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# Chapter 1

## LIGNIN-BASED UV PROTECTIVE SYSTEMS FOR TEXTILE APPLICATIONS: STRUCTURAL FEATURES, MODIFICATION STRATEGIES, AND PERFORMANCE EVALUATION

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## 1. INTRODUCTION

Solar ultraviolet (UV) radiation is a primary factor contributing to photochemical degradation in polymeric materials, textile surfaces, and human health. In particular, exposure to radiation in the UVA (315–400 nm) and UVB (280–315 nm) ranges leads to significant problems, including skin cancer, photoaging, pigmentation disorders, and material fatigue (Hanson et al., 2006; Nichols & Katiyar, 2010).

As a result, there is a growing need for substances with a high capacity to absorb ultraviolet light, both in the textile sector and in other industrial application areas. Nowadays, many people use synthetic organic UV filters, such as benzotriazole, benzophenone, and cinnamate derivatives (Krause et al., 2018). However, the creation of sustainable substitutes is required due to issues with bioaccumulation, environmental persistence, and the production of hazardous byproducts (Downs et al., 2014).

In this context, lignin stands out as a naturally derived biopolymer with an aromatic structure and functional groups that exhibit high UV absorption capacity. Accounting for approximately 15–30% of lignocellulosic biomass, lignin is obtained in large quantities as a by-product of industrial processes such as kraft, soda, and organosolv pulping. Structurally, it is an amorphous and heterogeneous macromolecule composed of a complex polymeric network formed by guaiacyl (G), syringyl (S), and p-hydroxyphenyl (H) units linked via ether and C–C bonds (Sadeghifar & Ragauskas, 2020). Due to chromophoric features such as aromatic rings, conjugated double bonds, quinone and chalcone structures, and metal complexes, lignin demonstrates high UV absorption in the 250–400 nm range. In addition, auxochromic groups such as hydroxyl, carbonyl, and methoxyl groups enhance its optical properties and strengthen its photophysical performance (Zhang & Naebe, 2021).

However, limited solubility, low purity, and dark coloration of lignin in its native form restrict its direct applicability. This has prompted the development of various modification strategies aimed at improving its functional properties. Chemical modifications such as acetylation, phenolation, amidation, and metal complexation have been studied. Additionally, approaches like particle size reduction, nanolignin production, and the formation of composites with polymer matrices have been explored (Zhang et al., 2019b). Nanolignin produced via microbial or solvothermal methods provides more homogeneous dispersion, a larger surface area, and strong binding capacity, allowing it to offer effective UV protection, especially on textile surfaces (Zimniewska et al., 2008).

The biodegradable nature of lignin, its lack of toxicity, low cost, and wide availability make it an environmentally friendly alternative to synthetic UV absorbers. In this regard, the utilization of lignin holds strategic importance within efforts to develop sustainable textile materials and low-impact protective systems. In this study, the chemical characteristics of lignin, the chromophoric structures underlying its UV absorption behavior, modification approaches for practical applications, and its potential use in the textile sector are examined from a holistic perspective.

## **2. CHEMICAL STRUCTURE OF LIGNIN AND ITS UV ABSORPTION MECHANISM**

Ultraviolet (UV) radiation constitutes the portion of the electromagnetic spectrum emitted by the sun that has a shorter wavelength than visible light and is classified into three main regions: UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm). Excessive exposure to UV radiation can lead to serious health problems in humans, including sunburn, photodegradation of skin tissue, and cancer in plants (Verma et al., 2024). It weakens photosynthetic activity, while in polymer-based materials, it causes structural degradation. A significant proportion of synthetic UV absorbers are photochemically unstable and, upon exposure to light, can generate radical species that exert toxic effects on biological tissues. In contrast, lignin is an aromatic biopolymer that naturally functions as a UV barrier in plants and provides protection against photo-oxidative processes (Gioia et al., 2025). Owing to its antioxidant properties and macromolecular structure, it effectively absorbs UV light and poses a low risk to both the environment and human health.

The energy of UV photons can promote electrons from bonding orbitals to antibonding orbitals. The amount of energy required for these electronic transitions varies depending on the molecular structure and the energy level of the electrons involved. The principal types of electronic transitions induced by UV radiation are classified into four categories: (1)  $\sigma \rightarrow \sigma^*$ , (2)  $\pi \rightarrow \pi^*$ , (3)  $n \rightarrow \pi^*$ , and (4)  $n \rightarrow \sigma^*$ . Among these, only  $\pi \rightarrow \pi^*$ ,  $n \rightarrow \pi^*$ , and  $n \rightarrow \sigma^*$  transitions can occur with photon energies corresponding to the 200–800 nm range of the UV and visible spectrum.  $\sigma \rightarrow \sigma^*$  transitions, on the other hand, require much higher energy and therefore generally occur at wavelengths below 200 nm, outside the UV-Vis analytical range (Picollo et al., 2019; Zhang & Naebe, 2021).

Accordingly, absorption of light in the UV-Vis region can only be achieved by functional groups containing  $\pi$  bonds or lone electron pairs (Zhang & Naebe, 2021). Structural units with some features such as aromatic rings, carbonyl groups (C=O), and oxygen- or nitrogen-containing functional

groups are referred to as chromophores and endow molecules with the capacity to absorb light (Paulsson & Parkås, 2012). In this context, lignin, a biopolymer rich in  $\pi$ -electron systems and lone electron pairs, is capable of effectively absorbing UV radiation. Owing to its aromatic structures and the lone pairs on oxygen atoms, pure lignin has a strong absorption capacity, especially in the 250–400 nm wavelength range. This makes lignin a promising material for developing natural UV-protective products (Sadeghifar & Ragauskas, 2020).

## 2.1. Aromatic Structure and the Role of Chromophore Groups

Lignin's structure contains a variety of chromophoric groups that contribute to its ability to absorb ultraviolet (UV) light. These groups consist of conjugated systems or functional units containing lone electron pairs, which absorb photon energy and enable electronic transitions. The primary chromophores responsible for UV absorption in lignin can be categorized into five main classes: (1) double bonds conjugated with aromatic rings ( $-\text{CH}=\text{CH}-$ ), (2) quinone methide and quinone derivatives, (3)  $\alpha,\beta$ -unsaturated carbonyl systems, (4) free radical centers, and (5) metal complexes associated with catechol structures (Zhang & Naebe, 2021).

Lignin consists of three main phenylpropane units, p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S), which are connected by linkages such as  $\beta$ -O-4,  $\beta$ - $\beta$ ,  $\beta$ -5, and 5-5, forming a complex and irregular macromolecular network (Zhang et al., 2025). Although this heterogeneous structure complicates its characterization, it enables the presence of chromophoric and auxochromic groups that contribute to UV absorption. Aromatic rings enable  $\pi \rightarrow \pi^*$  transitions, while double bonds in the side chains, oxidative products, and carbonyl groups contribute to  $n \rightarrow \pi^*$  transitions (Wang et al., 2019).

Lignin absorbs UV radiation within the 250–400 nm wavelength range because of the  $\pi$ -electron systems in its aromatic rings and the lone electron pairs on oxygen atoms. These electronic systems are activated by UV photons, allowing  $\pi \rightarrow \pi^*$  and  $n \rightarrow \pi^*$  transitions (Gioia et al., 2025). An increase in the degree of conjugation, meaning a broader delocalization of  $\pi$ -electrons, reduces the energy required for electronic excitation and shifts absorption toward longer wavelengths. Consequently, the color of lignin is directly linked to the types of chromophores it contains, their abundance, and the extent of conjugation (Ajao et al., 2018). The relationship between color and chromophore content is considered a key parameter in the development of lignin-based UV absorbers.

Technical lignins obtained through pulping processes contain UV-active functional units such as methoxylated phenolic rings, quinone structures, and conjugated carbonyl groups (Argyropoulos, 1994). These

chromophores produce distinct absorption bands in the UV-Vis region; phenolic structures, in particular, exhibit strong absorption in both the UVA and UVB regions (Nichols & Katiyar, 2010). Unsaturated functional groups, aromatic rings, and conjugated carbon-carbon double bonds are the primary light-absorbing entities that give lignin its dark brown to nearly black color. As a result, exposure to irradiation can lead to photo-yellowing in lignocellulosic fibers (Jiang et al., 2022).

The UV protective performance of lignin is also influenced by phenolic substructures, molecular weight, and dispersion characteristics. Phenolic groups help absorb UV light and also offer antioxidant activity. However, they can affect photostability, color changes, and the overall effectiveness of UV protection. Notably, syringyl (S) units, which contain more methoxyl groups, have been reported to absorb UV more effectively than other phenolic structures. Additionally, differences in lignin's molecular weight can influence its dispersion behavior and, consequently, its UV protection performance (Qian et al., 2015).

## **2.2. UV Behavior of Lignin Fractions**

The structural transformation of lignin occurs in two main stages: first, it is separated from lignocellulosic biomass, and then the isolated lignin undergoes chemical modification. The first stage involves extraction methods commonly used in the paper industry and biorefineries to separate lignin from the cellulose-hemicellulose matrix. The chemical, biological, or physical methods applied at this stage cause notable structural variations in lignin, affecting its molecular weight, functional group content, degree of conjugation, and aromatic character (Huang et al., 2019). Therefore, the extraction method directly influences both the chemical modification of the resulting lignin and its capacity to absorb UV radiation.

Chemical-based extraction techniques, particularly kraft, soda, organosolv, and lignosulfonate processes, shape the structural integrity and functional properties of lignin. The different types of lignin obtained through these methods, such as technical kraft lignin, lignosulfonates, and organosolv lignin, differ in terms of monomer distribution, molecular weight, and functional group content (Ahuja & Roy, 2020). Fractions with low molecular weight and high phenolic content generally exhibit higher UV absorption. However, these structures can also present challenges such as dark coloration and limited photostability. For instance, kraft lignin (KL) is typically rich in phenolic groups, possesses a highly aromatic structure, and is characteristically dark in color. In contrast, organosolv methods, owing to their milder processing conditions and use of organic solvents, enable the production of more homogeneous and lighter-colored lignin,

which is functionally advantageous, particularly in UV barrier materials (Zhang & Naebe, 2021).

Following extraction, the second stage involves the chemical modification of lignin. In this context, reactions such as acetylation, amidation, phenolation, metal ion complexation, and esterification are employed to improve the optical, photostable, and surface properties of lignin. These chemical modifications can improve lignin's UV absorption by changing the conjugation in aromatic rings or adjusting chromophore–auxochrome interactions (Figueiredo et al., 2018). At the same time, they can reduce color intensity, yielding a more acceptable appearance for applications in textiles, coatings, and composites. Therefore, lignin extraction and modification should be seen not just as structural changes but as crucial steps that determine the material's final performance.

### **3. ENHANCEMENT OF LIGNIN'S UV PROPERTIES: MODIFICATION STRATEGIES**

#### **3.1. Chemical Modifications**

The UV-protective properties of lignin are directly linked to the type and distribution of its functional groups. In this context, methoxyl groups are among the primary elements that determine the effectiveness of lignin against ultraviolet radiation. An increase in the amount of methoxyl groups enhances UV absorption capacity due to the lone electron pairs on the oxygen atoms of these groups. However, natural lignin may not be directly suitable for use. Its dark color, low solubility, high polydispersity, and limited binding capacity are among the main disadvantages. To overcome these limitations, various chemical modification techniques are applied to lignin (Zhang & Naebe, 2021). Modifications such as acetylation, esterification, amination, sulfonation, phenolation, polymer grafting, or complexation with metal ions aim to improve its solubility, dispersibility, color stability, and functional performance. Through these treatments, it becomes possible to regulate chromophore–auxochrome interactions, increase visible light transmittance, enhance photostability, and optimize adhesion to fiber surfaces (Mondal et al., 2023). In particular, the modification of phenolic OH groups enhances compatibility with polymer matrices, contributing to transparency and homogeneous dispersion. Additionally, the formation of complexes between lignin and metal ions such as  $Zn^{2+}$  or  $Ti^{4+}$  can improve both UV absorption efficiency and photostability. Limiting crosslink density through nanoparticle coating or structural rearrangement of lignin rings helps reduce color intensity and the rate of photodegradation (Komisarz et al., 2022).

Qian et al. (2016) compared different lignin types obtained from five technical sources (alkali lignin, low-sulfonate alkali lignin, organosolv lignin, enzymatic hydrolysis lignin, and sodium lignosulfonate) and examined changes in SPF values with 10% lignin incorporation. Organosolv lignin was reported to have the highest SPF value. Organosolv lignin, with the highest methoxyl group content, provided the most effective UV protection, whereas enzymatic hydrolysis lignin had the lowest methoxyl content. These findings indicate that methoxyl groups make a significant contribution to UV absorption due to their electron-donating role in the conjugated system.

Lee et al. (2019) compared the UV protection capacity of lignin obtained from *Miscanthus sacchariflorus* via 72-hour ball milling at room temperature with that of organosolv lignin. While organosolv lignin demonstrated higher UV protection performance in the 260–280 nm range, lignins milled in a neutral environment, such as 95% aqueous dioxane, were found to have a lighter color. This may offer an advantage in terms of color improvement for cosmetic and textile applications.

Tian et al. (2017) produced two types of lignin nanoparticles from lignins obtained using deep eutectic solvent (DES) and ethanol–organosolv methods. These spherical nanoparticles, approximately 200 nm in size with a low polydispersity index and low zeta potential, were reported to exhibit stable dispersion in aqueous media. Such features make lignin nanoparticles promising candidates for the production of light-colored nanocomposites and UV protection applications.

The choice of modification strategy varies depending on the source of lignin, the intended application, and the desired performance characteristics. Some treatments may reduce chromophore density and narrow the absorption range, while others may provide broader-spectrum protection yet increase color intensity. Therefore, optimizing modification degree, light absorption behavior, and color properties through regular feedback based on experimental spectral analysis is of critical importance.

### **3.2. Lignin nanoparticles (LNPs)**

Lignin nanoparticles (LNPs) reduce surface and dispersion problems of lignin and increase its surface area, which improves UV absorption efficiency. These properties enable LNPs to improve emulsion stability and positively contribute to the sun protection factor (SPF) (Piccinino et al., 2021).

Tan et al. (2019) reported that spherical lignin nanoparticles derived from organosolv lignin exhibit superior UV protection performance compared

to irregularly shaped organosolv lignin particles. This benefit is due to the larger surface area of the spherical particles, which enables more phenolic OH groups to remain on their surfaces. The hydrophobic aromatic skeletons spontaneously form spherical structures, further facilitating effective UV shielding by the lignin nanoparticles.

Moreover, the high surface area of lignin nanoparticles allows for a greater density of chromophores per unit mass, enhancing UV protection efficiency. This property reduces the amount of lignin required to achieve a certain level of UV protection, enabling the production of lighter-colored materials. High particle concentration and extensive surface area thus play a critical role in improving overall UV shielding performance (Zhang & Naebe, 2021).

### **3.3. Lignin-Based Hybrid Systems and UV Protection Strategies**

In recent years, interest in the use of lignin and its derivatives as UV-protective agents in textile applications has increased significantly. Lignin is considered an environmentally friendly alternative due to its renewable nature, low toxicity, phenolic structure, and high UV absorption capacity.

#### **3.3.1. Combination with Inorganic UV Absorbers**

Inorganic UV blockers are widely employed in textile materials due to their high photostability, non-toxicity, and long service life. These compounds primarily reduce UV radiation by physical scattering or reflection (Lowe, 2006). Talc, kaolin, iron oxide ( $\text{Fe}_2\text{O}_3$ ),  $\text{TiO}_2$ , and ZnO are among the most commonly used inorganic agents. In particular,  $\text{TiO}_2$  and ZnO nanoparticles offer protection against both UVA and UVB radiation due to their high refractive index and broad-band absorption characteristics (Hassanin et al., 2013).

Reducing ZnO nanoparticles to the nanoscale increases their surface area, thereby enhancing light scattering and absorption efficiency. Consequently, significant improvements in UV protection (UPF) have been reported for cotton fabrics coated with ZnO (Raman et al., 2022). A study has shown that ZnO nanoparticles fixed to textile surfaces via epoxy-based binders provide long-term UV protection.  $\text{TiO}_2$ , in addition to UV shielding, enables the production of antibacterial, self-cleaning, and superhydrophobic textiles through its photocatalytic activity (Kaur et al., 2021).

