Results of the LIFE BIOREFFORMED project (2019-2024)

LIFE Biorefformed

Use of forest biomass in biorefinery processes

An opportunity to exploit the biomass generated during forestry adaptation and restoration work?

TECHNICAL DOCUMENT FOR THE FORESTRY SECTOR

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CONTENTS

1 Use of forest biomass in biorefinery processes. An opportunity to exploit the biomass generated during forestry adaptation and restoration work?

Primary forest biomass is a renewable product with great potential in the transition towards an inclusive bioeconomy, while helping agroforestry landscapes become more resilient. The possible uses of forest biomass include using biorefinery processes to extract chemical components for various industries. This is seen as an increasingly viable alternative to replace compounds that are currently derived from oil.

Mediterranean forests, meanwhile, are undergoing great changes: it is becoming increasingly evident that many forests are at risk from climate change and its effects (drought, pests, high winds, fires, etc.). To tackle this issue, a range of forestry measures can be taken to make forests less vulnerable now and in the future, and to restore their productive, social and environmental function. But such action cost money, with little or no return in the short term.

LIFE BIOREFFORMED project (2019-2024)

The LIFE Biorefformed project (LIFE19 ENV/ES/000544) *Implementation of a Mediterranean biorefinery to promote sustainable forest management through the production of added value products*, explored the use in biorefinery processes of the forest biomass generated in forestry adaptation measures, examining the entire value chain, from extraction in the forest to the industry.

The project had two aims:

- To test the suitability of various Mediterranean tree and shrub species in torrefaction and pyrolysis processes to obtain renewable chemicals and biofuels.

- To explore whether these high value-added products could help finance forestry improvement actions aimed at making forests more resilient and boosting the value chain.

Biomass from adaptation and restoration measures in cork oak and Mediterranean pine forests

The LIFE BIOREFORMED project worked on **three priority forest types**:

1. **Young Aleppo pine stands with post-fire regeneration:** stands that successfully regenerated following forest fires but where the regrowth is too dense. If no forestry work is carried out, growth is stunted, the forests remain vulnerable to new fires for longer and, as pine nut production is delayed, the trees are less able to regenerate in the event of a later fire.

2. **Adult pine trees affected by a recent natural disturbance other than fire** (biotic or abiotic damage). Increased aridity weakens vegetation and makes it more prone to pests and diseases and to suffer more adverse effects. This is especially relevant in dense pine forests or those with an abundant undergrowth of oak species. These disturbances are cyclical and their severity and mortality rates are difficult to forecast. The disturbance itself, or subsequent sanitary cutting, can result in unstructured stands whose productive and ecological functions are compromised.

3. **Excessively dense old cork oak groves with signs of decline or cork oak groves that are highly vulnerable to drought or fire,** which need to be adapted to new climate conditions. It is believed that 2/3 of productive Catalan cork oak forests are currently located in areas that will be outside their ecological range by 2050.

The most appropriate forestry measures were identified for each of these scenarios based on a multi-functional approach intended to restore as many different ecosystem services as possible at the same time.

These measures were applied to 9 demonstration stands, under different conditions, to assess the technical and economic feasibility of using part of the biomass generated to obtain useful products for the chemical industry and to identify their potential limitations and opportunities.

The species and types of biomass tested for their viability in biorefinery processes were:

1. Young Aleppo pine (*Pinus halepensis*): wood with thin bark, branches and leaves.
2. Aleppo pine (*Pinus halepensis*): wood with bark.
3. Stone pine (*Pinus pinea*): wood with bark.
4. Holm oak (*Quercus ilex*): wood with bark.
5. Cork oak (*Quercus suber*): unstripped wood with bark.
6. Chestnut (*Castanea sativa*): dead chestnut wood, with bark.
7. Erica (*Erica arborea*): wood, branches and leaves.
8. Arbutus (*Arbutus unedo*): wood, branches and leaves

What products are obtained in a biorefinery?

Three fractions are obtained from a biorefinery: liquid (*bio-oil*), solid (*biochar* or torrefied biomass, depending on the process temperature) and gas.

