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Extraction, Characterization, and Utilization of Tea Leaf Extract in Textile Wet Process

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Abstract

The present review has attempted to describe the potential of tea leaf extract as an anti-pest, antimicrobial, and natural colorant in textiles. Moreover, an in-depth description of the chemical components present in tea leaf extract and their contribution has been discussed in this study. The review presents significant evidence that suggests tea leaf extracts as potential color generators for various textile fibers such as wool, silk, cotton, and more. However, in spite of numerous advantages, it was found that the tea leaf extracts comprise certain challenges, including inconsistency, scalability at the industrial level, and the like. More research effort should be explored to develop a standardized work process that can overcome such challenges and make it suitable for industrial applications. Although numerous reports suggested that topical treatment of tea leaf extracts has shown excellent antimicrobial and anti-odor functionalities. However, literature available on the tea leaf extracts and their potential use in the coloration of textiles is very limited, and it has great potential to add substantial value to dyeing, printing, and finishing in the allied field of textiles and fashion. The aim of the present review is to encourage researchers, industry personnel, and other stakeholders to undertake intensive research endeavors to standardize and develop an upgraded pretreatment and extraction process for the inference of biologically active and coolant-content cotton extracts to accomplish the desired functional property. The future work would focus on the extraction of tea leaf extracts with a variety of organic solvents under different conditions, optimization of extracting the coolant for cosmetic applications, cost analysis for the extraction of active compounds, and use of extracts in palette coloration over textiles at the laboratory scale. In conclusion, this review gives a futuristic vision of the potential of tea leaf extract in textile functional finishing as a natural colorant in dyeing and printing.

Keywords: Extract; Characterization; Tea Leaf Extract; Eco-friendly applications

Introduction

In the textile wet process, textile products are often subjected to various dyeing and finishing treatments. Synthetic dyes and chemicals are generally used to produce textiles with bright colors and improved functional properties. However, with the growing emphasis on sustainability in the textiles industry, there has been an increase in research on utilizing natural extracts in the textile dyeing and finishing process to reduce the consumption of dyestuff and auxiliary chemicals and reduce their hazardous impacts on the environment. [1-4] Tea is one of the commonly consumed beverages worldwide that is rich in natural antioxidant phenolic compounds and has the potential to be used as a colorant and an antibacterial agent in some textile applications. This study aimed to assess the feasibility of utilizing the natural tea leaf extracts for the textile wet process. This research was designed to answer three main questions: (1) how to extract the specific substances from the tea leaves? (2) how to characterize the specific substances including their physical-chemical properties and molecular structures? and (3) how to retain the specific substances on the

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fabrics and realize their application performance? [5-11]

Basic Information of Tea Leaf Extract: Tea leaf extract is one type of natural extract. Tea leaves contain a large amount of phytochemicals, including phenolic compounds, caffeine, flavonoids, and amino acids, which are influenced by many factors, such as the type of tea and its origin, as well as environmental variables such as temperature, humidity, sunlight exposure, and soil composition. Due to the different origin of the tea, the composition of the tea leaf extract differs. Teas can be classified into different types according to their degree of fermentation: non-fermented green tea, partially fermented oolong tea, semi-fermented jasmine tea, and completely fermented black tea. The non-fermented tea, green tea, contains the highest content of beneficial polyphenols, of which the most abundant is catechins. Catechins are further classified into (-)-epigallocatechin-3-gallate, (-)-epigallocatechin, (-)-epicatechin-3-gallate, (-)-epicatechin, and (-)-catechin. A typical composition of water extracts of green tea leaves showed that the main catechins are EGCG, EGC, ECG, EC, and C. [7, 12-16]

Background of Tea Leaf Extract in Textile Industry

Tea is one of the most ancient drinks, and tea extracts have been used in traditional medical systems in various countries since ancient times. In recent years, there has been a switch from synthetic dyes to natural extracts for the purpose of practicing eco-friendly processes in the textile industry. Tea is a natural derivative and is widely used worldwide for different purposes in the cosmetic, medical, and food industries. It is a complex mixture of various compounds, such as tannins, flavonoids, caffeine, vitamins, and amino acids, which contribute to their various types of activities, such as antioxidant, antibacterial, antifungal, and color-accumulating properties. Tea leaf extracts have been used in the textile industry for the coloration of various textiles as well as for the production of color-controlled fabric strips. 61721819There are various reports on the application of tea extracts in the textile and clothing domains in different ways, as well as on the extraction process and color-changing applications. All these findings suggest the potential calculated value of these extracts in these fields, one of which is the antimicrobial finishing of textiles by the saponins present in the tea leaf extract. Thus, due to their eco-friendly nature, herbal alternatives, as well as natural extracts, are periodically available in small quantities, but no comprehensive papers are available that review the current and potential applications of tea in the textile industry. [20-26]

Fat and sugar can spoil the color of tea, whereas protein can intensify the color of teas. In aqueous media, the principal components of tea are mainly composed of caffeine, proteins, amino acids, reducing sugars, chlorophyll, and, above all, polyphenolic compounds, particularly catechins, flavonoids, and finally tannins. In the dyeing process, the chemicals in tea play a functional role with mordant agents. These compounds form an insoluble compound with mordant agents, which in turn leave their compounds on fibers to intensify the color. In this process, tea leaves generate iron tannates of green to blue color, iron gallate of black color, and chromium tannates of yellow to green color, with specific functions of protein tincture. Numerous researchers have broad origins that report the extraction of natural dye extracted from tea used as tannin in the textile industry and utilize the best-faded Indian tea color. Tannins are plant polyphenolic compounds with differential biological activities; these derivatives are toxic to decolorizer-resistant bacteria, fish, and others. [27-34]

Extraction Techniques of Tea Leaf Extract

Tea leaf extract is one of the renewable and sustainable natural resources. In order to fully utilize the tanning and antimicrobial activities of tea leaf extract in textile wet processes, the extraction of bioactive ingredients from the tea leaves, mainly including polyphenols and alkaloids, should be considered to a large extent. This is yet another challenging aspect that needs to be examined in great detail to extract the optimum levels of bioactive components while preserving other properties of tea leaf extract that can add value to textile material. A large number of studies have been reported on the extraction of polyphenols and other active components from the tea leaves. In summary, the extraction of active compounds can be classified into three methods: water extraction, organic solvent extraction, and supercritical fluid extraction. However, few studies have focused primarily on tea leaf extract for textile material. [35-40]

Water extraction is the most commonly used extraction method, which is safe, simple, and straightforward. Organic solvent extraction is the most suitable for industrial scale and has the highest yield of active compounds; however, this method generates more chemical waste and is expensive. Supercritical fluid extraction is a more modern methodology that offers a cleaner product without any heavy residuals or hazardous chemicals; in addition, its maximum percentage of purity is one of the most attractive features of the latest scientific and technological era. The choice of an extraction technique should match the requirements for the end use. Detailing at its highest limited practicality is important and should be confirmed towards sustainable development programs. The choice of different extraction techniques directly affects the content yield of tannins, the ratio of composite structures, and many other active components present in the tea extract. The choice of the extraction technique is, in any case, a determinant of the quality of the final product. The researchers reported that with each increasing requirement, the alternative methods presented were more and more suitable. [41-47]

Water Extraction

Water extraction is an easy-to-perform, environmentally friendly procedure to extract products from natural resources. No harsh chemicals or hazardous agents are involved due to the application of water, promoting a safe working environment. The efficiency of water extraction depends on numerous factors, including the raw materials, the properties of the extracted compounds, and extraction conditions, such as the temperature and duration. Generally, increasing the extraction temperature, time, or both can enhance the extraction efficiency, as the temperature affects the rate of mass transfer, while the duration is directly related to the solubility of the compounds. The main compounds of tea leaf extract can be extracted using deionized water, with a temperature range of 60–100°C and extraction times of 60–180 minutes. This indicates that water extraction is feasible and also applicable in a textile wet process that requires high temperature and soaking phenomena. [48-54]

Water extraction has an easy industrial applicability, making it a practical method. However, the lower extraction yield of less polar compounds would make water extract less abundant in bioactive components. An examination was conducted at a boiling temperature for 1.5 hours to study the effect of water extraction conditions on the characteristics of obtained tea leaf extract. It was found that the extract size can be adjusted by controlling the boiling duration. Recent literature focused on optimizing the water extraction conditions to obtain the ideal ratio of basic compounds in tea leaf extract. More specifically, one study aimed to enhance the content of free radical scavengers in the extract by modifying the extraction conditions. The results showed that water-extracted tea leaf components can be used as natural dyes and finishing agents, and their properties are maintainable. Despite this advancement, detailed exploration for each application with desirable impacts is necessary. [55-61]

