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Work Programme 1 – Shared modelling framework and learnings

D1.1 – Summary on case study data and collection of sector data

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This document is the ALIGNED project (grant no. 101059430) deliverable. It contains an overview of five bio-based sectors and five exemplary case studies .

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Acronyms and abbreviations

ABBREVIATIONS	Description
AAF	Aldehyde Assisted Fractionation
BTG	Biomass Technology Group
BREEAM	Building Research Establishment's Environmental Assessment
CAGR	Compound Annual Growth Rate
CCU	Carbon Credit and Utilization
CEPI	The Confederation of European Paper Industries
CLT	Cross-Laminated Timber
EC	European Commission
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
EUTR	EU Timber Regulation
EWP	Engineered Wood Product
FLEGT	Forest Law Enforcement, Governance and Trade
FSC	Forest Stewardship Council
GDP	Gross Domestic Product
GHG	Greenhouse gas
GOTS	Global Organic Textiles Standard
GP	General Public
INSA	Institut National des Sciences Appliquées
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LVL	Laminated Veneer Lumber
MMCF	Man-Made Cellulosic Fibre
MSI	Material Sustainability Index
NTNU	Norges teknisk-naturvitenskapelige universitet
OCS	Organic Cotton Standard

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OSL	Oriented Strand Lumber
PEF	Product Environmental Footprint
PEFC	Programme for the Endorsement of Forest Certification
PET	Polyethylene terephthalate
PLA	Polylactic Acid
PM	Policy Makers
PP	Polypropylene
PU	Polyurethane
RCF	Reductive Catalytic Fractionation
SC	Scientific Community
STeP	OEKO-TEX® Sustainable Textile & Leather Production
WP	Work Package
XPS	Extruded Polystyrene
YoY	Year-over-year

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Executive summary

This document summarizes the main findings from five sector overviews and will give a short description of the companies and value chains of the selected case studies within the ALIGNED project.

The ALIGNED project aims to improve the Environmental Sustainability of five industrial bio-based sectors: construction, woodworking, textiles, pulp and paper, and bio-based chemicals:

- For the **construction** sector, the focus will be on bio-based insulation materials. More specifically, on bio-based phenolic insulation foam. Insulation materials play a significant role in improving the overall energy efficiency and sustainability of the EU's buildings. While the most common insulation materials are made from mineral wool and plastic foams, the use of bio-based insulation materials is growing at a significant rate. Both insulation and bio-based materials are thus important to the developments of the EU construction sector.
- The **woodworking** sector is already largely bio-based, as the main feedstock is wood. However, to make many woodworking products, additives are needed, such as preservatives and adhesives. The woodworking sector is the world's largest user of adhesives, with 70% of the world's volume being used in woodworking products. Most of the preservatives used for the impregnation of wood are fossil-based, of which some are known as probable carcinogens. As such, the woodworking product assessed in the case study takes many different factors into account, such as wood preservation using hardwood and the bonding of wood.
- The production and consumption of **textiles** has a major effect on the environment. Cheap low-quality clothes are produced using synthetic fibres and discarded quickly, resulting in great amounts of waste. The use of synthetic fossil-based fibres is increasing, while the share of natural fibres is decreasing. It is also estimated that less than one percent of textiles are recycled into new textiles. Natural fibres can be more difficult to recycle, as mechanical recycling methods reduce fibre length, and thereby quality. The increasing use of mixed fibres has also made recycling more difficult, as many different types of fibres would need to be separated. As such, the case study will be applied to an innovative recycling process of work clothing made from a mixed polyester-cotton fabric.
- The **pulp and paper** production process gives various by-products, such as black liquor, crude sulphate turpentine, tall oil and lignin. After cellulose, lignin is the most abundant bio-based polymer on earth. Currently, about 98% of the lignin produced in the pulp and paper sector is used for combustion heating or power generation, while less than 2% is used for other applications. The traditional pulp and paper facilities are shifting towards multi-output biorefineries, where bioenergy, bio-based materials and bio-based chemicals are simultaneously produced. This gives great opportunity for lignin to be used in other applications. As such, the lignin valorisation process using aldehyde assisted fractionation (AAF), will be examined in the case study.
- One of the main feedstocks of the **bio-based chemical** sector are oil-based crops. A significant share of bio-based chemicals is produced using vegetable oils from, for example, rapeseed, sunflower, and soy. The chemical compounds derived from natural fats and oils are also known as oleochemicals. Oleochemicals help the chemical sector become more biodegradable, can have a lower toxicity and environmental impact. As such, Hydrogenated Dimer Acids will be studied in the case study, as these products undergo different steps specific to oleochemistry.