Owing to these advantages, inorganic UV absorbers have become essential components in the development of sustainable and multifunctional protective textiles. A major limitation of metal oxides, especially ZnO, is that they tend to aggregate. This aggregation can reduce surface uniformity

and lower UV protection performance. In this context, lignin emerges as a low-cost, photostable, biodegradable, and non-toxic alternative (H. Wang et al., 2017). In lignin–metal oxide composites, ZnO or TiO<sub>2</sub> nanoparticles are better dispersed, photocatalytic activity is minimized, and toxicity is reduced.

### **3.3.2. Combination with Organic UV Absorbers**

Organic UV absorbers typically comprise benzene derivatives, benzotriazoles, cinnamates, benzophenones, and triazine-based structures. These compounds prevent photodegradation by converting absorbed UV energy into heat through vibrational relaxation (Wu et al., 2019). In the textile industry, they are commonly applied via surface coatings or covalent bonding to fibers. Additionally, natural compounds such as aloe vera, green tea, polyphenols, flavonoids, tannins, carotenoids, and plant extracts are increasingly recognized as eco-friendly organic UV barriers (Saha et al., 2024). Beyond UV protection, these natural compounds impart antimicrobial and antioxidant properties, enabling the development of multifunctional textiles.

### **3.3.3. Integration into Polymer Matrices**

Lignin has been utilized in biopolymers, synthetic polymers, and composite systems to develop materials with enhanced UV resistance. In biopolymer-based systems like cellulose acetate and polylactic acid, lignin coatings or its dispersion within the matrix offer UV protection as well as antimicrobial and coloring properties. Due to the limited wash fastness of lignin, chemical modifications such as esterification, amidation, or conversion into nanoparticle form are commonly employed to improve its durability (Saha et al., 2024).

In lignin composites prepared with gelatin, clay, or cellulose derivatives, UV absorption can reach levels of 95–98%, although transparency varies depending on the lignin concentration. Similarly, in composites with synthetic polymers such as PLA, PVA, PBS, and PEO, lignin incorporation enhances not only UV protection but also mechanical performance and optical properties (Zhang & Naebe, 2021).

### **3.4. Solving Color and Transparency Problems**

Despite its strong UV-absorbing properties, the dark color of lignin remains a major barrier to the commercial adoption of lignin-based UV-protective products. When light interacts with chromophores in the 200–800 nm wavelength range, absorption in the visible region (400–800 nm) leads to the characteristic dark color of lignin. In contrast, UV protection requires absorption only in the 200–400 nm range. While chemical bleaching methods can lighten lignin, these treatments often result in the

loss of UV-active chromophores (Lee et al., 2019). Similarly, incorporating dark-colored technical lignin can enhance UV protection but reduce the transparency of the composite. Therefore, a major challenge is to lighten lignin's color while still maintaining or improving its UV-protection ability (Zhang et al., 2019a). Recent studies indicate that this issue can be addressed by minimizing particle size and optimizing the morphology of lignin. Small, spherical lignin particles enhance UV-blocking performance and also help produce lighter-colored composites.

#### **4. Lignin-Based UV-Protector Application Areas**

Lignin is a natural macromolecule capable of effectively absorbing UV radiation due to its aromatic structure. This property allows lignin to serve as a standalone UV absorber and also to enhance the protection performance, reducing potential toxicity when combined with inorganic, organic, or biopolymer-based UV filters. The parameters used to evaluate UV protection vary depending on the material type (Zhang & Naebe, 2021). In sunscreen products, this function is assessed using the Sun Protection Factor (SPF) (ISO, 2019), whereas in textile surfaces it is expressed as the Ultraviolet Protection Factor (UPF). SPF indicates the reduction in UV radiation reaching protected skin compared to unprotected skin. For textile materials, measurements are typically based on the 400 nm wavelength, and UV-visible spectrophotometric techniques are commonly employed (Downs & Harrison, 2018).

**Sunscreen formulations:** Lignin and lignin-derived nanoparticles (LNPs) are being studied as natural and sustainable UV filters in sunscreens. Adding these particles can boost SPF levels, and combining lignin with mineral oxides (such as  $\text{TiO}_2$  or  $\text{ZnO}$ ) offers broad-spectrum protection while balancing product performance with appearance (Lima et al., 2012). However, the brownish color of lignin remains a limiting factor for cosmetic appeal.

**Packaging films and coatings:** The incorporation of lignin into polymer-based packaging materials holds potential for reducing UV-induced photodegradation, particularly in food packaging applications. Studies have shown that lignin addition can limit UV damage, although it may also reduce optical transparency. Therefore, achieving an optimal balance between transparency and protection is of critical importance (Sadeghifar & Ragauskas, 2020).

**Textile and coating applications:** Lignin or lignin-based hybrid coatings provide UV stabilization on textile surfaces, thereby improving material durability. Within paint and coating systems, lignin contributes not only to

UV protection but also to overall performance enhancement due to its antioxidant properties (Raman et al., 2022).

**Polymer composites and outdoor applications:** Lignin can be used as a functional additive or filler in polymer matrices. Besides absorbing UV capability, it can affect mechanical properties, which is especially beneficial for composites used in outdoor conditions. In such systems, lignin is effective in slowing down surface photodegradation processes (Ridho et al., 2022).

Research efforts on the development of lignin-based UV-protective composites for applications such as food packaging, solar panels, and healthcare products are steadily increasing.

## **5. LIGNIN-BASED UV PROTECTION SYSTEMS IN TEXTILE APPLICATIONS**

Ultraviolet (UV) radiation can exert various harmful effects on human health, including severe sunburns and skin cancers. Additionally, UV exposure can cause photosensitivity reactions in people taking certain medications, and, although rare, it may lead to mutations in genetic material. In this context, lignin, a naturally occurring phenolic biopolymer, has gained attention as an effective UV-blocking material due to its strong UV-absorbing properties and is increasingly employed in diverse applications.

The performance of lignin-based UV-protective systems is typically assessed using various analytical methods. For textile or film-based systems, the Ultraviolet Protection Factor (UPF) is commonly employed, providing a quantitative measure of the extent to which UV radiation is blocked. Additionally, UV–Vis spectral absorption and transmission measurements over the 280–400 nm wavelength range allow evaluation of the system's protective efficacy across specific UV bands (Petkovska et al., 2022; Sadeghifar & Ragauskas, 2020). These analyses are critical for optimizing the performance of lignin-based UV systems and assessing their suitability for targeted applications.

### **5.1. The Effect of Fabric on UV Protection Factor (UPF)**

The ultraviolet protection factor (UPF) is one of the primary indicators used to assess the protective capacity of a textile material against UV radiation, and this value is directly influenced by the physical, chemical, and structural properties of the fabric.

**1. Fiber chemistry:**

The chemical composition of the fiber is a key determinant of UV transmission through the fabric. Naturally occurring components within the fiber, such as lignin and pectin-like substances, can enhance its capacity to absorb UV radiation (Attia et al., 2022). Lignin exhibits strong UV-absorbing behavior due to its aromatic structure. Among natural fibers, silk shows higher UV absorption compared to cotton and wool. Wool fibers offer low transmittance in the 280–400 nm range, while among synthetic fibers, polyester tends to provide higher absorption relative to acrylic and polyamide (Sankaran et al., 2021).

**2. Moisture content:**

The moisture-retention capacity of the fiber is another parameter that affects UPF. Hydrophilic fibers absorb more water and swell, which increases the cross-sectional area of the fibers. As a result, the spaces between yarns are reduced, fabric density rises, and UV transmittance decreases. Since viscose fibers are highly sensitive to moisture, this effect is particularly pronounced. The dense, fine structure of silk fibers enhances water uptake through capillary action, which helps strengthen the UV barrier (Saha et al., 2024).

**3. Yarn structure:**

The physical characteristics of the yarn influence the optical path of light within the fabric and thus affect UV protection. Twist level, fiber compactness, and surface smoothness directly impact porosity. Yarns with higher twist reduce the voids through which light can pass. As yarn linear density decreases, the fabric becomes more porous and UPF drops. Therefore, fabrics produced with thicker, tightly twisted yarns offer a more effective UV barrier (Stankovic et al., 2009).

**4. Cover factor and porosity:**

The cover factor (Cf) of a fabric refers to the area occupied by warp and weft yarns on the surface and is generally associated with yarn density (EPI/PPI). There is a positive correlation between UPF and Cf: as density increases, porosity decreases, and UV transmittance is reduced. Additionally, as fabric weight and thickness increase, blocking UV radiation becomes easier. In this context, woven fabrics generally offer higher UPF than knitted fabrics, which naturally have larger loop-based gaps (Polona Dobnik Dubrovski & Golob, 2009).

**5. Fabric construction:**

The weave type of the fabric is another major factor determining UV transmittance. Plain, twill, and satin weaves differ in their permeability. Structures such as satin and twill contain fewer voids and thus provide

higher UPF values. Even at similar weights, loosely constructed fabrics allow greater UV transmission.

### **6. Chemical finishing processes:**

Processes such as bleaching, dyeing, and finishing can significantly alter the UV protection capacity of a fabric. During bleaching, lignin and natural pigments are removed, which causes a reduction in UPF. Numerous studies have shown that different dye types and colors can markedly influence transmittance depending on the fiber type (Sarkar, 2007).

In conclusion, a textile's UV protection is influenced not just by the fiber type, but also by moisture content, yarn structure, fabric construction, porosity, cover factor, and chemical treatments. Each of these variables influences the optical, physical, and chemical properties of the fabric and contributes to the final UPF value. Therefore, in developing textiles that provide high levels of protection, these parameters must be optimized in a holistic and balanced manner.

### **5.2. Textile Application Techniques**

Enhancing the UV protection capacity of textile materials is primarily achieved by integrating UV-absorbing compounds onto the fabric surface. The incorporation of lignin-based UV protection systems into textiles can be carried out through various approaches. The most common methods include surface coating (dip-coating, pad-dry-cure, sol-gel applications), impregnation (saturating fibers with lignin dispersions), production of lignin-loaded nanofibers via electrospinning/microencapsulation, and composite fiber manufacturing (Mavrić et al., 2018).

In coating methods, lignin dispersions are applied to the fabric using a suitable binder, which ensures adhesion between the lignin and the fibers, allowing the coating to anchor effectively. Parameters such as coating homogeneity, particle size distribution, the chemical structure of the binder, number of layers, and drying-curing conditions directly influence UV performance (Pandit, 2021). In the impregnation approach, fibers are immersed in dispersions containing lignin nanoparticles, enabling penetration not only to the surface but also to internal regions. Reducing particle size increases surface area, thereby enhancing UV absorption efficiency. Lignin-loaded nanofibers, produced by methods like electrospinning, can be used as surface coatings or incorporated into textiles by blending with natural or synthetic fibers. In composite fiber production, fibers are spun using polymer matrices containing lignin, embedding lignin directly into the fiber structure. This method can reduce surface-related losses; however, lignin-polymer compatibility, thermal stability, and process optimization must be considered.

When applying lignin-based UV systems to textile surfaces, several performance criteria must be considered, including the UV protection level (UPF value), visible light transmittance, wash durability, resistance to rubbing and abrasion, breathability, and visual and tactile aesthetics (Bashari et al., 2019). Achieving a balanced optimization among these parameters is the key factor determining the success of the application.

Among the most frequently used techniques in textile surface modification for UV protection is the dip-coating method. In this method, the fabric is immersed in a solution containing UV absorbers, with the aim of achieving a homogeneous distribution of the compound on the surface. Its ease of application, low cost, and controllable coating properties make it widely preferred at the industrial scale. Additionally, nanoparticle-form UV absorbers are often employed to enhance long-term stability. Due to their large surface area, nanoparticles can form stronger interactions with the fabric and improve durability (Tang & Yan, 2017).

The pad-dry-cure method is another commonly employed strategy in textile modification. In this approach, the fabric is immersed in a solution containing the UV absorber and then passed through squeezing rollers to remove excess solution. Following the drying process, the curing stage enables fixation of the active compounds onto the fiber surface (Shen et al., 2022). This method is highly efficient for integrating active substances such as nanoparticles and microcapsules into the textile structure. Controlled application of the curing stage promotes uniform compound distribution and sustained release over time (Downs & Harrison, 2018).

Overall, the methods used for modifying textile surfaces for UV protection enhance fabric functionality and create durable and long-lasting barriers against harmful solar radiation. Such strategies provide a strong foundation for the development of environmentally sustainable, durable, and high-performance UV-protective textiles.

## **6. FUTURE PERSPECTIVES**

Lignin-based UV protection systems provide broad-spectrum UV absorption owing to their natural aromatic structures. In addition, lignin exhibits antioxidant activity and can interact synergistically with synthetic UV absorbers. These attributes make it a promising sustainable material. However, several structural and technical limitations encountered at the application scale restrict its industrial use.

Lignins obtained from the pulp and paper industry are predominantly dark in color, which limits their application in cosmetics, food packaging, and transparent film systems (Zhang et al., 2019a). Current modification efforts typically aim to enhance lignin's UV protection or lighten its color, while strategies that improve both simultaneously are rare. Alkaline or acidic processes and the use of organic solvents during production tend to further darken lignin, making it difficult to obtain light-colored and UV-active lignins through sustainable methods. Therefore, the development of environmentally friendly strategies that enable the production of lignin with both high UV protection and lighter appearance remains an active area of research.

The long-term degradation products and toxicological effects of lignin and lignin-derived systems have not yet been fully characterized. Particularly in applications involving skin contact or food contact, comprehensive toxicological data are required to ensure safe use (Tran et al., 2021). In textile applications, various technical challenges also persist, with one of the most critical issues being the poor wash durability of lignin-treated fabrics.

An effective UV protection system should leverage lignin's UV-blocking capacity while maintaining visible light transmittance, ensuring stability under prolonged UV exposure, preserving performance through washing, avoiding negative effects on fiber strength, and remaining economically feasible.

## **7. RESULTS AND OVERALL ASSESSMENT**

Lignin is a bio-based component that has attracted considerable attention in the development of sustainable UV-protective materials due to its broad-spectrum UV absorption capacity, antioxidant activity, and chemical processability. Lignin's color and UV protection efficiency depend on phenolic groups with high methoxyl content and oligomer fractions of specific molecular weights. For instance, methoxyl groups in lignin enhance UV absorption but simultaneously darken its color.

Despite its strong UV-absorbing properties, the dark coloration of lignin constitutes a major barrier to the commercialization of lignin-based products. Lignin-based composites can interact synergistically with various UV absorbers in protective applications. These combinations offer a wide range of potential uses from food packaging to biomedical materials and sunscreen formulations by optimizing the mechanical strength, dispersion characteristics, and optical transparency of the composites.

Overall, lignin and its derivatives hold significant potential as UV-blocking agents in the textile industry due to advantages such as low cost, environmental sustainability, biocompatibility, and high UV protection efficiency. However, further research is needed to optimize color stability and surface bonding mechanisms. If these technical challenges can be overcome, lignin-based UV-protective coatings are expected to play a key role in the development of long-lasting, environmentally friendly, and economically viable functional materials for the textile sector.

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# Chapter 2

## LIGNIN-BASED FUNCTIONAL TEXTILES: STRUCTURE, PROPERTIES, AND ANTIMICROBIAL APPLICATIONS

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## 1. INTRODUCTION

Textiles are an integral part of daily life and, because they are in constant contact with the human body, provide a favorable environment for the transmission and development of microorganisms. Particularly in products such as sportswear, medical textiles, and underwear, factors such as humidity, temperature, and skin contact create ideal conditions for pathogen growth. This presents a significant problem for both user health and product hygiene. With increasing health awareness, the need for hygienic and functional textile materials that can prevent microbial contamination is increasing (Bibi et al., 2024). Conventionally, metal nanoparticles such as silver, copper, and zinc oxide, or synthetic antibacterial agents (e.g., chitosan, N-Halamine, quaternary ammonium compounds) are used for this purpose (Shah et al., 2022; Emam et al., 2018). However, due to the environmental toxicity, bioaccumulation, and cost issues of these substances, the development of sustainable and bio-based alternatives has become crucial (Babaeipour et al., 2024). In this context, lignin attracts attention as the most abundant aromatic component of plant biomass (Tao et al., 2020).