Organic Solvent Extraction

The method provides preference in tea leaf extract and profitable utilization and the study of impacts on characteristics of natural fibers such as wool and silk by tea leaf extract. First, organic solvent extraction is an efficient and alternative method to water extraction of extracting bioactive compounds, including tea leaf extract. In this section, we survey trends of organic solvent extraction towards efficient extraction, improved extract properties, and reduced solvent usage with the lowest environmental pollution. Afterward, improving the safety of using organic solvents in the extraction will be addressed as our future work. At the same time, the information about efficient extraction and a valuable extract with organic solvent extraction will be reviewed. The principle of organic solvent extraction is to dissolve the components into the solvent used according to the solvent properties, composition of the vegetable matrix, or a combination of both, which can dissolve the most or a wider range of solutes quickly at room temperature or higher temperature. Several critical factors will impact the extraction performance, including solvent selection and its property, particle size, solvent to solid ratio, extraction temperature and time, and solvent extraction with or without microwave-assisted extraction. The effect of estimating the preferred solvents such as ethyl acetate and ethanol of various concentrations at room temperature. The use of the sugar compounds in the crude extract, as well as its antioxidant and antimicrobial effects on cellulosic fabrics, was certified following identification of the extracted components. The major disadvantages of using organic solvent for extraction are its potential to form organic-rich waste from extraction. Next, we will address potentially 'green' solvents. In fact, this approach can be economically useful with distinctive and excellent results despite the mounting evidence of the environmental and toxicological issues associated with the usage of these solvents. [62-67]

Supercritical Fluid Extraction

Supercritical Fluid Extraction (SFE) is an advanced extraction technique that has recently started to draw the interest of the textile community. It exploits the use of supercritical fluids, where the conventional liquid and gaseous states overlap. In the textile field, supercritical carbon dioxide is mainly preferred as the supercritical fluid. As for the textiles, SFE is much touted as a green extraction method. The selectivity of SFE is one of the fascinating features that are drawing researchers' attention towards employing SFE for the extraction of active tea compounds. This technique's environmental benefits are widely recognized, as it leaves no toxic residues in the extracted material. The increasing focus on the optimization of SFE process parameters is also noteworthy, with a view to attaining the maximum yield of tea active principles. [2, 68-73]

Technically, SFE is the process of separating one component from a mixture under supercritical fluid conditions. Among diverse optimization studies, pressure and temperature have always been considered the most important factors to tailor the yield rate and composition of the extracts. SFE operates at lower temperatures, which can protect the stability of the tea extracts. Several studies demonstrated the success of SFE's selective extraction of some target compounds including caffeine, catechins, epigallocatechin gallate, theaflavins, and thearubigins. However, the capital and running costs of SFE, as well as the requirement of specific and sophisticated equipment, are drawbacks that can be serious obstacles in the use of this technology. Superficially, SFE is an efficient way of obtaining high-quality clean extracts free from solvents, water, and oxidative residues that could be potentially detrimental in textile applications. Thus, functionalized natural additives obtained from SFE are expected to allow the development of a wide range of high-value textiles, although the actual applications need to be deeply investigated. [74-79]

Characterization Methods of Tea Leaf Extract

Characterization methods are the most crucial part to gain information about properties, as well as utilization, from tea leaf extract. Based on pharmacognosy, spectroscopic analysis using UV-Vis and FTIR is frequently used to analyze the preliminary profile of bioactive fractions using functional groups to enable functional group identification for qualitative and semiquantitative analyses. FTIR provides a qualitative analysis, whereas UV-Vis is commonly used to perform quantitative analysis. To decipher the presence of the individual types of phenolic components in the extracted solution, chromatographic techniques are mostly used. High-performance liquid chromatography is employed to identify the wide variety of polyphenolic compounds in a pure form and a wide range of terms and conditions. Light rays are used to separate the individual components at high pressure, and it is widely applied in measuring such complexes because it can separate and identify the individual compounds from a complex mixture. [80-85]

The extraction process can be interrelated with various results of characterization. However, characterization details must be made to gain a clear picture of understanding and interesting content to be communicated. Light microscopic examination can be used to reveal the nanostructure of a tubular nanofiller composite material obtained by the tea extract in two extraction methods. Nevertheless, the phenomenon and surface characteristics of the tea extract during the extraction process still need to be investigated. Briefly, the characterization of tea leaf extract reveals substantial quantities of bioactive substances, with the tea extract process conferring a reduction in extract production time, thereby being helpful for improving utilization in the textile process. [16, 86-90]

Spectroscopic Analysis

Spectroscopic analysis has become a quick and non-destructive tool for the identification and characterization of natural dyes and plant extracts used in textiles. The active components of tea leaves used in textile finishing can also be identified using spectroscopic analysis at the atomic or molecular level. All spectroscopic techniques do not require extensive sample preparation, and the most commonly used spectroscopic methods for bioactive component analysis and identification in plant extracts are UV-Vis spectroscopy, FT-IR spectroscopy, Raman spectroscopy, and ATR-FTIR. The main limitation of NMR and FT-IR spectroscopy is the requirement of labeling with isotopes. The analysis is quite sensitive with NMR, but it is somewhat costly. The UV-visible spectra are widely used for determining binding constants and for studying the electronic absorption spectra, and it is also a helpful tool to find out the ml value. The functional groups of the characteristic peaks of bioactive components like tannins, alkaloids, flavonoids, and saponins can be confirmed using FTIR. Thus, the isolation of functional components can be confirmed using FTIR and UV-Vis. Hence, these two techniques are classified in the current study. [91-98]

UV-Vis spectroscopy is often used to confirm the presence of catechin in Camellia sinensis because the wavelength lies in the range of flav. [99-101

Chromatographic Techniques

Chromatographic techniques play a critical role in the detailed investigation of complex components, and they are significantly employed to separate and quantify these components. High-performance liquid chromatography and gas chromatography make direct quantification of target components in complex matrices possible. High-performance liquid chromatography is used for the analysis of carbohydrates, glycosidic compounds, proteins, amino acids, and phenolic compounds. Gas chromatography is employed for qualitative and quantitative analysis of volatile aroma precursors. Dry needling, supercritical fluid chromatography, thin-layer chromatography, etc., have also been conducted in our few studies. These chromatographic methods have obvious advantages, including high resolution, high sensitivity, rapid analysis, low quantitation limit, low limit of detection, and high reproducibility, which make them suitable for the analysis of tea extracts. [102-106]

Recently, various chromatographic methods have been used to analyze the separated and modified products of green tea extract solution characterization and its components to be used in textile products. High-performance liquid chromatography and LC-MS spectra are compared to size low molecular weight phenolics and polar substances that are convenient to be used as antioxidants. Derivatization of catechins by high-performance liquid chromatography was applied from the standard calibration curve for the use of GCEs in the microemulsification technique. However, using the available pre-treated thin-layer chromatography and spectroscopic equipment, the data could be well interpreted without analysis using Q-tof LC-MS. Also, due to the low possibility of obtaining approximately correct limit of detection and limit of quantification, the developed method still needs improvement. Complete laboratory analysis of white yarn dyeing using conventional methods and using a master box, microemulsions, and microsphere fabrics to characterize BRF includes interactions in the dyed fabric and comparison with conventional mixed dyeing methods. HS-GC-MS analysis is also very expensive for solvents, and it is not considered the dye of a 70% solid fabric coverage. Hence, further development is still possible. These chromatographic techniques, however, do not provide a complete insight into the chemical composition of tea leaf extracts compatible with textile applications. Their results were basic and provided only information on free catechins or volatiles, not detailed qualitative identification, and quantitative quantification for each extract composition in honey precipitation occurring during black tea processing. In order to achieve aromatic properties on various textile substrates, it is essential to know the actual compositions of each extract prepared with various solvents. High-resolution chromatographic techniques should be used. It is also important to optimize the method according to the solvent used. [107-112]

Microscopic Examination

Tea leaf extract is a complex mixture of various chemicals and could be used to modify the properties of textile fibers by the impregnation method. Microscopic examination is a crucial characterization tool to describe the morphological structure of the sample. A common way to perform microscopic examination is by using light microscopy or optical microscopy, which could also employ staining to facilitate visualization. Scanning electron microscopy (SEM) is better used to characterize the surface morphology of the samples. Information about the morphology of the sample is valuable, especially when the target is to modify textile fibers. Tea leaf extract contains tannin, caffeine, and moisture suspended in water. The description of the size, shape, and distribution of these suspensions, if present, would be beneficial and could be used as evidence of the extract's capability. This subsection elaborates on results from microscopic studies that could facilitate an understanding of the efficacy of tea leaf extraction. [35, 113-115]

Further examination by microscopic techniques is required to analyze the morphological characteristics of the tea leaf extract in order to optimize the conditions of extraction and the performance of the extract in textiles, such as dyeing and finishing processes. Larger suspensions could block the pores and cause inhomogeneity in the samples; thus, the extract in the conventional process could not bond properly to the textiles. However, sample preparation for microscopic observation, such as dilution of the extract in this study, is also a problem, particularly in representing the real condition and may produce a bias. Thus, a combination of various characterization techniques is required to clarify the actual conditions of the extract, such as light and scanning electron microscopy. This could be the aim of our future work to examine the structure of tea leaf extract-polyphenolic conjugates. The extract is indicated to contain more than 10% total polyphenols. Moreover, various chemical structures are present, such as catechins, anthocyanins, flavonol glycosides, and condensed tannins purified by extraction to ethanol. [116-120]

