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D2.1 FUNCTIONAL REQUIREMENTS OF BIO-BASED TEXTILE ADDITIVES

HALO·TEX

HALOPHYTE BIOREFINERY PROCESS FOR SUSTAINABLE PRODUCTION OF TEXTILES, COMPOSITES, AND HIGH-VALUE BIOCHEMICALS

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EXECUTIVE SUMMARY

This document provides a summary of the deliverable D2.1 corresponding to the "Functional requirements of bio-based textile additives" of the HALO-TEX project. Bio-based additives for coatings in textile sector regard both sustainability and performance requirements. By adhering to established international standards and optimizing formulation parameters, the project ensures that the functionalized textiles meet the target performance levels while remaining suitable for real-world applications. This integrated approach will facilitate the transfer of laboratory results to practical, scalable solutions, paving the way for eco-friendly, high-performance textiles.

1. INTRODUCTION

1.1. Description of the document and pursuit

In recent years, the textile industry has been facing a profound structural transition, driven by increasingly stringent environmental regulations, sustainability commitments undertaken by global brands, and growing consumer awareness regarding the environmental and health impacts of textile products. In this context, there is a strong interest in the development of functional materials capable of imparting advanced properties to textiles, such as antibacterial activity, ultraviolet (UV) protection, antioxidant properties, and flame retardancy. These functionalities have traditionally been achieved through the use of conventional fossil-based textile chemicals or metallic nanoparticles, such as silver and titanium dioxide. However, these approaches present significant drawbacks, including potential toxic effects on human health, poor biodegradability, limited adhesion to textile substrates, and the release of harmful substances during the washing of treated fabrics.

Due to these challenges, there is increasing interest in bio-based, renewable, and low environmental impact materials, in line with the principles of the circular economy and regulatory frameworks such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), ZDHC (Zero Discharge of Hazardous Chemicals), and the European Union Green Deal. Among the most promising bio-based solutions there are compounds such as chitosan, cellulose derivatives, phosphorus-containing biopolymers, plant polyphenols, and lignin-based materials, which are emerging as strategically relevant alternatives to conventional fossil-based textile chemicals. Notably, the most established bio-based materials have already reached medium-to-high levels of commercialization, particularly in European markets, finding applications in areas such as medical textiles, sportswear, home textiles, and certain technical applications.

The HALOTEX project is based on the development of bio-based additives for textile coatings aimed at imparting protective properties such as UV resistance, antimicrobial activity, and flame retardancy. Specifically, lignin-based additives will be developed for UV protection, while polyphenol-based additives will be designed to provide antimicrobial properties. Polyphenols, due to their phenolic structure, adhesive capability, and the wide range of functionalities they can confer to textiles, represent a highly promising class of bio-based compounds and are receiving increasing attention from both the scientific community and industry. In parallel, lignin - a natural aromatic polymer and a by-product of the pulp and paper industry - although still at an early stage of industrial adoption in the textile sector, shows remarkable multifunctional potential. Scientific studies report effective UV absorption, antibacterial activity, and significant char-forming behaviour contributing to flame resistance, making lignin a strategic raw material for the future development of high-value functional textile systems [1-5].

The aim of this report is therefore to provide a critical literature review on the use of lignin- and polyphenol-based materials in the textile field, analysing their interaction mechanisms with textile substrates, the main application methods, the functionalities achieved, and their level of technological and commercial maturity. Particular attention is given to the contribution of these materials to improving environmental sustainability and reducing potential risks to human health, as well as to future perspectives for development and industrialization in the textile sector. In addition, this Deliverable D2.1 reports the requirements - UV resistance, antimicrobial activity, and flame retardancy - in textile sector.

1.2. Market Overview and Commercial Landscape

The textile industry faces increasing pressure due to its intensive use of water, energy, and chemical inputs. Regulatory frameworks such as the EU Green Deal, REACH, and ZDHC place strong emphasis on the adoption of environmentally friendly and bio-based alternatives, making these materials a strategic necessity rather than an optional innovation.