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1. Introduction

The ALIGNED project aims to improve the Environmental Sustainability of five industrial bio-based sectors: construction, woodworking, textiles, pulp and paper, and bio-based chemicals by improving the overall performance of bio-based products from these sectors and improving the methods by which this Environmental Sustainability is measured and analyzed and to make sure these methods are aligned to each other.

The ALIGNED project will deliver a modelling framework to assess and optimize the environmental and socio-economic performance of bio-based products. In order to test this framework, it will be applied to five case studies in five bio-based sectors. Additionally, to translate the findings from the case studies to learnings for the whole sector, an overview of each of the five sectors at large was compiled with a specific focus on their bio-based products.

This document summarizes the main findings from the sector overviews and provides a short description of the companies and value chains of the selected case studies within the ALIGNED project. Finally, an overview of the shared feedstocks between the 5 bio-based sectors is given.

The full sector overview documents are being prepared for publication and will be made available via the ALIGNED website: https://alignedproject.eu/.

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2. Construction sector

2.1 Sector overview

The construction sector provides the buildings and infrastructure needed by the rest of the economy and society. This includes the extraction of materials, the manufacturing and distribution of construction products as well as the design, construction and management of construction works.

The construction sector is one of the largest consumers of resources in the EU, as it consumes about 50% of the materials extracted in Europe (European Commission, 2023). In the EU, buildings account for 40% of the total energy consumption and 36% of energy-related emissions, mostly come from the usage of buildings (European Commission, 2020). Greenhouse gas emissions from the construction and renovations of buildings are estimated to be about 5-12% of total national GHG emissions in the EU (European Commission, 2023). The construction sector also accounts for around one-third of the EU's freshwater consumption and the construction and demolition of buildings and infrastructure generate a lot of waste, accounting for over one-third of the EU's total waste generated (Pozzi, 2022).

While the sector has some major environmental impacts, it should be noted that the sector is also of great size. The construction sector is the EU's leading industrial employer. The sector directly employs about 19.8 million people, which is about 4.4% of the total EU population. The EU Member States with the most people working in construction are Germany and France with 4.5 million and 2.3 million workers, respectively. Additionally, with a turnover of 2.66 trillion euros in 2020, the construction sector contributes to roughly 9% of the EU's GDP. The highest construction turnover also comes from Germany and France, who collectively account for 40% of the total construction turnover (ECSO, 2023).

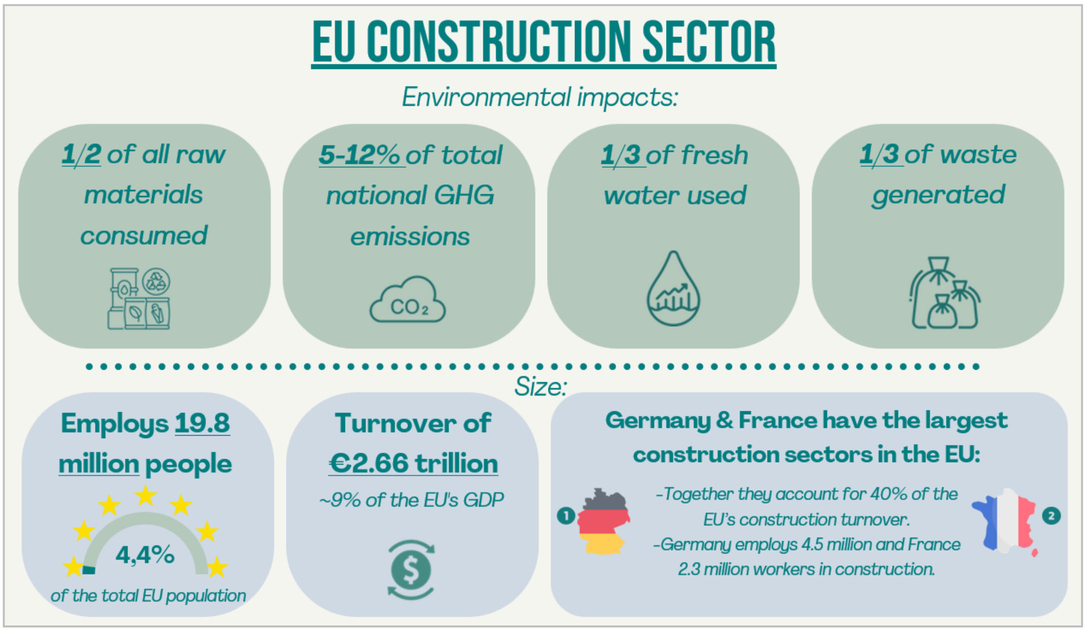

Figure 1, EU construction sector overview, own image.