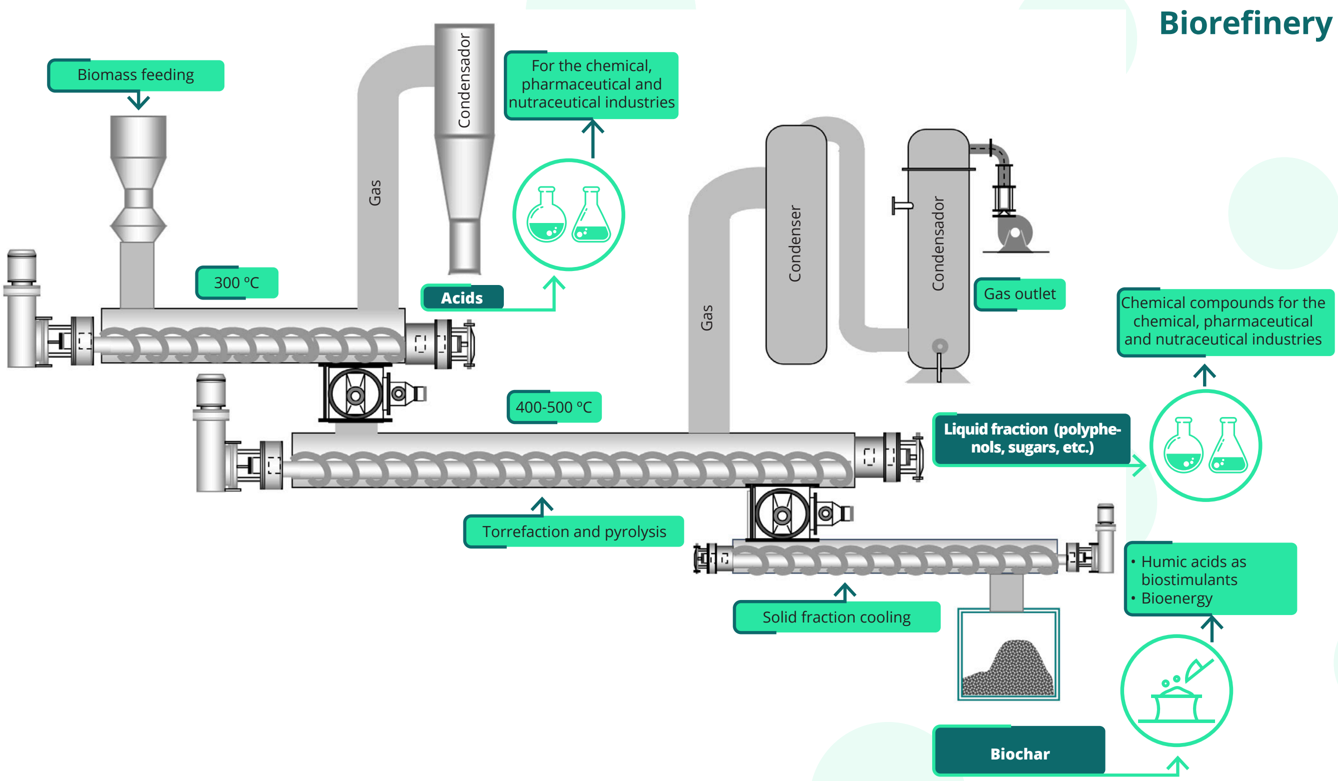


Figura 1. The biorefinery process.

A number of compounds that can be used in the nutraceutical, food, cosmetic, pharmaceutical and chemical industries, such as sugars, antioxidants (polyphenols), acids or phenolic resins, can be extracted from the **liquid fraction** (bio-oil). This requires a second transformation, which has been performed at laboratory scale for the project. These technologies need to be scaled up, in order to achieve industrial-scale implementation. The results referring to the yields and impact of the biorefinery relate only to the first transformation of biomass into bio-oil.

The **solid fraction** obtained is known as torrefied biomass when obtained at low temperatures (up to 300 °C) or as biochar, if obtained above 400 °C. Humic and fulvic extracts can be obtained from the torrefied biomass, which are used as biostimulants in agriculture. Biochar, meanwhile, can be used as a soil structuring agent for carbon sequestration and improving water retention or as a biofuel.

2 Main results of the LIFE BIOREFFORMED project

Process and final products obtaineds

- The forest biomass has been transformed through the process of pyrolysis, and **biochar (solid) and bio-oil (liquid) have been obtained**, with different uses depending on their properties.

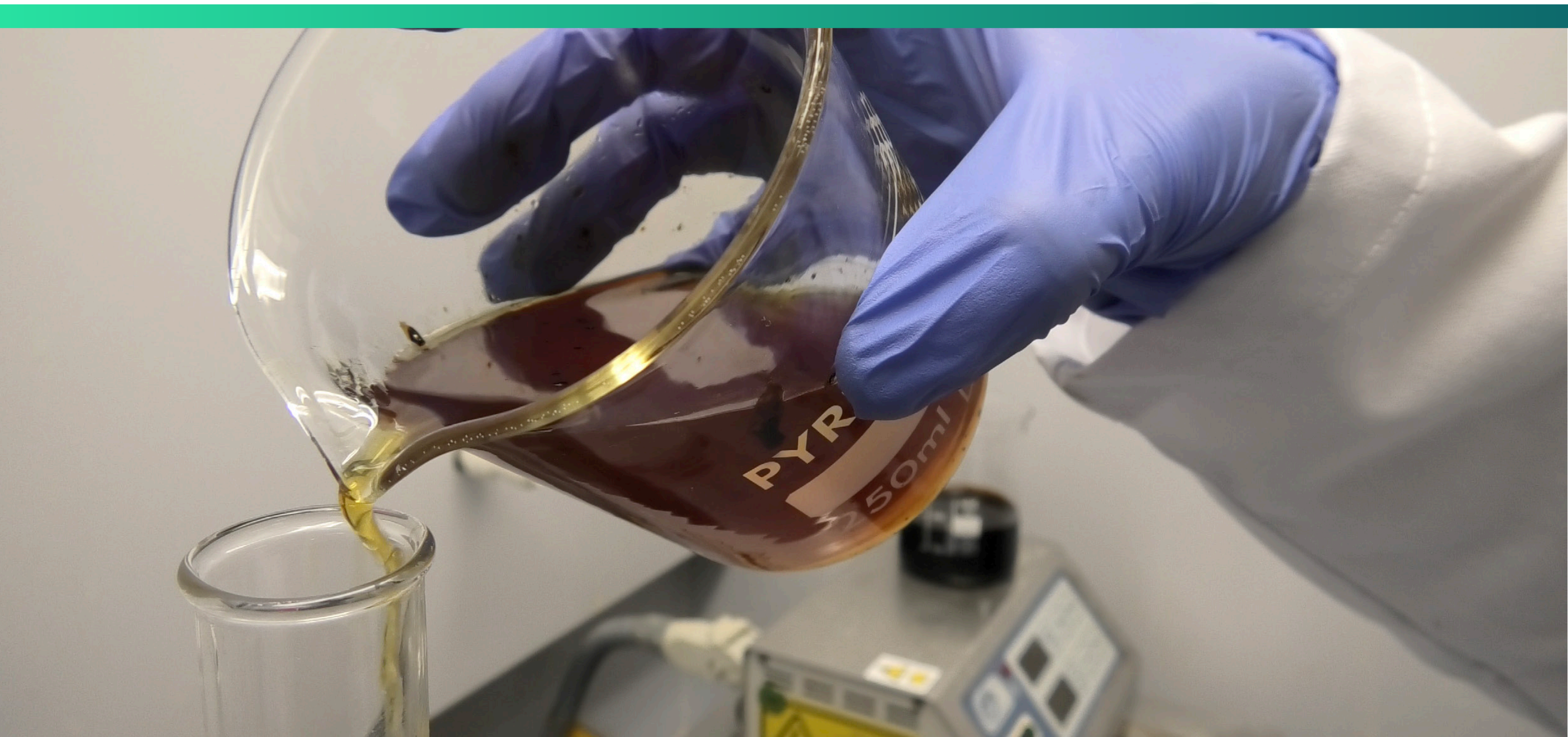
- The optimum **temperature** for producing bio-oils, higher quality useful compounds and biochar from forest biomass was found to be 450 °C. The optimum temperature for the production of biostimulants used in agriculture from the solid fraction, however, is 300 ºC.