According to the Preferred Fiber & Materials Market Report published by Textile Exchange, the share of preferred and bio-based materials within the global textile raw material portfolio has been increasing steadily. European markets, in particular, show accelerated adoption of bio-based textile chemicals in order to comply with regulatory requirements and sustainability commitments [12].

In Turkey, the use of bio-based materials in the textile industry is primarily driven by export-oriented manufacturers. Sectoral analyses and reports published by governmental and industry bodies indicate that producers supplying the European Union are increasingly adopting bio-based and low-impact chemical systems to meet buyer and regulatory expectations.

The market for bio-based textile materials is expanding in parallel with global sustainability initiatives and increasing consumer awareness. Functional textiles, sportswear, and technical textiles represent the key growth segments for bio-based materials, supported by regulatory incentives and brand-driven sustainability strategies [13,14].

1.3. WPs and tasks related to the deliverable

This deliverable refers to Task 2.1 included in WP2: Process stream conversion to textile additives and cosmetic ingredients.

These work package tasks are listed in the table below:

Table 1. List of Tasks.

Tasks	Description	Month	Lead partner
T2.1	Functional requirements of bio-based textile additives	M1-M12	NTT
T2.2	Extractives concentration for the use in antioxidant textile coatings	M12-M36	AAU
T2.3	Functional bio-additives preparation for textile surface treatment	M12-M36	CEL
T2.4	Cosmetic formulations with halophyte fractions as active ingredients	M24-M36	DERMA

2. Lignin-Based Materials in Textile Finishing

Lignin is a naturally occurring aromatic polymer and a major by-product of the pulp and paper industry. Reports from the European Commission and IEA Bioenergy identify lignin valorisation as a strategic pillar of the bio-based economy [6, 7]. In textile applications, lignin is being explored as a functional finishing and coating material due to its high carbon content and phenolic functional groups. Its inherent UV absorption, antioxidant capacity, antimicrobial potential and char-forming behaviour make it a multifunctional candidate for textile finishing [8].

Lignin-based coatings have demonstrated the ability to impart UV protection, antimicrobial activity, flame retardancy, and water repellence to textile substrates. Studies report that lignin–silica coatings combined with phosphorus-containing additives significantly reduce peak heat release and total heat release in cotton fabrics, while also improving mechanical strength [8, 11]. Superhydrophobic lignin-based coatings have achieved water contact angles exceeding 150° and maintained durability after laundering and exposure to extreme pH conditions [9].

The main properties associated with lignin are summarized below:

- Antimicrobial properties: scientific studies report that lignin exhibits antibacterial activity owing to its phenolic hydroxyl groups, which can damage bacterial cell structures. Lignin nanoparticles derived from kraft and organosolv lignin have demonstrated effectiveness against Staphylococcus aureus and Escherichia coli when applied to textile substrates. These findings highlight lignin's potential for medical and hygiene-oriented textile applications [9, 10].
- UV protection properties: due to its aromatic molecular structure, lignin can effectively absorb UV-A and UV-B radiation. Peer-reviewed publications demonstrate that lignin-containing coatings and composites significantly increase the UV protection factor of textiles, suggesting that lignin may serve as a natural alternative to synthetic UV absorbers [9, 10].
- Flame retardancy properties: lignin's high carbon content and strong char-forming behaviour make it a promising candidate for bio-based flame-retardant systems. The literature reports enhanced flame-retardant performance when lignin is combined with phosphorus-based bio-additives, resulting in reduced flame propagation and lower toxic emissions during combustion [8, 11].

