saffron, turmeric, colors from stones, and muds. Conventionally one of those natural dye plants namely jackfruit was utilized by Shukla and Vankar, for coloring cotton, silk, and wool fabric. The array of earth shades was obtained Artocarpus heterophyllus as shown in Figure 1 [8].

The dye uptake of 70% was observed with silk fabrics. The dye exhaustion percentage (E %) was calculated according to the following Equation 1 [8].

\[
E(\%) = \frac{A_o - A_r}{A_o} \times 100
\]

where \( A_o \) and \( A_r \) are the absorbances of the dye bath before and after dyeing, respectively.

The study defends that metallic mordants expended in the process are to the minimal and eventually degrade nor do they linger back on treated fabric therefore safe. However, for future sustainability depleting the mineral ore for metallic mordants would not be encouraged. Hence, further research investigations with
bio mordants from the plant are embarked upon [8]. This would propel natural dyes and additives market meaningfully.

Figure 1. Earth shades obtained with Jackfruit on Cotton, Silk, and Wool [8].

Morin, Artocarpin, and Isoyclohydrophyllin were found to be chief coloring components. The K/s values were enhanced due to mordants and were chelated the best with Ferrous, refer to Figure 2 and Table 1 [8].

Figure 2. K/s values of wool fabric colored with Jackfruit [8].
Jackfruit exhibited good fastness properties on cotton fabric as in Table 2 and satisfies the standards set by BS EN ISO 105. The rating of 4 and above is recommended for commercial end-use [8]. However, mineral mordants are to be replaced with plant-based biomordants.

Though natural dyes are 3000 B.C. old dyes, the recent upsurge in natural dyes research is remarkable. The Tintex color technology, utilized bio-active compounds from plant-based materials such as boldo, chestnut, thyme, peppermint, and gambier on natural fibers as cotton, wool, and Lyocell. Thus, producing responsibly colored fabrics with anti-microbial properties. The process does not utilize salt in the production, it is eco-friendly, low-heat surface treatment. These extract treatments have appropriate light and wash fastness. Color durability and anti-microbial property are befitting. Thus, producing sustainable and functional textiles. This new collection is called “sensing smarts” as they enhance wellbeing and are for green safe future [10]. A similar healing mechanism applies to textile fabrics printed with herbal biomaterials however there is a dearth of literature to justify the prevailing theory.

**Table 1.** CIELAB colorimetric values of silk fabric colored with Jackfruit [8].

<table>
<thead>
<tr>
<th>Method</th>
<th>Mordants</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>C</th>
<th>H</th>
<th>K/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>66.18</td>
<td>0.93</td>
<td>16.66</td>
<td>16.69</td>
<td>86.76</td>
<td>14.45</td>
</tr>
<tr>
<td>Mordants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alum</td>
<td>67.30</td>
<td>0.56</td>
<td>19.48</td>
<td>19.49</td>
<td>88.29</td>
<td>14.25</td>
</tr>
<tr>
<td></td>
<td>Copper sulfate</td>
<td>70.77</td>
<td>2.86</td>
<td>27.75</td>
<td>27.90</td>
<td>84.08</td>
<td>44.85</td>
</tr>
<tr>
<td></td>
<td>Ferrous sulphate</td>
<td>66.65</td>
<td>2.50</td>
<td>18.41</td>
<td>18.58</td>
<td>82.21</td>
<td>45.62</td>
</tr>
<tr>
<td></td>
<td>Potassium</td>
<td>66.69</td>
<td>0.61</td>
<td>17.84</td>
<td>17.85</td>
<td>88.00</td>
<td>15.58</td>
</tr>
<tr>
<td></td>
<td>Dichromate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stannous chloride</td>
<td>68.99</td>
<td>-1.01</td>
<td>22.96</td>
<td>22.98</td>
<td>92.57</td>
<td>15.84</td>
</tr>
<tr>
<td></td>
<td>Stannic chloride</td>
<td>68.42</td>
<td>1.49</td>
<td>22.00</td>
<td>22.05</td>
<td>86.07</td>
<td>19.00</td>
</tr>
</tbody>
</table>

**Table 2.** Fastness properties of cotton fabric colored with Jackfruit [8].
Likewise, Buffy introduced eucalyptus fabric sheets dyed with natural dyes. A plant-based innovative cloth colored with natural dye acquired from a mix of berries, spices, and plants. A grey tone was developed from a mixture of tea, eucalyptus, and pomegranate. A blush tone was created from turmeric, gardenia, and walnut. And the brand would market blue hues from indigo, safflower, and rose in late 2019. Buffy beddings sought-after ultrasonic dyeing process created in 1941 which is safe for the people. It is sustainable and eco-friendly. It curtails the use of enormous volumes of water, compounds, and energy. The run-off water into the environment is biodegradable. The plant-based naturally dyed eucalyptus beddings are breathable. They are fast to sunlight [11]. To, meet the market demand for natural dyed sustainable eco-friendly products it has become mandatory to explore new sources of natural dyes, increase the color palate, and accentuate their functional properties. Also, to further reinforce the sustainability agenda herbal materials for textile applications are often from surplus leaves, stems, twigs, flowers, fruits, fruit peels, and barks with no harm to the environment.

Consequently, a detailed overview of ancient biomaterials and ecological processing could inspire us towards the slow fashion sustainable textile industry. The overview primarily focuses on plant-based printing with natural colors to align with the contemporary predisposition towards low on water and energy demand consumption in textile print processing for sustainable outcomes. However, the remarkable studies on herbal dyeing and coating are meticulously included to rationalize and capture the functionally healing properties of herbal biomaterials which ought to be implemented with ecological printing on textiles.
in-depth probe on the subject propels towards an exceedingly cumulative trend towards natural plant-based biomaterials for future fabrics.

2. **Herbal biomaterials in textile printing since ancient times to modern age**

2.1 **Plant-based biomaterials in block printing**

Block printing, traditional block printing is an eco-friendly process involving wooden blocks, natural fabric, and natural color. Madder for reds, indigo for blues, and pomegranate rind and turmeric for yellows are some key natural dyestuffs that have come down the ages to be used on their own or in combination to produce a range of shades [12].

Ancient inks are herbal concoctions with fluorescence, medicinal and aromatic properties. In India, the application of herbal inks on paper, textiles, and skin tattoos are prevalent since 3000 BC. The component biomaterials are conducive to both human and environmental health. For instance, kalamkari ink painting on fabric, wherein the washed cotton fabric is soaked for 20 minutes in cow milk with chebulic myrobalan fruit powder dissolved in it. Dried in sunlight for 6 hours and stored at room temperature for a day. It is a pre-treatment that prevents herbal color inks from spreading while painting with a bamboo pen. Burnt tamarind stick charcoal is utilized for drawing outlines on fabric. Myrobalan gives the light yellow color to the fabric, a concoction of jaggery, iron rust, and water gives black color, indigo, pomegranate, catechu, and Algerian obtain blue, golden yellow, rosemary, and, red respectively. Alum in water imparts a grey tone to the fabric and the cow milk wash given to the fabric as finishing highlights the colors [13]. It is thought-provoking to note that herbal biomaterials are intense and functionally subtle.

Similarly, Sabnani demonstrates, Ajrakh prints of, Kachchh, Dhamadka, in India, wherein the camel dung, soda ash, and castor oil are utilized to prepare the cotton cloth. A mixture of alum, gum arabic, and clay along with the mixture of lime and gum arabic are utilized as the resist. A mixture of water, iron rust, tamarind seeds, and jaggery is utilized for black color prints with wooden blocks. Indigo, madder root, henna, rhubarb is utilized for blue, red, green, and pale brown colors, respectively. The processed fabric is
dried naturally for 3 days [12]. Thus, medicinally rich cloth infused with herbal benefits & eco-friendly process is created refer to Figure 3. However, plentiful clinical trials would be imperative to justify the functional theory.

Figure 3. Madder printed the Ajrakh print of India [14].

Yet another unique ancient print is the Dabu, which is for dabaana, means “to press”. The fabric is pre-treated with myrobalan seed extract as mordant. Wooden printing blocks are coated with mud paste of black clay, calcium, limestone, gum, wheat, and water then pressed onto a cloth and dried. When the cloth is dipped in dye, the mud keeps the color out – it resists the dye and so this method is called resist printing. Mud clay confers good resist to acquire design [14]. A sustainable alternative to wax and synthetic resists commercially utilized. Figure 4 represents Indigo resist printed cotton fabric.

Figure 4. Indigo printed Dabu resist print of India [14].
After printing the sawdust is sprinkled over the printed area to prevent smudging. The fabric is sun-dried and then vat dyed for coloration. Thereafter, when the mud is washed off, you can see the pattern that the block created. Dabu is practiced mainly in Rajasthan Bagru and Sanganer in India. Thus, also known as Bagru prints and Sanganer prints. It is noteworthy that the entire process is biodegradable. Indigo and madder are widely utilized as herbal colorants enriched with medicinal benefits, soft to the skin, and eye-soothing effect imparted to the wearer [14]. A zero-carbon footprint process. Indigo and Madder being most ancient dye plants are portrayed in Figure 5.

With inspiration from the above ancient methods conventionally, Viscose rayon fabric was block printed by Kanade and Patel with plant-based colors from harde, madder, and turmeric. Tamarind kernel powder of 50% concentration was utilized as a thickening agent. Inorganic metallic salts of 50 gpl were mixed in the paste namely, aluminum sulfate, copper sulfate, and ferrous sulfate. Appropriate rheology of the print was maintained. Adequate lightfastness and decent wash fastness were obtained. The fabrics had good resistance against microbes as revealed by the bromophenol test [15].

![Indigofera Tinctoria (Indigo)](image1) ![Rubia Cordifolia (Madder)](image2)

**Figure 5.** The most ancient natural dye plants utilized in Kalamkari, Dabu, Sanganer, and Ajrakh prints of India a) Indigo and b) Madder [12] [13] [14]. They manifest excellent fastness and medicinal properties on treated natural fabrics.
Similarly, Degummed and bleached proteinic silk fabric was the block, screen, or stencil printed with natural dyes dolu, mahua, Indian madder, Khair, haritaki, lac, tea, pomegranate, annatto, Indigo, Haldi, and onion. The prime coloring pigment present in the natural dye were chrysophanic acid, quercetin dihydroquercetin, purpurin, catechin, elagitannic acid, laccaic acid, theaflavin and thearubigins, ellagitannin-flavogallol, bixin and nor-bixin, indigotin, curcuminoids, curcumin, quercetin, respectively. Natural gum indulka was utilized as a thickener. Metallic mordants were mixed along namely aluminum, ferrous, and copper sulfates. Acidic pH of 4.5 was maintained for proteinic fabric printing. The printed and dried fabrics were steamed at 100°C for 30 minutes. Washed in non-ionic soap and air-dried. A good wash, light, and rub fastness were obtained except for Haldi and annatto [16]. The plant phytochemicals play a vital role in imparting functional properties to the treated fabrics however the study overlooks the same.

It would be interesting to note that the plant-based biomaterials were further explored by Bains and Sethi, wherein the Khadi silk fabric was printed with natural dye from Arjun bark with wooden blocks and 2.5% and 5% of Cassia tora as a natural thickener. 2% ferrous sulfate and 5% alum performed as mordants. The L* = 0 specifies black and L* = 100 designates white. Here the values for L* were low indicating dark shades obtained. a* value of 3.91 indicated the red shades and 24.42 value of b* indicated yellow shades obtained on samples. The L*a*b* values are given in Table 3 below. Colorfastness to wash, light and perspiration were found to be good to very good for most of the samples. Thus, establishing the conclusion that Cassia tora seed pods can be effectively utilized as a natural thickener for block printing khadi silk fabric [17].

Table 3. Research trials with varied percentage of innovative gum and their color scan on color matching software [17].
Thus, the captivating treasure of herbal biomaterials for textile coloration and functionality is age-old. Sequentially, it would be highly rewarding to utilize varied natural gums, binders, and thickeners as additives to facilitate the eco-processing of textiles as investigated in the above-given studies. It is primarily highly recommended for the cottage textile industry, artists, and designers, that would culminate in the high value of resource conservation, otherwise considered as waste, and consecutively propel the circular economy. However, copious research and development are required to justify the functionality of sustainable herbal fabrics and replace the metallic mordants with plant-based renewable alternatives.