- The **products obtained from the bio-oil at 450 °C** from Aleppo pine were **antioxidants** (4 g per kg biomass), **sugars** (11 g per kg biomass), **acids** (35 g per kg biomass) and **phenolic resins**. The end product with the highest added value is the sugars, both in terms of the quantity obtained and their high market price.

- **A comprehensive multi-objective extraction and separation process based on biorefinery techniques of value-added compounds from bio-oil has been successfully developed,** so that with a single process all the chemicals described can be obtained, with a purity equal to or higher than expected.

- The **biochar** generated in this process has been shown to have no inhibitory effect on microbial activity in the soil and can therefore be used as a soil structuring agent or for water retention. This biochar can also be used as biofuel with a low calorific value range of 23-30 MJ/kg.

- The **bio-stimulants obtained from torrefied forest biomass at 300 °C** are of high quality and could be improved further. Their properties are similar to biostimulants obtained from plant compost.



Efficiency of the different types of forest biomass tested

- Similar amounts of useful compounds were obtained from the different types of forest biomass processed during the project. It can therefore be concluded that **there are no major differences between hardwood and softwood tree species, or between these and shrub species**.

- This implies that, firstly, **it is viable to use all the forest species tested in this type of biorefinery** and, secondly, that **they could be mixed, thereby exploiting biomass with few alternative** uses such as i) brush and small trees with bark and leaves from undergrowth or sapling thinning operations, ii) unstripped cork oak (wood and cork) from selective cutting operations, or iii) mixed wood of different species and types from post-disturbance measures that generate small volumes of wood.

- Among the **tree species** studied, **pine** (especially Aleppo pine) were the best for producing antioxidant compounds (such as guaiacol, catechol, phenol and vanillin). **Chestnut** and **cork oak** gave the best results for the production of humic extracts used to stimulate soil microbial activity and plant growth. **Shrub species** such as erica were very good for producing acids such as acetic acid.

Table 1.1. Yields at 400 ºC (g product/kg biomass) and potential use of the products obtained from processing biomass from the demonstration stands in the LIFE BIOREFFORMED microbiorefinery.

	Bioproducts obtained	Regenerated Aleppo pine	Aleppo pine	Stone pine	Oak	Cork oak	Chestnut tree	Strawberry tree	Heather	
Liquid fraction	**Acids** Acetic acid Formic acid	21,1	17,6	16,0	19,8	17,6	11,5	11,9	25,6	Pharmaceutical chemicals or food additives
	Sugars Levoglucosan	8,3	9, 5	6,9	5,9	2,7	5,9	2,9	9,6	Compounds of high economic value with applications in the chemical and food industry for use as a chemical platform
	Aldehydes and ketones Hidroxiacetone, Methylcyclopentenolone, Furfural, 5HMF	6,4	5,4	3,8	6,0	2,9	2,1	2,4	5,4	Diversity of applications in the chemical and food industry, from flavorings to chemical platforms
	Antioxidants Phenol, Catechol, Vanillin, Guaiacol, p-creosol, p-cresol	4,4	4, 6	4,0	2,5	1,1	0,7	0,6	2,3	Cosmetic, pharmaceutical, nutraceutical, chemical and food industries, for use as antioxidants, flavorings and reagents for the synthesis of phenolic resins
	Phenolic resins	2,38	1,43	3,33	2,01	1,34	2,33	1,67	2,01	Adhesive or additive in paints
	Pyrolytic lignin	13,5	8,1	18,9	11,4	7,60	13,20	9,50	11,40	Fuel, precursor of carbonaceous materials and synthesis of adhesives and additives
Solid fraction	**Humic acids** (g/100 mL) Extraction at 300ºC	1,37	1,19	1,46	1,55	2,31	2,37	1,63	1,43	Fertilizer of agricultural soils
	Biochar (MJ/kg) Extraction at 450 ºC	25,8	26,2	29,9	24,2	16,6	22,7	22,1	23,1	Agricultural soil amendment or biofuel

Yields and impact of forest biomass extraction

- **The use of biomass in biorefineries can make the partial extraction of biomass from adaptation/ restoration measures viable**. This biomass is often left chopped up in the forest.

- **The obstacles to using biomass from adaptation/restoration measures are the low yields/ha** (the average yield in the demonstration stands was 13 t/ha) and **the high cost of extracting it**, which is currently done manually. The data sheets complementing this document give details of the values obtained from the different demonstration stands.

- **When extracting biomass for biorefinery use in mature forests it is vital that the crowns are left in place**, as the crown (branches and leaves) contains 60% of the nitrogen and potassium in the aerial part of the tree and up to 50% of the phosphorus, which is very difficult to recover naturally. **Biomass from regenerated Aleppo pine or brush is extracted in many places, with the removal of the whole tree**. However, harvesting is concentrated in accessible areas (strips along the sides of roads), which at stand scale **represents 10% of the total biomass**. It also contributes to preventing forest fires.

- These operations logically reduce the above-ground carbon stock due to the cutting and removal of part of the biomass. However, **the reduction in CO_2 stocks can only be counted as a net CO_2 emission if the material is used for biofuel in the short term**. A **CO_2 sink effect** is likely, due to increased growth following the measures, but this remains imperceptible over the short periods involved.

- Forestry management that also **exploits the historical socio-ecological heritage** (tangible and intangible) of the forest can help strengthen the **Cultural Ecosystem Services** that forestry estates provide. Measures involving the preservation of oral lore and traditional knowledge about forests and how to manage them help foster the transmission of knowledge, while serving as a **strategy to promote resilience**.