2.1.1 Lignin-Based Materials Market

The global lignin market was valued at approximately USD 1.32 billion in 2024, and it is projected to grow steadily toward higher value-added applications [12]. While current lignin use is dominated by dispersants, binders and energy applications, textile finishing is recognized as an emerging niche field. An analysis of EU-funded research projects and academic publications indicates that lignin-based textile applications remain at a very early stage of commercialization. However, reports from the Bio-based Industries Joint Undertaking (BBI JU) emphasize the growing interest in lignin as a functional additive for polymer and textile applications [7]. In Turkey, lignin-based textile applications are predominantly explored within university-industry collaborations and R&D

projects. TÜBİTAK-supported programs frequently include lignin and lignocellulosic biomaterials as research topics for sustainable and functional textile development. While the global lignin market is currently dominated by energy, binder, and dispersant applications, market and policy reports indicate a gradual shift toward higher value-added uses. For textile industry, we can say that there is no currently available lignin-based finishing product on the market [12, 6].

Table 2 provides a structured comparison of bio-based and lignin-based materials with respect to their functional properties, level of commercialization, and maturity within the textile industry. This assessment is based exclusively on published scientific literature and official market and policy reports [6, 7, 13].

Table 2. Comparative Analysis of Bio-based and Lignin-based Materials.

	Bio-based Materials	Lignin-based Materials
Raw material source	Renewable biomass (starch, cellulose, chitosan, plant extracts)	By-product of the pulp and paper industry (kraft lignin, organosolv lignin)
Antibacterial performance	Well-documented and commercially applied, particularly with chitosan and plant-based extracts	Proven antibacterial activity due to phenolic structure; very limited commercial applications
UV protection	Widely applied using natural polyphenols and pigments	Strong UV absorption due to aromatic structure; mainly pilot-scale applications
Flame retardancy	Commercially available systems based on phosphorus-containing biopolymers and protein-based formulations	High char-forming ability; synergistic phosphorus-based systems mainly at R&D stage
Commercialization level	Medium to high, especially in European markets	Low to medium, primarily R&D and pilot-scale
Regulatory compliance	High compliance with REACH and ZDHC requirements	High regulatory compatibility; standardization efforts ongoing
Cost structure	Medium, depending on biomass source and processing route	Low raw material cost; requires more process optimization
Textile application areas	Sportswear, medical textiles, home textiles	Technical textiles, functional coatings, R&D-driven products

3. Polyphenols-Based Materials in Textile Finishing

Polyphenols are naturally occurring chemical compounds widely distributed in the plant kingdom and found in bark, roots, leaves, fruits, and seeds, as well as in numerous agro-industrial by-products. From a chemical perspective, they are characterized by the presence of one or more aromatic rings associated with phenolic hydroxyl groups (-OH), which are responsible for their high reactivity. Based on their chemical structure, phenolic compounds can be classified into five main categories: phenolic acids, flavonoids, tannins, stilbenes, and lignans [15]. The scheme of the polyphenol classification is reported in ***Figure 1***. Among these, flavonoids and tannins play a particularly important role in textile applications due to their antimicrobial, antioxidant, and UV-absorbing properties. The bioactive properties of polyphenols - such as antibacterial, antioxidant, anti-inflammatory, and antifouling activities - make them especially attractive as functionalizing agents for sustainable textile materials [1].