### 2.2 Plant-based biomaterials in screen printing

Screen printing involves a wooden frame fitted with transparent mesh with design, a squeegee to spread the color, and the color paste. An overview of screen printing with eco-friendly biomaterials is discussed here.

An eco-friendly approach was taken in the said study, the Lyocell fabric was screen printed with Madder and Katha with gaur gum and chitosan as natural thickeners and fixed by steaming at 100°C for 1 hour. It was observed that fabric samples printed with natural colors combined with 25% guar gum + 75% chitosan, 75% guar gum + 25% chitosan, and 50% guar gum + 50% chitosan thickeners, all performed anti-microbial
activity towards E. coli and S. aureus. And the samples had 4-5 to 5 rating of wash fastness, sunlight fastness, and perspiration fastness. The fabrics were concluded to be a suitable alternative to synthetic-based textile materials. They were suggested for medicinal textiles, kids' clothing, smart textiles, and carpet end-use [18]. However, prodigious clinical analysis is mandatory before commercial implementation.

Alternative minor cellulosic grey jute fabric was bio scoured and mordanted with both alum and myrobalan. The jute fabric was screen printed with natural dyes from the Manjistha, ratanjot, and annatto with natural guar gum as thickener and urea as a humectant. A very good wash and rub fastness were obtained. Thus, eco-friendly printing was established for jute fabric suitable for decorative, apparel, and furnishing purpose. The Natural dye plants in the said research with their modern color classification is specified in Table 4 below [19]. However, there is a dearth of systematic nomenclature of natural colorants that calls in for massive efforts in the field.

Table 4. Ancient natural dyes with modern classification [19].

<table>
<thead>
<tr>
<th>Common name</th>
<th>Botanical name</th>
<th>Parts used</th>
<th>Color index number</th>
<th>Chemical class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manjistha</td>
<td>Rubia cordifolia</td>
<td>Roots</td>
<td>C.I. natural red 16</td>
<td>Anthraquinones</td>
</tr>
<tr>
<td>Ratanjot</td>
<td>Onosma echoides</td>
<td>Bark</td>
<td>C.I natural red 20</td>
<td>Naphthoquinone</td>
</tr>
<tr>
<td>Annatto</td>
<td>Bixa Orellana</td>
<td>Roots</td>
<td>C.I natural orange 4</td>
<td>Carotenoid</td>
</tr>
</tbody>
</table>

Likewise, the cotton fabric was screen printed with 10%, 20%, and 30% dye strength of madder, onion peels, and Sappanwood natural dyes. The printing was done on (1) Cotton fabric pre-mordanted with 5% alum and printed with 2 % natural guar gum stirred in dye color solution to form a print paste and (2) Cotton fabric printed with alum, guar gum and dye stirred together in the print paste called Meta mordanting. The printed fabrics were dried at 80°C for 5 minutes. Then steamed at 100°C for 5 minutes. It was concluded that K/s values were directly proportional to dye strength. The wash, light, and rub fastness properties were very good for madder and onion peels [20].
Concurrently, to circumvent the environment and human health problems associated with non-renewable and oil-based inks an attempt was made by Shaw, to develop vegetable inks for textile screen printing and paper-based on CMYK color system of modern printers. To obtain cyan, indigo, woad, and Japanese knotweed was utilized. For yellow, weld and buckthorn were considered. To obtain magenta, madder, elder, pokeweed, and brazilwood were utilized. And for black, logwood, walnut hulls, oak galls, sumac, elder and Adler, mixtures were attempted. The author identified traditional naturally occurring gums and starches that were utilized for printing in textile namely, gum tragacanth, gum arabic, maize, wheat, potatoes, alginates, sago, arrowroot, cherry gum, linseed, rice starch, gum karaya, agar, gomma, bassora gum, and gommeline. However, for the study, potatoes starch, seaweed alginates, and gum arabic were utilized [21].

Shaw further investigated that traditionally vegetable oil, glycol, honey, molasses, or glucose were mixed with gums and starch to refute drying and thus maintain the desired ink viscosity for printing. Preventol (0.5 % formaldehyde) was also utilized. Interestingly vegetable sources of preservatives were identified namely, sorbic acid naturally occurring in the fruits of mountain ash. Sorbic acid when neutralized converts to potassium sorbate can also be utilized as a natural preservative. Benzoic acid can be extracted from the fruits of the elder. Salicylic acid is found in olive oil, tea, wine, willow, and myrtle others [21]. Thus, an exhaustive literate is available on alternative surplus natural materials for prospective application on textile substrates, however abundant of research experimentation would be obligatory. Also, concurrently we ought to accomplish our responsibility of protecting biodiversity and planting them back in nature to continue the vicious and harmonious cycle of our relationship with nature for a sustainable future.

Authors express his concern over typical water-based commercial screen-print ink formula which is a 60% non-renewable Petro based composition. It consists of 15% pigment, 45% carboxylate acrylic emulsion, 15% styrene/acrylic emulsion, 0.5% ammonia, 5% microcrystalline wax emulsion, silicone defoamer, 1% levelling agent, 4% dowanol, and 14% water. Thus, vegetable inks are sustainable alternatives. He mentions the medicinal utilization of synthetic Indigo Carmine in the review of the literature. The author
finally summarizes that the viscosity and drying time of the ink plays a vital role in printing. The addition of natural anti-bacterial and anti-fungal materials to ink enhances its self-life [21].

In adherence to the above concerns, it is motivating to note that prodigious research inputs are made to drive towards the sustainable textile industry. Wherein, consistent attempts are made to explore plant-based biomaterials for functional textiles. However, there is a dearth of connecting research to verify the functionality and environment factors. It could be accomplished with a supplementary research focus on tissue engineering, clinical trials, and life cycle assessment of the final products.

2.3 Plant-based biomaterials in digital printing

Digital printing, Digital ink-jet printing is a “process by which the pattern with its colors is built up by projecting tiny drops of ‘ink’ (special dye liquors) of different colors, in predetermined micro-arrays (pixels), onto the substrate surface” [22].

Digital printing is the innovative technology of today, low on water and energy demands. It can be customized on varied substrates. Therefore, sustainable. Herbal biomaterials are experimented with for digital printing with natural plant-based colors. In one of the studies envisaged by Savvidis et al, amylase desized cotton knit fabric was inkjet printed with 4 natural dyes, namely annatto, cutch, pomegranate rind, and golden dock. The inks were formulated with an 80/20 water/2-n-butoxyethanol system and homogenized. The prepared inks were tested for its surface tension, conductivity, viscosity, and pH. Refer to Figure 6 for stability analysis of Surface tension and the Viscosity parameter.

These properties were measured at atmospheric pressure and room temperature for up to 90 days. The inks were filtered, the ink-jet cartridges were filled with inks and utilized for printing with Epson Stylus SX218 ink-jet printer. The cotton fabric was pre-treated with Fixotol Eco FF and ironed smooth to be printed digitally. The formulated inks had remarkable stability for above 90 days. The wash and rub fastness improved when the printed fabric was after treated with a cationic fixing agent. Lightfastness was low for
both treated and untreated cotton fabrics. K/s values were satisfactory. The hue obtained was red yellow with positive a* and b* values. [23]. However, the inclusion of synthetic additives in herbal ink formulations would not resonate well with the sustainability aspect. Also, it camouflages the functionality and aromatic advantages of herbs.

![Figure 6. Plant-based ink formulations tested for their surface tension and viscosity properties [23].](image)

1) 2% Annatto  
2) 4% Annatto  
3) 2% Cutch  
4) 4% Cutch  
5) 2% Pomegranate fruit  
6) 2% Golden dock

Similarly, annatto for yellow, red from madder and sandalwood, blue from indigo and grey from acacia are under trials for digitally printing the cotton fabric. The trial inks are tested for their rheological properties. The pH of the neutral region, surface tension in the range of 21-48 m Nm\(^{-1}\) and viscosity of low value as 2 cp are considered as conducive for ink-jet printing. The Annatto ink was found to be stable over 28 days’ timeline. Water-based annatto ink gave the pale yellow color of K/S value 0.42. Wash fastness was good [24]. However, the data provided was restricted to Annatto ink.

Concurrently, research is envisaged to obtain the CMYK range for digital printing of cotton and wool fabrics with natural dyes. Plant-based mordants are in-cooperated in the study. Natural soap nuts are utilized
as a source of saponins for washing the cured fabrics. The functionality of herbal biomaterials is entrapped on the fabrics digitally. And further enhanced with plasma surface modification of textiles fabrics in research. Thus, obtaining digitally printed UV protective and antimicrobial fabrics with herbal biomaterials. The entire processing is kept eco-friendly. The research would be a noteworthy contribution to the field of biomaterial engineering of herbal textiles for a sustainable future [25].

Alternatively, environment-friendly inks such as inks from vegetable oil namely soybean oil and corn oil can replace petroleum or mineral-based oil inks. Secondly, UV inks (acrylic epoxy), they get cured only when exposed to UV lights, are low on solvents and VOC emissions. And thirdly the waterless inks, which transports inks from the computer to silicon plate to substrate thus eliminating the need for chemicals and water in the printing process [26]. Also, natural dyes from red amaranth leaves were extracted which yield green color in ethanol extraction and red-violet color in distilled water extraction. Indicating the presence of betalain and chlorophyll pigments, respectively. They exhibited good photosensitizing properties for solar cell activation and textiles applications [27].

Systematically, the review paper accomplishes the reporting of the biomaterials implemented in the textile industry from ancient origins until digital prints. As identified from the above review of literature the digital print technology in association with natural dyes is the least explored area, thus, it is a highly recommended area to explore for a sustainable future.

2.4 Miscellaneous

The functionality of sustainable plant-based biomaterials is observed in manifold aspects that indirectly relate to textiles. The research findings that are relevant and significant for future researches on plant-based bio-material engineering for textiles are comprehensively presented here.

As per the literature review, ancient Palm leaf manuscripts were traditionally preserved with the application of extracts from plants. The chromatographic study established the presence of herbal fungicides and
insecticides on palm-leaf manuscripts of Odisha. Several herbs were present namely, cinnamon tree extract (Cinnamic acid), Artemisia oil (Isogeraniol), walnut wood (Syringealdehyde), Cirsium root (Hexahydroaplotaxene), Rhizophora leaf, (Caprylone) equisetum stem (Hexahydrofarnesyl acetone), tobacco plant oil (Neophytadiene) and tick plant (Lignocerol). These bio-active components are functionally anti-microbial. The Fourier Transform Infrared spectroscopy (FTIR) revealed the coexistence of natural gums such as pectin (carboxamide) and polysaccharides (starch, cellulose, and hemicellulose). The gums were mixed with pigments for binding action for writing inks on palm leaf. Additionally, as per literature, the study mentions the applications of plant-based sustainable extracts that were traditionally utilized for palm leaf preservation namely, citronella oil, neem oil, cedarwood oil, ajwain, clove oil, sandalwood oil, nirgudi, camphor oil, sweet flag, turmeric, and datura [28]. Nature is enormously resourceful, humanity ought to synchronize with nature and nurture nature in this joint interdependent connection.

Interestingly traditional Mahi inks were scientifically analyzed, it is composed of herbal materials from fruits, flowers, barks, and leaves of Hilika, Amlakhi, Kehraj, and Mango trees. The materials are processed in an earthen pot with an alkaline bull urine and iron nails solution as a solvent. The ink color range is black, brown, and reddish-orange. The ink obtained with all the ingredients in it has black color with an 11 ml yield. pH 7.10, electrical conductivity 10.8 mS/m, iron content 26.1 mg/L, copper content was 2.1 mg/L and surface tension was 46.8 mN/m. The FTIR of the lyophilized Mahi samples, peak analysis, revealed the bio-active plant metabolites predominantly phenolic acids, polyhydric phenolic, flavonoids, tannins, and saponins. With non-destructive Raman spectroscopy, high peaks were observed with iron samples due to iron-polyphenols complex formation [29].