Lignin is a structural component of plant cell walls and, along with cellulose and hemicellulose, a major component of the lignocellulosic matrix. Millions of tons of lignin are produced annually worldwide as a byproduct of the pulp and biofuel industries, but the majority of this material is burned as a low-value fuel (Al-Zagameem, 2020; Souza et al., 2020). However, lignin's polyphenolic structure, biocompatibility, UV-absorbing capacity, natural antioxidant and antimicrobial activity make it an environmentally friendly additive for functional textiles (Babaeipour et al., 2024).

Recent studies have shown that lignin can have a direct inhibitory effect against microorganisms and that this feature is due to the phenolic hydroxyl and methoxy groups. (Shu et al., 2021). It has been shown that lignin can be used in both free and nanoparticle form to provide antimicrobial, antioxidant and UV protective functions to textile surfaces (Ali et al., 2022). Thus, lignin is considered as a functional agent that is both natural and environmentally compatible within the scope of sustainable textile design. The use of lignin in the development of sustainable textiles not only provides environmental advantages but also creates added economic value (Raman et al., 2022). Lignin supports the circular economy by utilizing agricultural waste or industrial byproducts (Tardy et al., 2023). Therefore, lignin is considered an important biopolymer source for both materials science and textile engineering, within the framework of "green chemistry" principles (Jiju et al., 2025).

## 2. CHEMICAL STRUCTURE AND PROPERTIES OF LIGNIN

Lignin is the second most abundant biopolymer after cellulose and the most abundant aromatic polymer in nature (Beisl et al., 2017). Anatomically, lignin is an important structural material for forming the cell wall of terrestrial vascular plants (Bruijninx et al., 2015). In the cell wall, lignin fills the spaces between cellulose, hemicelluloses, and pectin, covalently binds to hemicellulose, serves as a binding agent for various plant polysaccharides, and ultimately provides integrity to the plant cell wall (Doherty et al., 2011). Lignin is present in plants in varying proportions. Softwoods contain 25–35% lignin, while hardwoods contain 20–25% lignin (Christensen, 2013). Lignin is synthesized via radical polymerization of phenylpropanoid units (C9 units) from three building blocks, namely p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) (Zhao et al., 2010). Lignin obtained from softwoods consists primarily of moieties derived from coniferyl alcohol (G), hardwoods lignin contains residues derived from both coniferyl and sinapyl alcohols (G-S), and lignin obtained from herbaceous plants contains three basic phenol units (H-G-S) (Fengel and Wegener, 1984). The proportion of monolignols in each lignin group also varies depending on the plant species (Gellerstedt and Henriksson, 2008).

Lignin contains a variety of functional groups; the most common are aromatic methoxyl and phenolic hydroxyl, aliphatic hydroxyl, and a small amount of carbonyl groups. The monomeric C9 unit is linked by C–O–C and C–C bonds to form a polymer. Approximately 50% of the interunit bonds in lignin (approximately 45% in softwoods and up to 60% in hardwoods) are  $\beta$ -O-4 ether-type bonds. Other common lignin interunit bonds are  $\alpha$ -O-4, resinol ( $\beta$ - $\beta'$ ), phenylcoumaran ( $\beta$ -5), 5-5', and 4-O-5. The number of these structures varies in different lignins (Mandlekar et al., 2018). Lignin serves four fundamental roles in plants: providing rigidity to the cell wall, bonding different cells together in woody tissues, making the cell wall hydrophobic, and protecting wood against microbial degradation (Flores et al., 2015).

Traditional lignin extraction methods from lignocellulosic biomass can be obtained by different chemical methods such as sulfur-containing (sulfite and kraft method), non-sulfur (soda, organosolv), steam explosion, ionic liquids and deep eutectic solvents, or mechanical methods, depending on the final application of lignin and other by-products (cellulose and hemicellulose) (Lobato-Peralta et al., 2021).

Lignin, thanks to its natural phenolic structure, high aromatic content, and rich functional groups, is a sustainable biopolymer with versatile potential in energy, polymer, environmental, agricultural, and biomedical

fields. It is used as a filler or additive in polymer and composite systems to provide mechanical strength, UV resistance, and oxidation resistance (Kai et al., 2016). It is also utilized in the production of carbon fiber, activated carbon, and biofuel (Fang et al., 2017). In environmental applications, it is used as an adsorbent for the removal of heavy metal ions and organic pollutants; in agriculture, it serves as a fertilizer carrier and pesticide stabilizer (Naseer et al., 2019). In recent years, lignin has emerged as an antioxidant, UV protector, and drug delivery agent in the biomedical field, and its antimicrobial properties have also led to its prominence (Shu et al., 2021). Due to its antimicrobial activity, lignin has great potential for various applications including biomedical field, food field, water treatment field, textile field and cosmetic field (Li et al., 2023).

### **3. ANTIMICROBIAL MECHANISM OF LIGNIN**

Lignin, due to its inherent phenolic structure, is one of the most important biopolymers exhibiting activity against microorganisms. Aromatic rings, methoxyl, carbonyl, and especially phenolic hydroxyl groups derived from the phenylpropanoid skeleton play key roles in lignin's antimicrobial activity (Lobo et al., 2021). The antimicrobial activity of lignin depends on its genetic origin, preparation method, chemical structure, working concentration, and intended microorganism strain (Tao et al., 2020).

#### **3.1. Reactive oxygen species (ROS) formation and oxidative stress**

Lignin polyphenols, particularly due to the oxidative potential of their phenolic hydroxyl groups, trigger the formation of reactive oxygen species (e.g., superoxide anion, hydroxyl radical, and hydrogen peroxide) within the cell or on the surface. These free radicals cause oxidative damage to lipids, proteins, and DNA in the bacterial membrane. Lipid peroxidation reduces membrane fluidity, leading to increased permeability and leakage of cell contents. At the same time, effects such as DNA oxidation and protein denaturation lead to disruption of bacterial metabolism and cell death (Wang et al., 2017).

#### **3.2. Disruption of cell wall and membrane integrity**

Lignin nanoparticles, particularly due to their surface charge and hydrophobic properties, adsorb to the bacterial cell wall and cause structur-

al deformations. In Gram-negative bacteria, they bind to the lipopolysaccharide layer of the outer membrane and in Gram-positive bacteria, to the peptidoglycan structure, weakening membrane integrity. This interaction results in ionic imbalance, intracellular leakage, and ultimately cell lysis (Ali et al., 2022).

### **3.3. Intracellular pH changes and ATP depletion**

ROS production not only creates oxidative stress but also disrupts intracellular pH balance. Disruption of proton balance reduces ATP synthase activity and causes a decline in energy metabolism. Depletion of intracellular ATP leads to an inability to maintain membrane potential and the cessation of cellular processes (e.g., DNA replication, protein synthesis) (Yang et al., 2018).

### **3.4. Alteration or inhibition of metabolic protein expression:**

Lignin particles, and especially aromatic compounds found in lignin derivatives, can target cell metabolism by directly interacting with cytoplasmic components. These interactions can suppress the functions of ribosomal proteins or enzymes (Reyes et al., 2024).

### **3.5. Surfactant properties and antifungal activity**

Certain types of lignin (especially those with high aliphatic side chains and low molecular weight fractions) can act as surface-active compounds. These lignins interact with lipids and proteins in the fungal cell membrane, disrupting its structural integrity. Disruption of the cell membrane leads to loss of ionic balance, leakage of intracellular components, and inhibition of fungal growth. Furthermore, the hydrophobic regions of lignin can bind to the fungal cell surface, inhibiting nutrient uptake and reducing metabolic activity. Therefore, lignin is considered a potential natural antifungal agent (Amat et al., 2023; Reyes et al., 2020).

### **3.6. Antiviral effect and inhibition of viral entry**

Some lignin particles, particularly modified lignin derivatives containing sulfonate or carboxyl groups, can interact with glycoproteins in viral envelopes. This interaction prevents the virus from attaching to the host

cell surface and entering. Studies against enveloped viruses such as HIV and influenza have shown that lignin derivatives inhibit virus attachment and fusion within the cell (Gordts et al., 2015; Kimura et al., 2022).

## 4. FABRICATION TECHNIQUES OF TEXTILES

Textile surface coating methods are advanced technological processes applied to textile materials to impart functional or aesthetic properties (Sanchez, 2022). In these methods, performance properties such as water repellency, antibacterial, UV protection, fire retardancy, antistatic properties or durability can be improved by applying a film, polymer layer, nanomaterial or chemical agent of a certain thickness to the fabric or fiber surface (Hasan et al., 2025; Attia et al., 2023).

Surface coating is usually achieved by physical or chemical means and is widely used in both conventional textiles and technical textiles (Ielo et al., 2021).

### 4.1. Dip Coating

Dip coating is one of the simplest and most widely used methods. In this method, the fabric is dipped into the prepared coating solution or dispersion, and then the excess liquid is removed by squeezing or straining, and dried to form the coating film (Sen, 2008). This method, which is a simple and low-cost process, not only can produce high-quality coating films on large and complex surfaces, but also stands out with its repeatability, safety and suitability for coating large areas at low temperatures (Tang et al., 2017). It is preferred in coatings with various functional properties such as water repellency, antibacterial activity, or self-cleaning capabilities (Javaid et al., 2022).

### 4.2. Spray Coating

In the spray coating method, the coating solution is atomized using compressed air and sprayed onto the fabric surface in fine droplets. This method offers rapid application and the ability to achieve a thin, homogeneous film layer on the surface (Trabucco et al., 2021). It is particularly preferred for functional coatings containing nanomaterials (Bashari et al., 2018).

### **4.3. Sol-gel Coating**

This method is based on the formation of a colloidal sol from precursors such as inorganic precursors or metal alkoxides, which is then gelatinized and applied to the textile surface. Following the drying and curing processes, a thin and durable coating film forms on the surface. It offers advantages such as high efficiency, low cost, and low chemical consumption (Mollick et al., 2023). This method is highly suitable for nanostructured and multifunctional coatings. The sol-gel method can produce water-repellent, UV-protective, or self-cleaning surfaces. However, processing temperatures and material costs may limit its widespread use (Ghosh et al., 2025).

### **4.4. Layer-by-Layer (LbL) Coating**

The layer-by-layer (LbL) method is based on the application of oppositely charged polyelectrolytes to the fabric surface in successive layers (Stawski, 2012). Strong bonding between the layers is achieved through electrostatic interactions or hydrogen bonds (An et al., 2018). This technique is preferred in the development of multifunctional textile coatings because it allows for the combination of layers with different functions. However, the processing time can be long, and the wash resistance of the layers can be limited (Javaid et al., 2025).

### **4.5. Pad-Dry-Cure Coating**

It's a method based on impregnation and fixation, widely used for coating textile materials with functional chemicals. In this method, the fabric is immersed in a pre-prepared chemical solution (padding), and the excess solution is then passed between two rollers to remove it. This step ensures the fabric absorbs the desired amount of chemical. The fabric then undergoes a drying process, where the solvent is removed and the chemicals are evenly distributed across the fiber surface. The final step, curing, involves applying heat under specific temperature and duration conditions to permanently bond, or cross-link, the chemical agents to the fiber structure (Patti, 2025). The pad-dry-cure method is a versatile wet process widely used on an industrial scale; however, it has significant environmental and health drawbacks, such as high water and energy consumption and the release of harmful emissions. Furthermore, chemical evaporation can cause uneven surface coating (Naebe et al., 2022).

Lignin's natural polyphenolic structure allows it to form strong chemical and physical interactions with textile fibers. Application of lignin to textile surfaces can be done by different methods such as pad-dry-curing, dipping, spraying, sol-gel and layer-by-layer deposition (LbL). The method chosen depends on the fabric type, lignin solubility, targeted function, and processing costs. (Juikar and Vigneshwaran, 2017; Repon et al., 2022; Lehtonen et al., 2025).

Babaeipour et al. (2024) developed an innovative coating method using hybrid polyaromatic nanoparticles derived from biobased lignin and natural fatty acids to simultaneously impart antibacterial, UV-protective, water-repellent, and self-cleaning properties to textile surfaces. In this study, lignin was obtained from kraft lignin (BioPiva 395) and chemically esterified using tall oil fatty acid (TOFA) and lauric acid chloride (LaCl). This resulted in the synthesis of hybrid lignin nanoparticles (LNPs) with particle sizes between 47 and 140 nm, which both increased their hydrophobicity and facilitated surface interaction. The coating process was carried out using the layer-by-layer (LbL) technique. In this method, cotton fabric or cellulose nanofibril (CNF) film was immersed in dispersions of positively charged poly-L-lysine (PLL) and negatively charged lignin nanoparticles, respectively, to form successive thin film layers. Antibacterial tests were conducted against *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative) bacteria. Results showed that TOFA-modified lignin nanoparticles exhibited the highest antibacterial activity (51% inhibition), while pure lignin nanoparticles achieved 46% and lauric acid-modified LNPs provided approximately 20–25% inhibition. Antibacterial activity was reported to be related to the cell membrane permeability disruption effect of lignin's phenolic hydroxyl groups and fatty acids. The higher susceptibility of Gram-positive bacteria (e.g., *S. aureus*) is due to their more permeable cell wall structure (Babaeipour et al., 2024).

In a study conducted by Zimniewska et al. (2008), kraft lignin was converted into nanostructures using ultrasonic treatment, and these nanolignin particles were applied to the fabric surface ten times using the padding method. A 150 g/m<sup>2</sup> woven fabric made from flax (*linum*) fibers was used in the experiments. Different ratios of silicone emulsion (5%, 25%, 50%) were added to enhance the adhesion of the lignin coating to the fabric. Antimicrobial tests were conducted according to the AATCC 147-1998 standard, and the results revealed that nanolignin-coated linen fabrics exhibited bactericidal activity against eight different bacterial species (*Corynebacterium xerosis*, *Bacillus licheniformis*, *Micrococcus flavus*, *Staphylococcus haemolyticus*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Escherichia coli*, and *Pseudomonas aeruginosa*). The results

obtained indicated that both UV protection and antimicrobial activity can be achieved by applying lignin to the textile surface. Furthermore, the lignin coating did not adversely affect the fabric's breathability, softness, or antistatic properties. These findings demonstrate that lignin, as a non-toxic, biodegradable biopolymer, offers an environmentally friendly alternative for textile surface modifications and holds great potential, particularly for medical, hygienic, and summer clothing applications (Zimniewska et al., 2008).

Ferreira et al. (2025) developed sustainable antibacterial coatings for textile surfaces using raw kraft lignin obtained from the paper industry. In the study, lignin was applied directly to cotton and polyester fabrics by knife-coating at different rates (5%, 10%, 20%, 30% w/v) without any chemical modification or functionalization. Antibacterial activity was tested on *Staphylococcus aureus* (Gram positive) and *Klebsiella pneumoniae* (Gram negative) strains by the dynamic contact method. The results revealed that the lignin coating had a high bactericidal effect, especially on Gram-positive bacteria. When the lignin content reached 10% in cotton fabric, a 96.5% bacterial reduction against *S. aureus* was achieved, while this reduction was 84.3% in polyester fabric. On the other hand, no significant reduction in *K. pneumoniae* strains was observed in both cotton and polyester fabrics (Ferreira et al., 2025).

In a study by Chen et al. (2025), AL/CC hydrogel fibers were produced by dissolving cotton cellulose and alkaline lignin in N,N-dimethylacetamide/lithium chloride (DMAc/LiCl). These hydrogel fibers were immersed in glycerol and dried in an air atmosphere to obtain AL/CC-g fibers. In addition, Ag/AL/CC-g fibers were produced with AgNP, and Ag/AL/CC-g fabrics were woven. The AL ratio in the AL/CC content was determined at different concentrations (0.5, 10, 20, 30, 40, and 50%). The antibacterial activities and UV protection properties of these fibers against *Staphylococcus aureus* and *Escherichia coli* bacteria were determined. While no antibacterial activity was observed in fibers containing no AL, the antibacterial activities of AL/CC-g fibers increased with increasing AL content. In the AL/CC-g-50 fiber, the ratio reached 95.3% against *E. coli* and 96.4% against *S. aureus*. Furthermore, when AgNPs were added, they exhibited a synergistic effect with AL, exhibiting excellent antibacterial activity exceeding 99.99% against both bacteria. Furthermore, with increasing AL content (Ag/AL/CC-g-50 fabric), the ultraviolet protection factor (UPF) value reached over 40, demonstrating "excellent" UV protection according to the European standard (EN 13758-2) (Chen et al., 2025).