Utilization of Tea Leaf Extract in Textile Wet Process

In fact, tea leaf extracts have wide applications in textile wet processing such as coloring, printing, and finishing treatments. The challenges and strategies to utilize natural dye in coloration textiles have been elaborated. Natural dye has been found to be less strong with relatively poor color fastness. Several researchers have showcased the potential of tea for antifungal, UV protection, and fabric modification as multifunctional performance finishing agents. Currently, increasing attention has been directed toward the use of natural plant extracts in textile applications due to their potential applications in different areas. In this section, the full application of tea leaf extract in textile wet processing is reviewed, and practical considerations on aesthetics, functionality, and health aspects of tea dye textiles are also presented. [4, 8, 121-124]

Tea is a natural eco-friendly plant that can be applied to dye and finish textile substrates such as wool, silk, cotton, and bamboo-based fibers to improve aesthetics and impart multifunctional properties. According to different classes of textile wet applications, tea-based leaf extracts can be formulated to use as simple and antioxidant dye in wool and silk textiles, antimicrobial agents in bamboo fibers, and also UV protective and wrinkle-free textile finishing via conventional and eco-friendly approaches. With all these attributes, tea-based leaf extracts find potential applications in the development of tea-dyed and finished textile products, particularly in sports suits, school uniforms, knitwear, etc., as potential commercial printed colored product supplies. Manufacturers' knowledge and skill in the standardized formulation and development of tea leaf extracts for use as antioxidants, antimicrobials, and UV protectants on various natural and artificial polymers are required to attract the market. These extracts can have several potential applications in the development of multifunctional tea dye textiles. The results obtained in the current study explore the previous developments and the practical uses of tea-based leaf extracts in textiles. Some researchers have worked on evaluating various effective bio-finishing processing parameters on tea-dye-treated cotton knitted fabrics. This product can absorb the sweat coming from the body and wick away moisture. The dried samples of functional tea-dye treatment finishing of grey cotton knitted fabric after bio-finishing applications can be measured for their physical and antibacterial tests. Furthermore, based on the available literature, no standard determination has been carried out for development. Moreover, there were no standardized conditions to evaluate the ultraviolet/antioxidant and antibacterial properties of cotton knitted activewear fabrics. Hence, these results are necessary for the up-to-date scientific and practical development of the tea-based dye textiles industry. [6, 125-29]

Dyeing and Printing Applications

Applications of tea leaf extracts are most prominent and evident in dyeing and printing textiles. Commercially, various researchers have utilized tea extracts to pigment textile materials following different techniques and processes. Immersion is the most commonly used application process, but color can also be applied through spray. The dye has been mobilized using other natural mordants such as alum acetate, copper, and ferric ions, all of which work with tea extracts to fix the dye. Compared to synthetic dyes, tea extracts win great attention and preference as a natural colorant for textiles. The toxic effects of chemical colorants lead to harmful effects on the consumer's body in the form of allergies, cancerous effects, sensitivity, and other hazards. Moreover, the effluent's high pollution load is not easily treatable, affecting the global environment. In contrast, natural tea color and its bioactive attributes exhibit low toxicity and possess the potential to be easily degraded. Pale yellow to darker caramel shades with better color absorbance can be achieved by optimizing parameters such as material to liquor ratio, temperature, and process time. The dye yielding from the extracts varies significantly with respect to pH levels, having better yield at pH 6.5 for neutral extracts and at pH levels between 4.5 and 5.5 for mild acidic tea extracts during dyeing and printing, respectively. At a lower pH level, wash fastness and CIE L* value optimization exhibit better shades than mild acidic pH. This inspired some scaling up research works involving the dyeing of silk, wool, cotton, and their blends. These textiles were subjected to utilization studies in pictured garments and fabrications of canvas shoe uppers. Some of the dyed textiles with tea extracts have been tested for UV protection. Besides, some antibacterial textiles using tea polyphenols at extract levels have been reported. Despite several results initiated by the use of tea extracts in dyeing and printing, there are some unresolved issues and potential applications detailing the prospects and applications, particularly in the textile sector. As an innovation, it is essential to ascertain future prospects and the trend of using tea extracts in textiles. [3, 18, 91, 130-134]

Antimicrobial Finishing

Textiles can become contaminated with microorganisms from the environment and may also be a source of infection. To safeguard people against skin irritations, allergies, illnesses, and their transmission, all such textiles should be treated with antimicrobial agents that are non-toxic and do not cause any harm to human health. Since the active compounds found in tea, primarily polyphenols, demonstrate strong antimicrobial properties, their extract can be effectively used in textile finishing. The presence of multiple hydroxyl groups in the phenolic group serves to prevent bacterial growth. Higher antimicrobial activity was reported for the tea flavonol extract than for green tea. The presence of phenolic compounds, alkaloids, and flavonoids, as well as the tea leaf tannins, provides antimicrobial, antifungal, and anti-yeast functions to several processed forms of leather. [135-139]

To impart an antimicrobial finish to textiles in an environmentally friendly manner and to fully utilize the bioactivity of these extracts, many researchers have taken the initiative to combine antimicrobial agents derived from plant sources with simple and available application techniques. The pad-batch technique has been used for the exhaustion of black tea extract onto textiles based on cotton, viscose, and cellulose-polyester blended fabrics. The wet pick-up during pad-batch exhaustion principally depends on the woven structure of the fabric. The tea extract with a ratio of 60% was also pad-reduced to a shade of 2.1% on the weight of fabric using a fabric to concentrate as a mild reducing agent and again pad-batched to the target pickup of 60%. The antimicrobial activity of the green tea and black tea treated fabrics was tested against various bacteria using modified methods. A reduction in bacterial cell count indicates the antibiotic effect of the textile sample. The antimicrobial efficacy of the green tea and black tea pad-batched and also pad-reduced and pad-batched fabrics against selected bacteria was evaluated. Though it showed values for the antibacterial activity against the tested pathogens, only green tea treated materials showed antimicrobial efficacy for the samples padded with reduced green tea extract. [140-144]

All the details in the previous sections create an evaluated background supporting the potential of tea leaves and waste extracts for different purposes, including textile application, particularly in terms of the antimicrobial function. Thus, the need of the time is to introduce another perspective: tea leaves as a potent antimicrobial agent in textiles. We have divided this section into two; the first sub-section discusses antimicrobial finishing on a general level and the need for antimicrobial agents in textiles as well as their importance. In the modern century, there is an urge for a greener approach at every level, so the use of extracts from nature is the need of the hour. The focus of the second main sub-section has been laid on the use of environmentally friendly bioactive agents, and the section concludes with a critique and the significance of the use of tea leaf extracts as a potent agent at the laboratory scale, with the suggestion that a wide-scale investigation could open up an extended role for tea leaf extract in the field of textile materials. [5, 20, 121, 145-147]

UV Protection Finishing

UV rays can cause harm to skin and textiles. Wearing clothes with good UV protection is important for health. Currently, the requirement from people in outdoor activities and sunbathing has highly increased. Some of them suffer from sunburn or develop an additional risk of skin cancer. People are well informed about possible risks and the offered products for skin protection, such as lotions, clothes, sunglasses, and umbrellas. [148-153]

Extracts prepared from tea leaves are being studied in dyeing, antimicrobial finishing, and the enhancement of other antioxidants and functional groups. Because of criteria in green production of a competitive industry, the increased demands for functional wear, and the benefits of tea extract, polyphenolic compounds are major chemicals in extracting the tea leaf with significant terms and conditions such as solvent or processing conditions. These are affected by the green tea origin from the tea plant, the species, parts of the plant, and time of separation. In practice, the extracts can be applied as a solution for textiles or through impregnation in textiles by dyeing, pads, coating, and adding to fiber bundles. The UV filters in textiles are also normally conjugated onto fabrics by different methods of impregnation, pad-dry-cure, or application of a coating via the sol-gel method. This advantage is also provided by blending extraction with other processing or finishing treatments. [10, 12, 20, 111, 154, 155]

Although many serious allergic reactions are reported both in photofunctional fabrics by encapsulation of a mixture of chemical filters and even in the textile dye carrying tetraaniline to a chemically allergic patient, the finalized effects and the protection of the permanent use of extracts in textiles may be solved by confirming the clinical results. Techniques and methods for measurement of UPF are more intensively developed, including using textiles containing UV-protection finishes. The stability of natural dye is addressed by finding or designing a new technique or technology, e.g., water-extracting dye or solvent dye at a relatively low temperature. Tea leaf extract is developed in dyeing and is also improved for colorfastness properties. In addition to the protection function, the aroma in the protection may release a tea plant smell on the skin of clothing, which is attractive for people in the mood for stress relief or a sense of freshness. [15, 20, 82, 156, 157 [

Tea leaf extracts are abundant in antioxidants, which can protect textiles from harm due to allergic reactions to naturally colored dye and antioxidants, improve protection from harmful solar light, and provide cost-effective UV protection for textile products with added value. Both health properties and the extraction from tea leaves may promote an advantage for customers seeking good functionality in wear. However, the oxidants in the protective textile must be kept stable over time, and the UV protection of a textile product blended with tea leaves is a test of time. The extraction or compound from the tea plant can be applied to protective textile production using a relatively simple technique for squeezing dye from water or organic solvent extracts for blending processing. Examples of simple impregnation to achieve fading protection for linen clothing are also beneficial. [1, 24, 69, 121, 157, 59, 160]