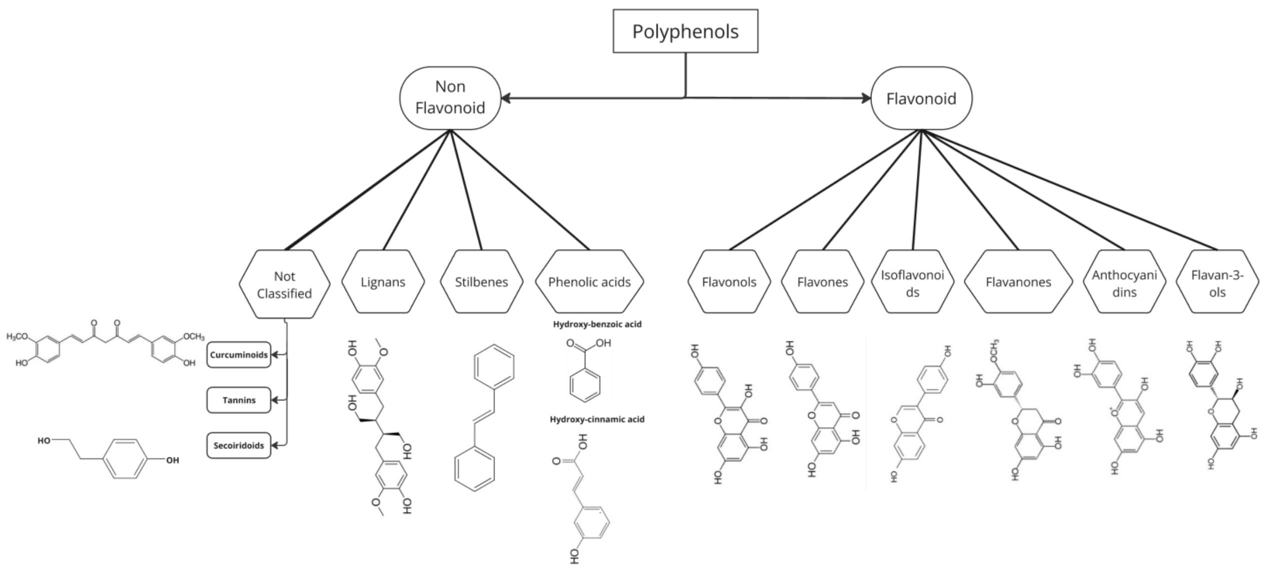

Figure 1. Classification of polyphenols [1].

The effectiveness of polyphenols as textile finishing agents is related to their ability to interact with natural fibers such as cotton, wool, and silk, which are characterized by their hydrophilic nature and the presence of numerous reactive functional groups. Phenolic hydroxyl groups enable polyphenols to establish both non-covalent interactions - such as hydrogen bonding, electrostatic interactions, and π–π interactions - and covalent interactions, including coupling and coordination reactions [2].

The main methods for applying polyphenols to textiles include direct deposition, oxidative polymerization, and the formation of metal-polyphenol networks. In particular, oxidative polymerization allows for the formation of more stable coatings through the creation of covalent bonds, while metal–polyphenol networks can enhance antibacterial activity, although they may present potential cytotoxicity risks due to the excessive presence of metal ions [2].

The main properties associated with polyphenols are summarized below:

- Antimicrobial properties: the antibacterial activity of polyphenols can be attributed to the ability of phenolic groups to interact with bacterial cell membranes and essential intracellular components. As reported in Figure 2, the mechanisms of action include disruption of the cell membrane, inhibition of gene expression, interaction with DNA and RNA, chelation of metal ions required for cellular metabolism, and alteration of metabolic pathways [1]. Experimental studies on wool fabrics treated with polyphenols extracted from plant by-products, such as mango seeds and feijoa peels, have demonstrated high antibacterial activity against Staphylococcus aureus, Klebsiella pneumoniae, and Pseudomonas aeruginosa, according to the AATCC 147 method [3]. These results highlight the potential of polyphenols as a sustainable alternative to synthetic antibacterial agents.

