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VALORIZATION OF OAK BARK AS A SUSTAINABLE SOLUTION FOR PRODUCING CHEMICALS AND BIOCHAR DERIVED MATERIALS

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Abstract
Bark is typically regarded as a by-product of the wood industry and is often utilized as a horticultural substrate or incinerated for energy production due to its heterogeneous composition and high impurity content. However, its high ash content limits its efficiency as an energy source, as ash elements decrease heating value and cause fouling in combustors. Bark, however, contains a significant fraction of extractives and lignin (up to 50% on a dry basis), offering potential as a renewable source of aromatic chemicals for applications such as panels, tannins, resins, foams, and bio-oils. In this case study, the valorization of oak bark (Quercus robur) was evaluated through chemical extractions and the solid content processed via pyrolysis, yielding products such as biochar or bio-oils. The resulting biochar and bio-oils are evaluated in terms of yields and material characteristics such as surface area, pore volume, and surface functional groups. The integrated valorization of bark biomass into chemicals and biochar-derived materials demonstrates a sustainable approach to waste management. This process contributes to circular economy goals by optimizing resource utilization and promoting the development of bio-based materials.
Keywords: *aromatic chemicals, biochar, environmental remediation, oak bark, waste valorization*

JEL Classification: Q55

1. INTRODUCTION

Global forestry currently harvests about 1.92 billion m^3 of industrial roundwood per year, and projections from the FAO's Global Forest-Sector estimates this number will rise to 2.5–2.9 billion m^3 by 2050 (FAO, 2022). Since bark typically constitutes 9–15 % of the volume of each log, this growth implies that the global bark stream currently estimated at 0.17–0.29 billion m^3 annually, could reach up to 0.87 billion m^3 by 2050.

In most cases, bark is treated as a low-value by-product of the wood industry. Due to its high mineral content in form of ashes, it performs poorly as a biofuel, lowering calorific value and causing slagging and fouling in the combustion systems. These limitations undermine energy recovery and run counter to the European Green Deal's Circular Economy Action Plan (CEAP), which calls for product life-cycle optimisation and minimisation of incineration across resource-intensive sectors.

Although bark is commonly downcycled into horticultural substrate, animal bedding or decorative mulch, it is in fact a chemically rich natural resource. Up to 50% of its dry mass consist of lignin and polyphenolic extractives, including condensed and hydrolysable tannins, making it a promising renewable source of aromatic compounds. These constituents can be valorised into bio-based chemicals, rich bio-oils and carbon-negative biochar, effectively transforming bark from a disposal liability into a key feedstock for circular-economy applications and climate-neutral materials strategies.

On these grounds, integrated bark valorization through extraction and pyrolysis offers both environmental and societal benefits. It reduces waste and greenhouse gas emissions by diverting biomass from incineration and capturing carbon in stable products like biochar (Şen, Esteves and Pereira, 2023). Simultaneously, it replaces fossil-derived inputs with renewable, bio-based alternatives. Recent EU monitoring shows that circular use of biomass remains below target levels, highlighting both a clear policy gap and market opportunity.

This work explores the integrated valorisation of *Quercus robur* bark through a two-step cascade process involving the extraction of bioactive compounds followed by pyrolysis of the residual biomass. The aim is to evaluate both the chemical potential of the extracts and the material properties of the resulting biochar, highlighting their applicability in sustainable material development. Valorising bark is aligned with Europe's climate and resource-efficiency goals, supporting the transition toward low-carbon, bio-based industries.

2. METHODOLOGIES

The valorisation of oak bark (*Quercus robur*) was carried out using a cascaded biorefinery approach, consisting of two main stages: (1) chemical extraction of high-value compounds, and (2) thermochemical conversion of the residual biomass into biochar. This integrated pathway is designed to maximise resource efficiency and product diversification while aligning with circular economy principles (Figure 1).

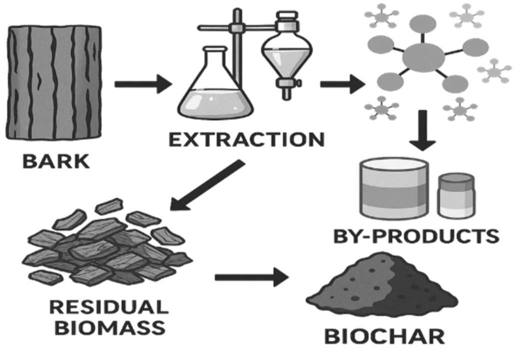

Figure 1. Stages of valorisation of residual bark.