Biorefinery yields and impact

- For the biorefinery to be profitable, inputs of 1-2 t of woodchips per hour are needed, approximately 6,000 to 10,000 t of biomass per year. **The optimal scenario would be to make the biorefinery profitable with small plants that use less than 1 tonne per hour (microbiorefineries)**. This would reduce the cost and impact of transport, while there is also the **possibility of the plant being mobile**.

- Within the operating costs of the biorefinery, **the highest cost is the purchase of biomass followed by the cost of electricity.** The high consumption of electricity makes it difficult to locate them in areas with difficult access to electricity and it is necessary to explore alternatives to generate energy such as the use of biomass, biochar or solar energy.

- **Biomass extraction and transport operations must be optimised** to improve the profitability of the whole process while also reducing its environmental impact. This involves finding strategic locations for the biorefineries and **optimising pre-treatment operations** (storage and second chipping) and the loading of the product to be processed.

- **Seeking the production of bio-oil from biomass makes sense, from an environmental point of view**. The biorefinery, with a pyrolysis temperature of 400° C, has turned out to be a viable and sustainable alternative: **the production of bio-oil and acids is 3.7 times less impactful than the combined production of the same products through industrial processes**. The overall impact in terms of CO2 eq emissions is 0.5 kg CO2 eq/kg biomass input for most products, with the largest proportion associated with chipping, followed by forestry work and transport.

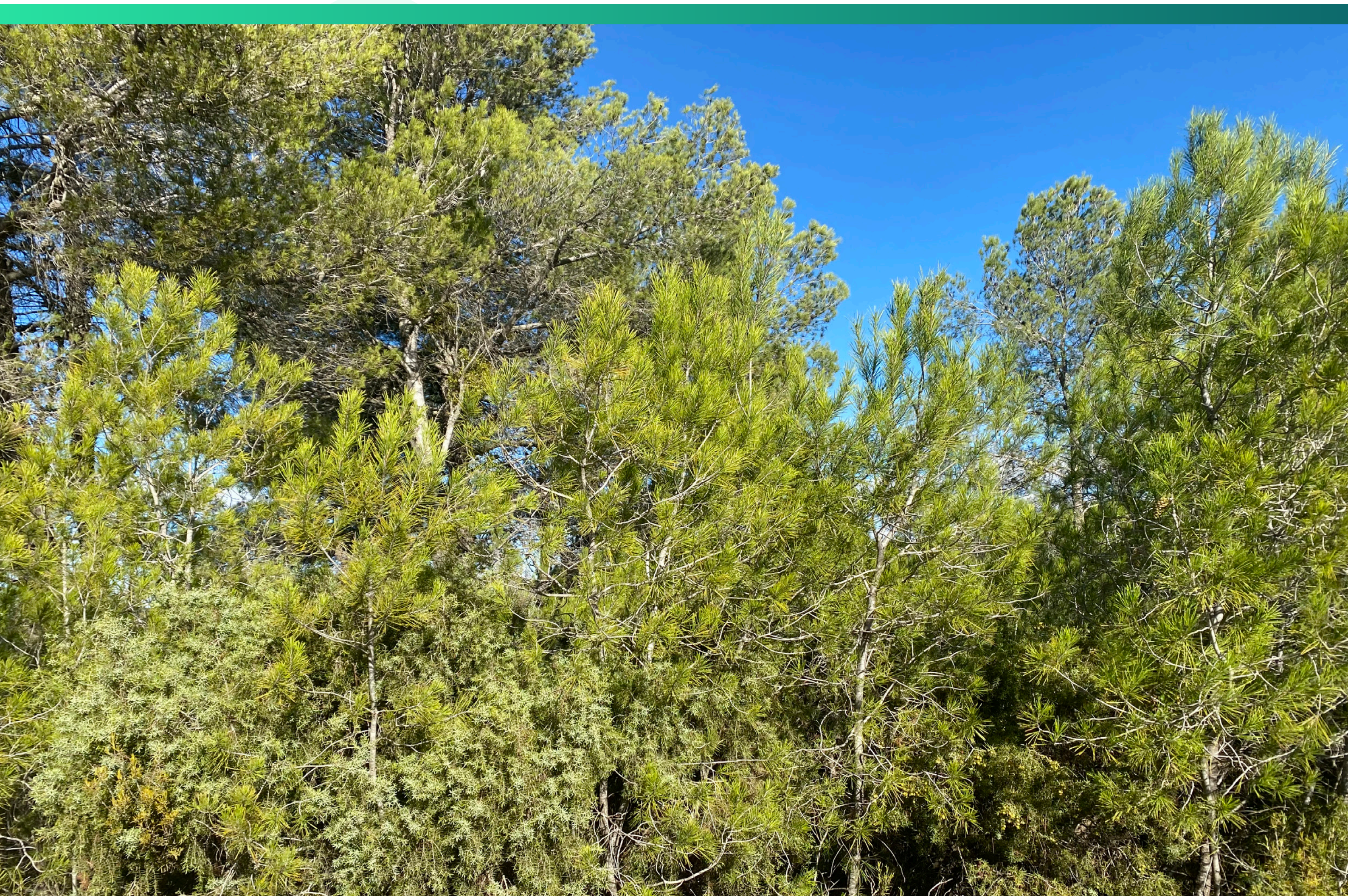
- The profitability of the biorefinery and its overall impact could be further improved if the sale of the products generated were to be complemented by the **potential sale of CO_2, credits linked to the production of biochar** as a carbon sink.

3 Biorefinery use of biomass from Aleppo pine stands with dense post-fire regeneration

Aleppo pine is extremely well-adapted to fire and climate change due to its great ability to colonise poor soils; its high resistance to periods of drought; the presence of a seed bank in the canopy (serotinous pine cones) that disperse after a fire and quickly produce viable seeds. These last two characteristics show the species has adapted to withstand frequent fires.

In Catalonia, forests dominated by Aleppo pine (*Pinus halepensis*) cover approximately 315,000 hectares. From 1986 to 2020, a total of 40,000 hectares of this species have burnt, of which it is estimated that more than half (about 28,000) now contain regenerated pines to which forestry measures could be applied. Post-fire regeneration tends to be naturally dense, but if fires recur frequently regeneration may be compromised.