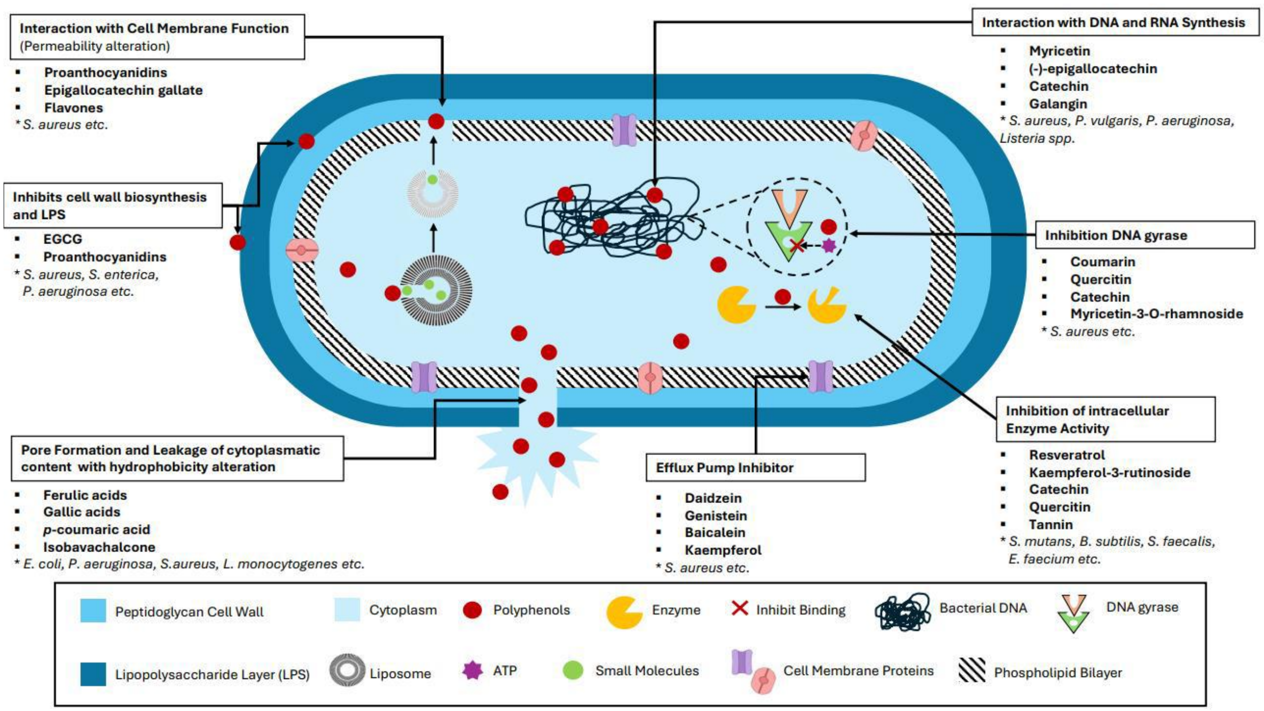

Figure 2. Antimicrobial mechanisms of polyphenols on a cell membrane [1].

- UV protection property: polyphenols, particularly flavonoids, are known for their ability to absorb ultraviolet radiation. The application of polyphenolic extracts to natural textiles enables a significant increase in the ultraviolet protection factor (UPF) [4]. In the case of wool fabrics dyed with aqueous orange peel extracts, a significant increase in UPF was observed compared to untreated samples, with good levels of protection maintained even after 30 washing cycles, although with a partial reduction in effectiveness [5].
- Flame retardancy property: this property is particularly attributed to condensed tannins, which are characterized by high thermal stability—as well as antistatic properties and insect resistance, as reported in several studies on textiles treated with natural polyphenolic extracts [3].

3.1. Polyphenol-based materials market

The global market for polyphenol-based products is experiencing steady growth, driven by increasing consumer demand for natural, bio-based, and health-promoting ingredients. This growth is primarily driven by the rising awareness of the health benefits associated with polyphenols, including antioxidant, anti-inflammatory, and anti-aging properties. As a result, polyphenols are increasingly used across multiple sectors, including functional foods and beverages, dietary supplements, cosmetics, and textiles. Among these, the functional food segment represents the largest market share, accounting for approximately 35% of total revenue, followed by functional beverages and pharmaceutical applications. Overall, the polyphenols market presents significant commercial potential, supported by macro-trends such as the shift toward natural ingredients, preventive healthcare, and sustainable materials. These trends are expected to further expand the application of polyphenols beyond traditional sectors, including emerging uses in textiles, packaging, and bio-based functional materials [16].