Bio-based construction materials

The construction sector is one of the EU's largest consumers of resources. The sector's main materials used are concrete, clay and aggregates, such as sand and gravel (Herczeg, et al., 2014). The main bio-based construction material is wood, which can be used for the framing and

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structures of buildings. About 70% of the wood consumed in the EU is used in furnishings and construction and an estimated 8-10% of EU single-family homes have a wooden frame (European Commission, 2023). The majority of wood used in construction is softwood, as this is typically less expensive as it usually grows faster than hardwood and can be of lower quality (Diffen, 2023). Solid timber products can be used in construction, such as beams, planks and posts, but wood can also be modified (potentially using bio-based additives) to create an engineered wood product (EWP). These man-made wood products can offer benefits, such as greater strength and durability. The three main types of EWPs are panel products, such as plywood and fibreboards; mass timber products, such as cross-laminated timber (CLT) and glue-laminated timber (glulam); and structural composite lumber products, which includes laminated veneer lumber (LVL) and oriented strand lumber (OSL) products. As the strength of some of these EWPs is comparable to steel, the use of these products in construction means the possibility of greater and taller wooden buildings and increased use of wood in construction (Hetemäki, et al., 2017).

There are also other bio-based materials used in construction, including bio-composites. Composites are formed using a combination of two or more materials. The added components have a functional and specific contribution to the composite material, as they are used as reinforcement, a filler, dye or coating, etc. Commonly used composites in the construction sector are concrete and fibreglass, in which plastic is reinforced using glass fibres (Williams, 2015). There are also various types of composites which use bio-based components, such as agricultural residues, and fibres, including wood, flax, jute and bamboo fibres. These bio-based fibres can be used to reinforce materials, creating products such as fibre cement (van Dam & van den Oever, 2019).

While most insulation materials within construction are made of mineral wool or plastic foams, there are also bio-based alternatives (Pavel & Blagoeva, 2018). The most commonly used bio-based insulation materials come from wood fibres, cellulose from recycled newspapers, straw, and plant fibres, such as from hemp, cotton and flax (Schulte et al., 2021). There are various other less-commonly used bio-based materials for insulation, such as seagrass, lime from shells, mycelium, reed, rice husks, coconut husks, natural cork and sheep's wool (van Dam & van den Oever, 2019).

Environmental sustainability

There are several ways to assist in improving the environmental impacts of the construction sector. This includes the use of building certifications, such as BREEAM and LEED; material certifications, such as Cradle-to-Cradle, PEFC and FSC; various ISO and EU standards; and the utilization of environmental assessments, such as Environmental Product Declaration (EPD), Product Environmental Footprint (PEF) and Life Cycle Assessment (LCA).

The EU is working towards a more circular construction sector with an increased energy efficiency. Insulation materials play a great role in improving the overall energy efficiency and sustainability of the EU's buildings. The insulation of buildings is a major technology in saving energy and resources. By improving the energy efficiency of buildings, energy losses through walls, floors and roofs can be avoided. While the most common insulation materials are made out of mineral wool (glass wool and stone wool) and plastic foams (EPS, XPS and PU), the use of bio-based insulation materials is growing at a significant rate (Pavel & Blagoeva, 2018). The bio-based insulation market has grown by 40% in the last three years and is estimated to now have a market share of 10% in the EU (Lecompte & Picandet, 2022). As such, both insulation and bio-based materials are important to the development of the EU construction sector. The environmental sustainability of specific bio-based insulation materials will therefore be assessed within the ALIGNED project as a case study.

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2.2 Case study

Introduction to the company and the case study

WP2 covers the construction sector with a case from the Kingspan Group. The company operates globally with 6 operating divisions covering the complete building envelope towards "future-proofed buildings that are energy-efficient, optimise natural resources and promote wellbeing". In 2022, it counted with more than 22,000 employees, with over 212 manufacturing sites across more than 80 countries (Kingspan, 2023). More information can be found on the Kingspan website: 'https://www.kingspan.com/'.