Juikar and Vigneshwaran (2017) converted lignin isolated from coconut fibers into 27.5 nm nanolignin by microbial hydrolysis via the ligninase-secreting fungus *Aspergillus nidulans*. This nanolignin was applied to cotton and linen fabrics by the pad-dry-cure method. The application of nanolignin provided 100% antibacterial activity against *Staphylococcus aureus* and *Klebsiella pneumoniae*. After the first machine wash (equivalent to five hand washes), 100% antibacterial activity was maintained against both bacterial species on both cotton and linen fabrics. However, after the second machine wash (equivalent to ten hand washes), complete bacterial inhibition continued for *Staphylococcus aureus*, while no reduction in *Klebsiella pneumoniae* was observed. The greater susceptibility of *S. aureus* to nanolignin is thought to be due to the permeability properties of its Gram-positive cell wall, while Gram-negative *K. pneumoniae* is more resistant due to its outer membrane structure. Furthermore, due to the nanolignin finish, the UPF value of cotton fabric increased from 6.18 to 28.66 and that of linen fabric from 5.20 to 10.26. High antioxidant activity, as determined by the DPPH method, was also observed in the fabrics (Juikar and Vigneshwaran, 2017).

Dai et al. (2025) chemically modified lignin using sulfonation, reducing both color intensity and increasing its hydrophilicity. Lignin (SL), supplemented with sulfonic acid groups, was used as an end group in water-based polyurethane (WPU) production. Chain extenders containing phosphorylcholine (PC) were also added to enhance the zwitterionic (double-charged) character of the polymer. This structure creates strong hydrogen bonds and ionic interactions between the polyurethane chains, resulting in high elasticity, self-healing, and antibacterial properties. The resulting sulfonated lignin-based polyurethane (PCPUSL) coatings were applied to cotton fabrics. The coatings: Demonstrated over 99% antibacterial activity (against *S. aureus* and *E. coli*). Minimized color change, largely preserving the textile's original appearance. Due to its self-healing properties, it healed scratches within 4 minutes at 60°C. It provided high mechanical strength, strong abrasion resistance, and thermal stability. These results demonstrate that lignin can be used in the textile industry as a renewable antimicrobial additive and contribute to the development of environmentally friendly, water-based, and self-healing coatings (Dai et al., 2025).

Sunthornvarabhas et al. (2017) investigated the potential of lignin extracts isolated from sugarcane pulp using an alkaline method by coating them on fabric surfaces to test their potential for antimicrobial textile applications. The study determined the minimum inhibitory concentration (MIC) of the lignin extracts against *Staphylococcus epidermidis* bacteria to be 4096 µg/mL, and the minimum bactericidal concentration (MBC)

to be 8192 µg/mL. The striking results of the study showed that a 16 cm<sup>2</sup> glass microfiber surface showed an approximately 40-fold increase in bacterial colony count within 12 hours when not coated with lignin. In contrast, a surface coated with lignin at one times the MBC completely inhibited bacterial growth over the 24-hour experimental period. At higher lignin loadings—at two and four times the MBC—the coatings reduced bacterial colony counts to bactericidal levels in less than 12 hours and 6 hours, respectively. These findings revealed that lignin coatings exhibit dose-dependent antimicrobial effects and that the coating can be applied to textile surfaces without creating pressure drop (Sunthornvarabhas et al., 2017).

## 5. CONCLUSION

Textile surface coatings are not only an aesthetic element in the modern textile industry, but also a critical technology that enhances the functional performance of textiles. Methods such as sol-gel, pad-dry-cure, spray, and layer-by-layer enhance the lifespan and value of fabrics by imparting water repellency, antibacterial activity, UV protection, fire retardancy, and mechanical durability. While these techniques offer advantages in terms of ease of application and industrial scalability, they should be carefully selected, considering factors such as energy and water consumption, chemical use, and environmental impacts.

Lignin, a natural polymer, offers great potential in textile coatings with its aromatic structure and rich functional groups. Thanks to its phenolic and hydroxyl groups, lignin exhibits strong antimicrobial and antioxidant properties, while also providing additional functions such as UV absorption, mechanical reinforcement, and chemical stability. These properties make lignin stand out as an environmentally friendly and biobased alternative to synthetic coating chemicals. Lignin-based coatings contribute both to the development of functional textile products and the efficient use of natural resources.

The focus of textile coating technologies in the future will be on simultaneously achieving sustainability and functionality. The use of bio-based and naturally sourced materials, particularly compounds derived from byproducts such as lignin, will both reduce the environmental burden and increase the added value of textile products. Combined with nanotechnology and multifunctional coating systems, lignin-based coatings will play a leading role in the development of smart, durable, and environmentally friendly textiles. Furthermore, this approach will support industrial sustainability by reducing chemical use and energy consumption in

textile production processes.

In conclusion, the integration of natural polymers and lignin-based coatings in textile engineering will not only enhance product performance but also play a decisive role in the coming period as a strategic approach for the development of environmentally friendly and innovative textile solutions. This perspective offers new opportunities for both academic research and industrial applications, enabling a vision of a future where sustainability, functionality, and innovation are integrated in the textile industry.

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# Chapter 3

**IMPORTANT NATURAL DYE PLANTS, MORDANTS,  
AND PHENOLIC COMPOUNDS**

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## 1. INTRODUCTION

The primary purpose of including this topic in the book is to provide material that will assist students in their courses and serve as a reference for academics. In general, attention has been given to natural dye plants historically used in dye production and significant for our country, the collection of these plants, the application methods of natural dyes, the natural and chemical mordants used in natural dyeing, and the concept of phenolic compounds, which also includes natural dyes. In this context, this book chapter is considered to serve as a summarized reference for anyone studying or working with natural dyes.

Plants are treasure troves, extremely rich in biologically active compounds of natural origin. In recent years, interest in the use of natural plant materials in various fields has increased. One of these application areas is the production of natural dyes. Natural dyes are defined as compounds with high color intensity that can be utilized in a wide range of sectors, including textiles, paper, wood, varnish, leather, ink, food, cosmetics, pharmaceuticals, and toothpaste (Krishnamurty et al., 2002). Natural dyes are defined as color-giving compounds naturally present in various parts of plants, such as roots, stems, leaves, fruits, and fruit peels, or in certain animals, particularly shellfish, snails, and cochineals (Bebekli, 1998).

Although the use of natural dyes has been widespread throughout history, comprehensive scientific studies in this field remain limited. In recent years, interest has increased due to the environmentally friendly properties of natural dyes. Although synthetic dyes can be produced at lower costs, the rich diversity of natural dye sources enhances their competitiveness in the global market (Ögütgen, 2008; Dixit & Jahan, 2005). Especially in the food and textile sectors, the rising interest in natural dyes obtained from plants that are eco-friendly, non-toxic, antioxidant, anticarcinogenic, antibacterial, and antiallergenic has initiated a “green wave” movement (Atılgan et al., 2013; Kizil, 2005).

In recent years, the importance of natural dyes has increased due to ecological balance, biodegradability, and their better adaptation to the environment. Turkey has a long historical tradition in natural dyeing and possesses a rich potential regarding natural dyes and dye plants. However, this richness is not fully reflected in the number of plant species currently used in dyeing. Nevertheless, producing these natural dye plants according to certain standards would enrich agricultural lands, allow their re-introduction in handicrafts—particularly in carpets and rugs—and contribute significantly to the country’s export revenue. This situation would

enhance tourism and provide an income source for producers (Üstün Özgür et al., 2013).

Research aimed at developing safer and harmless alternatives to products that have negative effects on human and environmental health has been increasing across many fields. The growing awareness of environmental and health issues in society has led governments to establish stricter protection standards. As a result, natural dyes have emerged as a sustainable and safe alternative to synthetic dyes, which can harm both the environment and human health, and they are gaining social demand (Calgero & Marco, 2008; Kamel et al., 2005; Luciana et al., 1997; Atilgan et al., 2013). Natural dyes are superior in terms of biodegradability and are generally highly environmentally compatible. They are non-toxic, non-allergenic to the human body, non-carcinogenic, easily obtainable, and renewable (Adeel et al., 2009; Saha & Dutta, 2007; Önal, 1996).

The majority of natural dyes do not bind directly and spontaneously to fibers due to their chemical structure. Even when binding occurs, it is often inefficient. Therefore, these dyes are attached to fibers by using intermediary chemical substances that facilitate interaction with the fiber (e.g., alum, ferrous chloride). These types of chemical intermediates are called "mordants." In the application of acidic dyes, mordants with basic properties are preferred, whereas for basic dyes, acidic mordants are used (Bebekli, 1998).

Ancient people directly used various plant extracts and insect-derived substances to color their existing textiles. Some of the results obtained were resistant neither to washing nor to friction, while others were not resistant to light. To prevent these issues and to achieve the desired quality of color, they developed their techniques and enhanced the use of mordanting. By around 3000 BCE, significant efforts were made in this area, and from approximately 2000 BCE onwards, especially in India, mordanting processes and substances began to be used technically. This development enabled the use of many dyes that could not be applied directly to fibers, and the applications rapidly increased (Eyüboğlu et al., 1983).

Phenolic compounds are a widespread and chemically abundant group in the plant kingdom. These compounds contribute to color formation in plant organs such as flowers, leaves, and fruits while also playing a role in the development of plant-specific aromatic characteristics. Another important function of phenolic compounds is their effective protection of plants against pathogenic microorganisms and harmful organisms. Sensory properties in vegetables and fruits, such as characteristic astringent taste and color, largely depend on the presence of these compounds; addi-

tionally, certain phenolic types are known to cause bitter taste. In foods, phenolic compounds are considered important components due to their roles in flavor and aroma profile development, color stability, antimicrobial and antioxidant properties, and inhibition of specific enzyme activities; they are also sometimes evaluated as indicators of purity in certain products (Anon., 2013).

### **Collection, Drying, and Use of Natural Dye Plants**

For some groups of dye plants, the whole plant is used for dyeing, whereas for other plants, specific parts (flowers, leaves, bark, roots, seeds, fruits) are utilized.

The collection of dye plants and their subsequent preparation through drying for use is extremely important. The manner in which plants are harvested greatly affects the quality of the dye. This is because the use of certain plant parts—such as leaves, seeds, fruits, and flowers—requires harvesting these organs at different times. Each organ (fruit, flower, etc.) is harvested at a specific period. Flowers are collected when they are fully matured, leaves when the plant is flowering, seeds during the ripening period, and bark is harvested when the plant sheds its leaves, without causing damage to the tree. In addition to the harvest time directly affecting dye quality, factors such as soil conditions, climate, fertilizers used, and the maturity of the plant also directly influence the amount of dye present in the plant structure (Bebekli, 1998).

## **1.2 Application Methods of Natural Dyes**

Natural dyes can be applied to the material to be dyed in different ways. These dyeing methods are presented below.

### **1.2.1 Direct Dyeing**

Some dye plants, such as walnut, contain components like juglone that exhibit direct dyeing properties, and are therefore classified as “direct dyes.” In dyeing with such dyes, no mordanting or reduction (vatting) process is required between the fiber (e.g., wool) and the dye. During the direct dyeing process, the dye interacts directly with the fiber and binds through chemical bonds (Bebekli, 1998).

### **1.2.2 Vat Dyeing**

Vat dyeing, a traditional method used in natural dyeing, is generally performed using plants containing indigo. After harvesting, indigo-containing plants are subjected to controlled fermentation to release the dye. Since the resulting dye is insoluble in water, it is reduced to a soluble form using various reducing agents (e.g., sodium hydroxide, sodium hydrosulfite, or lime). The fiber is then immersed in and removed from the dye bath containing the reduced dye; upon exposure to air, the reduced indigo reacts with oxygen and oxidizes, producing a permanent blue hue on the fiber. This method is primarily preferred for obtaining the blue component of blue and green colors. However, in some historical textile examples, it has also been used to obtain the blue component of purple dyes (Karadağ, 2007).

### **1.2.3 Mordant Dyeing**

The majority of natural dyes do not bind directly and spontaneously to fibers due to their chemical structure, or, if binding occurs, the result is often inefficient. Therefore, these dyes are attached to fibers by using intermediary chemical substances that facilitate interaction with the fiber (e.g., alum, ferrous chloride). These types of chemical intermediates are called “mordants.” Basic mordants are used for acidic dyes, whereas acidic mordants are applied to basic dyes. In Turkey, all dye plants containing natural dyes used in Anatolia are chemically basic and are applied with acidic mordants. The only natural dye substance that is acidic in character and applied with a basic mordant is berberine dye obtained from the root of karamak. As a basic mordant, tannic acid derived from fresh sumac is used. In addition, fresh thuja is used in acidic dye baths to increase the color intensity of the dye and darken the tone (Bebekli, 1998). The term “mordant” is derived from the French word “mordre,” which means “to bite.” Mordants have been used as auxiliary agents to ensure a stronger bond between natural dyes and wood fibers.

### **1.3 Some Mordants Used in Natural Dyeing**

Mordants are used to enhance the effectiveness of plant-based natural dyes, and a wider color range can be obtained through various dyeing techniques (Ölmez, 2004). The primary function of mordants is to fix dyes onto fabrics or other surfaces and to allow the emergence of different color tones (Demir et al., 2010).

Different mordants are used to improve the adherence of natural dyes to the dyed material. From past to present, a wide variety of both chemical and natural mordants have been employed.

### 1.3.1 Chemical Mordants

Ancient people obtained natural dyes from plant extracts and certain insect species. After extracting the dyes, they carried out direct dyeing. Over time, they observed that the colors of the dyed materials faded, were lost due to friction, or washed out upon contact with water. To overcome these drawbacks of natural dyes, they later discovered certain binding agents called mordants. Some of these mordants are chemical in nature.

#### **Alum ( $KAl(SO_4)_2 \cdot 12H_2O$ )**

Although precise information regarding the history of alum production is not available, it has been the most commonly used mordant in traditional wool dyeing in Anatolia. The easy availability of alum in nearly every region is an important factor contributing to its preference. In terms of dyeing quality, the purity of the alum used is of great importance. Alum, a compound that appears soda-like, colorless, and crystalline, may contain colored particles such as iron compounds, which can affect the color of the dyed material and cause darkening of the tone (Parlak, 1997).

#### **Bluestone ( $CuSO_4 \cdot 5H_2O$ )**

Bluestone, chemically known as copper(II) sulfate pentahydrate with the formula  $CuSO_4 \cdot 5H_2O$ , is widely available as it is also used in agriculture for plant treatment. It produces brownish-green colors with many dyes and some dark, unremarkable tones with others. It is used as a secondary mordant, particularly in obtaining green shades (Eyüboğlu et al., 1983).

#### **Dichromates ( $K_2Cr_2O_7$ , $Na_2Cr_2O_7$ )**

Chromates, whose chemical name is potassium and sodium bichromate, are widely used by shoemakers in Anatolia and in the mordanting of woolen fabrics. With chromium, mustard shades can be obtained from yellow dyes, and occasionally dark pastel green tones. When used as a

secondary mordant, chromium enhances the darker tones of the initial color. The combined mordanting method is not applied because when free chromium is present in solution, it can cause precipitation of some dyes. Potassium dichromate is sensitive to light and should be stored in dark-colored bottles. Additionally, fibers mordanted with chromium should be dyed immediately. Chromium salts provide wash fastness to the dyed fibers (Kaplanoglu, 2010).

### **Iron(II) sulfate heptahydrate ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ )**

Commonly known among the public as “stone dye” or “black dye,” this mordant, chemically in the form of iron(II) sulfate heptahydrate ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ), is widely used in natural dyeing, particularly for achieving dark and black shades. It is known that iron sulfate, when used with different dyes, can produce near-black tones and exhibits a high level of light fastness (Kaplanoglu, 2010).

### **Tin Chloride ( $\text{SnCl}_2$ )**

Tin(II) chloride ( $\text{SnCl}_2$ ) has no historical records indicating its use in traditional Anatolian dyeing techniques. Today, it is obtainable through commercial chemical suppliers and is particularly notable for enabling the production of bright and light colors. However, the light fastness of such colors is generally lower compared to other mordants (Eyüboğlu et al., 1983).

## **1.3.2 Natural Mordants**

In addition to chemical mordants, various auxiliary substances are commonly used in traditional natural dyeing in rural areas of Anatolia. These natural additives include mud, urine, clay, soot, ash, citric acid, and particularly rusted metal pieces (especially nails). Inspired by these traditional materials, natural mordants are currently being developed in laboratory settings and evaluated in scientific research. Below is a brief overview of the usage characteristics of some of these additives.