The complex enhances the UV-visible spectral absorption. UV fluorescence revealed red autofluorescence due to the occurrence of phenolic acids, flavonoids, and chlorophyll pigments. Visible absorption intensified with the presence of iron. The analysis reveals that the presence of alkaline cow urine and plant phytochemicals renders the ink non-corrosive, anti-oxidative and anti-fungal, thus preserves ancient
manuscripts. The Mahi ink surface tension (46.5 mN/m) is remarkably lower than that of clean H₂O (72.5 mN/m). Due to which the otherwise insoluble polyphenols and the iron compounds in Mahi inks are rendered soluble even in the lack of an additive like gum Arabic. Eco-smart and intelligent formulations with noteworthy fluorescence capability could be tapped upon from plant-based Mahi ink as reflected in Figure 7 at the wavelengths of (a) 265 nm, (b) 300 nm, (c) 350 nm and (d) 400 nm. Similarly, the plant-based formulations can be extensively researched to further validate the naturally occurring theory of the fluorescence phenomenon.

Plant-based inks were similarly established from four species namely, Beta vulgaris, Citrus limonene, Pentas lanceolata, and Bauhinia purpurea. The beetroot, citrus peel, butterfly flow petal, and butterfly tree were ground, boiled in water for 45 minutes to extract the inks. The colors obtained were marron, yellow, red, and purple, respectively. 5 to 10 ml of alcohol or vinegar was auxiliary to the intense ink formulation. The solution was stored in air-tight glass bottles away from direct light. All the inks were analyzed by Lagad et al, utilizing ink pens and were observed to be free-flowing, non-clogging, stable to UV rays, permanent up to 8 days, drying time varied from 7 to 12 seconds and each ink had its characteristic taste. These inks can be utilized to color cellulosic and protein-based fabrics, wood, food, and cosmetics effectively. They are sustainable and biodegradable [30].
Our skin is a natural proteinic fabric. Our clothing protects our skin from day-to-day UV radiation. However, UV radiations below 316 nm are beneficially required for vitamin D synthesis. A study was piloted to analyze the result of fabric type, color, fit, and wetness on the beneficial UV transmission with the help of Dosimeters made-up from polysulfide film. As this would eventually affect vitamin D absorption. Black and white knitted T-shirts of two knitted fabric types were tested. Parisi and Wilson concluded that the knitted fabric with a high UV protection factor is conducive to transmit the beneficial UV. T-shirt fit and fabric construction structure were predominately influencing rather than wetness of fabric and fabric color. Natural fibers namely bamboo and hemp have intrinsic UV protective and microbial resistant properties. These sustainable minor fibers are to be implemented for the higher well-being of humankind and the environment. They both are eco-friendly and sustainable [31].
Additionally, the traditional Chinese Hu kaiwen ink made since 12th century BC consists of pine branches having medicinal properties namely anti-septic and anti-moth, which are combined with animal bone glue to make ink. Huizhou Inksticks are the best in quality. The ingredients and the finished product are a shade or cool dried and protected from sunlight to keep the herbal qualities intact. The researcher's Wang et al, have utilized the ink to efficiently cure cancer cells. Currently, photothermal therapy is utilized, wherein nanomaterials are inoculated in cancer cells. The nanomaterial is heated with a laser that kills the cells. However, the said process is toxic, complex, and expensive.

And surprisingly the Hu-ink has a similar nanomaterial and thin carbon layer which can withstand much higher heat with laser as compared to the current photothermal therapy. The ink is non-toxic, biocompatible, eco-friendly, and therapeutic. On experiments with mice, they could cure cancer cells and act as a probe as well to locate metastatic lymph nodes and tumors as it can absorb near-infrared rays though the skin. Both in vitro and in vivo experiments with medicinal ink were successful wherein no damage to other organs was established. Statistically, t-test and one-way ANOVA were utilized for multiple group analysis. 0.05 of probability obtained was concluded to be significant for the said research. Results were expressed as mean ± standard deviation. An astonishing application of plant-based biomaterial engineering is offered in the research study [32].

An apprehension was highlighted in this study wherein, synthetic tattoo inks for the protein nature of human skin are utilized to decorate the skin permanently with micro dermal injections of colors from pigments, dyes, and lake precipitates. Other synthetic additives such as diluters, pH controllers, thickeners, and stabilizers are auxiliary to tattoo ink mixture. The qualitative and quantitative assessment of chief trademark tattoo inks was conducted with Synchrotron radiation X-ray fluorescence spectroscopy, in concurrence with atomic absorption and Raman spectroscopy. The toxic metals and additives were detected in tattoo inks. Calcium, Ferrous, Copper, and Strontium were existing in all the testers. TiO2 was prominently present moreover as a transporter for dyes or as a pigment [33].
Additionally, latent lethal elements, Hg (0.0012–0.0027 μg/g), Pb (0.80–9.0 μg/g) and Cu (3–13,900 μg/g) Cr (3 μg/g), Ni (0.40 μg/g), and Cd (0.163 μg/g) were detected. Cr and Ni are hypothetically hazardous to sensitive skin. They exceed the limits set by the “Council of Europe, resolution ResAP” (2008). The coloring dye Violet 23, color blue 15, and dye green 7 identified in violet, blue, and green inks, correspondingly, appear in the restricted gradient of chemicals of “Council of Europe, resolution ResAP” (2008). There have been reports of the allergies and granulomas occurring within a year or immediately on the application of tattoo inks [33]. Therefore, the suggested alternatives were the neolithic tattoo inks as they are plant-based and non-toxic and safe. They were made from natural fruits, flowers, stems, leaves, barks grasses, seeds, roots, trees, and berries. The molecules of natural origin are biodegradable. Whereas the molecules of synthetic chemicals lack biodegradability and remain back in the environment releasing toxic fumes [28]. In an examination specified herein, a detailed probe is presented into the material analysis of the ancient gall inks for application on cellulosic substrate paper. Refer to the results presented in Table 5. The inks recipes in the review were plant-based formulations that were patented.

**Table 5. 19th-century iron-gall ink recipes studied with FTIR [34].**

<table>
<thead>
<tr>
<th>No.</th>
<th>Ink</th>
<th>Ink Color</th>
<th>Water (%)</th>
<th>Aleppo galls (%)</th>
<th>Ferrous sulfate (%)</th>
<th>Gum arabic (%)</th>
<th>Other (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>British ink</td>
<td>Black</td>
<td>79.9</td>
<td>12.1</td>
<td>4.0</td>
<td>2.0</td>
<td>Potash alum (2.0)</td>
</tr>
<tr>
<td>8</td>
<td>USA ink</td>
<td>Red</td>
<td>56.7</td>
<td>7.6</td>
<td>2.6</td>
<td>2.6</td>
<td>Silver nitrate (0.1), sugar (11.3), glycerol (18.9),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>-----------------------</td>
<td>-----</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Wine ink</td>
<td>Green</td>
<td>18.5</td>
<td>10.9</td>
<td>8.1</td>
<td>White wine (62.5)</td>
<td></td>
</tr>
<tr>
<td>ii</td>
<td>Instant ink</td>
<td>Cyan</td>
<td>62.7</td>
<td>18.3</td>
<td>11.0</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>ii+v</td>
<td>Vinegar ink</td>
<td>Dark blue</td>
<td>59.6</td>
<td>17.4</td>
<td>10.4</td>
<td>7.7</td>
<td>Vinegar (5.0)</td>
</tr>
<tr>
<td>10</td>
<td>Boiled galls</td>
<td>Blue</td>
<td>80.4</td>
<td>10.8</td>
<td>4.7</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Fermented galls</td>
<td>Light green</td>
<td>82.0</td>
<td>10.3</td>
<td>5.1</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Canneparius</td>
<td>Brown</td>
<td>8.3</td>
<td>2.8</td>
<td>5.5</td>
<td>White wine (83.4)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8.** Chemical structure of Gum arabic molecule [34].
The overhead charted ink formulations were deliberated for research with Fourier Transform Infrared spectroscopy (FTIR). Their molecular assemblies were portrayed as shown in Figures 8, 9, and 10. The in-depth probe on dry materials and their liquid formulations delivered substantial data. The peak material intensities were distinguished as shown in Figures 11 and 12 for dry materials and its corresponding liquid inks respectively. It was witnessed that high peaks of iron influenced the ink age and substrate paper age [34].

![Figure 9. Chemical structure of Penta galloyl-glucose molecule [34].](image)

![Figure 10. Chemical structure of the Gallic acid molecule [34].](image)
Primitively materials and processing were conducive to both the environment and human health. However, we lost the track and got submerged in over synthetics especially due to over industrialization, overpopulation, and overconsumption. However, Neddo enlightens how the contemporary artists of today are marching towards sustainability and prefer to take a closer look at the surrounding landscapes to harvest the materials required for paints and prints as done by our ancestors. Right from the scratch the canvas board frame is manufactured from the wood obtained from nature. At the same time responsibility is taken to sow back the seeds for a sustainable future and protect biodiversity. Handmade paper made from plants namely papyrus, bamboo is utilized to base the board. Which performs excellent with charcoals and natural herbal powders, pigments, and inks extract from nature. Charcoal is one of the most ancient pigments utilized by artisans. It is the carbon remains of the burned objects. Dead and fallen twigs, stems, and barks of varied sizes and shapes form the fire pit [35].

![Figure 11. FTIR of dry materials (a) Aleppo galls (b) Gallic acid (c) Sucrose (d) Glycerol (e) Acetic acid (f) Potash alum (g) Ferrous sulfate and (h) Gum arabic [34].](image-url)
After the fire cools off the fragments of coal are scavenged upon for artwork. Grape wine, willow rods, firewood are commonly utilized for the same. Charcoal kilns utilized for cooking can supply coal for artwork. Charcoal shades would give one of the most exhaustive greyscales. Tannins, iron nails in vinegar, walnut hulls obtain darker blue-back inks [35]. The author demonstrates a plethora of colors that can obtain a rainbow of colors from nature. An array of browns from tea and coffee can be filtered by simply soaking them in tap water. Reb cabbage, beetroot, spinach, berries of varied colors can be crushed for pigments. Salt or vinegar can be stirred into the colored inks as a preservative. Natural saliva, honey, tree resins, molasses, and lignin perform as natural binders for inks. Thus, fruit inks and vegetable inks for a sustainable future. Tannins, iron nails in vinegar, walnut hulls obtain darker blue-back inks. From our local bioregion, we can access hollow oak twigs, bamboo, black walnut, elderberry, sumac, staghorn, reeds, and quails and functionally utilize them as unique pens with characteristic nibs. Certain aromatic herbs are like rosemary, thyme, the orange extract is stirred into inks for pleasant strokes [35].

Figure 12. FTIR of liquid ink samples of varied colors formulated as in the table above [34].
Mud vessels, cotton, and wool fibers felt work as ink holders. Varied grasses namely pine needles, deer fur, and palm bark form bristles. And fibrous twigs like beech, elm, birch, oak, agave, wild grapes vine work as brushes. Renaissance of Stone Age ventures from the above review. There is an intense and ingrained feeling of us in nature and nature in us due to our same 5 elemental composition of ether, air, fire, water, and earth. Our harmony with nature ought to be inborn [35].

The above studies provide us with a diverse perspective on the application of eco-friendly resources on cellulosic and protein-based substrates. The applications are multiple from medical textiles to luxury textiles with natural colors and formulations from plants. It is overwhelming to notice the abundance of natural resources and the peace of disease-free and pollution-free Stone Age. An immense treasure of surplus sustainable resources going unnoticed and untapped ought to be conserved and reinforced with adequate logical, scientific, and technical evidence.

3. Chemistry of bio-active plant phytochemicals

3.1 Phytochemicals and their healing mechanism

It is all about chemistry. In the context when it comes to biomaterial engineering, the botany and plant phytochemicals play a vital role in the formulation and functionality of the engineered product. It would eventually determine the end-use.

“Phytochemicals are biologically active, naturally occurring chemical compounds found in plants, which protect plant cells from environmental hazards such as pollution, stress, drought, UV exposure and pathogenic attack especially the flavonoids, alkaloids, sterols, terpenoids, phenolic acids, stilbenes, lignin’s, tannins and saponins” [36].

The “Ayur vastra” textile and clothing can enhance the skin’s capability to perform as an obstruction to outdoor and ecological pollutants, thereby enhancing the wearer's well-being. The healing is attributed to
plant phytochemical’s entrapped in naturally processed fabrics. The traditional Ayurvedic healing mechanism is clinically explained here, wherein the ministry of health, Kerala state government, India, initiated a 6-month study. Marked improvement was observed in healing blood disorders, skin ailments, arthritis, and rheumatism with ayurvastra (herbal processed fabrics). Ayurveda identifies seven layers of the skin. They are “Avabhasini, Lohita, Shweta, Tamra, Vedini, Rohini and Mamsadhara”. The “fourth layer, Tamra”, maintenance the immune system. It acts as a barrier. Skin toxicities reflect a disparity in this layer. “Ayur vastra” provides a protective material layer next to the skin and prevents infections. An example is cited in Figure 13 [37].