Advantages and Challenges of Tea Leaf Extract in Textile Industry

Environmental considerations always come first and play a vital role in the sustainability of any processes. Hence, the utilization of natural compounds like TLE in various wet processes of textiles may well replace some toxic or harmful synthetic compounds. Apart from the eco-friendliness, other attractive properties of TLE, such as non-toxicity, biodegradability, and easy availability, further enhance the value of this natural resource. A huge amount of tea leaves, which is the precursor to TLE, is produced every day from the beverage industry and consequently can be the primary source of natural colorants. Similarly, many botanicals are known to be rich in bioactive phytochemicals, and supplementation of TLE in practical diets, which is mostly non-toxic in nature, offers different beneficial health approaches. At the same time, this member of tea extract is being extensively employed as an alternative antioxidant and antimicrobial agent for retarding the deterioration of dairy products and the skin of animals. Many important compounds obtained from tea leaves mostly exist in the form of secondary metabolites. Due to the presence of these compounds, they have been shown to possess various medicinal, dietary, and physiological properties. The economic value of the tea plants includes the harvest of the leaves and flower buds for human consumption, as well as the extraction of compounds with medicinal applications such as alkaloids, amino acids, phenolic compounds, and polyphenols, which are not accessible by chemical synthesis. The above-stated facts are solid support for the utilization of TLE in textile wet processes. [161-165]

However, a few challenges hinder its potential as a natural alternative. The first challenge is in the reproducibility of plant extracts, as their composition varies with the method of extract preparation, maturity of the plant part, part of the plant used, and the plant population. Though many workers have extracted and employed TLEs for different purposes, seldom has the extraction of TLE been carried out to make extracts with the composition that is favorable to the textile wet process. In addition, although extraction from fresh leaves is possible, the extraction process for large volumes of fresh tea leaves can prove practical at an industrial level, as these leaves are rich in water content and need to be dried in order to end up with a cost-effective method. Second, the quantification and the changes happening in the chemical composition of the leaves during the drying period have not been systematically reported. Third, although it is believed that the compounds present in TLEs can have antimicrobial properties, no comparative study has been performed to show if the extraction process has an effect on this activity. Furthermore, the application of natural colorants (including TLE) in the textile industry for dyeing and finishing poses certain problems, such as fastness properties, fulling and fabric quality, and value addition, and how to effectively extract the desirable compounds to cover various textile products is very important. Based on these inadequacies, the TLE extracted from the black tea plant may well render the necessary components required for value addition in textile wet processing. In such a scenario, a cost-effective extraction process is of paramount importance. [125, 166-169]

Future Directions and Potential Research Areas

It is anticipated that future developments in fiber and textile research relating to tea would need to address the underpinning mechanisms of tea extraction, potentially develop new extraction methods, find the right combination of biopolymers in tea for ease of extraction in various textile processing steps, and optimize extraction and after-extraction processing in terms of adjuvant chemistry. The physics and biology of tea in textile processes are currently key drivers in the innovation and sustainability of commercially dyed textiles. While research has shown potential benefits of using tea leaf extract in textiles, the research areas that have not been currently investigated could focus on how the extract was obtained from the leaves of the plant, how the subsequent chemical processing altered the performance of the extracts, how to achieve more reproducible and standardized methods for the application of the tea extracts onto textile substrates, understanding more about the extract and textile interactions at a molecular level, including the use of chemical modifiers and tracers, and investigating the extraction of tea and other extracts from different parts of a range of Camellia species. Emerging trends are likely to be in the efficacy of systems that combine antimicrobials with other bioactive agents, including antiviral and insect repellents, with a view to developing textiles that are multifunctional.

Growing collaborations with researchers in academia, industry, local authorities, and policymakers are also gaining considerable traction and support. Our recent dialogue regarding the environmental credentials and safety of such products has very much underlined this level of potential movement further. We invite authors of future work to look at this as an area in which to focus, determine what approach could increase the radioprotective properties of tea if used in a blend with other natural products, and what part fermentation of the tea leaves could play with regard to the performance of the product. We would suggest that an increase in collaboration and funding support from both academia and an increased number of industries from the materials and consumer goods sector would enhance innovation in an expanding number of research areas. Such holistic approaches will help drive innovation and launch the "next stage" in the commercial relevance of this research.

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Conflict of Interest

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References

1. Pizzicato B, Pacifico S, Cayuela D, Mijas G, Riba-Moliner M. Advancements in sustainable natural dyes for textile applications: A review. Molecules. 2023 Aug 8;28(16):5954. mdpi.com
2. Pranta AD, Rahaman MT. Extraction of eco-friendly natural dyes and biomordants for textile coloration: A critical review. Nano-Structures & Nano-Objects. 2024. [HTML]
3. Singh M, Vajpayee M, Ledwani L. Eco-friendly surface modification of natural fibres to improve dye uptake using natural dyes and application of natural dyes in fabric finishing: A review. Materials Today: Proceedings. 2021. [HTML]
4. Ragab MM, Hassabo AG. Various uses of natural plants extracts for functionalization textile based materials. Journal of Textiles, Coloration and Polymer Science. 2021 Dec 1;18(2):143-58. ekb.eg
5. Pavun L, Spasojević D, Ivanovska A, Lađarević J, Milenković MT, Uskoković-Marković S. Characterization of tea aqueous extracts and their utilization for dyeing and functionalizing fabrics of different chemical compositions. Macedonian Journal of Chemistry and Chemical Engineering. 2023;42(2):263-73. bg.ac.rs
6. Garg H, Singhal N, Singh A, Khan MD, Sheikh J. Laccase-assisted colouration of wool fabric using green tea extract for imparting antioxidant, antibacterial, and UV protection activities. Environmental Science and Pollution Research. 2023 Jul;30(35):84386-96. [HTML]
7. Vastrad JV, Badanayak P, Goudar G. Phenolic compounds in tea: phytochemical, biological, and therapeutic applications. Phenolic compounds-Chemistry, synthesis, diversity, non-conventional industrial, pharmaceutical and therapeutic applications. 2022 Feb 23;23:452. intechopen.com
8. Zhang W, Wang X, Zhang Y, Wu S, Liu R. Flavonoid dyes from vine tea (Ampelopsis grossedentata) have excellent bioactive properties for dyeing and finishing of silk fabrics. Sustainable Chemistry and Pharmacy. 2022 Sep 1;28:100708. [HTML]
9. Ivanovska A, Milenković J, Lađarević J, Mihajlovski K, Dojčinović B, Ugrinović V, Škaro Bogojević S, Kostić M. Harnessing the power of green and rooibos tea aqueous extracts for obtaining colored bioactive cotton and cotton/flax fabrics intended for disposable and reusable medical textiles. Cellulose. 2024 Sep 18:1-20. [HTML]

10. Yılmaz F, Bahtiyari M. Use of tea and tobacco industrial wastes in dyeing and antibacterial finishing of cotton fabrics. AATCC Journal of Research. 2020. [HTML]

11. Haji A, Bahtiyari M. Natural compounds in sustainable dyeing and functional finishing of textiles. Green chemistry for sustainable textiles. 2021. [HTML]

12. Bag S, Mondal A, Majumder A, Banik A. Tea and its phytochemicals: Hidden health benefits & modulation of signaling cascade by phytochemicals. Food Chemistry. 2022. [HTML]

13. Wong M, Sirisena S, Ng K. Phytochemical profile of differently processed tea: A review. Journal of Food Science. 2022. wiley.com

14. Mutha RE, Tatiya AU, Surana SJ. Flavonoids as natural phenolic compounds and their role in therapeutics: An overview. Future journal of pharmaceutical sciences. 2021 Dec;7:1-3. springer.com

15. Shahrajabian MH, Sun W, Cheng Q. The importance of flavonoids and phytochemicals of medicinal plants with antiviral activities. Mini-Reviews in Organic Chemistry. 2022 May 1;19(3):293-318. [HTML]

16. Yu M, Gouvinhas I, Rocha J, Barros AI. Phytochemical and antioxidant analysis of medicinal and food plants towards bioactive food and pharmaceutical resources. Scientific reports. 2021. nature.com

17. Fang J, Meng C, Zhang G. Agricultural waste of Ipomoea batatas leaves as a source of natural dye for green coloration and bio-functional finishing for textile fabrics. Industrial Crops and Products. 2022. [HTML]

18. Uddin MA, Rahman MM, Haque AN, Smriti SA, Datta E, Farzana N, Chowdhury S, Haider J, Sayem AS. Textile colouration with natural colourants: a review. Journal of Cleaner Production. 2022 May 15;349:131489. mmu.ac.uk

19. Hossain S, Jalil MA, Mahmud RU, Kader A. Natural dyeing of silk and jute fabric with the aqueous extract of coconut leaves–an eco-friendly approach. Pigment & Resin Technology. 2024 Jul 15;53(5):631-7. researchgate.net

20. Islam MR, Mahmud RU, Jalil MA, Huda MN. Captivating coloring and antimicrobial properties of tea leaf and eucalyptus bark on jute–cotton union fabric. Pigment & Resin Technology. 2024 Jul 25. [HTML]