### **Tannin**

Tannins are phenolic compounds naturally found in various parts of

plants, such as roots, bark, leaves, wood, and fruits. Their primary applications are in dyeing and leather processing. Tannins are also effectively used in clarifying wine and beer, improving the flow properties of drilling muds in petroleum wells, and preventing scale formation in steam boilers (Uğur, 1988).

### **Natural Grape Vinegar (CH<sub>3</sub>COOH)**

Vinegar is an acidic substance obtained through fermentation and is widely used as a food additive. It is generally produced from fruits with high acid content—particularly grapes or apples. In other words, vinegar is an aqueous compound containing acetic acid, formed as a result of the natural fermentation of wine, low-alcohol beverages, or sugar- and starch-containing solutions (Atılğan, 2009).

### **Oak Ash**

In traditional dyeing practices using acorns, various auxiliary materials are also employed in addition to mordants. Natural substances such as ash and mud serve as supportive agents in this process. Acorns are typically soaked in water for a day, either whole or ground, prior to dyeing. The resulting dark-colored extract is used to dye wool that has been pretreated with mordants such as alum, chrome, blueston, or iron(II) sulfate (FeSO<sub>4</sub>). The fiber is boiled over low heat for approximately one hour and then allowed to cool. Using this method, tones ranging from khaki green to mustard yellow can be obtained (Gönen, 2008).

### **Animal Urine**

Before the widespread use of synthetic mordants, animal-derived substances were also employed in traditional natural dyeing processes.

In this context, animal urine was used as an auxiliary material due to its alkaline nature. This property facilitates the dissolution and transfer of dyes with low water solubility, such as indigo, onto fibers. In particular, aged human urine, containing bacterial populations and organic compounds, has the capacity to initiate fermentation processes. Additionally, its highly alkaline nature promotes the reduction of indoxyl, serving as an effective reducing agent in indigo dyeing (Gönen, 2008).

## **Mud**

Muds obtained from natural sources—particularly from lakes, water bodies, or mountainous terrains—contain rich mineral content due to varying soil and water compositions. These muds, especially containing iron compounds and other metallic salts, play a significant role in darkening the tones of textiles dyed with natural dyes and in achieving long-lasting, black-like colors (Parlak, 2007).

## **Clay**

Chemically defined as calcium oxide (CaO), clay is an alkaline inorganic compound obtained by heating calcium carbonate at high temperatures, which removes carbon dioxide. Generally white or light gray in color, this substance is used as a supplementary mordant, particularly in vat dyeing applications. In certain regions of Anatolia, the high clay content of the soil has facilitated the widespread use of this compound in traditional dyeing processes (Gönen, 2008).

## **Soot**

Soot is defined as the residue or thermal substance resulting from the burning of wood or decayed plant materials. In Europe, it was used as a primary mordant to obtain different colors and was particularly preferred alone for achieving yellow-brown tones. Additionally, in primitive societies, soot was also used in dyeing garments through fumigation methods (Sekar, 1999).

## **Citric Acid (Lemon Salt)**

Citric acid and lemon, due to their strong acidic properties, are widely used to enhance dye color intensity and brightness, serving as auxiliaries in mordant applications (Yalçın, 2010).

## **Rusty Nails**

Certain acids, such as oxalic acid, sulfuric acid, and vinegar, dissolve rusty nails and are used to obtain black colors with some dyes (Yalçın, 2010).

## 2. SOME PLANTS UTILIZED FOR DYEING PROPERTIES

### 2.1 Madder (*Rubia tinctorum* L.)

Other names: dye çılı, madder root, madder sprout, climbing madder, dyer's herb, "tongue-staining," red dye, red root, sticky, and egg dye (Eyüboğlu et al., 1983). Figure 2.1 below shows the general appearance of the madder plant (A) and its root shoot (B).



**Figure 2.1** General appearance of the madder plant (A) and its root shoot (B) (Yavuzcanli, 2023)

Madder is a rhizomatous, perennial plant that can grow up to 1–2 meters in height and thrives in fertile soils. The plant continues its growth during the summer, producing pale yellow flowers that fall in winter but bloom again in spring. The leaves, numbering 4 to 6, emerge in a circular arrangement from the same node. Madder is believed to be native to Anatolia. Its natural distribution, however, extends to the Caucasus, Iran, Central West Asia, and the Himalayan region (Gönen, 2008).

The roots are used for dyeing purposes. Dark red, thick, and gnarled roots, sometimes as thick as a finger, spread horizontally underground. Roots from plants that are at least three years old yield the best results. They are harvested in spring and autumn (Eyüboğlu et al., 1983).

The key chemical compounds in madder roots that are important for dyeing include rubierythrin acid, purpuroxanthin, munjustin, purpurin glucoside, pseudopurpurin, and rubiadin glucoside. The dye content in the root structure of madder is approximately 10% (Bebekli, 1998).

### 2.2 Cehri (*Rhamnus petiolaris*)

Cehri, also known by local names such as golden tree, Alacahır, dyer's thorn, and Akdiken, is a spiny shrub or small tree that can reach up to 3

meters in height. It naturally grows at elevations of 1000–1300 meters in mountainous, hilly, and rocky areas; on sunlit slopes, forest clearings, and under or at the edges of sparse forests.

A total of 22 species belong to the genus *Rhamnus*. While some of these species are evergreen, *Rhamnus petiolaris* is a deciduous species. This plant produces small, inconspicuous yellowish-green flowers during May and June. The fruits that develop from these flowers are initially greenish-yellow, maintaining this color for an extended period, and gradually turn brown or black as they mature. The fruits, approximately 6–7 mm in diameter, have a brown outer surface and a yellow inner portion. *Rhamnus petiolaris*, popularly known as the “golden tree,” is an endemic plant species native to the Central Anatolia region (Karadağ, 2007). Figure 2.2 shows the collected and dried seeds of the cehri plant.

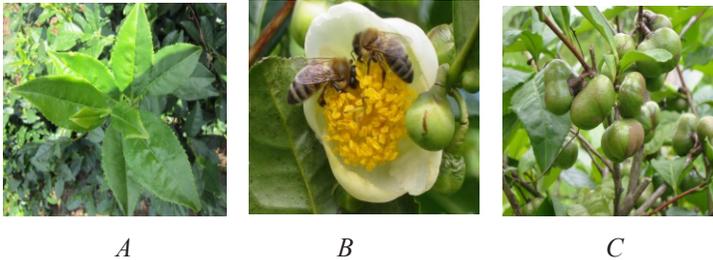


**Figure 2.2** Collected and dried seeds of the cehri plant (*Rhamnus petiolaris*) (Karadağ, 2007).

Cehri has historically been a well-known, cultivated, and commercially significant dye plant. As a dye material, cehri was once considered valuable enough that one *batman* could be sold for one gold lira; for this reason, it became popularly known as the “golden tree” and was reported to be grown in many regions of Anatolia. During the Ottoman period, cehri was exported through the ports of İzmir and Samsun, primarily to European countries such as France, Germany, and England. This export increased between 1951 and 1961 and then gradually declined from 1963 onward. *Rhamnus petiolaris* is generally found in temperate and warm climate zones worldwide. In Anatolia, its natural distribution includes provinces such as Kayseri, Çorum, Gaziantep, Sinop, Afyon, Uşak, Yozgat, Tokat, Nevşehir, Niğde, Ankara, Kahramanmaraş, and Konya (Kayabaşı & Arlı, 2001).

### 2.3 Tea Plant (*Camellia sinensis*)

Tea is the second most consumed beverage in the world after water (Tosun & Karadeniz, 2005). Approximately two-thirds of the global population consumes tea (Cooper et al., 2005; Fisunoğlu & Besler, 2008). Tea production, in terms of volume, is carried out in about 30 countries, with India, China, Sri Lanka, Japan, and Taiwan being the primary producers. In Turkey, tea production and consumption are also widespread (Cooper et al., 2005; Henning et al., 2003). Today, the three main commercial tea types cultivated are black, green, and oolong teas (Fisunoğlu & Besler, 2008; Tosun & Karadeniz, 2005). Globally, approximately 76% of tea produced is black tea, 22% green tea, and 2% oolong tea (Tosun & Karadeniz, 2005; Trevisanato & Young-In Kim, 2000). Figure 2.3 shows the tea plant's leaf (A), flower (B), and seeds (C).



**Figure 2.3** Tea plant leaf (A), flower (B), and seeds (C) (Uzun, 2013).

### 2.4 Onion (*Allium cepa*) Peel

Onion is a cultivated crop that does not grow naturally in the wild. The dye content of the plant is particularly concentrated in its outer peels. With an agricultural history of approximately 3,000 years, the origin of onion is believed to be Central Asia. In the wall paintings of ancient Egyptian tombs, onions appear more frequently than other plants. Onion peels, containing yellow-toned dyes, are widely recognized as a natural dye source; historically, they were also reportedly used by Christians for coloring eggs during Easter rituals (Karadağ, 2007).

Globally, the area of dry onion production continues to increase annually. Turkey ranks third in dry onion production, following India and the United States (Karahocagil, 2003). In Turkey, where production is high, the outer peels of onions constitute a significant amount of agricultural waste. These outer peels of *Allium cepa* L. have long been used in the textile industry for natural dyeing and are valued as a source of natural dyes, providing economic added value (Keskin et al., 2010; Önal, 1996).

The peels of dry onions, commonly used in cooking and salads, are typically discarded as waste. When utilized as a dye raw material, they can serve as an alternative natural dye source in the hand-woven carpet and kilim industry, potentially providing significant foreign exchange revenue for Turkey (Yaman, 2012).

In the onion plant, leaves develop in a tubular shape around the apical bud. For dyeing purposes, the dried outer leaves (peels) are primarily used. Traditionally in Anatolia, onion skins have been employed for dyeing wool and coloring eggs during Easter. Depending on the mordants applied, the outer peels can produce various shades, including khaki, green, and olive green. In terms of cultivation areas, onions are grown throughout almost all regions of Anatolia, with intensive cultivation for vegetable production in provinces such as Tekirdağ, Bursa, Manisa, Balıkesir, Kocaeli, İzmir, Niğde, and Kayseri (Ünal, 2011).

It has been estimated that the utilization of natural dye plants could generate an annual income of approximately 110 million USD for Turkey from onion peels. However, no data were found regarding the retail or wholesale sale of onion peels (Yaman, 2012). Ground onion peels are shown in Figure 2.4.



**Figure 2.4** Ground onion peels (Keşmer, 2020).

Onion skins contain a dye compound called pelargonidin (Önal, 1996), which gives them a low pH value.

### **2.5 Pomegranate Fruit Peel (*Punica granatum L.*)**

Pomegranate (*Punica granatum L.*) is a plant that can grow up to 5-6

meters tall, with sparse branches and a broad crown, looking like a small tree or shrub. Its leaves are strap-shaped, and it produces bright red flowers in May and June. The fruits, maturing in autumn, are initially green and gradually exhibit color transitions ranging from yellow to red. The pomegranate peel naturally contains yellow-toned dye compounds. Additionally, the use of different mordants allows the production of alternative color tones, such as dark brown and khaki. Pomegranate peel is rich in important dye components, including tannin, gallic acid, and ellagic acid (Atılgan, 2009).

The high tannin content in pomegranate peel is widely used in the leather processing industry, clarification of fruit juices, and prevention of zinc poisoning. Furthermore, pomegranate peel and flowers are utilized in dye and ink production. Pomegranate seeds contain oil in a similar amount to cotton seeds, and the pulp remaining after being used in the oil industry is among the richest plant sources containing estrogen hormone (Ögütgen, 2008). Figure 2.5 shows the pomegranate fruit and peel as A and B, respectively.



A

B

**Figure 2.5** Pomegranate fruit and seeds (A) (Atılgan, 2009) and peel (B) (Kulkarni et al., 2011).

In dyeing, the outer peels of pomegranate fruits are used either fresh or dried. Dried and ground fruit peels are preferred in mordant-based dyeing processes (Karadağ, 2007).

## 2.6 St. John's Wort (*Hypericum* sp.)

St. John's Wort (*Hypericum* sp.) has a wide distribution in Turkey, represented by 69 species. While the plant has been the subject of recent medical research due to its therapeutic properties, it is considered undesirable in agriculture because it can be harmful to crops and livestock. Some species of St. John's Wort are known to be used in dyeing (Öztürk & Aksoy, 2000). Figure 2.6 shows *H. perforatum*, one of the most common St. John's Wort species.



**Figure 2.6** *H. perforatum*, the most common St. John's Wort species (Çırak & Kurt, 2014).

This plant species has a perennial underground organ, while its above-ground part is annual. The plant produces new shoots in spring and loses its aerial structure as winter approaches. It blooms with yellow flowers in June. Its natural distribution areas include open, dry, rocky, and sandy soils, as well as the edges of agricultural lands (Alptekin, 1974).

### **2.7 Safflower (*Carthamus tinctorius*)**

Safflower (*Carthamus* spp.), also known by various names such as cartham, aspur, asfur, false saffron, parrot feed, and dye safflower, is an herbaceous plant. It includes annual or biennial species, growing up to 60–70 cm, and produces yellow, red, or orange flowers between July and September depending on the species. In addition to being cultivated as an oilseed crop, safflower is used as a natural dye in painting, paper, textile, food coloring, and cosmetics. In Turkey, it is widely cultivated, particularly in the provinces of Ankara, Afyon, Kütahya, Eskişehir, Çankırı, Isparta, and Şanlıurfa (Karadağ, 2007).

### **2.8 Blood**

The color, viscosity, and origin from an organic source indicate that blood can be considered a natural dye (Değirmenci, 2017).

As a natural dye essential for human life, blood has been frequently used in various rituals throughout history. Humanity associated blood with life, emphasizing mortality through bloodshed and suggesting that immortality belongs solely to the gods. This connection between blood and life was also linked to the theme of death; due to its color, the terms “red” and “blood” were sometimes used interchangeably, demonstrating a strong associative relationship between the two concepts. Historically, especially in hunter societies, individuals returning from a hunt would smear their bodies with blood to draw attention, display courage, and gain social status. This behavior was interpreted as an indicator of the individual’s bravery during the hunt and helped secure their share of the game (Uğurlu, 1990).

### **2.9 Woad (*Isatis tinctoria* L.)**

Woad is an herbaceous plant reaching 40–90 cm in height, with a biennial life cycle and yellow flowers. Its natural blue dye is obtained through the fermentation of its leaves. Native to the slopes of the Caucasus, woad has a wide distribution extending from the Far East to the Himalayas. In Turkey, approximately 30 species of this genus occur naturally (Karadağ, 2007).

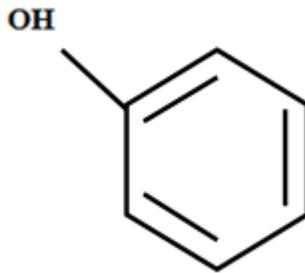
### **2.10 Saffron (*Crocus sativus* L.)**

The saffron plant was widely used during the Middle Ages not only in culinary culture but also in dyeing. Its cultivation is similar to bulb planting; saffron bulbs planted in May–June are harvested in autumn, and their threads are dried in a wind-free environment. Prior to use as a dye, the threads are ground into a paste using a mortar. During drying over heat, saffron undergoes a color transformation from yellow to red (Mazaheri, 1972). Approximately 80,000 to 200,000 flowers are required to obtain just one kilogram of saffron dye. When mordanted with alum, this dye produces a range of shades from yellow to orange (Dölen, 1992). Additionally, during the Middle Ages, saffron was used to dye clothing, paper, and official documents (Bakır, 2005). In Europe, saffron was introduced during the Crusades, which also marked the beginning of its trade (Dölen, 1992).

Saffron, which belongs to the group of yellow dyes, can also yield red-dish tones when processed using different mordanting methods (Akiniz, 2017).

### 3. PHENOLIC COMPOUNDS

Phenolic compounds are organic molecules containing at least one aromatic ring to which one or more hydroxyl groups are attached. Compounds with multiple hydroxyl groups in their structure are referred to as polyphenols. In general, all compounds that possess an aromatic structure substituted with hydroxyl groups are classified within the phenolic group (Figure 3.1 shows the chemical structure of phenol).