![Figure 13](image)

(a) Turmeric extract  (b) Curcumin in Turmeric  (c) Turmeric extract solution & (d) Application

**Figure 13.** The ayurvastra herbal treated fabric with turmeric extract for clothing that heals [37] [38].

Incoherence with the above coloration curcumins in turmeric is one of the yellow but not flavonoids that impart a yellow color to the textile substrates as elaborated by Cardon and Higgitt. Besides this, a massive literature is elaborated by the same on numerous chemical structures of the natural colorants. Refer to Figure 13 for the structure of curcumin [38].

The conventional theory explains that during the processing of fabrics with natural sources of chemically bioactive compounds, the micronutrients and phytochemicals from the sources remain in nanoparticles within the microfibrillar fabric structure. On wearing the natural components entrapped within the fabric are released. They interact with the skin, in the areas of contacts and the benefits are passed onto the wearer.
A subtle drug delivery mechanism theory applies here, fabrics thus help in gradual healing of the corresponding ailments as alternative medicine.

The process of microencapsulation on cotton fabric enhances the tapping and transfer of these phytochemicals. For instance, the Cannabidiol [CBD] is a marijuana plant extract infused in Acabada Proactive Wear range of women’s sportswear by microencapsulation. The bioactive Cannabidiol interacts with the human body system and induces relief from pain and insomnia. It has anti-inflammatory properties that speed up recovery after exercise. Technically 25 g of CBD is infused in the sportswear garment and is designed to withstand 40 wear and wash cycles, thereafter they can be upcycled. They are sustainably made in Portugal in compliance with European employment laws and standards. The theory is widely applicable for compression garments infused with medicinal healings for enhanced functionality [10]. The theory remains to be evident with herbs printed textiles.

3.2 Phytochemical screening

It is defined as “the extraction, screening, and identification of the medicinally active substances found in plants”. The medicinal value of plants is attributed to the presence of bioactive compounds. Since the pathogens have developed resistance against antibiotics these secondary plant metabolites are to be tapped for their valuable healing efficiency [39]. They are extensively utilized for functionality in textiles as discussed further in point 4. Here, the chemical structure is deliberated for an in-depth probe. A subtle and robust role of plant phytochemicals as studied by Nyamai et al. is highlighted.

a. “Phenolic compounds have one or more aromatic rings with at least one hydroxyl group”. They protect plants and humans from ultraviolet radiation (UV). Refer to Figure 14 [39].
b. “Flavonoids, flavonoids are polyphenolic antioxidants with low molecular weight”. Refer to Figure 15 [39].

c. Anthocyanins have anti-inflammatory and antibacterial properties; they hinder the development of free radicals. Refer to Figure 16 [39].
d. **Phenolic acids** are 1 - cinnamic acid 2 - benzoic acid derivatives. They are ferulic acid and caffeic acid with antioxidant activity. Refer to Figure 17 [39].

![Phenolic acids](image)

**Figure 17. Phenolic acids.**

e. **Stilbenes** are phenylpropanoid that consists of a “trans-ethene double bond”. It is replaced with a “phenyl on both carbon atoms of the binary bond”. Stilbenes have anti-inflammatory and anticancer properties. Refer to Figure 18 [39].

![Stilbenes](image)

**Figure 18. Stilbenes [39].**

f. **Lignans**, lignans are planting polyphenolic compounds. They fill in for cinnamic acid alcohol. They have anti-cancer effects. Refer to Figure 19 [39].
g. **Tannins**, tannins are polyphenols. They are profusely present in the plant bark, wood, fruit, leaves, roots, and in-plant gall. Refer to Figure 20 [39].

h. **Terpenoids**, are complexes formed from five-carbon isoprene units primarily isopentenyl pyrophosphate and its isomer dimethylallyl pyrophosphate by terpene synthases”. Terpenoids mend the skin quality, escalates the absorption of antioxidants in injuries, and reinstate inflamed flesh. Also, anti-fungal. Refer to Figures 21 and 22 [39].

---

**Figure 19.** Lignans [39].

**Figure 20.** Tannins [39].
i. “Alkaloids contain nitrogen. They are derived from varied amino acids”. They demonstrate the antioxidant and antimicrobial properties. Refer to Figure 23 [39].
j. **Cardiac glycosides**, cardiac glycosides are planted subordinate metabolites that have a glycoside unit. Digitalis is a cardiac glycoside both customarily contain two glycosides, digitoxin, and digoxin whose edifices differ only by an extra hydroxyl group on digoxin”. Refer to Figure 24 [39].

![Figure 24. Cardiac glycosides [39].](image)

k. **Saponins**, Saponins are plant amalgams that occur as steroid alkaloids, glycosides of triterpenoids or steroids”. Saponins have antifungal and hypocholesterolemic effects. Saponins from soap nut, Areetha nut are utilized as emulsifiers and biosurfactants in the food, pharmaceutical, and textile industry. Saponins are found to be anti-microbial, anti-mosquito, antioxidant, and anti-fungal. Refer to Figures 25 and 26 [39].

![Figure 25. Saponins [39].](image)
As researched by Thakker, the natural herbs Areetha nut and Shikakai are high in saponins. They could be effectively implemented for preparing cotton and in daily wash and care of cellulosic and proteinic fabrics. They confer the fabrics with anti-microbial, healing, aromatic and soft to skin saponins. They are provided in table 9 [40].

Figure 26. Saponins [39].

l. “Sterols, phytosterols are a subcategory of steroids that have constructions and roles like cholesterol. Phytosterols occur as sterols or stanols”. β sitosterol is anti-inflammatory. Refer to Figure 27 [39].

Figure 27. Sterols [39].
A reflect on the plant phytochemicals structures and their relevant medicinal functionality scientifically befits them for application in various fields namely food, textiles, cosmetics, oil, and packaging. A further mull over in conjugation with their functionality in textiles is covered ahead. As mirrored in Table 6 below [41] and discoursed ahead in Point 4.

**Table 6** Herbal biomaterials with medicinal benefits for health-care textile applications [41].

<table>
<thead>
<tr>
<th>Natural Dye</th>
<th>Chemical Pigment</th>
<th>Image</th>
<th>Color</th>
<th>Medicinal Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turmeric</td>
<td>Curcumin</td>
<td><img src="image1" alt="Turmeric Image" /></td>
<td>Yellow</td>
<td>Antioxidant, Anti-Septic and Anti-Viral</td>
</tr>
<tr>
<td>Saffron</td>
<td>Crocin, Crocetin, Picocrocin, Safranal</td>
<td><img src="image2" alt="Saffron Image" /></td>
<td>Golden, Yellow, Orange</td>
<td>Anti-Inflammatory, Anti-Depressant, Gingival Sedative</td>
</tr>
<tr>
<td>Safflower</td>
<td>Carthamin</td>
<td><img src="image3" alt="Safflower Image" /></td>
<td>Red</td>
<td>Rheumatism, Cytotoxic, Anti-Platelet</td>
</tr>
<tr>
<td>Annato</td>
<td>Carotenoids - Bixin, Norbixin</td>
<td><img src="image4" alt="Annato Image" /></td>
<td>Reddish, Orange</td>
<td>Astringent, Anti-Microbial, Antioxidant</td>
</tr>
<tr>
<td>Pomegranate</td>
<td>Anthocyanins -</td>
<td><img src="image5" alt="Pomegranate Image" /></td>
<td>Red</td>
<td>Anti-Carcinogenic, Anti-Viral, Anti-Atherosclerotic</td>
</tr>
<tr>
<td>Plant</td>
<td>Pigments</td>
<td>Color</td>
<td>Medical Benefits</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------------</td>
<td>-----------------</td>
<td>-----------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Tomato</td>
<td>Carotenoids – Lycopene, Lutein</td>
<td>Yellow</td>
<td>Antioxidant, Vitamin-A</td>
<td></td>
</tr>
<tr>
<td>Paprika</td>
<td>Carotenoids - Capsanthin, Capsorubin</td>
<td>Red</td>
<td>Rheumatism, Lumbago, Neuralgia</td>
<td></td>
</tr>
<tr>
<td>Tagetes</td>
<td>Lutein</td>
<td>Yellow to Orange</td>
<td>Aromatic, Sores, Ulcers, Eczema, Rheumatism</td>
<td></td>
</tr>
<tr>
<td>Henna</td>
<td>Lawsone</td>
<td>Green</td>
<td>Aromatic, Anti-Inflammatory, Anti-Bacterial, Analgesic</td>
<td></td>
</tr>
</tbody>
</table>

The chemical pigments highlighted in the above table by Chengaiah et al, impart coloration to textile fabrics and at the same time confer corresponding medicinal benefits upon textiles as cited above.

### 3.3 Environment compatibility of natural colorants

The textile industry is parading towards sustainability for a paradigm shift. In the current scenario, the technology and tests devised to assess sustainability and eco-compatibility of each step involved from conception until the disposal of a product are mandatory. Life cycle assessment test, textile standards sets by the “International Association for Research” and “Testing in the Field of Textile and Leather Ecology” (OEKO -TEX), “The Global Organic Textile Standards” (GOTS) are massively contributing in the detoxifying textile industry. Similarly, techniques have been developed to identify and qualify the eco-parameters of the biomaterials in research and it would be mandatory to adhere to them for the sustainability values. For example, the credentials for ecology for natural colorant Eucalyptus globulus would be as
follows in Table 7. The environment profiles as publicized in Table 8, therefore, forms an essential portion of biomaterial engineering for sustainable and functional textiles [8].

Table 7. Quantitative analysis of trace elements in Eucalyptus globulus (Eg) [8].

<table>
<thead>
<tr>
<th>Samples</th>
<th>Cu</th>
<th>Zn</th>
<th>Cd</th>
<th>Co</th>
<th>Pb</th>
<th>As</th>
<th>Hg</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eg extract</td>
<td>0.02</td>
<td>0.10</td>
<td>Absent</td>
<td>0.20</td>
<td>0.08</td>
<td>1.00</td>
<td>Absent</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Eg on fabric</td>
<td>0.01</td>
<td>0.08</td>
<td>Absent</td>
<td>0.16</td>
<td>0.08</td>
<td>0.95</td>
<td>Absent</td>
<td>0.07</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 8. Quantitative analysis of pesticides in parts per million (ppm) in Eucalyptus globulus (Eg) [8].

<table>
<thead>
<tr>
<th>Pesticides</th>
<th>Eg solution</th>
<th>Eg on fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHC</td>
<td>0.03</td>
<td>Nil</td>
</tr>
<tr>
<td>Methyl parathion</td>
<td>0.06</td>
<td>Nil</td>
</tr>
<tr>
<td>Malathion, Endosulfan, DDT</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>DDE, DDD, 2,3 D/ 2,4,5T</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Aldrin, Dieldrin, Ethion</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Dimethoate</td>
<td>Nil</td>
<td>Nil</td>
</tr>
</tbody>
</table>

The bio-degradability aspect during the life cycle assessment of textile products before they are commercialized would be mandatory for the future textile industry. Refer to the example given in Figure 28. A 4-week study was initiated by the German Hohenstein institute to observe the degradability of non-woven cotton, casein protein wool, and cotton-polyester and polyester fabrics in natural soil and temperature. The graph above denotes that non-woven (NW) materials of natural fibers cotton and wool decompose 100% after 4 weeks timeline. And the NW polyester being strongest remains intact after 4 weeks timeline. Thereby zero decomposition value after 4 weeks. It reflects how they would behave in the landfill. The plastic would take millennia to decompose [42].
The biocompatibility of natural dyes is required to be supplemented accurately. However, it is scientifically established by researchers experimenting with natural dyes that there are no potential health and environmental hazards [8]. Yet, natural processing itself must be entirely bio-degradable for the ideal success of the sustainability cycle. It would be essential to justify and adhere to propelling theories namely the “cradle to cradle” theory [7], for sustainable and functional textiles from plant-based biomaterials, refer to Figure 29.