The environmental and socio-economic risks are greatest during the regeneration phase from the appearance of seedlings until the establishment of a mature forest. During this period, the low yields and high costs, together with a lack of income, lead owners to give up on managing their forests, threatening their conservation and biodiversity, and the associated value chain.



Recommended forest restoration and adaptation measures

Rapidly regulating the density of a stand makes it less vulnerable to fire in the medium term, allowing trees to grow without competing for resources, avoiding stunted growth and ensuring cones develop sooner to ensure stand continuity in the event of another fire. The recommended measures are:

- **Seedling thinning.** The density of trees is considerably reduced, leaving all the trees equally spaced from each other and optimising the final density according to the preferred management model. Depending on the stage of development, low-level thinning (manual or mechanised) or selective thinning can be carried out, to prevent competition with trees that have already grown taller.

- **Treatment of cutting waste**. Large quantities of whole felled trees are chopped up and evenly distributed to avoid the accumulation of dry biomass and to accelerate decomposition. This practice also reduces the risk of fire, provides nutrients for the soil and improves water retention.

Types of biomass available for the biorefinery

Sapling thinning has no commercial benefits: saplings of unstocked diameters (<7.5 cm), or with diameters of no more than 15 cm, are cut and treated as debris, chopped and left in situ.

The proposal for this project is to **extract felled pines from both sides of the main tracks** so they can be economically exploited in a biorefinery. **Bundles of young Aleppo pine** will be shredded whole, so the woodchip produced will include **thin pine wood biomass mixed with bark, twigs and leaves**.

This type of operation, limited to trackside areas, will produce an estimated yield of 10 t/ha from the project demonstration stands.

Yields and costs associated with biomass extraction operations

For the harvesting of small diameter trees, it is recommended to cut at the base of the stem and extract whole trees to maximise the amount of product and to facilitate removal by bundling. Extracting bundles is costly work so the proposal is to only extract bundles along tracksides, taking advantage of current regulations that require a 20 m zone on either side of the road to be kept clear of waste vegetation. The operations and costs of the recommended works are shown in table 3.1.

Table 3.1. Unit cost1 of each operation or forestry work (excluding VAT) for post-fire management

Operation	Unit cost (€/ha)
Manual seedling thinning with chainsaws	1.250
Debris processing using chainsaws	650
Manual removal of bundles collected from the sides of the tracks (€/ha)	360
Chipped and stacked at roadside or at loader with tractor and chipper	150[2]

[1] Figures derived from an analysis of tariffs published by the forestry authorities, including prices set by Forestal Catalana, benchmark prices in the Forest Management Instruments issued by the Catalan Forest Owners Centre (CPF) and the benchmark prices for the 2024 Sustainable Forestry Management (GFS) grants, and other prices based on estimates and the results of work done for the project.

[2] Based on extracting 10 t/ha and chipping costs of 15 €/t.

Main technical and logistical challenges

Typical treatments do not generate commercial products, so extracting and transporting them raises new technical issues to be taken into account:

- The use of whole pines with a small diameter (less than 15 cm) at the trackside changes the dynamics of seedling thinning.
- Removing the bundles manually is economically unviable and cumbersome. Looking at ways to mechanise the process, a previous study on the potential use of this type of biomass for energy purposes (Lopez, 2014; *https://cris.ctfc.cat/docs/upload/28_175_Silvicultura-70_lopez.pdf*) recommended the use of a grapple attached to the tractor rather than winching because it gives better yields at the same hourly cost.
- In terms of transport, bundles of regenerated saplings take up a lot of space and weigh little. On-site chipping therefore seems to be the most viable option.
- The infrastructure must be prepared to allow lorries transporting forest products to pass and, if necessary, a chipper installed at the track entrance or by the loader.

Biorefinery products and yields obtained

Aleppo pine biomass from seedling thinning operations has been used in a biorefinery to produce chemical compounds such as **antioxidants** (90% purity), **phenolic resins** (minimum 30% phenol substitution), sugars (minimum 40% purity) and **acids** (70% purity), as well as **biochar**. The production of humic soil conditioners for agriculture from torrefied biomass (at 300 °C) has also been tested. Table 3.2 shows the main results obtained from the project demonstration stands.

Taula 3.2. Rendiments a 400 ºC (g producte/kg biomassa) i ús potencial dels productes obtinguts en el processament de la biomassa de regenerat de pi blanc a la biorefineria del LIFE BIOREFFORMED

Bioproducts extracted		Quantitat de producte obtingut (g/kg de biomassa) Regenerat de pi blanc	Aplicacions
Liquid fraction	**Acids**	21,10	Chemicals and pharmaceuticals or food additives
	Sugars	8,30	Compound with high economic value with applications in the chemical and food industry
	Aldehydes and ketones	6,40	Range of applications in the chemical and food industry
	Antioxidants	4,40	Cosmetic, pharmaceutical, nutraceutical, chemical and food industry, such as antioxidants, flavourings and reagents for the synthesis of phenolic resins
	Phenolic resins	2,38	Adhesives or paint additives
	Pyrolytic lignin	13,50	Fuel, precursor of carbonaceous materials and synthesis of adhesives and additives
Solid fraction	**Humic acids** (300º C) (g/100 mL)	1,37	Agronutrient industry
	Biochar (450 ºC) (MJ/kg)	25,80	Biofuel Agricultural soil conditioner

Of these results, it is worth noting:

- ✓ Of the species tested in this project, **Aleppo pine produced the best yields for the production of antioxidant compounds** (such as guaiacol, catechol, phenol and vanillin).
- ✓ Biomass composed of wood chips from small trees with bark and leaves, which has few alternative uses, **can be used in a biorefinery without issues**, meaning it could be possible to commercially exploit biomass generated in post-fire Aleppo pine sapling thinning operations.