The selected case for ALIGNED relates to the "Insulation" division of Kingspan (boards and technical insulation solutions), which represents 20% of the product sales. More specifically, the target is the following: premium performance rigid thermoset phenolic insulation foam for walls. At Kingspan's, these products are referred to as 'Kooltherm', and come with different thickness and facings (e.g., glass tissue, composite foil), depending on the intended application (e.g., cavity wall, rainscreen façade, external wall). An overview of the different Kooltherm insulation products for wall and other applications (e.g., K5, K8, K12, K15, K17, K20) is available on the Kingspan website. Accordingly, the service to be supplied is a thermal insulation service for buildings.

The geographical scope considered for the analysis is the Netherlands, in other words, the production of the bio-based insulation foams (foreground system) is considered to take place in the Netherlands. This will influence the type of utilities considered, as well as the applying legislation context (e.g., residues management), among others. The analysis involves feedstock and supplies produced within and outside the Netherlands (background system), and these are of course considered in the analysis. While the production of (petrochemical) phenolic foam is well established and mature, bio-based alternatives are currently not produced (i.e., at the time the ALIGNED project started).

Product: Bio-based phenolic insulation foam

The main materials involved today in the production of Kingspan' phenolic foams are phenolic resin (70-80%; mass) with added catalyst and additives (15-20%) which are encapsulated in the final foam. The resin (purchased from a supplier) is obtained from the exothermic reaction of (petrochemical) formaldehyde (~35%) with phenol (~65%). The end-of-life of the final phenolic foam is assumed to be approximately 70% recycling and 30% incineration.

The two bio-based alternatives studied in ALIGNED cover the resin, hereby referred to as phenolic resin. More precisely, they both target the phenol portion of the resin, where the vision is to either totally or partially replace the petrochemical phenol by bio-based phenol. These replacements could result in changes to the properties of the phenolic foam insulation and need to be further documented. In the LCA for ALIGNED, the use of bio-based phenolic resin is not considered to affect, either positively or negatively, the thermal insulation performances and other properties of the foam (reaction to fire, compression strength, lifetime, etc.). The performances and properties of the foam will also have to be further documented.

To produce the phenolic foams for insulation purposes, Kingspan aims to use bio-based phenolic resin The bio-based phenolic resin is produced from lignin, which is a renewable bio-based material. The production of the phenolic foam at Kingspan is not likely to change when using either one of the lignin-based phenolic resins (LBPR). This is important to note for the LCA, as the use of lignin for phenolic resin has the ability to make a difference.

At this step, the parameters to be defined are associated with lignin-based phenolic resin (LBPR) production. There are two main ways to provide lignin for the production of resin:

1. Lignin obtained as a co-product of different bio-based processes such as the production of pulp and paper could be used as the raw material for LBPR. Lignin is often obtained as the co-product in pulp and paper industry and is already a well-developed product.

2. Lignin obtained as the main product from biomass, through a process called "Lignin-first" could be used in the production of resin. Reductive catalytic fractionation (RCF), aldehyde-assisted fractionation (AAF) (BLOOM Biorenewables), and organosolv are the current options to extract lignin as the main product from biomass.

To the best of our knowledge, there are several research centres and universities, in which this technology was tested in a pilot-scale (up to 50 lit reactors), but there is no information on the industrial production available yet.

Detailed process description:

If lignin obtained from the RCF method is selected for this case study, the production process would be as follows: initially, there is the cultivation of biomass and the size reduction, using a mill or crusher. These steps would be the same for RCF or AAF methods, however the next step, the fractionation is different between the methods. The difference for each process is related to the materials used and the outlet of the process, and by-products for each of them. These parameters (by-products, chemicals used, reaction and process details and condition, and final outstream) need to be determined specifically for each case. The main product is bio-oil which must undergo a downstream separation process, and this is also affected by the method applied for lignin separation and extraction. Finally, this product could be used for phenolic resin production and foam production.

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3. Woodworking sector

3.1 Sector overview

Wood can be used for various purposes, including pulp and paper, furniture, and woodworking products. Woodworking includes the production of sawn wood, wood-based panels and wooden construction materials and products. The EU woodworking sector employs over a million people in 184 thousand firms. The majority of these firms are small or medium-sized enterprises (SMEs), with the exception of the sawmilling and wood-based panels sub-sectors, which are often large enterprises (European Commission, 2023).