**Figure 3.1** *Chemical structure of phenol*

Various studies have reported that phenolic compounds possess anti-allergic, anti-inflammatory, antidiabetic, antimicrobial, antipathogenic, antiviral, and antithrombotic properties, and also exhibit protective effects against cardiovascular diseases, cancer, osteoporosis, diabetes mellitus, and neurodegenerative diseases. More than eight thousand phenolic compounds have been identified by the early 2000s, and this number is reported to be steadily increasing. In recent years, some plant-derived phenolic compounds have gained prominence due to their antioxidant properties and are being commercially produced. In this context, determining the bioavailability and required intake of these compounds in foods is considered important to utilize the protective effects of dietary antioxidants (Kolaç et al., 2017)

#### **.3.1 Effects of Phenolic Compounds on Color**

Consumers have specific expectations regarding the color of each food product; in this context, color significantly influences both consumer preferences and the visual appeal of the product. In particular, in fruits, color emerges as one of the primary parameters for quality evaluation. In quality control processes, fruit color is frequently used as an indicator reflecting the degree of quality, making color a decisive factor in the commercial value of products. Flavonoids, a broad class of compounds, contribute not only to the flavor profile but also play an active role in the development of color in foods. To date, over 4,000 flavonoid compounds

have been identified in plants. Plant-based foods can contain several grams of flavonoids per kilogram on a fresh weight basis. Daily individual intake of flavonoids ranges approximately between 50 mg and 1 g, making flavonoids a consistent component of human nutrition. About half of the total flavonoid intake consists of anthocyanins, catechins, and oxoflavonoids. The intensity of colors produced by anthocyanins varies depending on factors such as the pH of the medium, the presence of metal ions, the effect of copigments, and the processing and storage conditions of the product. Anthocyanins appear red-purple at low pH levels and greenish-blue at high pH levels. The same anthocyanin structure can manifest in different colors in different plant tissues depending on the environmental pH conditions. For example, the anthocyanin petanin reaches its maximum color intensity at pH 8.1. Additionally, literature reports indicate that anthocyanin-derived colors can be preserved through various processing techniques (Anon., 2013).

### **3.2 Importance and Applications of Plant-Derived Phenolic Compounds for Human Health**

Plant-derived phenolic compounds are utilized not only in the dyeing, paper, and cosmetic industries but also in the food industry as natural colorants and preservative additives (Bravo, 1998).

Findings from various epidemiological studies indicate that diets rich in vegetables, fruits, and plant-based products (e.g., tea and wine) may offer protective effects against a range of chronic diseases, particularly cancer. These protective effects are thought to be primarily due to the phenolic compounds present in these plants (Moure et al., 2001; Lima et al., 2006). Polyphenols have been reported to exhibit a wide range of biological activities, including antiallergic, antiatherogenic, anti-inflammatory, antimicrobial, antibacterial, antiviral, antimutagenic, anticarcinogenic, anti-ulcer, antioxidant, and antithrombotic effects (Balasundram et al., 2006; Moure et al., 2001). Information on the classification of phenolic compounds is presented in Figure 3.2.

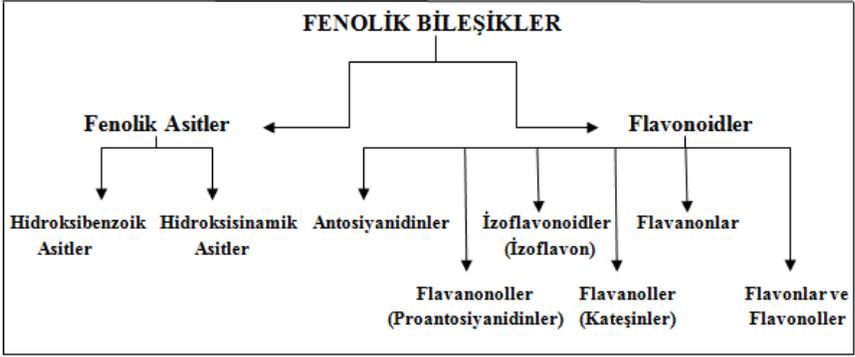


Figure 3.2 Classification of Phenolic Compounds (Anon., 2016; Keşmer, 2020)

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# Chapter 4

## USAGE POSSIBILITIES OF TURKISH RED PINE BARK

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## 1. INTRODUCTION

This book chapter consists of an introductory section providing general information about tree bark; a second section describing the anatomical and chemical properties of the bark and general uses; a third section describing the botanical, anatomical properties of the Turkish red pine tree and its uses; a fourth section summarizing the usage possibilities of Turkish red pine bark and academic studies on Turkish red pine bark; and a total of five chapters containing an evaluation of the book chapter and recommendations. This study addresses the chemical and anatomical properties of tree bark and the general purposes of its use. In particular, academic studies on the usage possibilities of Turkish red pine bark (which is the most widely distributed coniferous tree species in Turkey, 30% of which is covered by forests, and is distributed on an area of 5.2 million hectares (OGM, 2025)) are examined .

Ecosystems are defined as holistic interaction systems formed through the energy and matter cycle between living organisms and their inanimate environments (Kunduz, 2011). In this context, forests, one of the fundamental elements of the ecosystem, are not only the habitat of plant, animal, and microorganism communities, but also strategic natural resources with their own ecological balance and renewal capacity, providing the basic needs for human life (Akyüz et al., 2014). Today, the increasing world population, along with social, cultural, economic, and technological developments, is rapidly increasing the demand for renewable resources in Türkiye. To reduce the negative impacts caused by this demand and to ensure the transfer of forest assets to future generations, renewable organic raw materials obtained from forests must be utilized with the highest efficiency. In this direction, to make optimal use of forest-derived organic raw materials, it is of great importance to determine their structural properties in detail and to meticulously apply appropriate isolation methods (Gönültaş, 2008; Atılğan, 2018).

With a surface area of 78 million hectares, Turkey is a rich country in terms of its mountainous structure and ecogeographic diversity. This ecological diversity enriches forest ecosystems in terms of species and composition. Forests cover 23.3 million hectares nationwide, corresponding to approximately 30% of the total surface area (OGM, 2025b). Within Turkey's forests, Turkish red pine ( *Pinus brutia* ) is the most widespread coniferous species, covering 5.2 million hectares. This value constitutes 47% of the total coniferous forest area and 22% of the total forest area (OGM, 2024).

The most important representative of the *Pinus* genus in Turkey, the

Turkish red pine, naturally spreads throughout the Mediterranean basin and is most widely distributed in Turkey. Its moderately valued wood is used extensively in the production of lumber, building materials, packaging, panel production, wire, mine poles, and fuel. Turkish red pine bark, with its high tannin content and biomass potential, is a significant raw material for industrial tannin production. However, while its wood is widely used in the forest products industry for the production of fiberboard, particleboard, and paper, the bark currently has no specific application. Creating potential areas for utilizing this waste bark in various sectors is important for both resource efficiency and contributing to the national economy (OGM, 2015). **269 different uses of Pinus species** have been recorded. The most common of these uses is **for medicinal purposes**, particularly **for the treatment of respiratory diseases**. They are also used in various fields such as **food, veterinary medicine, paint, fuel**, and **handicrafts**. **While** the most ethnobotanically used species are *P. brutia* and *P. nigra*, which have wide distribution areas, there is no usage record of *P. halepensis* due to its narrow distribution (Kızıllarslan and Sevgi, 2013).

Research conducted on non-wood forest products in Türkiye, particularly in the second half of the 20th century, made significant contributions to the national economy through exports. Within this product group, bark has attracted attention both as an export item and as a distinct research topic. The first studies on bark began in the 1950s, and in the 1970s, studies based primarily on literature reviews and of a propositional nature were conducted. In the 1980s, two original scientific studies focused on the utilization of bark as agricultural compost and the production of glue from red pine bark extract. In the 1990s, research on the potential of bark in particleboard and fiberboard production contributed to both academic knowledge and industrial applications. While original studies on the chemical composition and analysis of bark have become prominent in recent years, research on its industrial-scale utilization appears to be limited (IÜOFD, 2006).

## 2.BAR (TREE'S BAR TEXTURE)

The increase in the global population and the changing consumption habits of societies are causing the rapid depletion of natural resources; this necessitates the reduction of resource use and the expansion of recycling activities (Atılğan, 2018). Barks, which were generally considered waste in the forest industry in the past and constituted 8–22% of the total tree volume (Dönmez and Dönmez, 2013; Krajnc, 2015), are now released

in large quantities during the logging, paper pulp, and paper production processes. This rate is reported to be around 12.5% on average in Türkiye (Kurt and Mengeloğlu, 2006). While the high ash (4%) and moisture content of barks limit their direct use, their utilization in chemical product production provides both economic benefits and contributes to the reduction of environmental pollution (Akyüz et al., 2013). In recent years, studies on the utilization of tree barks, which have long been considered waste in the forest industry, have accelerated. One of the main reasons for this research is the high amount of bark accumulation resulting from centralization and integration processes, particularly in logging, paper pulp, and paper production facilities (Demetçi, 1982). On an industrial scale, bark is often used as fuel; however, adverse properties such as high moisture and ash content lead to technical problems in its use. However, converting bark into high-value-added chemical products both increases economic returns and contributes to the reduction of environmental pollution (Balaban, 2001).

The bark produced as a result of processing logs in forest enterprises and wood processing facilities is an important by-product and leaving it as waste causes economic and environmental problems. Research into the conversion of bark, traditionally burned for energy, into biobased chemical products through extraction has increased in recent years. Studies on the anatomical and chemical properties of bark aim to transform this byproduct into high-value-added materials. While waste bark from hardwood and coniferous trees is primarily used as fuel in Türkiye, its scientific importance is increasing due to its high chemical content.

Bark generally has a specific gravity in the range of 0.40–0.65 g/cm<sup>3</sup>, and its chemical composition varies depending on the extraction method and species. In this context, the bark content consists of approximately 10–30% extractive matter, 15–45% cellulose, 15–40% lignin, tannin, and various carbohydrates (Eroğlu and Usta, 2000). It is stated that the amount of bark can vary between 8% and 22% depending on factors such as tree species, age, and habitat characteristics (FAO, 1990; Harkin and Rowe, 1971; Kantay and Köse, 2006; Özlüsoylu, 2022). In Türkiye, the average bark ratio is stated to be 12.5%. It is also emphasized that approximately 2 million m<sup>3</sup> of bark waste can be obtained annually from the primary and secondary forest products industry (Kurt and Mengeloğlu, 2006; Özlüsoylu, 2022). The bark located on the outer part of the cambium surrounding the trunk, branches and roots has a structurally complex and heterogeneous texture.

## 2.1 Anatomical Structure of the Bark

When the anatomical structure of tree bark is examined, it has been determined that it has three primary functions. First, it contributes to the transport of nutrients synthesized in the leaves; second, it protects the sensitive cambium layer against the effects of desiccation; and third, it provides defense against insects and other pests by protecting the tree against strong winds and mechanical effects (Sakai, 2001). The tree trunk is composed of three main layers: wood, cambium, and bark. Wood comprises the heartwood and the surrounding sapwood, while bark is divided into two main parts: the inner bark (phloem) and the outer bark (rhytidome). Wood structure contains high-molecular-weight polymers such as cellulose, hemicellulose, and lignin, as well as lower-molecular-weight extractive components (Gindl and Teischinger, 2003). Bark, on the other hand, is distinguished from the wood structure by the cork layer located primarily on its outer surface. This layer consists of the “cork cambium,” also known as phellogen tissue, located on the outer surface of the inner bark. Although fungal tissue contains lignin, carbohydrates and hydroxy acid groups, it does not contain extractive components (Browning, 1967).

Bark is the second-largest tissue in the tree trunk, comprising approximately 10–20% of the total volume. This proportion varies depending on the species, habitat, and climatic conditions; it can reach 20% to 35% near the top and branches, with higher values observed in the roots and base compared to the trunk (Özdemir, 2010; Tsoumis, 1968; Fengel and Wegener, 1984). Bark structure is highly complex and heterogeneous (Harkin and Rowe, 1971).

## 2.2 Chemical Structure of the Bark

Effective evaluation of bark requires examining not only its anatomical features but also its chemical composition. Anatomically, it is present in all plant organs, and the main components of wood and bark are presented in Table 1 (Howard, 1971; Harkin and Rowe, 1971; Özlüsoylu, 2022).

*Table 1. Main components found in bark and wood (Harkin and Rowe, 1971; Özlüsoylu, 2022)*

Basic Components	Coniferous Trees		Leafy Trees	
	Wood	Bark	Wood	Bark
Lignin (%)	25-30	40-55	18-25	40-50
Polysaccharides (%)	66-72	30-48	74-80	32 – 45

Extractives (%)	2-9	2 – 25	2 - 5	5-10
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Chemically, bark varies depending on morphological factors in different tree species. Many compounds found in wood tissue are also present in bark, but the proportions of these compounds vary (Gönültaş, 2008). Bark distinguishes itself from wood by its polyphenol and suberin content, relatively low polysaccharide content, and high extractive substance content. A general trend is that extractive and polysaccharide amounts decrease from the inner bark to the outer bark, while the proportion of lignin and polyphenolic compounds increases (Fengel and Wegener, 1984). Furthermore, the amount of inorganic matter in bark is higher than in wood. The chemical structure of bark is quite complex and varies among species due to differences in morphological components. While many compounds found in wood tissue are also present in bark, their amounts vary significantly (Sjöström, 1992). Bark distinguishes itself from wood by its polyphenol and suberin content, low polysaccharide content, and high extractive substance content. In addition, the mineral content in the bark is significantly higher than in the wood. In a study by Usta and Hafızoğlu (2005), the chemical compositions of bark from various tree species are presented in Table 2.

Table 2. Chemical analysis of some barks (Usta and Hafizoglu, 2005).

Species	Cold Water		Hot Water		Alcohol-Benzene		1% NaOH		Cellulose		Lignin		Ash	
	Solution (%)		Solution (%)		Solution (%)		Solution (%)		(%)		(%)		(%)	
	External	Bark	External	Bark	External	Bark	External	Bark	External	Bark	External	Bark	External	Bark
<i>P. brutia</i>	10.3	13.5	11.6	14.5	15.2	18.3	39.2	46.9	37.7	31.93	29.3	34.6	3	4.6
<i>P. nigra</i>	3.8	7	5.2	9.4	15.8	20.8	37.2	41.1	37.5	31.4	31.5	34.1	2.2	3.3
<i>P. Sylvestris</i>	6.8	9.5	10.2	14.6	12.6	15.4	40.2	45.8	38.4	33.9	31.5	33.8	2.2	3.4
<i>P. Pinea</i>	7.6	8.3	9.1	12	11.3	14.2	403	42.3	38.5	33.7	35.8	36.8	2	2.4
<i>P. halepensis</i>	5.7	7.8	8.6	10.9	11.5	18.3	41.6	48.7	38.7	33.2	27	28.1	2	3.8
<i>Picea orientalis</i>	5.8	7.5	13.3	17.7	13.3	17.7	39.3	43.7	39.5	31.9	15.7	20.2	2.5	4.8
<i>Cedrus libani</i>	8.6	15	13.2	19.8	13.2	19.8	35.2	45.9	38.7	25.3	28.9	35.1	4.7	6

### 2.2.1 Soluble Compounds

**Extractive Components:** Extractive substances found in tree bark are generally divided into two main groups: lipophilic and hydrophilic. The total amount of these compounds is generally higher than in wood and varies between species, making up approximately 20–40% of the dry weight of the bark. Extractives have a heterogeneous structure and mostly contain components specific to the bark (Özlüsoylu, 2022).

**Lipophilic Substances:** The lipophilic fraction, obtained using nonpolar solvents (e.g., ethyl ether, benzene, dichloromethane), consists of oils, waxes, terpenoids, and higher aliphatic alcohols. Terpenoids, resin acids, and sterols can be found in resin canals in bark, fungal cells, and the pathological secretion (oleoresin) of wounded wood (Sjöström, 1992).

**Hydrophilic Substances:** Hydrophilic compounds in the peel contain high phenolic content, which can be extracted with water and polar solvents (ethanol, acetone) (Sjöström, 1992). Polyphenols are classified according to their molecular weight and solubility; low molecular weight ones include procyanidins and di-/trimeric flavanones (Porter, 1974; Yazaki and Hillis, 1977), while higher molecular weight condensed tannins (phlobaphenes) are hot water-soluble and may be present in the peel at 5–50% (Fengel and Wegener, 1984).