4 Biorefinery use of biomass from pine forests affected by natural disturbances (biotic or abiotic)

Mediterranean pine forests (*Pinus halepensis*, *Pinus pinea* and *Pinus pinaster*) are affected by disturbances other than fire, which has always been a feature of these ecosystems. In recent years these stands have been affected by recurrent and longer periods of drought and (or, in combination) other disturbances such as high winds and pests, which have significantly reduced their area.

Major **wind and snow storms** occurred in Catalonia in 2008-09 and in 2014, affecting thousands of hectares and leaving some areas completely devastated. In the winter of 2008-09, Catalan forests suffered heavy snows that destroyed more than 25,000 ha, and high winds just over a month later seriously or very seriously damaged more than 1,000 ha, generating between 150,000 and 180,000 m^3 of timber. In the winter of 2014-15, in the Vallès Oriental and Vallès Occidental regions, wind storms affected 650 hectares, 520 of which were stands of Aleppo pine and holm oak.

In terms of **biotic damage**, longer, recurring droughts help **scolytids**, such as *Tomicus destruens*, to spread, a pest that caused severe damage between 2016 and 2018 in stands of stone pine in El Maresme (a study by DIBA and ICGC estimated that some 1,500 hectares were severely affected, 11% of the total affected). Drought also encourages **fungi** such as *Thyriopsis halepensis,* which mainly affects Aleppo pine and stone pine, or *Diplodia sapinea* and *Dothistroma* (there was a major outbreak in 2022 after a heavy hailstorm in Aleppo pine, Scots pine and black pine forests), as well as other pathogens which cause major economic and ecological damage.

Recommended forest restoration and adaptation measures

These disturbances lead to unstructured and under-capitalised pine forests that require a number of measures if their productive and ecological functions are to be speedily restored. Immediately after damage occurs, any part of the affected timber that is of commercial value is removed. In the years after that, measures to restructure the forest are recommended, generating low volumes of material of little value.

The types of measures proposed to improve the productive potential of a stand affected by biotic or abiotic damage are:

- **Improvement thinning/selective cutting/sanitary cutting**: during the years following the damage, it will be necessary to monitor the stand and to apply different improvement treatments according to the type of damage in order to structure the stand and make it more resistant and resilient to changes.
- **Selection of shoots/selective undergrowth thinning**: after a disturbance the forest undergrowth is opened to sunlight, causing brush, oaks shoots and leafy plants to proliferate. Although this is an opportunity to move towards mixed stands, this undergrowth needs to be treated to make it less vulnerable to fire and competition or to facilitate the regeneration of pines if the landowner wishes to retain them.
- **Enrichment planting**: if tree density is poor, it may be necessary to introduce new seedlings to improve density, or even to introduce other species to improve stand biodiversity and resilience.

In mature forests, the management objective behind these measures can **explicitly include biodiversity protection and restoration criteria**. This involves conserving those features that boost the stand's capacity to host biodiversity: sporadic tree species, live trees with microhabitats or large trees, and, where appropriate, leaving some of the large dead wood resulting from the disturbance in situ.

Types of biomass available for the biorefinery

The biomass generated by post-disturbance restoration measures comprises small volumes of wood of different species, of varying diameters and with different uses in current markets (mainly holm oak firewood and pine wood for shredding). This means the per tonne extraction and transport cost is high, often making its commercialisation unviable. The aim of the project was to test the technical and economic viability of using part of the wood generated in these actions in biorefinery processes. The specific products tested were:

- **Aleppo pine and stone pine wood with bark, of various sizes**.
- **Oak and/or holm oak wood with bark**.

In terms of volumes, for treatments carried out after wind or biotic damage a few years after the disturbance, the yields are estimated at between 15 and 20 t/ha.

Yields and costs associated with biomass extraction operations

The work to be carried out in order to exploit this biomass and the main associated costs are:

- Harvesting and extraction of small volumes of poor-quality timber.
- Cutting the crowns, which are left in the stand.
- Transport to industrial sites.
- Manual planting of a few specimens throughout the site.

The costs of the treatments applied are detailed in table 4.1.

Table 4.1. Unit cost1of each operation or forestry work (excluding VAT) for the management of Aleppo pine and holm oak stands affected by high winds and of stone pine and holm oak stands affected by scolytids, based on existing rates and project results

Operation	Unit cost (€/ha)
Selective thinning/cutting, selection of shoots and removal	1.300-1.400
Sanitary felling and removal (biotic impacts)	1.450
Manual selective undergrowth clearing	1.050
Debris processing using chainsaws	650
Enrichment planting with protective tubes	1.800
Chipped in forest	300[2]

[1] Figures derived from an analysis of tariffs published by the forestry authorities including prices set by Forestal Catalana, benchmark prices in the Forest Management Instruments issued by the Catalan Forest Owners Centre (CPF) and the benchmark prices for the 2024 Sustainable Forestry Management (GFS) grants, and other prices based on estimates and the results of work done for the project.

[2] Based on extracting 20 t/ha and chipping costs of 15 €/t.

Main technical and logistical challenges

In this type of stand, issues that make the measures more difficult and increase their costs include:

- Debris from the wind/snow that was not dealt with in the previous operation and is caught on higher branches, half fallen, etc., making both cutting and removal more dangerous.
- Many different tree species in the same stand. The stand has very dense patches and areas that have been extensively cleared (the worst affected). This means that the weight of the cut/cleared material is constantly changing and the team performing the work has to adapt the type and weight of the operation as it progresses. Likewise, extracting isolated trees scattered throughout the stand slows down the process and makes it difficult to mechanise.
- The products obtained are also very mixed (firewood, shredded wood, sawmill timber) and in small quantities, which makes handling and transport more expensive.
- Cutting healthy trees in areas affected by biotic agents may sometimes be necessary both to regulate competition and increase vitality and to prevent the spread of the pest or disease.
- Stands affected by a biotic agent must be constantly monitored for the possible appearance of new decayed trees in order to prevent new outbreaks. If dry trees keep reappearing, it is advisable to plant new species.
- Any enrichment planting carried out must be done manually

Chemical products obtained and yields

Stone pine, Aleppo pine and holm oak biomass from post-disturbance managed forests has been used in the LIFE BIOREFFORMED biorefinery to obtain bioproducts such as **antioxidants** (90% purity), **phenolic resins** (minimum 30% phenol substitution), **sugars** (minimum 40% purity) and **acids** (70% purity), as well as **biochar.** The production of humic soil conditioners for agriculture from torrefied biomass (at 300 °C) has also been tested. Table 4.2 shows the main results obtained from the project demonstration stands.