21. Venkatraman PD, Sayed U, Parte S, Korgaonkar S. Development of advanced textile finishes using nano-emulsions from herbal extracts for organic cotton fabrics. Coatings. 2021. mdpi.com

22. Yıldırım FF, Avinc O, Yavas A, Sevgisunar G. Sustainable antifungal and antibacterial textiles using natural resources. Sustainability in the textile and apparel industries: sourcing natural raw materials. 2020:111-79. [HTML]

23. Saha J, Chakraborty SS, Rahman A, Sakif R. Antimicrobial Activity of Textiles from Different Natural Resources. J. Res. Environ. Earth Sci. 2021;7:32-44. researchgate.net

24. Zaied M, Othman H, Ghazal H, Hassabo A. A valuable observation on natural plants extracts for Valuable Functionalization of Cotton fabric (an overview). Egyptian Journal of Chemistry. 2022 Apr 1;65(4):499-524. ekb.eg

25. Rulhania R, Arya N, Kumari B, Malik K, Grover A, Sodhi S, Dandu H, Poonia N, Kushwah N. Eco-Friendly Antibacterial Finish from Ghamra and Apamarga Leaf Extract for Textile Application. Journal of Natural Fibers. 2024 Dec 31;21(1):2302622. tandfonline.com

26. Tiwari G. Assessment of antimicrobial textile finish with Mangifera indica on Bamboo Union Fabrics and Phytochemical Analysis of the Extract. researchgate.net. . researchgate.net

27. Wang C, Han J, Pu Y, Wang X. Tea (Camellia sinensis): A Review of Nutritional Composition, Potential Applications, and Omics Research. Applied Sciences. 2022. mdpi.com

28. Sun Z, Chen D, Zhu L, Zhao Y, Lin Z, Li X, Dai W. A comprehensive study of the differences in protein expression and chemical constituents in tea leaves (Camellia sinensis var. sinensis) with different maturity using a combined proteomics and metabolomics method. Food Research International. 2022 Jul 1;157:111397. [HTML]

29. Paiva L, Lima E, Motta M, Marcone M, Baptista J. Variability of antioxidant properties, catechins, caffeine, L-theanine and other amino acids in different plant parts of Azorean Camellia sinensis. Current Research in Food Science. 2020 Nov 1;3:227-34. sciencedirect.com

30. Carvalho DG, Ranzan L, Jacques RA, Trierweiler LF, Trierweiler JO. Analysis of total phenolic compounds and caffeine in teas using variable selection approach with two-dimensional fluorescence and infrared spectroscopy. Microchemical Journal. 2021 Oct 1;169:106570. [HTML]

31. Tseng WY, Lai HY. Comprehensive Analysis Revealed the Specific Soil Properties and Foliar Elements Respond to the Quality Composition Levels of Tea (Camellia sinensis L.). Agronomy. 2022. mdpi.com

32. Zhou B, Wang Z, Yin P, Ma B, Ma C, Xu C, Wang J, Wang Z, Yin D, Xia T. Impact of prolonged withering on phenolic compounds and antioxidant capability in white tea using LC-MS-based metabolomics and HPLC analysis: Comparison with green tea. Food Chemistry. 2022 Jan 30;368:130855. [HTML]

33. Fu Z, Chen L, Zhou S, Hong Y et al. Analysis of differences in the accumulation of tea compounds under various processing techniques, geographical origins, and harvesting seasons. Food Chemistry. 2024. [HTML]

34. Li S, Zhang L, Wan X, Zhan J et al. Focusing on the recent progress of tea polyphenol chemistry and perspectives. Food Science and Human Wellness. 2022. sciencedirect.com

35. Negi T, Kumar Y, Sirohi R, Singh S, Tarafdar A, Pareek S, Awasthi MK, Sagar NA. Advances in bioconversion of spent tea leaves to value-added products. Bioresource Technology. 2022 Feb 1;346:126409. [HTML]

36. Nille OS, Patil AS, Waghmare RD, Naik VM, Gunjal DB, Kolekar GB, Gore AH. Valorization of tea waste for multifaceted applications: a step toward green and sustainable development. InValorization of agri-food wastes and by-products 2021 Jan 1 (pp. 219-236). Academic Press. researchgate.net

37. Fiallos-Cárdenas M, Ramirez AD, Pérez-Martínez S, Romero Bonilla H, Ordoñez-Viñan M, Ruiz-Barzola O, Reinoso MA. Bacterial nanocellulose derived from banana leaf extract: yield and variation factors. Resources. 2021 Nov 27;10(12):121. mdpi.com

38. Kumar KR, Dashora K, Krishnan N, Sanyal S, Chandra H, Dharmaraja S, Kumari V. Feasibility assessment of renewable energy resources for tea plantation and industry in India-A review. Renewable and Sustainable Energy Reviews. 2021 Jul 1;145:111083. academia.edu

39. Adeel S, Azeem M, Habib N, Hussaan M, Kiran A, Haji A, Haddar W. Sustainable application of microwave assisted extracted tea based tannin natural dye for chemical and bio-mordanted wool fabric. Journal of Natural Fibers. 2023 Apr 24;20(1):2136322. tandfonline.com

40. Bharti R, Singh B. Green tea (Camellia assamica) extract as an antioxidant additive to enhance the oxidation stability of biodiesel synthesized from waste cooking oil. Fuel. 2020. [HTML]

41. Galgano F, Tolve R, Scarpa T, Caruso MC, Lucini L, Senizza B, Condelli N. Extraction kinetics of total polyphenols, flavonoids, and condensed tannins of lentil seed coat: Comparison of solvent and extraction methods. Foods. 2021 Aug 5;10(8):1810. mdpi.com

42. Fraga-Corral M, García-Oliveira P, Pereira AG, Lourenço-Lopes C, Jimenez-Lopez C, Prieto MA, Simal-Gandara J. Technological application of tannin-based extracts. Molecules. 2020 Jan 30;25(3):614. mdpi.com

43. Abilleira F, Varela P, Cancela Á, Álvarez X, Sánchez Á, Valero E. Tannins extraction from Pinus pinaster and Acacia dealbata bark with applications in the industry. Industrial Crops and Products. 2021 Jun 1;164:113394. sciencedirect.com

44. Kamarudin NA, Muhamad N, Salleh NN, Tan SC. Impact of solvent selection on phytochemical content, recovery of tannin and antioxidant activity of quercus infectoria galls. Pharmacognosy Journal. 2021;13(5). phcogj.com

45. Ng ZX, Samsuri SN, Yong PH. The antioxidant index and chemometric analysis of tannin, flavonoid, and total phenolic extracted from medicinal plant foods with the solvents of different polarities. Journal of Food Processing and Preservation. 2020 Sep;44(9):e14680. [HTML]

46. Magangana TP, Makunga NP, Fawole OA, Opara UL. Processing Factors Affecting the Phytochemical and Nutritional Properties of Pomegranate (Punica granatum L.) Peel Waste: A Review. Molecules. 2020. mdpi.com

47. Tzanova M, Atanasov V, Yaneva Z, Ivanova D et al. Selectivity of current extraction techniques for flavonoids from plant materials. Processes. 2020. mdpi.com

48. Allafi FA, Hossain MS, Ab Kadir MO, Shaah MA, Lalung J, Ahmad MI. Waterless processing of sheep wool fiber in textile industry with supercritical CO2: Potential and challenges. Journal of cleaner production. 2021 Feb 20;285:124819. [HTML]

49. Haque MS, Nahar N, Sayem SM. Industrial water management and sustainability: development of SIWP tool for textile industries of Bangladesh. Water Resources and Industry. 2021. sciencedirect.com

50. Uddin MA, Begum MS, Ashraf M, Azad AK, Adhikary AC, Hossain MS. Water and chemical consumption in the textile processing industry of Bangladesh. PLOS Sustainability and Transformation. 2023 Jul 31;2(7):e0000072. plos.org

51. Jorge AM, Athira KK, Alves MB, Gardas RL, Pereira JF. Textile dyes effluents: A current scenario and the use of aqueous biphasic systems for the recovery of dyes. Journal of Water Process Engineering. 2023 Oct 1;55:104125. academia.edu

52. Azanaw A, Birlie B, Teshome B, Jemberie M. Textile effluent treatment methods and eco-friendly resolution of textile wastewater. Case Studies in Chemical and Environmental Engineering. 2022 Dec 1;6:100230. sciencedirect.com

53. Jahan N, Tahmid M, Shoronika AZ, Fariha A, Roy H, Pervez MN, Cai Y, Naddeo V, Islam MS. A comprehensive review on the sustainable treatment of textile wastewater: zero liquid discharge and resource recovery perspectives. Sustainability. 2022 Nov 19;14(22):15398. mdpi.com

54. Allam O, Elshemy N, El-Sayed H. Simple and easily applicable method for reducing freshwater consumption in dyeing of wool fabric. Journal of Natural Fibers. 2022. [HTML]

55. Endris J, Govindan N. Single-stage coloration and multiple finishing of cotton with eucalyptus leaves extracts. Journal of Natural Fibers. 2022. academia.edu