![Figure 28. Biodegradability of natural fibers [42].](image)

![Figure 29. Cradle-to-cradle theory, fundamentals of today [7].](image)
4. Medicinal value of herbal biomaterials for functionality in textiles

4.1 Herbal biomaterials on textiles for infection control

For a healthy lifestyle, our daily interaction with textiles demands extra protection from a microorganism that we encounter in our daily life. For wound infection control an eco-smart textile biomaterial was investigated by Kole, Gotmare, and Athawale, wherein, the cotton fabric was treated with nanoemulsion of anti-sceptic, and anti-microbial tetrahydroxy Curcumin. Response surface design and regression statistical analysis were performed. “The textile material was treated with 0.5 % of optimized nanoemulsion with nanoparticle size being 100-300 nm, zeta potential -30.1 to 31.1 mV and medicinal content 80-83.3 %”. “Cyclodextrin and polycarboxylic acid were employed as crosslinking agents applied by the exhaust method and optimized using surface response method”. The treated fabric was tested for anti-microbial efficiency against gram-positive and gram-negative bacteria. In this research, a pragmatic relationship was recognized and confirmed by a “secondary-order polynomial equation” founded on results obtained. “Analysis of variance, ANOVA, showed a high factor of determination value R²=98.41 for gram-positive bacteria and R²=96.36 for gram-negative bacteria as equated with the standard [43].

The 3D counter graphs reveal that amongst the selected variables, the even up effect of concentration, temperature, and time for both gram-positive bacteria B. Subtilis and gram-negative bacteria E. coli shows the largest effect on zone inhibition. As revealed in Figure 30. It was concluded that the response surface methodology was the most suitable method to optimize the anti-microbial properties and maximize the zone of inhibition”. An illustration of the same is given in Figure 31 below [43]. The study performs a clear and valuable statistical analysis with the latest tools. However, the paper overlooked the assessment of ecological parameters in research.
Textile supplies intended for hygiene end-use have required properties such as permeability, wettability, functionally antimicrobial, and eco-smart. They ought to be sustainable and certified such as GOTS (Global organic textile standard) [44]. The anti-infectious textiles coated with silver or a quaternary ammonium base are devised for skin infections namely atopic dermatitis. The ubiquitous germs Staphylococcus aureus is found to be responsible for promoting skin infections. The protective coating appears to circumvent the multiplication of these microbial colonies. The interaction of silver ions with the environment is under investigation. Simultaneously, with the recent upsurge in demand for a sustainable future, the key point in hygiene products is to curtail the massive use of oil-postulates synthetic materials. The major global textile players have made sustainability a priority [44].

**Figure 30.** 3D image counterplot for the zone of inhibition for a test sample of gram-positive bacteria [44].
Textile materials are vulnerable to microbial bouts as they provide enough surface area and absorb moisture vital for bacterial colonies to multiply. Cellulosic and protein (keratin) fibers provide the indispensable elementary necessities of dampness, oxygen, food, and temperature for bacterial growth and reproduction. These bacteria proliferate repeatedly leading to the unpleasant odor, dermal contagion, product corrosion, allergic comebacks, and other associated ailments. The expansion of eco-friendly and safe to humans, antimicrobial fabric finish is exceedingly vital as clothing stay in direct contact with the human body. The anti-microbial textile application would render the resultant cloth resistant to bacteria, fungi, and yeast attacks. Therefore, enhancing the fabric functionality, visual appeal and medicinal endue of the cloth. It would prevent the biodeterioration of the fabric due to mildew and mold growth. And form a protective shield against bed bugs [45].

To render the textile substrate functionally protective against microbes’ wide range of textile goods such as synthetic antimicrobial agent’s triclosan, metallic salts, phenols, and quaternary ammonium compounds are commercially marketed. However, they are not ‘hygienic’ and cause negative side effects. Thus, the alternative plant-based biomaterials are sought-after for antimicrobial applications. The natural chitosan and natural dyes are widely utilized for the same. Additionally, herbal extracts namely, aloe Vera, neem, tulsi leaves, tea tree oil, eucalyptus oil are utilized. An upsurge on plant-based bioactive components has opened new boulevards in this area of research for textile healthcare applications [45].
Plant-based bioactive antimicrobial coatings for cotton fabrics is an evolving technology in the production of medical cloths. They impart color to the fabrics along with functional property. The pigments could be extracted from fungi and bacteria for coloration however they do not impart any functional property to the substrate [45]. There is a huge proportion of humanity on earth they are religiously and ethically prohibited from the killing of any form. These sects do not favor microbial colored textiles. Plant-based renewable and exotic colorations would be a good natural alternative.

Also, researchers examined the antibacterial effectiveness of the cotton fiber’s burdened with silver nanoparticles (AgNPs) established by the eco-friendly procedure utilizing pure extracts of Eucalyptus citriodora and Ficus bengalensis. The magnitude of the silver nanoparticles was 20 nm. There was exceptional antibacterial action on the amalgamation of 2% leaf extract on cotton fibers. These fibers displayed greater antimicrobial motion after numerous wash cycles representing their possible usage in medical and infection inhibition applications [45].

Interestingly, cotton and bamboo non-woven fabric were coated with plant extracts of Cleome viscose, Morinda pubescens, and Eupatorium odoratum. The treated fabrics were observed for antimicrobial performance against “methicillin-resistant Staphylococcus aureus (MRSA), Enterobacter cloacae, Klebsiella pneumonia, Proteus mirabilis, and Escherichia coli”. The active wound restorative principles present in the extract were identified by GC/MS antimicrobial activity was assessed by an ISO method. The finished non-woven fabrics were assessed by the FTIR examination [46]. The cotton fabric treated with foliage extract of Morinda pubescens displayed substantial wound healing action. It was found to eliminate the unpleasant odor that originates from a wound. It showed a good antibacterial property. It can be utilized to develop insoles for diabetic with foot ulcers to avoid infections from microbes [46].

Herbal saponins from soap nuts namely areetha nut and shikkakai are methodically envisaged upon and revealed to be effective in cleaning cellulosic and proteinic fabrics. They impart functional properties to
linens. The treated fabrics were aromatic, soft to the skin, and clean. Further investigations were recommended for future anti-microbial justification and medicinal end-use verification. The functional saponins detected in raw herb and treated calico are classified in Table 9 below [40].

The Bombay Textile Research Association, (BTRA) study, processed cotton fabric with methanol extracted Tulsi and Anar powders. The dye extract component identification was done with gas chromatography and mass spectrometer. The fabric was treated with herbal extract by 4 eco-friendly methods. Direct, microencapsulation, cross-linking, and the combination of micro and cross and tested for their durability to washing. The superficial morphology of treated fabrics was established by Scanning Electron Microscope (SEM). All the methods showed a good anti-bacterial property to the fabric. This is attributed to the presence of micro phytochemicals like eugenol, germacrene, and phytol [47].

The durability to wash was low for simple direct method, this fabric can be end used for the disposable items like surgical cloth, gauze bandages, and sanitary napkins. All other treatments showed good durability to wash up to 15 cycles. The crease recovery angle decreased after microencapsulation and made the fabric water repellent to some extent. The tensile strength decreased little with the crosslinking method. But in the joint process, no noteworthy changes were observed in the physical properties of the treated fabric [47].

Table 9 The medicinal significance of detected saponins in herbal extract and treated calico [40].

<table>
<thead>
<tr>
<th>Name of Saponin</th>
<th>Chemical formula</th>
<th>Type of Saponin</th>
<th>Medicinal benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oleanolic Acid</td>
<td>C_{30}H_{48}O_{3}</td>
<td>Triterpenoid</td>
<td>Antioxidant, anti-viral, anti-inflammatory, anti-aging</td>
</tr>
<tr>
<td>Diosgenin</td>
<td>C_{27}H_{42}O_{3}</td>
<td>Phytosteroid</td>
<td>Natural estrogen hormone and anti-inflammatory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sapogenin</td>
<td></td>
</tr>
<tr>
<td>Soyasaponin</td>
<td>C_{48}H_{78}O_{18}</td>
<td>Triterpenoid</td>
<td>Antioxidant, anti-carcinogenic</td>
</tr>
</tbody>
</table>
Sarsasapogenin $\text{C}_{27}\text{H}_{44}\text{O}_3$ Steroidal Sapogenin Anti-microbial, antioxidant treats skin disorders like leprosy and psoriasis.

Ginsenosides $\text{C}_{30}\text{H}_{52}\text{O}_2$ Steroid Glycoside and Triterpene Saponin Antioxidant, anti-inflammatory 

Similarly, pioneering bioactive fabrics empowered with healing dimensions and envisioned for dermatological patients has been developed in Poland. The new textiles, created by a Polish team, allow producing clothing that can treat dermatoses with the use of microspheres containing active herbal extracts. The bioactive textiles can be used to produce clothing for handicapped and older individuals. The clothing is made of natural fibers, which are safe for human skin, that is, linen and organic cotton. Knitted and woven fabrics were dyed with natural dyestuff extracted from plants with anti-infectious and anti-inflammatory properties. The clothing’s functionality was ensured through the application of microcapsules filled with curing herbal extracts. The garments were personalized to fit them to patients’ needs regarding the type and location of skin diseases, as well as the shape and size of bodies. The developed bioactive clothing will have a major impact on improving the quality of life of its users by enabling them to carry out treatment therapies that are often cumbersome, and by ensuring their well-being and safety [48].

A research study was instigated to envisage the efficiency of the seed extract of the fruit Syzygium cumini Linn. On bleached cotton fabric for antibacterial potency, high inhibition percentage was observed for 1000 mg/mL Syzygium cumini [49]. However, the detailed analysis would be essential for potential applications with intensive experimental factors to be envisaged namely the influence of time, temperature, pH, particle size others. Characterization of elemental composition, qualitative and quantitative analysis would be called upon to investigate the percentage accumulations of healing bio-active components naturally occurring in sustainable sources. There is an urgent need to explore novel and efficient sustainable substances that are active towards pathogens of high resistance.
Concurrently, in yet another detailed investigation, it was initiated that the cotton fabric treated with a 50:50 ratio of wild turmeric and holy basil performed good anti-bacterial activity. “Gas Chromatography and Mass Spectrometry” (GC-MS) discovered the great peak intensities of bioactive compounds responsible for anti-bacterial, anti-inflammatory, anti-viral, and analgesic properties present in wild turmeric and holy basil. Namely, 2-Methylbenzimidazole-1-acetic acid hydrazide (30%), eugenol (27%), germacrene (11%), and, “4H-Furo (3, 2-c) (1) benzopyran-4-one, 2, 3-dihydro-2, 2, 3-trimethyl- (31%)” exhibit strong anti-fungal properties [50].

In an integrated approach, it was noted that iodine and silver chloride wound dressing are commercially available. Copper nanocrystals are utilized as an anti-bacterial and anti-fungal agent in coating’s mixture applied onto textiles and plastics. An herb Smilax china is a medicinally significant plant species. Thus, the nanocomposite solution of nanoparticles of copper oxide and herb smilax china was applied onto organic cotton and bamboo fabrics by the slurry-dip method and tested for its anti-bacterial performance by agar diffusion method against diabetic bacteria staphylococcus aureus. The topography report was obtained on a Scanning Electron Microscope (SEM) analysis. Good bacterial inhibition zones were observed. It was 52 and 51 nm for bamboo and cotton respectively. As evident in Figure 32 below. Thus, a novel approach toward wound dressing was developed [51].

![Image of wound dressing](image)

a) Bamboo  b) Cotton
Sequentially rigorous refinement of herbal biomaterial engineering is required reinforced with sufficient clinical investigations and life cycle assessment for functional implications. A sustainable approach, sophisticated technology, and cohesive material could assist in overcoming the limitations involved in the reviewed literature.