2.1. Extraction of bioactive compounds

Bark samples need first to be dried, milled, and sieved to a uniform particle size. The powdered bark then is subjected to solvent-based extraction using environmentally friendly and inexpensive solvents (e.g., water, ethanol, or hydroalcoholic mixtures). The extraction is usually performed under controlled conditions (temperature, time, solvent-to-solid ratio) to maximise recovery of phenolic compounds, including tannins and lignin-derived aromatics. Soxhlet and Ultrasound Assisted Extractions were used to compare the extraction efficiency. After filtration, the liquid extracts are separated and concentrated. These extracts are further characterized for their chemical composition and potential applications in bio-based adhesives, additives, antioxidants, and resins.

2.2. Processing of residual biomass

The solid residue remaining after extraction referred to as residual biomass was collected, dried, and used as feedstock for pyrolysis. This thermochemical process is conducted in an inert atmosphere at moderate temperatures to produce biochar or bio-oils, as explained in the Figure 2. According to Chun et al. (2021), biochar yield and quality are influenced by feedstock characteristics and pyrolysis parameters such as temperature, heating rate, and residence time. These process parameters such as heating rate, residence time, and final temperature are optimized to enhance the yield and quality of the products. The resulting biochar is analysed for its surface area, porosity, elemental composition, and in the case of bio-oil, the physicochemical characteristics and the functional groups. After this initial profiling, it is chosen its suitability for environmental or agricultural applications.

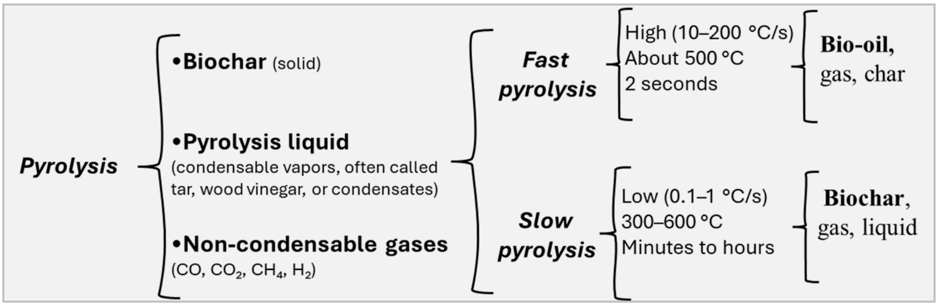

Figure 2. Thermochemical processes of residual bark.

2.3. Integration and by-product valorisation

The process applied in this study follows a cascaded approach, where oak bark is first used to extract valuable compounds, and then the remaining solid material is transformed into biochar. This means that every part of the bark is used with purpose, minimizing waste.

The liquid extracts obtained in the first step contain natural chemicals like tannins and antioxidants, which can be used in the production of bio-based materials. Meanwhile, the leftover bark solids are not discarded, instead, they are converted through pyrolysis into biochar, a carbon-rich material that can help improve soil, filter pollutants, or store carbon for long periods.

By combining both steps, this integrated process increases the value we get from bark. It also supports environmental goals by reducing waste, replacing fossil-based materials, and contributing to a more circular and sustainable use of forest resources

3. RESULTS AND DISCUSSION

3.1. Extraction of bioactive compounds

Oak bark is a rich source of bioactive molecules, particularly polyphenols, tannins, flavonoids, and lignin-derived aromatics, making it a valuable raw material for the sustainable production of functional chemicals. Various extraction methods have been explored to isolate these compounds, each with distinct advantages depending on the target compounds, environmental constraints, and final applications as is shown in Table 1.