### 2.2.3 Insoluble Compounds :

**Polysaccharides:** The primary hydrolyzed compound in the bark is glucose, which ranges from 16–41%. The outer bark has a lower glucose content than the inner bark. Bark cellulose is similar to the Cellulose I crystal structure in wood, but with a lower degree of crystallinity (Fengel and Wegener, 1984). On average, approximately 30% of the bark weight consists of cellulose, and the polyose structures found in wood are also present in the bark (Sjöström, 1992).

**Lignin:** Lignin is found in the cell walls of fiber and sclereid cells, but it has also been detected in periderm and rhytidome cells (Srivastava, 1966). Coniferous bark extracts contain compounds such as shikimic acid, ferulic acid, coniferaldehyde, and vanillin, which are formed as a result of lignin metabolism (Hergert, 1965; Holmes and Kurth, 1961). The amount of lignin in the bark can only be reliably determined by alkaline extraction because some polyphenols resist conventional solvents and hydrolysis, which can lead to high lignin values (Fengel and Wegener, 1984).

**Suberin:** Suberin, an insoluble compound found in the outer bark, is particularly abundant in cork cells. For example, cork oak contains 40–45% suberin, while other bark fungal cells also contain high amounts. Suberin is a complex polyester combined with phenolic compounds and waxes in the cell wall; it consists of long-chain fatty acids and hydroxy fatty acids and is cross-linked by ester and ether bonds (Fengel and Wegener, 1984; Sjöström, 1992).

#### **2.2.4 Inorganic Components**

Bark is richer in mineral content than wood. The ash content is generally over 10%, ten times greater than that in wood. The primary elements are calcium, potassium, and magnesium (Fengel and Wegener, 1984). Inorganic elements are more abundant in the inner bark than in the outer bark, with significant differences in potassium, magnesium, and phosphorus. These proportions also vary among species; for example, there are significant differences in the distribution of nutrient elements between pine and spruce bark. Nitrogen content does not vary among tissues (Fengel and Wegener, 1984).

### **2.3 Usage Areas of the Bark**

Despite the diverse potential of bark, its utilization is hampered by technological limitations and logistical and organizational shortcomings. Therefore, collecting and processing bark in suitable regions is a critical factor in ensuring its effectiveness. Furthermore, the peeling method and dimensions must be appropriate for the intended application. In production, ensuring consistent bark quality and consistent supply from specific tree species is crucial for establishing a stable and reliable market for the final product. The primary uses of bark can be summarized as follows:

#### **2.3.1 Tannin (Tanning Agent) Production**

The use of bark as a tanning agent is important due to its tannin content. Directly ground flour or tannin-based extracts from oak, spruce, and pine bark are generally preferred in leather tanning processes. Despite synthetic alternatives, plant-based tanning agents are still widely used (Bozkurt and Göker, 1981). During tanning, collagen, the leather protein, is structurally stabilized by the cross-links formed by tannins, making it insoluble in water. This increases the leather's resistance to water and

strengthens tear and rupture resistance by binding the protein molecules together (Uçar, 1978).

### 2.3.2 Energy Production

The direct use of bark in energy production stands out as an important potential application area. The calorific value of bark varies between 1000 and 5000 cal/g, depending on the moisture content (Cappaert, 1976). For energy boilers to operate efficiently, the bark moisture content must be between 55–60%, but when the moisture content reaches 75%, the calorific value decreases to almost zero. The energy value of the bark can be increased through pressing, reaching approximately 1700 kcal/kg. For the economical use of bark in energy production, enterprises need to have approximately 50,000 m<sup>3</sup> of bark available annually (Huş, 1976). In a study conducted by Şensöz and Can (2002), Turkish red pine chips were pyrolyzed at temperatures between 300–500 °C, and the resulting energy value was determined to be 23.1–25.4 MJ/kg. In addition, in studies conducted by the Forestry Research Institute, the upper calorific values of oven-dried bark of various tree species in Türkiye were determined and are presented in Table 3 (Erten and Önal, 1981).

*Table 3. Upper caloric values of oven-dried barks (cal/gr)*

	Oak	Beech	Alder	Larch	Scots pine
Body Bark	3768	4476	5087	5252	5310
Branch bark	4287	4637	4531	5227	4989

### 2.3.3 Soil reclamation

The use of tree bark as a mulch material in soil improvement offers several advantages, both ecologically and agriculturally. Mulching protects plant root systems against high temperatures and drought in summer and low temperatures and frost in winter. It also improves the soil's physical properties, increasing drainage capacity in heavy clay soils and increasing water retention potential in sandy soils (Demetçi, 1982).

### 2.3.4 Agriculture, Gardening and Other Uses

Tree bark, with its organic matter content exceeding 80% and its essential nutritional elements, is considered an important support material in agricultural and horticultural practices. In this context, bark is used as a micronutrient source for potted plants, for transporting and packaging bare-root seedlings, for preventing erosion, for landscaping golf courses,

and for aesthetic purposes (Sarles, 1973).

### 2.3.5 Use in the Medical Field

*P. brutia* bark is rich in phenolic compounds with antimicrobial properties, particularly tannins, flavonoids, and phenolic acids (Ucar, Ucar, Pizzi, & Gonultas, 2013). The resin found in its bark has been traditionally used for medicinal purposes in the treatment of abscesses and pain relief (Dıĝ & Hakkı Alma, 1999). Studies have shown that *P. brutia* bark extracts exhibit significant antimicrobial activity against gram-positive bacteria such as *Bacillus cereus*, *B. subtilis*, *B. megaterium*, *Staphylococcus aureus*, and *Mycobacterium smegmatis*, but are not effective against gram-negative bacteria such as *Escherichia coli* and *Klebsiella pneumoniae* (Kivrak et al., 2013).

### 2.3.6 Use as a Dyestuff

Recent academic studies have shown that Turkish red pine bark can be used as a natural dye. Due to its high quercetin content, Turkish red pine bark can be used to dye both wood fibers and textiles. It is known that fishing nets, in particular, were dyed with Turkish red pine bark in ancient times.

Where the dye obtained by water extraction from the bark of the red pine (*Pinus brutia*) tree was used with the leaf extract of the aloe vera (*Aloe vera L.*) plant as a mordant, a mordanting technique was applied by mixing the dye and the mordant. Bartın Forestry Faculty Journal 2024, Volume 26, Issue 2, Page: 124-132 128. Colorimetric measurement (CIE Lab system) technique was used in color measurements. It was determined that the brightness of the dyed paper increased linearly with increasing the amount of aloe vera. According to the study, it was concluded that the natural dye obtained from the Turkish red pine bark and the aloe vera extract could be used in paper dyeing by mixing and mordanting together (Keşmer and Gençer, 2022). Yalçın (2010) showed in his study that the light, washing and friction resistance of cotton, wool and silk fabrics dyed with Turkish red pine bark dye was at a sufficient level, while its use in polyester fabrics was limited.

### 3. TURKISH PINE ( *Pinus brutia* Ten.) TREE

Naturally growing in the Northern Hemisphere, the Turkish red pine ( *Pinus brutia* ) is the most widely distributed coniferous species in Anatolia and a key element of Turkey's forests. Approximately 30% of the country's surface is covered by forests, and with an area of 5.2 million hectares, the Turkish red pine is the most widely distributed species within these forests. Commonly found in the Mediterranean, Aegean, Marmara, and Black Sea regions, the Turkish red pine can grow in pure stands up to 1,300 meters above sea level and as individual trees up to 1,500 meters. A typical Mediterranean species, the Turkish red pine is frugal in terms of soil and water requirements, generally preferring sandy-loam soils, but can also thrive in calcareous and other soil types in the Taurus Mountains. In natural regeneration efforts to ensure the continuity of Turkish red pine forests, site conditions are carefully evaluated, excluding extremely steep, rocky, and erosion-prone areas. Due to its high light requirements, extensive clear-cutting is preferred during the regeneration process. Seed germination requires temperatures of 15–35 °C and relative humidity of 70%; techniques such as spreading branches and mulching are used to support the healthy development of young saplings. According to data from the General Directorate of Forestry, natural regeneration of Turkish red pine trees was carried out on a total of 164,779 hectares between 2019 and 2024, thus making significant contributions to both the sustainability of the forest ecosystem and the national economy (OGM, 2025).

The chemical composition and composition of plant resources, particularly *Pinus brutia*, are of significant importance due to their medicinal and aromatic properties. With the rise of various diseases, interest in the therapeutic use of plants is rapidly increasing. Forest plants, which can be consumed as food or converted into commercial products, have economic and pharmacological value due to the increasing diversity of products obtained. Extracts obtained from *Pinus* species have been found to contain terpenoids, steroids, proanthocyanidins, and flavonoids. These compounds exhibit antibacterial, antifungal, wound-healing, and antioxidant properties (Kivrak, Kivrak, Harmandar, & Çetintaş, 2013). *Pinus brutia*, which has a wide geographical distribution, Ten. and *Pinus nigra* grows in Turkey, particularly in the Northern Anatolia and Taurus Mountains, at altitudes between 400 and 2100 meters. The most striking feature of this species is its ability to thrive in areas where other pine species fail or develop poorly. *Pinus brutia* Ten. is a species naturally distributed in the Mediterranean, Aegean, and Black Sea regions of Turkey. The bark of this species, which covers approximately 25% of the country's forest area, is a significant by-product of the wood processing industry with high potential for utilization (Kivrak et al., 2013).

### 3.1 Botanical Characteristics of the Turkish Red Pine Tree

Turkish Red pine (*Pinus brutia*) is a thick-branched tree species, morphologically similar to Aleppo pine, typically reaching 15–20 m tall with a trunk diameter of approximately 60 cm. While its trunk structure is often irregular, with increasing altitude, the trunk becomes more uniform, reaching 20–25 m tall, the crown becomes pointed, and the branches become thinner (Öktem, 1987). Young shoots are hairless, thick, and dark reddish in color. Smooth branches arise from the trunk at right angles and have short shoots at the ends (Anşin and Özkan, 1993). The general morphology, trunk structure, and needle characteristics of Turkish red pine are presented in Figure 1.



Figure 1. General, trunk and leaf appearance of the Turkish red pine tree (Keşmer, 2020).

The Turkish red pine is a maritime pine species with high tolerance for soil conditions and can thrive in climates with mild winters and hot, dry summers. Although it can also grow in rocky, calcareous, or sandy soils, it grows more healthily and rapidly in suitable habitats. The most important pest is the pine processionary moth, and the risk of damage by storms is high in shallow soils. Its thick bark makes it highly resistant to forest fires (Gökşin, 2001).

The natural distribution of the Turkish Red Pine is between 15–45° east longitude and 32–45° north latitude in the Northern Hemisphere. Its westernmost point is the Calabrian Peninsula, and its eastern limit is the Zavita Atrush region in northern Iraq (Asmaz, 1993). In addition to

Anatolia, this species also occurs in Cyprus, Crete, the Aegean Islands, various regions of northeastern Greece and the Caucasus (Gagra, Gudak, Pitsun, northwest of Sokhum), Georgia, the former USSR, the Central Caucasus, the area around Sochi, the Black Sea coast of Russia, and the Crimean Peninsula (Kasaplıgil, 1952). It is also seen in small populations in Palestine, Jordan, Syria, Iraq, Lebanon, the Greek Islands, Italy, and Cyprus (Kayacık, 1965).

Turkish Red pine (*Pinus brutia* Ten.) is one of the most important species of the genus *Pinus* in Turkey and is a diploxyton pine species belonging to the subsection *Sylvestris*. Endemic to the Eastern Mediterranean, this species is most widely distributed along the Mediterranean coast of Turkey (Selik, 1963). Growing in regions with hot, dry summers and mild, rainy winters typical of the Mediterranean climate, Turkish red pine is not limited to the Mediterranean region but also spreads naturally in areas closer to the Mediterranean climate of the Marmara, Aegean, Central Anatolia, and Southeastern Anatolia (Şefik, 1965). In the Western and Central Black Sea regions, it is found in small populations in valleys and on southern slopes sheltered from the effects of cold weather; examples include the confluence of the Kelkit River and Yeşilirmak River near Erbaa, and the islets around Ayancık, Sinop, Boyabat, Amasya, and Zonguldak. The widest distribution of Turkish red pine is seen along the Mediterranean coastal zone and inland areas near the coast (Neyişi, 2001). In Turkey, the species can grow up to an altitude of 1500 meters and can form forest formations by mixing with pure or sparsely deciduous species in the Aegean, Southern Marmara, and Western Black Sea regions (Kasaplıgil, 1999).

### 3.2 Anatomical Features of Red Pine Tree

Examining the macroscopic properties of Turkish red pine wood reveals that the live wood naturally has a reddish hue, while the heartwood is reddish brown. Annual rings are clearly distinguishable. The lower parts of the trunk are generally grooved, while the bark is thick, deeply fissured, and reddish brown. Turkish Red pine also has an aromatic odor and secretes a sticky resin, particularly in spring and summer (Erten and Önal, 2001).

### 3.3 Areas of Use of Red Pine Tree

While thick-branched Turkish red pine wood is not generally consid-

ered high-value, it is exported for sleeper production and is widely used locally, particularly as packaging material. It is also used for wire poles, mining poles, building materials, yacht and boat construction, fence posts, various tools, crate production, and the paper - cellulose industry. Also important for resin production, Turkish red pine is a preferred species for afforestation in arid and barren areas (Neyişçi, 2001).

#### **4. TURKISH RED PINE ( *Pinus brutia* ) BARK**

Turkish red pine ( *Pinus brutia* Ten.) is an important coniferous species native to the Mediterranean and Aegean regions of Turkey. Its adaptability to arid and barren soil conditions makes it a popular choice for erosion control and afforestation projects. In the forestry sector, Turkish red pine bark is generally considered waste; however, its tannins, resins, and phenolic compounds make it a valuable biological and industrial raw material source. The bark can be economically utilized through recycling and the production of value-added products. Within the framework of sustainable forest management, research is ongoing on techniques for natural regeneration and efficient use of Turkish red pine.

Throughout history, tree bark has been used by indigenous peoples in a variety of traditional practices. These barks have been used to produce corks, peeling tools, tannin-containing products, dyes, gum, resin, latex, food and aromatic compounds, fishing and arrow poisons, antibiotics, and medicinal compounds (Harkin and Rowe, 2005).

Turkish Red pine bark contains high levels of Oligomeric Proanthocyanidins (OPC). OPC is 18–20 times more potent than vitamin C and 40–50 times more potent than vitamin E in terms of antioxidant capacity. This compound's primary function is to prevent the oxidation of blood lipids and cholesterol. In France, OPC, obtained from a mixture of grape seeds and pine bark, is used as a herbal medicine to treat weak blood vessels. For OPC to be used as a dye, it must be colored and able to form strong bonds with fibers; these properties make it possible to produce dyes from Turkish red pine bark (Demir and Demir, 2012).

##### **4.1 Uses of Turkish Red Pine Bark and Literature**

Turkish Red pine ( *Pinus brutia* ) bark has been used throughout history for medicinal purposes, including stopping bleeding, treating inflammation, making cough syrups, relieving toothaches, and healing wounds (Becit et al., 2017). This species, widely distributed worldwide and in Tur-

key, is referred to in the literature as “Turkish red pine” and is a tree species of high economic value and important for our country.

Turkish red pine is particularly valued for its resin and extractive substance content. The biological effects of the tree and its bark are based on their ability to scavenge nitrogen compounds and reactive oxygen species at the molecular level (D’Andrea, 2010). The polyphenols, phenolic acids, and flavonoids it contains provide the bark with strong antioxidant and free radical scavenging properties (Packer et al., 1999). Furthermore, the bark’s high radical scavenging capacity is directly related to the number of hydroxyl (-OH) groups, nucleophilic addition reactions, and the structure of the phenolic compounds (D’Andrea, 2010).