4. Requirements in textile sector

HALO-TEX aims to develop bio-based textile additives from halophyte biomass fractions, which represent a sustainable source of lignin, cellulose and polyphenols, which are known for their functional properties including UV absorption, flame retardancy, and antibacterial activity. In the specific, the project aims to convert the halophyte biomass fractions in high-value functional additives: UV-stabilizing lignin nanoparticles (LNP), flame retardant micro/nano-fibrillated cellulose (MNFC), and antibacterial additives (polyphenols).

Previous studies on lignin nanoparticles (LNP) have demonstrated their potential as UV absorbers due to aromatic structures capable of dissipating UV radiation. Similarly, micro/nano-fibrillated cellulose (MNFC) has been widely investigated for its flame-retardant properties, leveraging its high aspect ratio to form physical barriers that slow flame propagation. Polyphenol-based compounds have shown antibacterial properties through multiple mechanisms, including membrane disruption and enzyme inhibition in microorganisms. However, systematic application and validation of these additives in bio-based textile coatings remain limited, particularly regarding their simultaneous multi-functional performance. The textile sector requires comprehensive analyses to accurately assess specific functional properties of textile materials. In this context, Deliverable D2.1 presents the relevant standard regulations that serve as the benchmark for defining both the technical and functional requirements of the bio-based, functionalized textiles to be developed within the project (see Table 3). For the validation of the coatings developed in WP2 and applied in WP3, these standards provide a systematic framework for evaluating performance parameters, ensuring that the resulting textiles meet the targeted criteria for quality, safety, and applicability in real-world scenarios.

Table 3. International standards for textile sector.

Property	Standards
UV protection factor	UV standard 801
Flame retardancy	ISO 6941
Antibacterial property	ISO 20645 / ISO 20743

In addition, the viscosity of the textile coating formulations is a critical parameter that depends on the chosen application method, which in this project primarily includes impregnation and knife-coating. Impregnation requires formulations with lower viscosity, whereas knife-coating generally demands higher viscosity to achieve the desired coating thickness. The final viscosity target will be defined based on the specific application requirements and the intended coating properties. The partner responsible for applying the coatings on textile substrates - SUN - is equipped with the necessary instrumentation to measure viscosity; any measurements and subsequent optimizations will be performed at the laboratory scale to ensure that the formulations can be effectively applied to the textile substrates in accordance with the project's objectives.

During Task 2.1, the involved partners conducted a comprehensive screening of commercially available products currently used in the textile sector for fabric functionalization. The objective of this activity was to identify benchmark solutions providing key performance properties, specifically UV protection, antibacterial activity, and flame retardancy.

A selection of relevant commercial formulations was identified and analysed based on their functional performance, application methods, and compatibility with cellulosic-based textile substrates. These products represent the current state-of-the-art in textile finishing and serve as reference materials for the development of innovative bio-based alternatives within the project.

The identified commercial products are summarized in Table 4, where they are categorized according to the specific functional property they impart to the textile, namely UV protection, antibacterial performance, or flame retardant property. This classification facilitates a comparative assessment and supports the definition of technical targets for the development of bio-based coatings.

Table 4. Commercial products for textile sector.

Property	Commercial product	Brand	Application method
UV protection factor	Uvitex BUN	Huntsman	Padding
	Sarex UV-K	Sarex	Pad–dry–cure
	RUCO 3930	Rudolf Group	Spray-on application, pad or exhaust process
Flame retardancy	FLAMEGARD™ CP	Tanatex Chemicals	Finishing
	AFLAMMIT®MSG	THOR	Padding
	HERAFLAM PES	NF Kimya	Padding
Antibacterial property	ANTİBAC BG 50	BAYERTEKS	Finishing
	RUCO®-BAC AGP	Rudolf Group	Exhaust and padding
	Puretech	SANITIZED	Padding