4.2 Herbal biomaterials on textiles for UV protection

We ought to mandatorily note that, due to ozone depletion UV rays are causing skin ailments such as allergies, aging, carcinogenesis, and erythema. The synthetic dyes are a threat to the atmosphere and anthropoid health. Surface modifications and textile finishes with synthetic chemicals and wet processing are found to be highly polluting and harmful to human health [52]. Therefore, the Ultraviolet Protective Factor (UPF) of the fabric is calculated. Aracil et al., further explains, the Ultraviolet Radiations’ (UVR) are electromagnetic radiations up to 400 nm, they are divided into 3 as per their strength, UVA (315-400 nm), UVB (280-315 nm) and UVC (100-280 nm). UVC and UVB (90%) are absorbed by the ozone layer, water, carbon dioxide, and oxygen in the stratosphere. Therefore, UVB (10%) and UVA reaches the earth. Refer to Table 10 [53]. They pierce through the human skin and are proven to be detrimental. Ozone depletion has accelerated this process. Textile emission and effluents provide the momentum to ozone depletion. Therefore, it is essential to refute the dangers arising from the textile industry.

Table 10. The ultraviolet protection factor (UPF) [53].

<table>
<thead>
<tr>
<th>UFV</th>
<th>UVR block %</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-24</td>
<td>93-96%</td>
<td>Good</td>
</tr>
<tr>
<td>25-39</td>
<td>96-97%</td>
<td>Very good</td>
</tr>
<tr>
<td>40-50+</td>
<td>97%+</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Research findings provide breathing space wherein interestingly the old wisdom comes to rescue for the modern crisis. UV protective textiles with herbal biomaterials from plants for coloring and finishing are extensively researched and implemented. The natural bioactive components in herbs are antioxidants. It is found to circumvent the above subject in an eco-friendly manner.

Furthermore, the ultraviolet protection factor (UPF) of cotton material pre-treated with natural mordant chitosan and then dyed with tea extracts was evaluated. Chitosan imparts antimicrobial activity to cotton, thus considered as a potential for biomedical applications. Green, red and black tea were extracted by boiling in distilled water and cold ethanol: water extract. Total Antioxidant Capacity (TAC) was measured. Dyed trials were analyzed for their color values, CIELAB, and hue strength k/s values. It was observed that TAC was high with teas extracted by the boiling method as compared to the cold method. Green tea had the highest TAC of 32 nm by boiling method. The a* and b* values of tea-dyed cotton fabrics with cold extract were more towards the yellow-green zone and those with boil extract were in the yellow-red zone of the CIELAB color space plot graph. K/s value of the cotton fabric samples colored with green tea in the cold extract was the highest. The UPF value of the cotton fabric dyes with red tea boil extract was the highest. It was concluded that the method of extraction demonstrated a significant influence on the test result. As shown in Table 10 above [53].

Consecutively, the below Table 11 reflects that green tea catechin imparts UV protection property to the cotton fabric. The ammonia plasma increases the adsorption of the same. Thus, the increase in UV protection property of the treated cotton fabric as well [52]. There is a lack of research work accomplished in this area. Also, the applicability of the research work remains to be verified with herbal printed fabrics wherein it is hypothesized that herbal extract is in concentrated form therefore high on the functionality aspect.

<table>
<thead>
<tr>
<th>Cotton samples</th>
<th>UPF</th>
<th>UPF rating</th>
<th>UV-R protection</th>
</tr>
</thead>
</table>

Table 11. UV factor of herbal treated cotton fabrics [54].
<table>
<thead>
<tr>
<th></th>
<th></th>
<th>0</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Undyed</td>
<td>4.12</td>
<td></td>
<td>Non-rateable</td>
</tr>
<tr>
<td>Dyed with green tea</td>
<td>36.25</td>
<td>35</td>
<td>Very good</td>
</tr>
<tr>
<td>Ammonia plasma at 3s. Then dyed</td>
<td>77.19</td>
<td>50+</td>
<td>Excellent</td>
</tr>
<tr>
<td>Ammonia plasma at 300s. Then dyed</td>
<td>95.37</td>
<td>50+</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

Qingqing et al. cured the cotton fabric with silver nitrite nanoparticles and Aloe Vera leaf extract and characterized them with an X-ray spectrometer and Scanning electron microscope. It was revealed that the plant phytochemicals present in aloe vera imparted stabilizing and reducing property to the silver treated cotton fabrics. The anthraquinone compounds of aloe vera tautomer’s, changing the harmful ultraviolet radiations to harmless thermal energy which eventually gets absorbs into the wearer's skin, thus, confer UV protection to the wearer. Similarly, the silver nanoparticle loaded aloe vera coated fabric manifested high bacterial zone inhibition to gram-positive and gram-negative bacteria. Their fastness to washing was durable enough after 20 wash cycles. Performance textiles for a sustainable future [54].

The cotton fabric was coated by Mocanu et al., with chitosan and extract from 3 Violaceae plant species for antioxidant functionality. The amount of chitosan, plant extract, and antioxidant plant content sustained in fabric was determined by acid orange method, mean sweat composition, and DPPH (2, 2-diphenylpicrylhydrazyl) method, respectively. The controlled release of plant biomolecules was observed that enhanced the functionality of the resultant fabric imparting antioxidant qualities to the fabric and wearer. They are likely to be utilized for people with minor skin allergies [55]. The subtle and strong working of plant phytochemicals is accentuated to herein. However, it lacks clarity about the sustenance of UV functionality on herbal treated fabrics. Also, data from chronicles of botanical plants rich in antioxidants, metals, and antifungal phytochemicals would prodigiously contribute to the research and development of materials. Therefore, a collaborative approach could copiously yield the anticipated conclusions. Similarly, the cotton fabric treated with tannin-based dyes Q. infectoria showed high absorption in the UV region and good bactericidal activity. Mordants further enhanced the UV screening effect. The study was patented recently [56].
4.3 Herbal biomaterials on textiles for healing multiple disorders

The details on plant phytochemicals were a prelude to the succeeding studies wherein, the bio-active phytochemical’s in action deliver the essential healing to the wearer.

Table 12 by Sun and Pan reveals ancient plant colors and their functionality on textile substrates namely, cotton, wool, and silk. The responsible plant phytochemical group is also mirrored in the table [57]. Also, the pharmacological efficacy of ayurvastra was verified wherein a Clinical experiment on ayurvastra was conducted by the dravyaguna (pharmacology) Ayurveda College, India. A one-month pilot was carried out on patients with skin diseases like eczema, psoriasis, rheumatism. Ayurvastra beddings, rugs, and towels were utilized by 40 patients. The response was remarkably good with skin ailments and arthritis [37].

Table 12. Bio-active biodegradable herbal chemical groups for functional textiles [57].

<table>
<thead>
<tr>
<th>Natural dye plant</th>
<th>Chemical group</th>
<th>Color</th>
<th>Functional property on cotton and silk fabrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madder</td>
<td>Phenolic – quinone’s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anthraquinones – alizarin,</td>
<td>Red</td>
<td>Anti-bacterial and anti-</td>
</tr>
<tr>
<td>Cochineal</td>
<td>Carminic acid</td>
<td>Red</td>
<td>Anti-microbial.</td>
</tr>
<tr>
<td></td>
<td>Naphthoquinones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithospermum</td>
<td>Shikonin</td>
<td>Red</td>
<td>Anti-microbial and anti-</td>
</tr>
<tr>
<td></td>
<td>anthrochizone</td>
<td></td>
<td>inflammatory</td>
</tr>
<tr>
<td>Alkanna tinctoria</td>
<td>Alkannin</td>
<td>Red</td>
<td>Anti-microbial and anti-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>inflammatory</td>
</tr>
<tr>
<td>Plant Species</td>
<td>Phytochemicals</td>
<td>Color</td>
<td>Activity</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>------------------------------</td>
<td>---------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Lawsonia inermis</td>
<td>Lawsone</td>
<td>Dark red-brown</td>
<td>Anti-bacterial and anti-fungal.</td>
</tr>
<tr>
<td>Juglans regia</td>
<td>Juglone</td>
<td>Dark red-brown</td>
<td>Anti-bacterial and anti-fungal.</td>
</tr>
<tr>
<td>Carthamus tinctorius</td>
<td>Benzoquinones</td>
<td>Red</td>
<td>Free radical scavenging</td>
</tr>
<tr>
<td></td>
<td>Carthamidin</td>
<td>Yellow</td>
<td>Free radical scavenging</td>
</tr>
<tr>
<td>Weld</td>
<td>Flavonoids</td>
<td>Yellow</td>
<td>Anti-inflammatory and anti-microbial.</td>
</tr>
<tr>
<td></td>
<td>Flavones – luteolin</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Antiolexia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green tea</td>
<td>Flavones – quercetin</td>
<td>Yellow</td>
<td>Anti-fungal and anti-microbial.</td>
</tr>
<tr>
<td>Red grapes</td>
<td>Kaempferol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onion skins</td>
<td>Isorhamnetin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marigold</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceanothus and agapanthus praecox</td>
<td>Anthocyanin’s</td>
<td>Blue</td>
<td>Anti-microbial and antioxidant.</td>
</tr>
<tr>
<td>Grapes</td>
<td>Pelargonidin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blueberries</td>
<td>Cyaniding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blueberries</td>
<td>Delphinidin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blueberries</td>
<td>Peonidin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blueberries</td>
<td>Pet nidin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pomegranate</td>
<td>Tannins</td>
<td>Brown</td>
<td>Anti-microbial, anti-viral, and anti-inflammatory.</td>
</tr>
<tr>
<td>Quercus infectoria</td>
<td>Gallotannins</td>
<td>Black</td>
<td></td>
</tr>
<tr>
<td>Black tea, Gallnut</td>
<td>Ellagitannins</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.4 Innovative application of bio-active plant phytochemicals for functional textiles

This section confers ground-breaking novel applications with astonishing results for justifiable eco-future with herbal textiles.

**Facial mask**, Red seaweed plant extracts namely Kappaphycus Alvarezii and Acanthophora Spicifera were utilized by Janarthanan and Kumar, for constructing a fabric mask for anti-age treatment. The antioxidant
and anti-aging bio-active components present in the red seaweeds were identified with Fourier Transform Infrared Spectroscopy (FTIR). The fibroblast collagen layers impregnated with red seaweeds were assessed with a Scanning Electron Microscope (SEM). The FTIR revealed the presence of bio-active compounds namely, alkaloids, carotenoids, flavonoids, terpenoids, phlorotannins, and saponins. The antioxidant property evaluated with UV – Vis Spectroscopy increased with an increase in the concentration of red seaweed. The wicking ability, air, and water vapor permeability, of the red seaweed cured fabrics, was lower than the unprocessed fabrics. The in vitro cell morphology of cultivated fibroblast collagen with red seaweed extract with SEM clearly showed that there was high surface smoothness and cell aggregation of 95% with K. Alvarezii and 70% with A. Spicifera. Thus, facilitating skin firming, anti-bagging, and wrinkle-straightening properties. The study suggests its future applications for making dressings, surgical uniforms, face mask, gauze bandage, and compression garments [58]. However, the above study excludes anti-microbial investigations which could further support the theory in research.

**Yoga and baby beddings**, Ayurvastra, in Sanskrit, Ayur is for health, and vastra is for clothing. Herbs with medicinal properties are utilized for processing the organic fair-trade handloom cotton fabric.

- **Bleaching** – sunlight, soap nut, and grass.
- **Dyeing** – turmeric, myrobalan, tulsi, pomegranate others.
- **Washing and finishing** – plain clean water.
- **Softening** – coconut oil, castor oil.
- **Drying** – shade drying for color fixing.

Sustainable plants are utilized. When the processed fabrics are worn, the medicinal benefits are delivered through the skin to a wearer. They are highly recommended for yoga, meditation, baby clothing, and baby bedding, children garments as they are soft to the skin, soothing to eyes, and, with healing benefits [59].

**Rejuvenation and anti-infectious textile materials** are additionally supported by the moral fiber fabric. A hand-spun, hand-woven fabric – khadi is made in 100 % cotton, silk, wool, and blends. Eco-friendly materials, eco-friendly processing, and fair trade registered moral fabrics are zero carbon footprint fabrics.
Moral fiber is qualified as ‘non-allergic’. It uses natural materials and natural dyes that are not detrimental to the physique and the atmosphere. It diminishes the likelihood of suffering from skin allergies and respiratory illnesses by skin interaction and vapors of the injurious constituents from the fabric. It also guards the well-being of the artists working with ethical fiber. There is a direct relationship between health and ethical fiber bedsheets and other coordinates as well as clothing; feel-good-fashion. Interestingly, humans devote almost one-third of their existence time in slumbering and tranquil. Latent, revitalizing, and restorative processes while sleeping in fit, organic surroundings go hand in hand with moral products. The natural dyes and biomaterials fuel in healing [60].