The woodworking sector is heavily reliant on the European forestry industry. About 40% of the EU's land area is covered by forests and this share is growing. EU forests grow with almost 700,000 hectares annually (Eurostat, 2021). In 2020, the EU had an estimated 159 million hectares of forest area, which is 10% more than in 1990 (Eurostat, 2022).

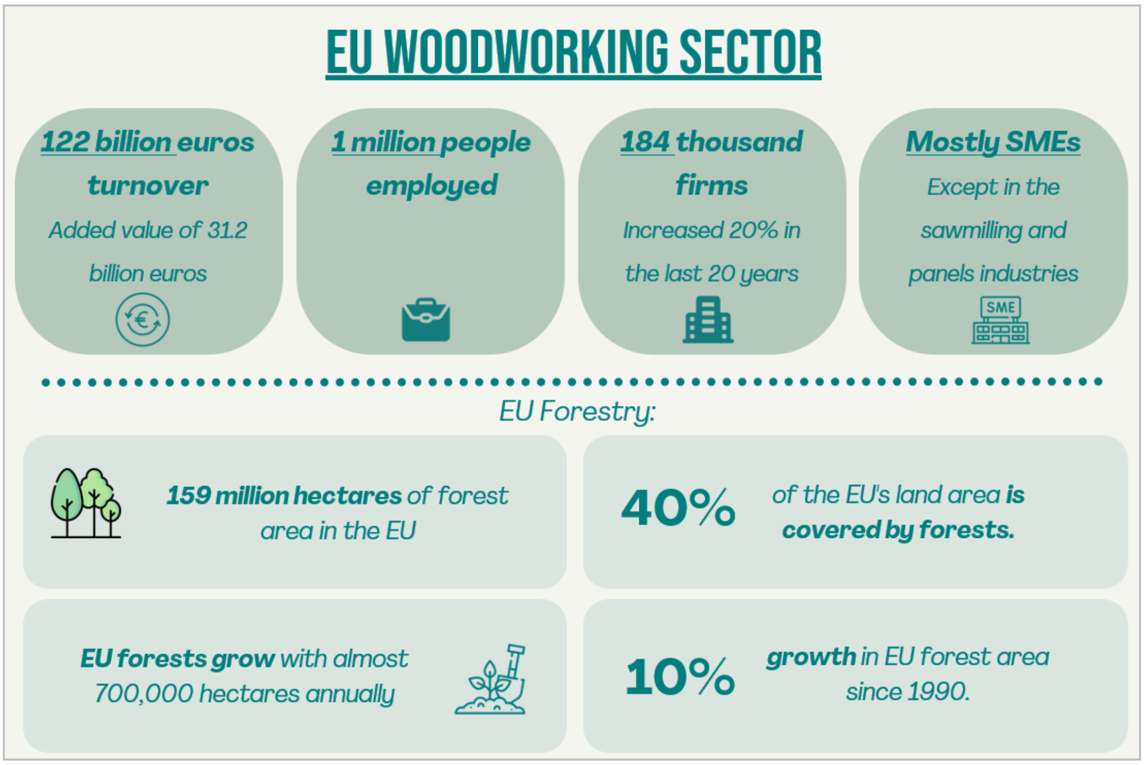

Figure 2, Overview EU woodworking and forestry, own image.

Wood often has a smaller carbon footprint than other materials, as the processing of wood often requires less energy than that of other materials and because wood can retain the carbon gathered by the trees (Rinne, et al, 2022). However, improper forest management and the illegal harvesting of trees can affect the population and habitat of species living in that area, causing losses of biodiversity. Unsustainable practices and illegal logging can cause deforestation, soil erosion, droughts, wildfires and desert encroachment (Nguyen, 2017). The EU battles deforestation and forest degradation through its Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan and EU Timber Regulation (EUTR), as well as through forest stewardship programs (European Commission, 2023).

The woodworking sector can also have a positive contribution to the environment. The development of the woodworking sector could lead to more demand for wood products and,

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through sustainable forest management, could lead to increases in forest area, the capture of CO_2 emissions and the reversal of the effects of climate change (Iordan et al., 2018).