Table 4.2. Yields at 400 °C (g product/kg biomass) and potential use of the products obtained from the processing of post-disturbance pine biomass in the LIFE BIOREFFORMED micro-biorefinery

Fraction	Final chemical compound	Quantity of product obtained (g/kg de biomassa)			Application
		Aleppo pine	Holm oak	Stone pine	
Liquid fraction	**Acids**	17,6	19,8	16	Chemicals and pharmaceuticals or food additives
	Sugars	9,5	5,9	6,9	Compound with high economic value with applications in the chemical and food industry
	Aldehydes and ketones	5,4	6,0	3,8	Range of applications in the chemical and food industry (e.g., flavourings)
	Antioxidants	4,6	2,5	4,0	Cosmetic, pharmaceutical, nutraceutical, chemical and food industry, such as antioxidants, flavourings and reagents for the synthesis of phenolic resins
	Phenolic resins	1,43	2,01	3,33	Adhesives or paint additives
	Pyrolytic lignin	8,1	11,4	18,9	Fuel, precursor of carbonaceous materials and synthesis of adhesives and additives
Solid fraction	**Humic acids** (300° C) (g/100 mL)	1,19	1,55	1,46	Agronutrient industry
	Biochar (450 °C) (MJ/kg)	26,2	24,2	29,9	Biofuel Agricultural soil conditioner

Of these results, it is worth noting:

- ✓ Biomass from the adaptive management of disturbed pine forests, which has few alternative commercial uses, could viably be used in a biorefinery by allowing the use of **mixed wood of different species and characteristics**, without reducing the quality of the final product.
- ✓ **Pine** (stone pine and, above all Aleppo pine) **produced better yields for the production of antioxidant compounds** (such as guaiacol, catechol, phenol and vanillin) than holm oak and the other species tested in the project.

5 Biorefinery use of biomass from the adaptive management of cork oak forests affected by climate change

Cork oak groves of *Quercus suber* L. are a natural habitat of Community interest (9330) with a long economic and socio-cultural history. Cork is the most valuable product, and one that regrows after harvesting. In Catalonia, forests dominated by cork oak occupy 69,000 hectares, and cork oak is recorded as a secondary species in a further approximately 55,000 hectares, 95% of which are privately owned.

Climate change represents a serious threat to the conservation of cork oak forests and to the long-term sustainable production of cork and the associated value chain. The three main impacts of climate change on cork oak forests are: (i) increased aridity, which leads to reduced vitality and growth and eventually to the replacement of cork oak by other more competitive species; (ii) pests, including the corkworm (*Coraebus undatus*), which affects the quality of the cork produced; and (iii) fires. The LIFE SUBER project analysed the vulnerability of cork oak forests to water shortages, concluding that approximately 2/3 of Catalan cork oak forests (about 30,000 hectares) are in locations that will be outside their ecological range by 2050.

From a biogeographical perspective, there are 2 main types of cork oak grove in Catalonia:

(a) **Humid Mediterranean groves (La Selva and L'Alt Empordà)**: well-preserved, dense and mostly pure forests. The cork is extracted every 12-16 years followed by minimal thinning. This management method, sustained over 150 years, has resulted in very dense and ageing cork oak groves, with limited productivity and a lack of viable regeneration, i.e., with few young, vital trees available to replace ageing stands or enable them to recover after fire.

(b) **Dry Mediterranean groves (Les Gavarres and El Montnegre)**: generally mixed forests with pines (stone pine, maritime pine), holm oaks or arbutus (strawberry trees), all with a competitive advantage over cork oaks and a highly developed undergrowth. Dry Mediterranean areas are more prone to attack by *Coraebus undatus* and are subject to limited management, especially in post-fire areas, due to their low profitability.

Recommended forest restoration and adaptation measures

To address these various challenges, the LIFE SUBER project (2012-2018) identified the following range of measures:

1. **More extensive thinning** to boost individual vitality, by reducing competition between cork producing trees, **and selective clearing** to increase collective vitality, taking advantage of environmental humidity as a complementary water resource.
2. **Encouraging the regeneration of cork oak trees in older stands** to improve forests and enable their rapid renewal in the event of fire.
3. **Promoting the presence of cork oak in the more humid parts** of mixed stands or in stands occupied by more productive species, helping the cork oak to adapt more rapidly to the new climatic conditions through densification planting or reforestation.
4. **Reducing fuel volumes and fuel continuity** to make forests more resistant to major fires without compromising environmental moisture conservation.

Types of biomass available for the biorefinery

Measures to adapt cork oak forests to climate change generate a number of by-products that are difficult to commercialise in current markets. The products tested for use in the biorefinery were:

1. **Unstripped cork oak wood (wood and cork)**. To use cork oak wood as fuel, the bark (cork) must first be removed, which is a costly process. Earlier tests showed that cork could give very interesting results in biorefineries but the excess gas produced has to be offset by burning it together with other material. The possibility of using unstripped cork wood in biorefineries does, therefore exist.

2. **Shrub species (*Erica* arborea and *Arbutus unedo*)**: shrubs from selective scrub clearance. Scrub waste is often left chopped up in the forest for nutrient recycling and moisture conservation purposes, but removing it from either side of forestry tracks to prevent fire is an option.

3. **Dead chestnut wood in a productive stand** where cork oak is to be planted or encouraged (favouring incipient regeneration or planting). In this case, cutting is usually carried out throughout the stand and all the wood generated is subsequently exploited. This is usually profitable, although chestnut trees affected by canker have little commercial value.