56. Adeel S, Salman M, Zahoor AF, Usama M, Amin N. An Insight Into Herbal- Based Natural Dyes: Isolation and Applications. Recycling from waste in fashion and textiles: A sustainable and circular economic approach. 2020 Jun 29:423-56. [HTML]

57. Oo ZM, Theingi M, Aung NN. SORPTION STUDY ON DYEING PROCESS OF NATURAL DYES EXTRACTED FROM CASUARINA EQUISETIFOLIA FORST.(KA-BWEE) BARK ON COTTON CLOTH. JOURNAL OF THE MYANMAR ACADEMY OF ARTS AND SCIENCE.;18(1C):31. maas.edu.mm

58. Mellino L. Development of a novel green process for spent tea leaves valorization. 2021. polito.it

59. Oloye-Akorede MT, Arawande JO, Obinwa EH, Jabar JM, Oderemi YO, Oyegoke DA, Quadri IO. Extraction and characterization of guinea corn plant extract for mordant assisted dyed cotton fabric. GSC Advanced Research and Reviews. 2024;19(3):074-85. gsconlinepress.com

60. Maulik SR, Debnath C, Pandit P. Sustainable dyeing and printing of knitted fabric with natural dyes. Advanced Knitting Technology. 2022. [HTML]

61. Boominathan S, KV, Balakrishanan S. Optimization of process parameters on color strength and antimicrobial activities of cotton fabric dyed with Rubia cordifolia extract. Journal of Natural Fibers. 2022. [HTML]

62. Usman I, Hussain M, Imran A, Afzaal M, Saeed F, Javed M, Afzal A, Ashfaq I, Al Jbawi E, A. Saewan S. Traditional and innovative approaches for the extraction of bioactive compounds. International Journal of Food Properties. 2022 Dec 31;25(1):1215-33. tandfonline.com

63. Jha AK, Sit N. Extraction of bioactive compounds from plant materials using combination of various novel methods: A review. Trends in Food Science & Technology. 2022. [HTML]

64. Ivanović M, Islamčević Razboršek M, Kolar M. … extraction techniques using deep eutectic solvents and analytical methods for the isolation and characterization of natural bioactive compounds from plant material. Plants. 2020. mdpi.com

65. Daud NM, Putra NR, Jamaludin R, Norodin NS, Sarkawi NS, Hamzah MH, Nasir HM, Zaidel DN, Yunus MA, Salleh LM. Valorisation of plant seed as natural bioactive compounds by various extraction methods: A review. Trends in Food Science & Technology. 2022 Jan 1;119:201-14. [HTML]

66. Rashid R, Wani SM, Manzoor S, Masoodi FA et al. Green extraction of bioactive compounds from apple pomace by ultrasound assisted natural deep eutectic solvent extraction: Optimisation, comparison and bioactivity. Food Chemistry. 2023. [HTML]

67. Da Silva RF, Carneiro CN, de Sousa CB, Gomez FJ, Espino M, Boiteux J, Fernández MD, Silva MF, Dias FD. Sustainable extraction bioactive compounds procedures in medicinal plants based on the principles of green analytical chemistry: A review. Microchemical Journal. 2022 Apr 1;175:107184. [HTML]

68. Carvalho VS, Dias ALB, Rodrigues KP, Hatami… T. Supercritical fluid adsorption of natural extracts: Technical, practical, and theoretical aspects. Journal of CO2 …. 2022. [HTML]

69. Sk S, Mia R, Haque MA, Shamim AM. Review on extraction and application of natural dyes. Textile & Leather Review. 2021. srce.hr

70. Asiri AM. Advanced nanotechnology and application of supercritical fluids. 2020. researchgate.net

71. Ksibi H. The synergy of bioresources and supercritical fluid media: pathways to sustainable green processing. Euro-Mediterranean Journal for Environmental Integration. 2024 Jul 27:1-21. researchgate.net

72. Mathur M, Hans N, Naaz F, Naik SN, Pant KK, Malik A. Valorization of microalgal biomass to value-added products using integrated supercritical CO2 extraction and sub-critical hydrothermal liquefaction. Journal of Cleaner Production. 2022 Nov 1;373:133925. [HTML]

73. Nortjie E, Basitere M, Moyo D, Nyamukamba P. Extraction methods, quantitative and qualitative phytochemical screening of medicinal plants for antimicrobial textiles: a review. Plants. 2022. mdpi.com

74. Koina IM, Sarigiannis Y, Hapeshi E. Green extraction techniques for the determination of active ingredients in tea: Current state, challenges, and future perspectives. Separations. 2023. mdpi.com

75. Raghunath S, Budaraju S, Gharibzahedi SM, Koubaa M, Roohinejad S, Mallikarjunan K. Processing technologies for the extraction of value-added bioactive compounds from tea. Food Engineering Reviews. 2023 Jun;15(2):276-308. springer.com

76. Šojić B, Putnik P, Danilović B, Teslić N, Bursać Kovačević D, Pavlić B. Lipid extracts obtained by supercritical fluid extraction and their application in meat products. Antioxidants. 2022 Apr 5;11(4):716. mdpi.com

77. Reis PM, Mezzomo N, Aguiar GP, Hotza D, Ribeiro DH, Ferreira SR, Hense H. Formation, stability and antimicrobial activity of laurel leaves essential oil (Laurus nobilis L.) particles in suspension obtained by SFEE. The Journal of Supercritical Fluids. 2020 Dec 1;166:105032. [HTML]

78. Boateng ID. … , capabilities, limitations, and economic stability outlook for extracting phenolics from agro-byproducts using emerging thermal extraction technologies and their …. Food and Bioprocess Technology. 2024. researchgate.net

79. Patil PD, Patil SP, Kelkar RK, Patil NP, Pise PV, Nadar SS. Enzyme-assisted supercritical fluid extraction: An integral approach to extract bioactive compounds. Trends in Food Science & Technology. 2021 Oct 1;116:357-69. [HTML]

80. Mannu A, Poddighe M, Garroni S, Malfatti L. Application of IR and UV–VIS spectroscopies and multivariate analysis for the classification of waste vegetable oils. Resources, Conservation and Recycling. 2022 Mar 1;178:106088. polimi.it

81. Kucharska-Ambrożej K, Martyna A, Karpińska J, Kiełtyka-Dadasiewicz A, Kubat-Sikorska A. Quality control of mint species based on UV-VIS and FTIR spectral data supported by chemometric tools. Food Control. 2021 Nov 1;129:108228. sciencedirect.com

82. Tarhan İ. A comparative study of ATR-FTIR, UV–visible and fluorescence spectroscopy combined with chemometrics for quantification of squalene in extra virgin olive oils. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy. 2020 Nov 5;241:118714. [HTML]

83. Pratiwi RA, Nandiyanto AB. How to read and interpret UV-VIS spectrophotometric results in determining the structure of chemical compounds. Indonesian Journal of Educational Research and Technology. 2022 Jun;2(1):1-20. upi.edu

84. Tarhan İ, Bakır MR, Kalkan O, Kara H. Multivariate modeling for quantifying adulteration of sunflower oil with low level of safflower oil using ATR-FTIR, UV-visible, and fluorescence spectroscopies: A …. Food Analytical Methods. 2021. [HTML]

85. Malavi D, Nikkhah A, Raes K, Van Haute S. Hyperspectral imaging and chemometrics for authentication of extra virgin olive oil: A comparative approach with FTIR, UV-VIS, Raman, and GC-MS. Foods. 2023. mdpi.com

86. Samanta S. Potential Bioactive Components and Health Promotional Benefits of Tea (Camellia sinensis). Journal of the American Nutrition Association. 2022. [HTML]

87. Verrillo M, Salzano M, Cozzolino V, Spaccini R, Piccolo A. Bioactivity and antimicrobial properties of chemically characterized compost teas from different green composts. Waste Management. 2021 Feb 1;120:98-107. [HTML]

88. Zhang F, Zhu F, Chen B, Su E, Chen Y, Cao F. Composition, bioactive substances, extraction technologies and the influences on characteristics of

Camellia oleifera oil: A review. Food Research International. 2022 Jun 1;156:111159. [HTML]

89. Liu Z, Bruins ME, de Bruijn WJ, Vincken JP. A comparison of the phenolic composition of old and young tea leaves reveals a decrease in flavanols and phenolic acids and an increase in flavonols upon tea leaf maturation. Journal of Food Composition and Analysis. 2020 Mar 1;86:103385. sciencedirect.com

90. …, Hori K, Subedi L, Adhikari-Devkota A et al. The science of matcha: Bioactive compounds, analytical techniques and biological properties. Trends in Food Science …. 2021. uts.edu.au

91. Selberg S, Vanker E, Peets P, Wright K, Tshepelevitsh S, Pagano T, Vahur S, Herodes K, Leito I. Non-invasive analysis of natural textile dyes using fluorescence excitation-emission matrices. Talanta. 2023 Jan 15;252:123805. [HTML]

92. Ding L, Gong T, Wang B, Yang Q, Liu W, Pemo R, Metok T. Non-invasive study of natural dyes in textiles of the Qing Dynasty using fiber optic reflectance spectroscopy. Journal of cultural heritage. 2021 Jan 1;47:69-78. [HTML]