#### 4.1.1 Literature

In their study, Yalçın (2010) evaluated the dyeing performance and fastness properties of natural pigment obtained from the bark of *Pinus brutia* Ten. (red pine) on textile fabrics made from different fiber types. In the scope of the study, plain-woven fabrics made of cotton, wool, silk, and polyester fibers were colored according to a total of 24 different dyeing recipes, with and without various mordants (alum, cream of tartar, tannin, sodium sulfate, and clay water). Following the dyeing processes, the fabric samples were subjected to washing, rubbing, and light fastness tests. Color measurements were taken with a colorimeter, and color difference ( $\Delta E$ ) values were calculated. The findings showed that the fastness values of cotton, wool, and silk fabrics dyed with Turkish red pine pigment met textile standards. However, low performance was observed in polyester fabrics. Consequently, it was determined that Turkish red pine pigment is suitable for use in natural fiber-based textile materials.

Özdemir (2010) investigated the feasibility of condensed tannin extracted from the bark of *Pinus brutia* (Turkish Red pine), a tree commonly found in Turkish forests, as a raw material for wood-based panel production. Barks obtained from *Pinus brutia*, *Picea orientalis*, and *Cedrus libani* were compared chemically, and it was determined that Turkish red pine bark was the most suitable species due to its high condensed tannin content. The resulting Turkish red pine tannin was added to phenol-formaldehyde adhesives, along with commercially available Mimosa and Kebraho tannins, and these adhesives were used to produce fiberboard. Physical and mechanical tests revealed that boards produced with Turkish red pine tannin performed similarly or superiorly in many parameters. However, the water uptake rate and thickness increase were high for all tannin-containing boards, and it was suggested that this problem

could be addressed with hydrophobic additives. The results demonstrate that Turkish red pine bark has industrial potential as an alternative tannin source.

In their study, Atılgan (2018) investigated the yield and composition of tannins extracted from the bark of *Pinus brutia* (Turkish red pine), a species widely distributed in Turkey. Bark samples collected from the Yalova region were subjected to different extraction methods, and their phenolic compound contents were analyzed. The findings revealed that microwave-assisted extraction was superior to conventional techniques in terms of both yield and tannin concentration. However, Soxhlet and traditional aqueous extraction methods were found to be less efficient due to their high solvent consumption and lengthy processing times. Classical extraction techniques based on elevated temperatures and prolonged durations resulted in oxidative degradation and reduced product purity. Overall, the study demonstrated the efficiency of advanced extraction technologies that enable the production of tannins with high yield and purity while minimizing chemical usage and energy consumption.

Seçkin and Karakaya (2018) developed wound dressings using *Pinus brutia* (Turkish red pine) extracts, which are rich in phenolic compounds, and investigated their healing effects. The extracts were obtained using microwave and ultrasonic extraction techniques in addition to the classical Soxhlet method. Microwave extraction, optimized with the Box-Behnken experimental design, provided high phenol and flavonoid contents and strong antioxidant activity. The use of ethanol during microwave extraction maximized total phenol and flavonoid values. The obtained extracts were applied to the textile surface via alginate gel and made into wound dressings. In vivo studies showed that wound dressings containing Turkish red pine extract provided significantly faster wound healing compared to the control group.

In their study, Hünler Dönmez (2021) evaluated the antimicrobial effects of various natural products and 2% chlorhexidine digluconate as a control group on *Enterococcus faecalis*, *Streptococcus mutans*, *Lactobacillus acidophilus*, and *Candida albicans*. The natural products used included stone water, pine turpentine essence, olive leaf extract, grape seed oil, coconut oil, propolis, tea tree oil, and Turkish red pine bark extract. Antimicrobial activity was tested using disk and well diffusion methods, and agents showing significant effects were detailed using microdilution tests. The obtained data were statistically analyzed using Shapiro-Wilk, Levene, Kruskal-Wallis, and Dunn tests. The results revealed that pine turpentine essence, propolis, tea tree oil, and Turkish red pine bark extract exhibited significant antimicrobial activity against the studied microorganisms. In

particular, tea tree oil exhibited higher antifungal activity than chlorhexidine on *C. albicans*. Pine turpentine essence and Turkish red pine bark extract were found to be as effective as chlorhexidine on *S. mutans* and *E. faecalis*.

In their study, Eyüboğlu (2024) extracted *Pinus brutia* bark using four different solvent systems (ethanol, methanol, ethanol–water, and methanol–water, 70:30 v/v), and the phenolic compound profiles of the obtained extracts were analyzed by HPLC–DAD. The probiotic supporting potential of the Turkish red pine bark extract was tested with *Lacticaceibacillus casei* and *Lactobacillus acidophilus* strains. In addition, the encapsulation of the extract with  $\beta$ -cyclodextrin was optimized using a central composite design approach. The encapsulation efficiency was determined as  $85.04 \pm 0.16\%$  and was correlated with the antioxidant capacity of the phenolics.  $\beta$ -cyclodextrin–methacrylate monomer was synthesized for dental applications, and structural and morphological confirmations were performed by FT–IR, SEM, and NMR analyses. The study indicates the antioxidant, probiotic supporting, and biomaterial potential of Turkish red pine bark.

In their study, Erol et al. (2025) analyzed the bark of the Turkish red pine (*Pinus brutia* Ten.), a common tree in the Mediterranean and Aegean regions of Turkey, for its phenolic content and used it at 0–1% levels in pasta production. Gallic and hydroxybenzoic acids were the main phenolic compounds. The addition of RBE increased the total phenolic content, antioxidant capacity (DPPH, FRAP), mineral content, and sensory acceptability of pasta, and reduced the glycemic index. A significant increase in bioavailability and nutritional value was observed in samples enriched with 1% RBE. The findings indicate that Turkish red pine bark has potential as a functional food ingredient.

Akpınarlı and Yalçın (2012) evaluated the bark of the Turkish red pine (*Pinus brutia*) as a natural pigment source. The resulting pigments were used to dye wool yarns with various mordants, such as alum, tannin, cream of tartar, clay water, and sodium sulfate. The results demonstrate the applicability of Turkish red pine bark in natural dyeing and its potential as an environmentally friendly alternative.

Erol et al. (2023) In this study, an ultrasound-assisted extraction process was optimized using a Box–Behnken experimental design to obtain bioactive compounds from the waste bark of Turkish red pine (*Pinus brutia* Ten.), which grows widely in Turkey. Extract yield, total phenolic content (TPC), total condensed tannin (TCT), ferric reducing antioxidant power (FRAP), and ABTS radical scavenging capacity were analyzed. The optimum ex-

*traction conditions were determined as 34.8°C, 6.5 min, and 116.3W; under these conditions, 13.16% yield, 103.09mg GAE/g TPC, 13.29mg CE/g TCT, 602.14mg TEAC/g FRAP, and 624.51mg TEAC/g ABTS values were obtained. The extracts showed low toxicity in healthy cells and significantly reduced proliferation in colon and pancreatic cancer cells. In addition, it exhibited low inhibitory activity against AChE and BChE enzymes associated with Alzheimer's disease, and high inhibitory activity against  $\alpha$ -glucosidase and  $\alpha$ -amylase associated with diabetes. The extracts also exhibited significant antimicrobial activity against bacteria such as *S. aureus*, *B. cereus*, *L. monocytogenes*, *S. Typhimurium*, and *E. coli*.*

*In their study, Taşdemir et al. (2020) showed that the addition of *Pinus brutia* bark extract to TRIS extender could reduce post-freezing oxidative stress in bull semen. Application at a dose of 50  $\mu$ g/ml preserved DNA integrity and reduced head anomalies; however, no significant effect on sperm motility was observed.*

In their study, Atay et al. (2016) produced biomass pellets at six different ratios using oil rose distillation waste, lignite coal dust, and Turkish red pine bark, and evaluated their physical and chemical properties and flue gas emissions. The pellets were prepared using a small-scale pelletizing machine and burned in a conventional stove. CO, CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub>, O<sub>2</sub> emissions, and combustion efficiency were analyzed. Except for the mixture with a 75% lignite ratio, all pellets produced emissions below the legal limit values and were found to be usable as fuel. The results indicate that oil rose waste and Turkish red pine bark can be utilized in the production of pellets for energy purposes. Furthermore, it was determined that adding lignite at appropriate ratios improved combustion properties.

Özdemir and Balaban Uçar (2016) investigated the use of condensed tannin obtained from Turkish red pine bark in glue production. Turkish red pine tannin performed similarly or better than mimosa and kebraho tannins. Thickness increase and water uptake were found to be high in the produced fiberboards, but it is believed that these problems can be addressed with water-repellent additives. Hexamethylenetetramine was successful as a hardener for Turkish red pine tannin, and paraformaldehyde for other tannins.

In Özlüsoylu's (2022) study, thermal and acoustic insulation boards were produced using black pine (*Pinus nigra* Arnold.) bark, using polymeric methylene diphenyl di-isocyanate (P-MDI) and urea formaldehyde (ÜF) adhesives. The boards were then coated with wood veneer and prepared into decorative forms. Their physical, mechanical, thermal, and acoustic properties were then examined. The findings indicated that

black pine bark-based boards produced at specific densities can be used for thermal and acoustic insulation in the construction industry.

Yeşiltepe and Gönültaş (2023) investigated the performance of urea-formaldehyde adhesives modified with Turkish red pine bark tannin. Modified adhesives were prepared by adding tannin to the adhesive solids at a rate of 5-50%. Viscosity, solids, gel time, pH, and free formaldehyde were measured. As the tannin content increased, viscosity and gel time increased, while the amount of free formaldehyde decreased (minimum 0.32%). Bond strength was assessed using the Lap Shear test; FTIR analysis revealed modification and new bond formation.

Çetin et al. (2013) investigated the use of Turkish red pine bark flour instead of Turkish red pine wood flour as a filler in high-density polyethylene (HDPE) matrix composites. Composite panels were produced by preparing seven different mixtures containing 10%–40% bark flour and 20% wood flour. Mechanical tests showed that as the bark flour content increased, tensile and impact strengths decreased, while flexural strength and modulus of elasticity increased. The values obtained exceeded the ASTM D6662-13 standard, indicating that these composites could be used in plastic lumber applications. The fracture surfaces were also analyzed by SEM.

Avcı (2015) conducted a study on wood-plastic composites. Wood-Plastic Composites (WPCs) are a rapidly developing material class in the composites industry and are new to the furniture industry. They offer advantages such as low water absorption, dimensional stability, and resistance to biodegradation. Research indicates that using larch, oak, and Turkish red pine bark as fillers can provide the necessary strength for outdoor furniture.

In their study, Akpınarlı and Yalçın (2012) conducted experimental studies on the dyeing of wool yarn using mordants alum, tannin, cream of tartar, clay water, and sodium sulfate, using a dye obtained from another study on Turkish red pine bark, and on the fastness levels. Color measurements were made using the “CIE Lab” system. Accordingly, dark golden brown was obtained from wool yarn mordanted with alum, saddle brown from wool yarn mordanted with tannin, Peruvian brown from wool yarn mordanted with clay water, sand brown from wool yarn mordanted with cream of tartar, dark brown from wool yarn mordanted with sodium sulfate, and wood brown from wool yarn dyed without a mordant.

Avinç et al. (2013) investigated the use of natural dyes derived from the bark of the red pine (*Pinus brutia*) for dyeing various textile products. Alum and natural oak ash were used as mordants in the dyeing process.

The results showed that the highest color yield was achieved in silk and wool fabrics. A comparison of mordant effects revealed that alum exhibited higher chemical performance, but the natural mordant derived from oak ash also offered sufficient quality values.

Keşmer et al. (2020a) investigated the use of natural dyes obtained by extraction from Turkish red pine and onion peels on paper pulp. Bleached *Eucalyptus grandis* wood pulp was prepared using the Kraft method and used in dyeing processes. Spectroscopic analyses determined that both natural dyes were effective on paper pulp. Furthermore, the effects of alum and grape vinegar as mordants were compared, and it was determined that alum increased dye adhesion more than grape vinegar. Furthermore, grape vinegar also improved dyeing properties compared to control papers, emphasizing its usability as an organic mordant .

Keşmer et al. (2020b) investigated the effects of natural dyes obtained from the bark of Turkish red pine (*Pinus brutia*) and onion (*Allium cepa*), which are common in Turkey, on paper pulp. In the study, control papers were first produced without dyes or mordants, followed by papers containing only dyes and mordants.  $Al_2(SO_4)_3 \cdot 12H_2O$  was used as the mordant . The results showed that papers containing mordant exhibited visually more desirable color properties than papers without mordants, a finding supported by spectroscopic data.

In the study conducted by Demirtaş (2020), the *Pinus brutia* bark extract used within the scope of the thesis was provided by a commercial company and was air-dried and ground as a pretreatment. The extraction process was carried out with distilled water at a 1/10 solid/liquid ratio at 55 °C for 6 hours, and then filtered to obtain a homogeneous liquid. The obtained extract was concentrated to 20% solids with a rotary vacuum evaporator and dried with a spray dryer. Turkish red pine bark is rich in polyphenols such as antimicrobial phenolic compounds, flavonoids, and phenolic acids. Since regular consumption is thought to reduce the risk of diseases caused by oxidative stress, it is considered a potential natural resource for the food and pharmaceutical sectors . Table 4 shows the antimicrobial phenolic compounds of Turkish red pine bark.

Table 4. *Antimicrobial phenolic compounds of Turkish red pine bark (Demirtaş, 2020)*

<b>Phenolic Compounds</b>	<b>µg/g</b>
Gallic Acid	2.2
Protocatechuic Acid	1.4
Catechin	6.4
p-hydroxy Benzoic Acid	0.9
Caffeic Acid	1.2
Epicatechin	5.8
Vanillin	0.4
P-Coumaric Acid	0.2
Ferulic Acid	0.2
Quercetin	17.7
Luteolin	0.2
Kaempferol	0.2
Apigenin	0.3

## 5. CONCLUSION AND RECOMMENDATIONS

Studies on Turkish red pine bark and other tree barks, which have an important place among non-wood forest products in our country, allow various conclusions to be drawn in terms of both the development of the forest products industry and the contribution to the country's economy.

Barks have a wide range of uses in forestry, agriculture, forest products industry and other business lines (medicine, chemistry, pharmacy, biology, petroleum industry, rubber, plastic, leather, etc.).

Natural dyes obtained from red pine bark using various extraction methods can be used in both the textile and paper industries, along with various mordants. Because the red pine bark pulp remaining from the production of natural dyes is a natural product, it does not harm the environment and can be used in the production of pellets for mulch, fertilizer, and thermal energy.

Turkish red pine bark can be used in the production of high-quality adhesives. Tannin, obtained from Turkish red pine bark using various methods, can be used as a raw material for glue.

Turkish red pine bark can also be used in medicine and veterinary medicine. Its extracts have antimicrobial and antifungal properties and can be used to heal wounds. These extracts have also been found to increase bull sperm productivity.

Extracts obtained from Turkish red pine bark by extraction methods have biomaterial potential as probiotic supplements and can be used in the foods we consume as functional food ingredients.

Phenolic compounds obtained from Turkish red pine bark can be used for the treatment of Alzheimer's and diabetes diseases.

Turkish red pine bark can be used in composite materials such as pellets for energy purposes and especially mixed with plastics in certain areas with special binding agents.

In recent years, it has been determined that the amount of formaldehyde leached from particleboard and fiberboard produced using Turkish red pine bark is lower than that produced from wood, and that this is influenced by the type of bark used. These studies are promising for the forest products industry.

Cork oak, whose bark is directly used for cork production, can be successfully grown in the Mediterranean Region of our country, provided that calcareous parent rocks are avoided.

It is possible to produce insulation boards, flooring parquet and linoleum from the bark of the oak tree (*Quercus cerris var. pseudocerris*) that grows in our Southeastern Anatolia Region.

In particular, the possibilities of using the resins contained in the sacs in the bark of our fir species can be improved.

Phlobafen obtained by extraction from the bark of some pine species can yield excellent plastic materials.

According to 2019 data from the General Directorate of Forestry, barkless Turkish red pine log production reached 8,433,852 m<sup>3</sup> (OGM, 2020). Calculations based on a study by Koparan (2015) indicate that approximately 1,134,000 m<sup>3</sup> of Turkish red pine bark was left to decay in forests. Approximately 30% of Turkey is covered by forests, with approximately 23.3 million hectares of forest area, 5.2 million hectares of which are Turkish red pine forests. This suggests a significant biomass potential if Turkish red pine bark is utilized. Therefore, the industrial-scale production of non-wood forest products such as Turkish red pine bark should be encouraged, and relevant projects should be supported. Furthermore, the necessary resources and support should be provided to studies on non-wood forest products conducted at universities and research institutions, and existing standards should be improved and deficiencies should be addressed quickly.

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