Table 1. Characteristics of extractives from residual bark

Extraction method	Solvents	Typical Yield (%)	Yield on this study (%)	Type of compounds extracted	Potential applications	References
Hot extraction Soxhlet	Water	2-5	3	Condensed tannins, hydrolysable tannins	Animal feed additives, antimicrobials	Nisca *et al.*, 2023; Quaratesi *et al.*, 2024
Ultrasound-Assisted Extraction	Water-Ethanol	2-13	13	Phenolic acids, flavonoids, catechins	Adhesives, antioxidants, preservatives, antimicrobials	Şen, Esteves and Pereira, 2023; Nisca *et al.*, 2023; Quaratesi *et al.*, 2024
Alkaline Aqueous Extraction	Water (1% NAOH)	30-40	38	Lignin fractions, phenolics	Resins, lignin derived materials	Borrega and Kalliola 2022

Conventional hot water extraction is widely used due to its simplicity and low cost, though it typically results in modest yields and limited selectivity. The combination of ethanol and water as a co-solvent increases the solubility of phenolic compounds and significantly improves extraction efficiency. Ultrasound-assisted extraction enhances mass transfer and accelerates extraction kinetics, allowing shorter processing times and improved yields at lower temperatures, preserving sensitive molecules. Finally, alkaline aqueous extraction is particularly effective for isolating lignin fractions while maintaining the cellulose-rich solid residue, offering opportunities for further valorisation in a cascading biorefinery context.

3.2. Pyrolysis of residual bark fraction

Following extraction of bioactive compounds, the residual oak bark biomass was subjected to slow pyrolysis to obtain biochar, a carbon-rich material with multifunctional applications in agriculture, environmental remediation, and materials engineering. The physicochemical properties of biochar were found to vary significantly depending on the prior extraction method, which acts as a pre-treatment influencing carbon content, ash levels, particle size, porosity, and surface functionality, as shown in Table 2.

Biochar obtained after alkaline aqueous extraction showed the highest carbon content (72%) and the lowest oxygen content (11%), suggesting a more condensed carbon structure, favorable for long-term carbon sequestration. In contrast, biochar from solvent extractions exhibited higher surface area and larger pore volumes, making them more suitable for adsorption applications such as pollutant removal from water.

Table 2. Thermochemical processes of residual bark

Pretreatment	Solvents	Biochar properties				
		C / N / H / O content (%)	Ash content (%)	Surface area (m^2/g)	Average pore size (nm)	Mean particle size (um)
Hot water extraction	Water	68 / 1 / 1 / 17	13	55	9	50
Ultrasound-Assisted Extraction	Water-Ethanol	71 / 1 / 1 / 14	13	19	19	51
Alkaline Aqueous Extraction	Water (1% NAOH)	72 / 1 / 1 / 11	16	23	6	80

Ash content ranged from 13% to 16%, with alkaline pretreatment resulting in the highest ash level, which can affect thermal stability and nutrient retention when used as a soil amendment. All samples showed relatively low hydrogen and nitrogen content, typical of slow pyrolysis products, reinforcing their suitability for environmental uses rather than high-energy combustion. Mukherjee *et al.,* (2022) showed that variations in feedstock type substantially alter surface area of biochar, porosity, and elemental composition, findings consistent with our observations.

3.3. Integration and by-product valorisation

This valorisation step closes the loop by turning a low-value solid residue into a versatile carbon material, reinforcing circularity. Depending on its tailored properties, biochar can function as a soil conditioner, pollutant adsorbent, catalyst support, or even as a filler in biocomposites. The ability to adjust biochar characteristics through prior extraction methods exemplifies a cascade biorefinery strategy, maximizing the resource value of oak bark.

4. CONCLUSIONS

This two-step cascade valorisation strategy supports circular economy principles by maximizing resource use, minimizing waste, and generating multifunctional outputs. The combined recovery of chemical extracts and functional carbon materials demonstrates how oak bark can be transformed from a disposal challenge into a renewable resource stream, supporting climate action and sustainable material development. These findings provide a scalable model for integrating bark-derived products into bio-based value chains, contributing to the EU's goals for carbon neutrality and industrial circularity.

This volume brings together academic contributions and scientific abstracts presented at the ECO4ALL International Interim Conference (Iași, 9–10 May 2025), organized within the framework of the COST Action CA22124 – ECO4ALL. The papers explore current topics regarding the consumer-centric circular economy, such as extended producer responsibility, cross-border consumer protection, green public procurement and legal regulations for sustainability. The volume reflects an interdisciplinary vision and contributes to shaping a common European agenda for the green transition.

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