**Pregnancy,** The USA, colors of the caldron botanical dyes are certified as safe to be brewed during pregnancy, Sasha Duerr, Professor, artist, and designer at California College of arts, had dyed her lime-yellow maternity top with sour grass, a Bermuda buttercup an invasive California weed. Botanical dye gardens and blooming interest on sustainable natural dyes is blowing around like so much pollen. Synthetic dyes gave her nausea and headache, she felt pointless creating art with a toxic process. Thus, she tracked down natural colors from fellow farmers and craftswomen. Dye gardens also green up the neighborhood. The alchemy thing is no joke with magical cheerful colors-colors oozing up on fabrics making you more aware of what is in the environment. Ms. Adornetto sees the garden as a color lab [61].

**Fibroblasts for wound dressing,** a composite wound dressing was devised as depicted in the picture below. A non-woven cotton fabric loaded with an oxidized-pectin gel of curcumin and aloe Vera. Antibacterial and healing bioactive components from the plants get embedded in the polymeric matrix that interacts with the bacteria at the wound site and prevents their proliferation as depicted in Figure 33. A pre-clinical approach mimicking the physiological conditions was adopted to test the efficiency of the coated matrix. It was concluded by Tummalapalli et al., that the fibroblasts treated with aloe were significantly efficient in providing 80% wound healing in 8 days. Therefore, Aloe bio composite dressings were projected as worthwhile materials for active wound management [62].
Composite crepe bandage, further to this, biomaterials micro complex of chitosan, alginate, and turmeric was formulated by Gnanamangai et al., applied on cotton crepe bandage and tested for its analgesic, antiviral, and anti-inflammatory healing properties. In vitro tests were conducted namely, radical scavenging activity and albumin denaturation. The microencapsulated matrix revealed good cytotoxic ability, good stability to enzymatic degradation, and excellent mechanical stability as well. The formulated nanostructure fulfills the required parameters that contribute to the repair and remodel of tissue. Thus, suitable for wound healing applications in tissue engineering [63].

Figure 33. Formulation and application of Curcumin and Aloe vera bio composite fibroblast for wound dressing [63].

Diabetic foot soles, in another recent & interesting study, the non-woven fabric of cotton and bamboo was coated by dip and dry process with herbal extracts of Morinda pubescens. Initially, three plant extracts Morinda pubescens, Cleome viscose, and Eupatorium odoratum were tested by agar well diffusion process, for their anti-bacterial activity. M. pubescens had the highest bacterial zone inhibition (mm). Thus, the M. pubescens treated fabrics were further tested for its anti-bacterial property by EM ISO 20645 method.
Interestingly, wound scratch assessment of this plant extract was also performed by the in vitro method. Gas chromatography-mass spectrophotometer analysis (GC-MS) was done of this plant extract [46].

And the FTIR graph was obtained from M. pubescens treated fabrics. As hypothesized, both cotton and bamboo treated fabrics performed anti-bacterial activity in the range of 30 to 42. The best part is the 100 µg/ml treated fabrics had twice more wound healing, reported after 24 hours as compared to the control group. Alkaloids, phenols, and glycosides were detected in FTIR analysis of the treated fabrics. It was concluded that effective wound healing medicinal textiles can be developed out of it. The said research is further utilized to construct foot soles for diabetic patients with foot ulcers [46]. The biomordant application is required to enhance the herbal healing potential of the final fabric.

Kitchen textiles, a study on kitchen textile fabric is noteworthy. It was biochemically identified that used kitchen fabrics proliferated Staphylococcus, Klebsiella, Shigella species of bacteria. The kitchen cotton fabrics were coated with Murraya Koenigii, Pomegranate peels, Banana peel, natural agents Casein & Cyclodextrin. The coated fabrics FTIR revealed the presence of phenols and amines. These herbal extracts were processed on the Soxhlet apparatus by methanol extract. After the anti-bacterial test, it was found that untreated fabric had 0 bacterial growth reduction %. A part presentation is given in Figure 34 below. Murraya Koenigii was 29.2 %, while of banana + casein + cyclodextrin was 82.05 % of bacterial growth reduction. Further biomedical investigations were suggested for possible applications as functional kitchen textiles etc. The eco-friendly mordant application would enhance the functionality of herbal coated fabrics [64].
Figure 34. Bacterial growth inhibition percentage of cotton fabric treated with natural extracts Murraya Koenigii and Pomegranate peel for kitchen textiles by AATCC 100 test method [64].

Multi-functional fabrics, with gallnut extract, were obtained by Eunmi and Hong, wherein the plasma-treated cotton and wool fabric were pad-dry-cured with gallnut extract and tested for their functionality on textiles. The Fourier transform infrared spectroscopy (FTIR) and Scanning electron microscope (SEM) were obtained for both cotton and wool of which the wool is represented below [65].

1) SEM of Wool fabrics. 2) FTIR of Wool fabrics.

Figure 35. The SEM and FTIR images of treated wool fabrics. (a) Untreated wool (b) Gallnut treated wool (c) Argon plasma-treated wool, (d) Oxygen plasma treated wool [65].

The FTIR diagram of wool fabrics is given in the graph of Figure 35 above. Wool fibers are structured with 18 and amino acids. The foremost functional assemblies comprise carboxyl (COOH), amino (NH2), and hydroxyl (OH) groups. Wool fibers demonstrated parallel uptake at the wavelengths of 3280 cm\(^{-1}\) (NH and OH), 2871 cm\(^{-1}\) (CH\(_2\)), 1632 cm\(^{-1}\) (amide I), 1518 cm\(^{-1}\) (amide II), and 1233 cm\(^{-1}\) (amide III). Interestingly additional points were observed at 1314 cm\(^{-1}\) and 1044 cm\(^{-1}\) in the FTIR profile of gallnut extract-cured wool fabrics. This is attributed to the ester (CO) elongating, instigated by ester bond created between the OH cluster indefinite amino acids such as wool protein serine and the COOH cluster of gallic acid in gallnut extract [65].
The bacterial reduction percentage and antioxidant scavenging activity were calculated using mathematical formulas as given below in Equations 2 and 3.

\[
\text{Reduction of bacteria} \, (\%) = \frac{B-A}{B} \times 100 \tag{2}
\]

\[
\text{Scavenging activity,DPPT} \, (\%) = \frac{C-S}{C} \times 100 \tag{3}
\]

Where B and A are the untreated and the gallnut-extract treated fabrics, respectively. Similarly, C and S are the absorbances of sample and control, respectively. The anti-microbial action heightened after gallnut extract application due to the presence of tannins. The antioxidant action increased due to the presence of phenolic acids. Plasma surface treatment influenced wool adsorption refers to the SEM graph of the wool fabrics as shown in Figure 35 [65].

**Sustainable luxury textiles**, revolutionizing the natural dyes from renaissance is accelerating towards luxurious sustainable fashion. The functionality of day-to-day textiles is widened with bio-material engineering. Author's appraised that the textiles that moisture, perfume the skin and protect the skin from UV radiations are being developed with plant-based materials namely aloe vera, chitosan, basil, sandalwood, jasmine, lavender, honey, and almonds. The healing fabrics of ayurvastra are marketed as high-end products offering more security and protection to vulnerable age groups including babies, women, and old. A holistic vision and approach endorsed by celebrities for naturally sustainable and luxuries fashion with natural dyes are launched world-wide by Pangaia, Eileen Fisher, Adidas, Nike, Patagonia, Lulu lemon, and several others.

The branded fashion lines are certified by Bluesign a Swiss company that duly tests and verifies that the branded products to be launched are eco-safe from factories with good practices [66]. The above applies are blueprints and benchmarks for sustainable luxuries fashion of today and tomorrow. A lot is derived
from the ancient traditional knowledge of healing from plant-based resources from nature and replanting them for protecting biodiversity. Accentuating the saying “From nature back to nature”. And with inspiration from Sir Hippocrates appropriately goes the quote, “Let clothes be the medicine, let medicine be the clothes”.

**Biosensors**, innovatively a universal pH sensor biocomposite has been developed by Devarayan and Suhk from natural pigment of red cabbage on nonwoven cellulosic nanofibers. The biosensor detects pH 1-14 exhibiting distinct color at each pH. This halochromic changeover is reversible. The biosensor is recyclable, stable to temperature and time. It is expected to be utilized for well-being monitoring purposes Refer to Figure 36 below [67].

![Figure 36. pH biosensor from Red-cabbage pigment on non-woven cellulosic nanofibers [67].](image)

**Solar cell activation**, moreover, the natural dyes from red amaranth leaves were extracted which yield green color in ethanol extraction and red-violet color in distilled water extraction. Indicating the presence of betalain and chlorophyll pigments, respectively. They exhibited good photosensitizing properties for solar cell activation and textiles applications [27]. There is a dearth of collaborating literature on the held theory.
Beetblue, the natural colors are safe to human health and environment therefore increasingly preferred for food, cosmetics, textile, and drugs endues. However, it is difficult to harness the natural blue pigment from animals and microorganisms which involves the adenosine triphosphate–fuelled enzymatic oxidation of luciferins. Similarly, blue petaled flowers namely, Blue hydrangea, Cornflower, Morning glory, and Speedwell contains blue metal-anthocyanin supramolecular complexes and polyacylated anthocyanins are unstable pigment therefore difficult to synthesize and apply. Red beetroots comprise antioxidant betalain widely utilized as a food colorant. Therefore, a quasibetalain, derived from betalamic acid with stretched π – conjugation was obtained by Freitas et al. The 1,11-diazaundecamethinium Beetblue chromophore is ethyl acetate acid-catalyzed by coupling of betalamic acid, extracted from beetroot juice and the carbon nucleophile 2,4-dimethylpyrrole. Refer to Figure 37 [68].

![Beetroot](image)

Figure 37. Synthesis of Beetblue chromophore [68].

The obtained Beetblue chromophore is highly water-soluble, stable, and could be applied on varied substrates as shown in Figure 38 [68].
The transitory investigation of dyeing property and photochemical analysis of Beetblue as obtained is given in Figure 39. The toxic dyes produce singlet oxygen that damages cells. However, Beetblue was examined to be safe for human hepatic and retinal pigment epithelial cells. Beetblue does not affect zebrafish embryonal growth thus safe as concluded by Freitas et al., [68]. The study is remarkable and preludes to enormous possibilities of research and development in green chemistry with plant-based renewable colors.
The innovations with natural colors are beyond imaginations and the functionality of plant phytochemicals benefiting the wearers' health when in adherence to textiles is miraculous. A massively untapped resource ought to be cultivated for the sustainable future of the textile industry and would prodigiously benefit human and environmental health alike.

5. Challenges

The emissions and effluents from the textile industry have profound ramifications on the environment and human health. Aftermath is increased Greenhouse gases and high carbon footprints. The European Chemicals Agency (ECHA) and U.S. Environment Protection Agency (EPA) have stringently scrutinized the suspected carcinogens such as synthetic colorant aniline ‘Indigo’, textile additive titanium dioxide and featured them under the restricted chemical lists (RSLs) [4]. They cause skin cancer and skin allergies associated with hypoxia and are toxic to marine life [3]. Plant-derived renewable sources of bio-colorants and bio-additives for textile processing were encouraged to be utilized [5]. Clothing affects our well-being. However, the dermal effects from textile additives and dyes are the most prevalent, along with toxic and respirational effects. Thus, the clothing is our second skin ought to be skin-friendly [2]. Our clothing protects and heals through constant interaction with the skin. Its bio-delivers nutrients with its microfibrillar structure to the wearer [44].

In November 2018, the UK declared a climate emergency. The intention is to make it motion led than just legislative, with the target of going down to net-zero carbon emissions [1]. Accentuating the agenda of Sustainable development Goals (SDGs), to adapt to sustainability, not as a trend, but on more serious terms as a way of life [6]. United Kingdom Climate Projections [UKCP18] ecological forecast demonstrates significant climate shifts, for example, 5.4°C increase in summer temperatures by 2070, 50% chances of hot summers by 2050, as experienced in 2018, and 1.15 meters increase in sea levels of London by 2100. We are almost there to experience intense floods, heatwaves, erosion, volcanoes, and hurricanes in short timescales from now [1].
A worldwide collaborative approach as devised by SDGs would provide resilient strategies to combat the global climate crisis, thus, to protect mother earth. UK’s net-zero GHG (Greenhouse gases) and F-gases (Fluorinated gases) target are 2050 and Scotland are 2045 [1]. Currently, we witness profound environmental ramifications due to speeding global industrialization leaving its mark upon the world. Explicitly noticed with the textile dye and fiber industry as well. United Nations Environment Programme G7 Summit emphasizes on the circular economy. The fashion pact and fashion charter being instrumental for the same [69].