4.1. Antimicrobial requirement

To evaluate the antibacterial properties of the functionalized textiles, the UNI EN ISO 20743 and UNI EN ISO 20645 standards provide established methodologies. The UNI EN ISO 20743 standard applies to all textile products, including yarns, garments, linens, and home furnishings, and it defines a quantitative test method that allows the determination of the level of bacterial reduction. According to this standard, textiles are classified into three reference categories based on their antibacterial activity: low, moderate, and high. For the purposes of this project, the functionalized textiles are expected to achieve at least a moderate antibacterial classification, with high performance being targeted for medical, protective, or high-contact applications. The UNI EN ISO 20645 standard provides a complementary qualitative method, based on the zone of inhibition, to visually assess the antibacterial efficacy of textile coatings.

In general, *Escherichia coli* and *Staphylococcus aureus* are the common microorganisms that can be found in the car environment, and the test method involves the inoculation of a known aliquot of these microorganisms for each sample. Other microorganisms can be involved according to the specific interest of the study and the end-use of the textile.

4.2. Flame retardancy requirement

To evaluate the flame retardancy of textiles, ISO 6940 standard provides established methodologies. This method evaluates the properties of textile materials when exposed to a flame under controlled conditions. It specifies a method for measuring the flame propagation time of textile materials and industrial products oriented vertically, in the form of single or multi-component fabrics (coated, quilted, multilayer, "sandwich" constructions, and similar combinations) when exposed to a small, defined flame. According to this standard, fabrics that exhibit a burning time equal to or greater than 20 seconds are classified as “non-ignitable,” i.e., flame-resistant. Flame retardancy is critical for many textile applications, including protective clothing and interior furnishings. The additives developed in WP2 should reduce flammability by forming a thermal barrier that slows the propagation of flames. Moreover, the chemical composition of the coating, the efficacy of this barrier will depend on the coating thickness, distribution of the additives in the coating and coating adhesion.

4.3. UV protection factor requirement

To evaluate the ultraviolet (UV) protection ISO 801 standard provides established methodologies. According to the standard, Ultraviolet Protection Factor (UPF) is measured, and a UPF rating above 30 provides very good UV protection, while ratings above 50 are considered excellent. Ultraviolet (UV) protection is an increasingly important feature for textiles used in outdoor applications and the development of bio-based textile coatings with high UV-protective efficacy remains a significant challenge. HALO-TEX project aims to optimize the coating formulations to achieve moderate UV-blocking performance, thereby enhancing the application potential of the resulting textiles for practical, real-world use.

5. CONCLUSIONS

A highly relevant aspect of the use of polyphenols and lignin in the textile sector is the possibility of utilizing agro-industrial by-products and waste as a source of functional compounds. Peels, seeds, bark, and processing effluents represent matrices rich in polyphenols and lignin, and their valorisation allows for waste reduction while promoting a circular economy model [4]. Proposing eco-friendly extraction strategies would have a positive effect by minimising environmental impact and reducing the use of hazardous solvents, thus making the process more sustainable overall.

The literature review highlights that lignin- and polyphenol-based products represent a viable alternative to conventional textile treatments, thanks to their natural origin, multiple functional properties, and effective adherence to textile fibers [2]. Key functionalities achieved include antibacterial activity, UV protection, antioxidant properties, and flame retardancy, with promising results also in terms of washing durability [3, 5].

Key challenges for lignin-based textile applications include variability in lignin structure, limited wash durability, and the lack of standardized processing routes. Nevertheless, advances in lignin fractionation, nanoparticle production, and hybrid bio-based systems are expected to accelerate commercialization. The integration of lignin and polyphenols into circular textile value chains presents a strong opportunity for innovation, aligning with market trends that increasingly sustainable, bio-based, and multifunctional textile solutions. In this context, the insights from the market overview, combined with the technical and functional requirements defined in Deliverable D2.1 — including antibacterial performance, UV protection, flame retardancy, and formulation viscosity — provide a comprehensive framework to guide the development, optimization, and industrial implementation of these novel functionalized textiles.

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