Depending on the type of forest, these treatments can produce around 15 t/ha of tree biomass, plus 10 t/ha of shrub biomass from roadsides. In the case of post-disturbance chestnuts (generalised felling), the operation produces about 85 t/ha.

Yields and costs associated with biomass extraction operations

It may be feasible to shred extracted wood directly at the biorefinery, while it is advisable to shred brush material at the track entrance, once it has dried out. The required operations and costs are shown in table 5.1.

Table 5.1. Unit cost1 of each recommended improvement operation or forestry work in cork oak groves (excluding VAT) based on current tariffs and project results

Operation	Unit cost
Selective felling and removal of cork oak (€/ha)	650
Selective and manual clearing of scrub and treatment of debris (€/ha)	1.470
Manual removal of scrub from a strip on both sides of the track (€/ha)	420
Chipped and stacked at roadside or at loader with tractor and chipper (€/t)	150-1.275[2]
Densification planting with protective tubes (€/ha)	250

[1] Figures derived from an analysis of tariffs published by the forestry authorities including prices set by Forestal Catalana, benchmark prices in the Forest Management Instruments issued by the Catalan Forest Owners Centre (CPF) and the benchmark prices for the 2024 Sustainable Forestry Management (GFS) grants, and other prices based on estimates and the results of work done for the project.

[2] Based on extracting 10 t/ha from cork oak groves and 85 t/ha from the generalised felling of chestnut trees affected by canker, with chipping costs of 15 €/t.

Main technical and logistical challenges

- Managing the operations with care: planting young trees, felling older trees that are, however, still productive, and selective clearing (especially if the aim is to conserve moisture in the stand) requires a change of approach and a certain level of "sacrificial felling" of cork oaks that are still producing in order to promote the vitality of the remaining trees.
- Mechanising the extraction and removal of shrubby material from tracksides, which is currently very costly work: in one stand, located in a dry cork oak grove in Les Gavarres, the abundant presence of rough bindweed made the work doubly difficult and costly.
- Optimising transport costs: Low yields in terms of tonnage must be offset by the hectares worked, proximity to the plant or the combined use of biomass from other operations.
- Biomass extracted from cork plantations can be used in drought adaptation techniques, using part of the generated forest chips (if shredded on site) or biochar by-product from the biorefinery as soil structuring agents. When generalised felling is carried out to replace trees, retaining secondary species provides initial shade that favours cork oak seedlings and biodiversity.

Chemical products obtained and yields

Biomass from adaptation operations in cork oak forests has been used in the LIFE BIOREFFORMED biorefinery to obtain bioproducts such as **antioxidants** (90% purity), **phenolic resins** (minimum 30% phenol substitution), **sugars** (minimum 40% purity) and **acids** (70% purity), as well as **biochar.** The production of humic soil conditioners for agriculture from torrefied biomass (at 300 °C) has also been tested. Table 5.2 shows the main results obtained from the project demonstration stands. .

Table 5.2. Yields at 400 °C (g product/kg biomass) and potential use of the products obtained from the processing of biomass from the adaptive management of cork oak forests in the LIFE BIOREFFORMED micro-biorefinery.

<table>
<tr><th colspan="2" rowspan="2">Extracted bioproducts</th><th colspan="4">Quantity of product obtained (g product / kg biomass)</th><th rowspan="2">Applications</th></tr>
<tr><th>Cork oak</th><th>Chestnut</th><th>Arbutus</th><th>Erica</th></tr>
<tr><td rowspan="6">Fracció líquida</td><td>Acids</td><td>17,6</td><td>11,5</td><td>11,9</td><td>25,6</td><td>Chemicals and pharmaceuticals or food additives</td></tr>
<tr><td>Sugar</td><td>2,7</td><td>5,9</td><td>2,9</td><td>9,6</td><td>Compound with high economic value. Applications in the chemical and food industry</td></tr>
<tr><td>Aldehydes and ketones</td><td>2,9</td><td>2,1</td><td>2,4</td><td>5,4</td><td>Range of applications in the chemical and food industry (e.g., flavourings)</td></tr>
<tr><td>Antioxidants</td><td>1,1</td><td>0,7</td><td>0,6</td><td>2,3</td><td>Cosmetic, pharmaceutical, nutraceutical, chemical and food industry, such as antioxidants, flavourings and reagents for the synthesis of phenolic resins</td></tr>
<tr><td>Phenolic resins</td><td>1,34</td><td>2,33</td><td>1,67</td><td>2,01</td><td>Adhesives or paint additives</td></tr>
<tr><td>Pyrolytic lignin</td><td>7,60</td><td>13,20</td><td>9,50</td><td>11,40</td><td>Fuel, precursor of carbonaceous materials and synthesis of adhesives and additives</td></tr>
<tr><td rowspan="2">Fracció sòlida</td><td>Humic acids
a 300⁰ C (g/100 mL)</td><td>2,31</td><td>2,37</td><td>1,63</td><td>1,43</td><td>Agricultural fertiliser</td></tr>
<tr><td>Biochar
a 450⁰ C (MJ/kg)</td><td>16,6</td><td>22,7</td><td>22,1</td><td>23,1</td><td>Agricultural soil conditioner or biofuel</td></tr>
</table>

Of these results, it is worth noting:

- ✓ **Biomass from the adaptive management of cork groves, which has few alternative commercial uses**, such as brush with branches and leaves from trackside clearing, **could viably be used in a biorefinery**, as can unstripped cork from selective cutting or mixed wood of different species and characteristics from thinning in mixed cork oak groves, and the mixed use of all these materials, without affecting the quality of the final product.

- ✓ The most abundant shrub species found in dry cork oak groves, such as erica, **produced very good results** in the biorefinery, **especially for the extraction of acids**, such as acetic acid, from the bio-oil obtained at 450 °C.

- ✓ **Chestnut and cork oak gave the best results for the production of humic extracts** from roasted biomass (at 300 °C). These are used to stimulate soil microbial activity and plant growth and may be superior to commercial biostimulants of fossil origin, such as leonardite.

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More information