Similarly, microfibers and microplastics are hidden culprits. Microfibers, as defined by the textile institute, is a fiber or filament of linear density below 1 decitex. Research from the Coastal Ocean Research Institute in Vancouver revealed 878 tonnes of textile microfibers washed into North America waterways every year. Wastewater treatment plants (WWTP) strains 99% of these pollutants as sewage sludge. They are spread onto the farmlands and find their way into the human food chain. Similarly, it applies to microplastics. Research scientist at Plymouth University UK, fathomed 1/3rd of the fish studied with at least 1 microplastic, with 75% of which was synthetic derived PET fibers, within their gut. Canadian scientists found aquatic zooplankton consuming microfibers in the North Pacific Ocean. The Salmon in British Columbia feeds on this zooplankton with pollutants [3].

However, DuPont, Lenzing, and others have aligned their lens to integrate sustainability with performance textiles. Wherein clothing enhances the wellbeing by infusing nutrients to the wearer by the bio-delivery mechanism of the fibers. Biomimicry, inspiration from nature that assists in solving problems to meet the “needs” sustainably look forward to plant-based renewable sources to circumvent depleting fossil fuels creatively and harmoniously [69]. In the words of Sir A. Einstein, “Look deep into nature and you will understand everything better”. Table 13 mirrors the future challenges for the sustainable future of the textile industry [7].
Table 13. Sustainability Challenges for the textile processing sector [7].

<table>
<thead>
<tr>
<th>Stages</th>
<th>Best practices to implement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber/fabric processing</td>
<td>Minimum steps, reuse, recycle, reduce consumption of resources.</td>
</tr>
<tr>
<td>Scouring</td>
<td>Utilize Plant-based materials, combine the steps, and lower the effluent pollution index.</td>
</tr>
<tr>
<td>Desizing</td>
<td></td>
</tr>
<tr>
<td>Bleaching</td>
<td></td>
</tr>
<tr>
<td>Dyeing</td>
<td>Plant-based natural dyes and dye assistants, simplify synthetic dyeing with right pH, auxiliary, enzymes and reduce the effluent quantity and toxicity.</td>
</tr>
<tr>
<td>Printing</td>
<td>Formaldehyde-free, urea free, non-volatile water-based inks, thickeners, and solvents.</td>
</tr>
<tr>
<td>Pre- and post-treatment</td>
<td>Non-metallic, non-ionic, biodegradable.</td>
</tr>
<tr>
<td>Surface modification’s and treatments</td>
<td>Mechanical, nontoxic, simple. Techniques that save energy and water usage.</td>
</tr>
</tbody>
</table>

The approach discussed further would assist in circumventing the above sustainability challenges. A massive and appropriate step for a sustainable future.

6. Future work

The German ban on carcinogenic inorganic amines based azo dyes in 1994 triggered an upsurge in ancient natural dyes for textiles. Currently, to meet the zero emissions and zero effluents target set by “Registration, Evaluation, Authorization & Restriction of Chemicals” (REACH) and “U.S. Environmental protection agency” (EPA) for 2050 [4], and “Sustainable Global Development Goals” (SDG’s) agenda, refer to Figure 40, set by UN for 2035, these governing bodies encourage the plant-based textiles additives and colorants
to be utilized for sustainable global textile future [6]. Consequently, 11% of market growth demand for natural dyes, pigments, and additives are predicted for 2025 by Wood [70].

Fossils derived textile dyes, additives, and fibers have eventually found their way into the human food chain in the form of microfibers and microplastics [3]. The clothing being second skin is exposed to textile dyes and additives that are cytotoxic, carcinogenic, genotoxic, and mutagenic causing DNA damage [2]. Thus, the European Chemicals Agency (ECHA) and the U.S. Environment Protection Agency (EPA) encourage the utilization of plant-based sustainable bio-colors and bio-additives for textile processing [5].

We cannot deny our intricate and indispensable, inter-dependent relationship with nature. However, we can be human by taking care of nature. We are dependent on nature. Nature nurtures us. It is our duty. And not to make it seem another way around for self-centered short-termed gains. There is no ‘Planet B’ or ‘Earth B’ for us. A radical and paradigm shift towards sustainability is expected with an emphasis on alternative eco-friendly, renewable, and functional biomaterials for the future sustainable textile industry. Therefore, to meet the above-set agenda, to refute the global crisis and prodigiously promulgate plant-based biomaterials a holistic approach is discussed herein for a sustainable future.
- Interdisciplinary approach
- Eco surface modification
- Low on energy & water demand process
- Updated technology for biomaterial engineering

For instance, an interdisciplinary research approach could be oriented towards integrating Chemistry, Medicine, Textiles, Technology, and Environment. Innovatively combining strengths of each to contribute towards each in return for a higher purpose and for enhanced well-being of the environment and human health alike as depicted in Figure 41. The plant-based biomaterial on fabrics is utilized in close contact with our skin biological systems and protects the skin from microbial attacks and UV burns [71]. A loud thought as it would sound but could protect against virus attack in the future as dreadful as coronavirus of today. Therefore, a humble step towards the protective measure for a healthy world with help of plant-based fabrics. Concomitantly goes the responsibility of planting the trees threefold in return and promulgating the theories such as sacred groves to propel afforestation. Therefore, allowing the vicious cycle of our give and take relationship with nature to continue in balance. There is massive land availability if ethically landscaped for sustainable textile processing. The consumers have a choice either to go for colorless textiles or to select renewable sources of coloration for guilt-free responsible clothing.
Concurrently attention on plant-based hydrogels for fabric processing can copiously benefit the textile industry. It is integral for the biomaterials to be biocompatible, non-toxic, and healing. Hydrogels are biomaterials found in nature. Ubiquitous plants are swollen hydrated structures in nature. Hydrogels, cross-linked polymers are smart, intelligent, and environment-friendly biomaterials. Natural hydrogels are fruit pectins from orange peels, apple peels, plant gelatine namely aloe Vera, cactus, and agars [71] are ought to be incorporated in future research for processing bio-compatible textile fabrics. They could be implemented in formulating bio-compatible composites, facial masks, and band-aids. The hydrogels drug delivery mechanism is excellent. Sustainable plant-based hydrogels could be of paramount benefit for sustainable medical textiles.

The appraisal provided in the review paper revolves around textile prints and paintings as we deliberately ought to move towards waterless functional mechanisms in the future to leave the natural water resources at peace. Citarum River in Indonesia is an example of textile dye house horror and a threat to the environment and human health in a big way [69]. Thus, the natural dyeing aspect is overlooked here and can be covered in future work.

However, as an exemplar, an inter-disciplinary future study is envisaged wherein, the author investigates on anti-microbial, anti-fungal, analgesic and antioxidant properties of banana, bamboo and merino wool fibers treated with natural biomaterials as illustrated in Figure 42 to 50. The treated samples would be examined for prospective implications in medical textiles, cosmetics, hygienic kitchen fabrics, and for day-to-day wear for protection from ubiquitous pathogens. The intensive study would be a noteworthy contribution as the herbs and fibers in research are hypothesized to be intrinsically condensed with therapeutic and aromatic properties. They also impart color to the fibers as shown in Figure 43 to 50 [72].
Figure 42. Original ready to dye fibers [72]

Cinnamon bark          MW          BN          BM
Figure 43. Cinnamomum Verum (Cinnamon) [72]

Katha bark           MW          BN          BM
Figure 44. Acacia catechu (Katha) [72]
Figure 45. Butea monosperma (Kesudo) [72]

Figure 46. Rubia cordifolia (Manjistha) [72]

Figure 47. Lawsonia inermis (Henna) [72]
With sustainability at its core, the study demonstrated above involves the processing of merino wool, bamboo, and banana fibers with natural biomaterials by low on energy and water demand method. The surplus bath is biodegradable, safe to aquatic life, and life on land [72]. The investigations herein are the culminating effort from the field of textiles, sustainability, environment, medicinal, phytochemical, and ecological technology at the international-individual stratum.
Even more, Greenpeace International investigations of the wastewater samples from rivers surrounded by textile manufacturing and washing companies of Indonesia and Mexico have revealed the presence of detergents and surfactants 2,4,7,9-tetramethyl-5-decyne-4,7-diol (TMDD), Nonylphenol (NP) and Nonylphenol ethoxylates (NPEs) [73]. These surfactants persistently contaminate the aquatic environment with hormone-disrupting properties. Herbal saponins from Areetha nut and Shikakai would be a sustainable alternative that would copiously benefit the textile manufacturing and washing companies. They are biodegradable and renewable sources of surfactants. Also, aromatic, soft to the skin and functionally healing as investigated in a study [40]. To sum up, to propagate plant-based biomaterials, a multidisciplinary research endeavor towards materials science and engineering is essential.

7. Conclusions

The review complied herein is exhaustive with enough probe into the past of plant-based biomaterials, their application, and functionality on textile fabrics. Plant phytochemicals working behind the scenes play a vital role. A massive renewable resource identified herein is sustainable. Nature imparts us with natural materials for protective functional wear in terms of UV-protection and anti-microbial properties as highlighted herein. Human’s in-turn ought to protect plant biodiversity for continuing our vicious relationship with nature by planting those trees for reoccurrence.

The details in the paper identify the vast scope of application of natural herbs for electronic conductivity in a sustainable way. The fluorescence phenomenon exhibited by natural materials can have astounding end uses. At the same time, they are non-toxic and biodegradable. Interestingly natural color used for microscopic identifications, forensic sciences, solar cells, and cancer detection is par excellence with no cumbersome side effects. Novel day-to-day and luxury functional textiles from herbs are must-have for each wardrobe. A subtle way in which they heal and infuse the aroma is ethereal. Copious scientific investigations are detailed in the review. However, the scope and challenges are prodigious to fine-tune the topic and commercialize it in the right way for mass benefit. The global strategies highlight by SDGs, REACH and EPA are holistic approaches to refute world crises.
Consequently, enormous researches are rigorously commenced worldwide for the same, for example, research was undertaken at the Heriot-watt University, Scotland in which the authors would formulate sustainable plant-based ink colorants for sustainable fabrics. The herbal pigment composite solution would be formulated of the desired rheology. The bamboo & silk fabric would be pre-treated and printed with innovative plant-based colors digitally. The research aims at biomaterial engineering for a sustainable textile future. A meticulously designed multidisciplinary approach as discussed above would be executed. The research implants eco-friendly plasma surface modification in the process to maximize the functional benefits of plant-based biomaterials. Eventually enhanced UV protection and anti-microbial fabrics with herbal inks are anticipated. The research would be a noteworthy contribution to the field and would trigger further scientific researches on functional herbal inks and digital software developments for printing with herbs. For future, the review paper highlight on multi-disciplinary research approach at global, institutional, and individual level of research to meet the anticipated holistic outcomes.

The review paper accentuates and senses that the herbal therapeutic healing benefits are gradual and subtle. However, subtle here is the strongest and with positive consequences. Plant-based fabrics are sustainable luxury textiles of today and the future. At the same time, they are enriched with an artisanal journey. Entrapping nature's aroma and feel. The family tree in grandmas’ quilts oozing with nature's vibration, harmony, and healing energies from nature is a textile treasure. Eco-medico textiles offer considerable long-lasting safety and security to both the environment and human health. Heritage textiles are now an Eco SMART fabric a new face of the sustainable textile industry of the future.

The eco-medico fabrics are thus, instrumental in holistic healing. In which, the wearer derives bodily healing due to plant phytochemicals, mental satisfaction of being responsible consumer and, soul-enriching harmony with nature. The paper is also a prelude to imminent multi-disciplinary work on plant-based biomaterial engineering for the sustainable textile cottage industry of tomorrow. Thrive ability justified scientifically for global enrichment.
Disclosure statement

No potential conflict of interest was reported by the author.

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Acknowledgment

The author is grateful to Anonymous sponsor for funding the sustainability-based research study.

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