93. García-Bucio MA, Casanova-González E, Mitrani A, Ruvalcaba-Sil JL, Maynez-Rojas MÁ, Rangel-Chávez I. Non-destructive and non-invasive methodology for the in situ identification of Mexican yellow lake pigments. Microchemical Journal. 2022 Dec 1;183:107948. [HTML]

94. Mabrouk N. Identification of natural dyes in some archaeological Iranian carpets by non-destructive MALDI TOF MS. J Archit Arts Hum Sci. 2021. aaciaegypt.com

95. Celani CP, Degano I, Chen C, Jaeger O, Speed AM, Booksh KS, Alcántara-García J. Identification of Historical Textiles via Non-destructive Spectroscopic Analysis and Multivariate Cluster Analysis. researchsquare.com

96. Celani CP, Degano I, Chen C, Jaeger O, Speed AM, Booksh KS, Alcantara-Garcia J. Exploring elucidation of red dye mixtures on woolen historical textiles via non-destructive spectroscopic analysis and multivariate cluster analysis. Heritage Science. 2024 Feb 7;12(1):48. springer.com

97. Modupalli N, Naik M, Sunil CK, Natarajan V. Emerging non-destructive methods for quality and safety monitoring of spices. Trends in Food Science & Technology. 2021 Feb 1;108:133-47. [HTML]

98. Ndlovu PF, Magwaza LS, Tesfay SZ, Mphahlele RR. Destructive and rapid non-invasive methods used to detect adulteration of dried powdered horticultural products: A review. Food Research International. 2022 Jul 1;157:111198. [HTML]

99. Swarnalatha G. Preparation and Characterization of Catechin Loaded Niosomes for Fortification of Milk. 2020. egranth.ac.in

100. Vital de Sousa Junior W. PEA PROTEIN ISOLATE-GREEN TEA CATECHIN PICKERING PARTICLES FOR OIL-IN-WATER (O/W) EMULSION STABILITY. 2023. hawaii.edu

101. de Sousa Junior WV. Pea Protein Isolate-Green Tea Catechin Pickering Particles for Oil-in-Water (O/W) Emulsion Stability. 2023. [HTML]

102. Cortese M, Gigliobianco MR, Magnoni F, Censi R, Di Martino P. Compensate for or minimize matrix effects? Strategies for overcoming matrix effects in liquid chromatography-mass spectrometry technique: a tutorial review. Molecules. 2020 Jul 3;25(13):3047. mdpi.com

103. Badawy ME, El-Nouby MA, Kimani PK, Lim LW, Rabea EI. A review of the modern principles and applications of solid-phase extraction techniques in chromatographic analysis. Analytical Sciences. 2022 Dec;38(12):1457-87. springer.com

104. Greer B, Chevallier O, Quinn B, Botana LM, Elliott CT. Redefining dilute and shoot: The evolution of the technique and its application in the analysis of foods and biological matrices by liquid chromatography mass spectrometry. TrAC Trends in Analytical Chemistry. 2021 Aug 1;141:116284. sciencedirect.com

105. Kanu AB. Recent developments in sample preparation techniques combined with high-performance liquid chromatography: A critical review. Journal of Chromatography A. 2021. sciencedirect.com

106. Liu D, Tang W, Yin JY, Nie SP et al. Monosaccharide composition analysis of polysaccharides from natural sources: Hydrolysis condition and detection method development. Food Hydrocolloids. 2021. [HTML]

107. Dai W, Hu Z, Xie D, Tan J et al. A novel spatial-resolution targeted metabolomics method in a single leaf of the tea plant (Camellia sinensis). Food chemistry. 2020. [HTML]

108. Sun MF, Jiang CL, Kong YS, Luo JL et al. Recent advances in analytical methods for determination of polyphenols in tea: A comprehensive review. Foods. 2022. mdpi.com

109. Huang H, Li Z, He Y, Huang L, Xu X, Pan C, Guo F, Yang H, Tang S. Nontarget and high-throughput screening of pesticides and metabolites residues in tea using ultra-high-performance liquid chromatography and quadrupole-orbitrap high-resolution mass spectrometry. Journal of Chromatography B. 2021 Aug 1;1179:122847. [HTML]

110. Yu XL, Sun DW, He Y. Emerging techniques for determining the quality and safety of tea products: A review. Comprehensive Reviews in Food Science and Food Safety. 2020 Sep;19(5):2613-38. [HTML]

111. Ahmad R, Ahmad N, Al-Anaki WS, Ismail FA et al. … solvent extraction (ASE) coupled with ultra-high-pressure liquid chromatography (UHPLC-PDA) for the determination of methyl xanthines in commercial tea and …. Food chemistry. 2020. [HTML]

112. Morlock GE, Heil J, Bardot V, Lenoir L, Cotte C, Dubourdeaux M. Effect-directed profiling of 17 different fortified plant extracts by high-performance thin-layer chromatography combined with six planar assays and high-resolution mass spectrometry. Molecules. 2021 Mar 8;26(5):1468. mdpi.com

113. Kc Y, Parajuli A, Khatri BB, Shiwakoti LD. Phytochemicals and quality of green and black teas from different clones of tea plant. Journal of Food Quality. 2020;2020(1):8874271. wiley.com

114. Suhag MH, Ahmad MF, Khatun A. Physicochemical Parameters of Black Tea and Antibacterial Activity of Extracted Caffeine. academia.edu. . academia.edu

115. Aderibigbe OR, Kareem OF, Akinwumi SG. Comparative evaluation of the effects of pretreatments on the nutritional and chemical properties of ginger leaf-based herbal tea. African Journal of Food, Agriculture, Nutrition and Development. 2023 Apr 2;23(2):22548-67. ajol.info

116. Antony A, Farid M. Effect of temperatures on polyphenols during extraction. Applied Sciences. 2022. mdpi.com

117. Lezoul NEH, Belkadi M, Habibi F, Guillén F. Extraction processes with several solvents on total bioactive compounds in different organs of three medicinal plants. Molecules. 2020. mdpi.com

118. Manso T, Lores M, de Miguel T. Antimicrobial activity of polyphenols and natural polyphenolic extracts on clinical isolates. Antibiotics. 2021. mdpi.com

119. Dobrinčić A, Repajić M, Garofulić IE, Tuđen L, Dragović-Uzelac V, Levaj B. Comparison of different extraction methods for the recovery of olive leaves polyphenols. Processes. 2020 Aug 19;8(9):1008. mdpi.com

120. Deseo MA, Elkins A, Rochfort S, Kitchen B. Antioxidant activity and polyphenol composition of sugarcane molasses extract. Food Chemistry. 2020. academia.edu

121. Hassabo AG, Reda EM, Ghazal H, Othman HA. Synthesis of AgNPs and ZnONPs using tea leaves extract and their utilization to improve dyeability, printability and functionality of cotton and wool fabrics. Inorganic Chemistry Communications. 2023 Apr 1;150:110525. [HTML]

122. Ragab MM, Hassabo AG, Othman H. An overview of natural dyes extraction techniques for valuable utilization on textile fabrics. Journal of Textiles, Coloration and Polymer Science. 2022 Sep 1;19(2):137-53. ekb.eg

123. Win KH, Khaing T, Naing HH, Khaing YK. Extraction of tannin as a natural mordant from tea leaf for dyeing of cotton cloth. 2020. meral.edu.mm

124. El-Sayed GA, Diaa M, Hassabo AG. Potential uses of aloe veraextractionin finishing and textile wet process. Journal of Textiles, Coloration and Polymer Science. 2021 Dec 1;18(2):159-69. ekb.eg

125. Ghazal H, Elshamy M. Ecofriendly finishing and Dyeing of textile using bioactive agents derived from plant extracts and waste. Journal of Textiles, Coloration and Polymer Science. 2024 Dec 1;21(3):569-90. ekb.eg

126. Zohora KF, Arefin MR. Tea and Tea Product Diversification: A Review. Turkish Journal of Agriculture-Food Science and Technology. 2022 Dec 20;10(12):2334-53. agrifoodscience.com

127. Mueed A, Shibli S, Al-Quwaie DA, Ashkan MF, Alharbi M, Alanazi H, Binothman N, Aljadani M, Majrashi KA, Huwaikem M, Abourehab MA. Extraction, characterization of polyphenols from certain medicinal plants and evaluation of their antioxidant, antitumor, antidiabetic, antimicrobial properties, and potential use in human nutrition. Frontiers in Nutrition. 2023 Jun 21;10:1125106. frontiersin.org

128. Ghazal H, Elshamy MN. Journal of Textiles, Coloration and Polymer Science. 2024. ekb.eg

129. Hosen MS, Madhu B. Health Benefits of Herbal Tea: A Review. 2023. researchgate.net

130. Samanta P. A review on application of natural dyes on textile fabrics and its revival strategy. Chemistry and technology of natural and synthetic dyes and pigments. 2020 Jan 4:1-25. intechopen.com

131. Ebrahim SA, Mosaad MM, Othman H, Hassabo AG. A valuable observation of eco-friendly natural dyes for valuable utilisation in the textile industry. Journal of Textiles, Coloration and Polymer Science. 2022 Jun 1;19(1):25-37. ekb.eg

132. Nambela L, Haule LV, Mgani Q. A review on source, chemistry, green synthesis and application of textile colorants. Journal of Cleaner Production. 2020. [HTML]

133. Hassabo AG, El-Salam A, Neaama A, Mohamed NA, Gouda NZ, Khaleed N, Shaker S, El-Aziz A. Naturally extracted inks for digital printing of natural fabrics. Journal of Textiles, Coloration and Polymer Science. 2024 Jun 1;21(1):109-19. ekb.eg

134. Rather LJ, Zhou Q, Ali A, Haque QM, Li Q. Valorization of natural dyes extracted from Mugwort leaves (Folium artemisiae argyi) for wool fabric dyeing: optimization of extraction and dyeing processes with simultaneous coloration and biofunctionalization. ACS sustainable chemistry & engineering. 2020 Jan 27;8(7):2822-34. [HTML]

135. Liu S, Zhang Q, Li H, Qiu Z et al. Comparative assessment of the antibacterial efficacies and mechanisms of different tea extracts. Foods. 2022. mdpi.com

136. Musial C, Kuban-Jankowska A, Gorska-Ponikowska M. Beneficial properties of green tea catechins. International journal of molecular sciences. 2020 Mar 4;21(5):1744. mdpi.com

137. Amankwaah C, Li J, Lee J, Pascall MA. Antimicrobial activity of chitosan- based films enriched with green tea extracts on murine norovirus, Escherichia coli, and Listeria innocua. International Journal of Food Science. 2020;2020(1):3941924. wiley.com

138. Pavlović T, Dimkić I, Andrić S, Milojković-Opsenica D, Stanković S, Janaćković P, Gavrilović M, Ristivojević P. Linden tea from Serbia–an insight into the phenolic profile, radical scavenging and antimicrobial activities. Industrial Crops and Products. 2020 Oct 15;154:112639. [HTML]

139. Teixeira AM, Sousa C. A Review on the Biological Activity of Camellia Species. Molecules. 2021. mdpi.com

140. Singhee D. Review on natural dyes for textiles from wastes. Chemistry and Technology of Natural and Synthetic dyes and pigments. 2020 Aug 14:99-122. intechopen.com

141. Natarajan G, Rajan TP, Das S. Application of sustainable textile finishing using natural biomolecules. Journal of Natural Fibers. 2022. [HTML]

142. Periyasamy AP, Militky J. Sustainability in textile dyeing: recent developments. Sustainability in the textile and apparel industries: Production Process Sustainability. 2020:37-79. researchgate.net

143. Periyasamy AP. Recent advances in the remediation of textile-dye-containing wastewater: prioritizing human

health and sustainable wastewater treatment. Sustainability. 2024. mdpi.com

144. Abdel-Aziz E, Bakr M, Zayed M, Othman H, Hassabo AG. Microencapsulation and its application in textile wet processing: A review. Journal of Textiles, Coloration and Polymer Science. 2022 Sep 1;19(2):189-202. ekb.eg

145. Bibi A, Afza G, Afzal Z, Farid M, Sumrra SH, Hanif MA, Jinadasa BK, Zubair M. Synthetic vs. natural antimicrobial agents for safer textiles: a comparative review. RSC advances. 2024;14(42):30688-706. rsc.org

146. Riaz S, Ashraf M. Recent advances in development of antimicrobial textiles. Advances in Functional Finishing of Textiles. 2020. [HTML]

147. Pardi H, Fitriyah D, Silitonga FS, Edelwis TW, Wardani RK, Permana D, Priyangga A, Subagyo R, Ramdhani EP. The antimicrobial potential of ZnO-chitosan/pandan leaves: advancing antimicrobial textile technology. Journal of Dispersion Science and Technology. 2023 Dec 16:1-0. researchgate.net

148. Sankaran A, Kamboj A, Samant L, Jose S. Synthetic and natural UV protective agents for textile finishing. Innovative and emerging technologies for textile dyeing and finishing. 2021 Feb 1:301-24. researchgate.net

149. Kamal MS, Mahmoud E, Hassabo A, Eid MM. Effect of some construction factors of bi-layer knitted fabrics produced for sports wear on resisting ultraviolet radiation. Egyptian Journal of Chemistry. 2020 Nov 1;63(11):4369-78. ekb.eg

150. Pargai D, Jahan S, Gahlot M. Functional properties of natural dyed textiles. Chemistry and technology of natural and synthetic dyes and pigments. 2020 Jan 11:1-9. intechopen.com

151. Uddin F. Environmental hazard in textile dyeing wastewater from local textile industry. Cellulose. 2021. [HTML]

152. Huang R, Zhang S, Zhang W, Yang X. Progress of zinc oxide- based nanocomposites in the textile industry. IET Collaborative Intelligent Manufacturing. 2021 Sep 1;3(3):281-9. semanticscholar.org

153. Saleem H, Zaidi SJ. Sustainable use of nanomaterials in textiles and their environmental impact. Materials. 2020. mdpi.com

154. Arora L, Kaur R. A Study on Antimicrobial Finish on Textile Using Plant Extract. International Journal of Innovative Research in Computer Science & Technology. 2022 Mar 30;10(2):224-8. acspublisher.com

155. Adeel S, Anjum MN, Ahmad MN, Rehman F, Saif MJ, Azeem M, Hassan A, Imran M, Amin N. Eco-friendly dyeing of cotton fabric with waste tea leaves-based tannin natural dye. Global Nest J. 2021 Nov 1;23(3):365-9. gnest.org

156. Shariful Islam SM, Alam M, Akter S. Investigation of the color fastness properties of natural dyes on cotton fabrics. Fibers and Textiles. 2020. academia.edu

157. Hayat T, Adeel S, Batool F, Amin N, Ahmad T, Ozomay M. Waste black tea leaves (Camelia sinensis) as a sustainable source of tannin natural colorant for bio-treated silk dyeing. Environmental Science and Pollution Research. 2022 Apr;29(16):24035-48. [HTML]

158. Mandal S, Venkatramani J. A review of plant-based natural dyes in leather application with a special focus on color fastness characteristics. Environmental Science and Pollution Research. 2023 Apr;30(17):48769-77. [HTML]

159. Zayed M, Ghazal H, Othman H, Hassabo AG. Psidium guajava leave extract for improving ultraviolet protection and antibacterial properties of cellulosic fabrics. Biointerf. Res. Appl. Chem. 2022. bu.edu.eg

160. Otaviano BT, Sannomiya M, de Lima FS, Tangerina MM, Tamayose CI, Ferreira MJ, Freeman HS, Flor JP, da Costa SA, da Costa SM. Pomegranate peel extract and zinc oxide as a source of natural dye and functional material for textile fibers aiming for photoprotective properties. Materials Chemistry and Physics. 2023 Jan 1;293:126766. [HTML]

161. López-Malo A, Alzamora SM, Paris MJ, Lastra-Vargas L, Coronel MB, Gómez PL, Palou E. Naturally occurring compounds–Plant sources. Antimicrobials in food. 2020 Nov 10:527-94. [HTML]

162. Stéphane FF, Jules BK, Batiha GE, Ali I, Bruno LN. Extraction of bioactive compounds from medicinal plants and herbs. Natural medicinal plants. 2021 Aug 27:1-39. intechopen.com

163. Kurniawan YS, Priyangga KT, Krisbiantoro PA, Imawan AC. Green chemistry influences in organic synthesis: A review. Journal of Multidisciplinary Applied Natural Science. 2020 Oct 16;1:1-2. hal.science

164. Romani M, Warscheid T, Nicole L, Marcon L, Di Martino P, Suzuki MT, Lebaron P, Lami R. Current and future chemical treatments to fight biodeterioration of outdoor building materials and associated biofilms: Moving away from ecotoxic and towards efficient, sustainable solutions. Science of the Total Environment. 2022 Jan 1;802:149846. sciencedirect.com

165. Iqbal S, Ansari TN. Extraction and application of natural dyes. Sustainable practices in the textile industry. 2021. [HTML]

166. Gustiani S, Septiani W, Kasipah CI, Sukardan D, Helmy Q. Antimicrobial effect of Piper betle leaves extract on cotton fabrics for vaginal discharge sanitary napkins. Advanced Materials Research. 2021 May 6;1162:159-65. [HTML]

167. Koskelo L. Garden lupin (Lupinus polyphillus) as a textile fiber-chemical treatments for cellulose extraction. 2023. aalto.fi

168. Hoque MT, Benrui T, Grethe T, Mahltig B. Evaluation of chitosan based pretreatment for cotton and linen dyeing with direct dyes and reactive dyes. Communications in Development and Assembling of Textile Products. 2023 Jul 1;4(2):187-200. qucosa.de

169. Norman C, Marland V, McKenzie C, Ménard H, Daéid NN. Evaluation of fentanyl immunoassay test strips for rapid in-situ detection of fentanyl and fentanyl analogs in seized samples and alternative matrices. International Journal of Drug Policy. 2023 Aug 1;118:104102. sciencedirect.com