Woodworking products

A little under half of the wood harvested in the EU is used as saw and veneer logs. These logs can be processed into solid-sawn timber products, such as planks, beams and posts, as well as engineered wood products (EWPs). An overview of the different woodworking products is shown in Figure 3.

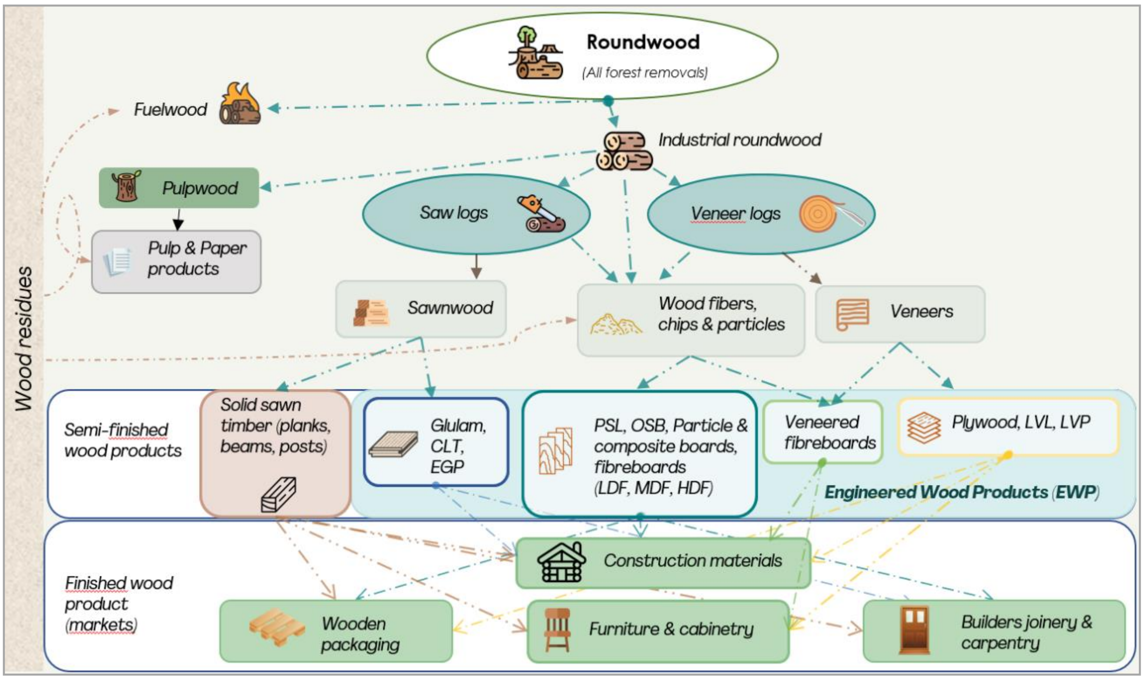

Figure 3, Overview woodworking products, own image.

Wood is a heterogeneous product, with variable properties. Especially in the construction sector, these differences in wood products can be overcome by using engineered wood products (EWP), which have a more consistent and predictable performance (European Commission, 2023). Engineered wood products are man-made wood products, meaning that they are created from different products such as wood fibres, sawdust, adhesives and chemicals, creating a product that can be cut and sawed like timber (Balasubramanian, 2022). Engineered wood products can be more affordable than traditional wood products and offer benefits such as greater strength and products that are more durable.

Sawnwood are the logs sawn into different shapes and sizes, which can be used as solid sawn timber but can also be engineered to create EWPs such as glue-laminated timber (glulam) or cross-laminated timber (CLT). These products are mostly used in the construction sector. Wooden veneers, thin slices of wood, can also be used to create EWPs such as plywood and laminated veneer lumber (LVL). The parts of the logs that are not suitable for veneer, sawmill or pulp and paper processes are used as fuelwood for energy generation, or to manufacture wood-based composites. Other residues from the sector can also be used for this purpose. Wood-based composites include a variety of composite boards and fibreboards, as well as EWPs such as medium-density fibreboard (MDF), parallel strand lumber (PSL) and oriented strand boards (OSB). These EWPs can be used in construction, furniture, builders' joinery and carpentry, as well as wooden packaging, such as crates and pallets (Sandberg, 2016).

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Additives in woodworking

The woodworking sector is already largely bio-based, as the main feedstock is wood. However, additives are needed in order to make many woodworking products. These additives include preservatives to protect the wood against biological degradation or fire, coatings for protection or for appearance, adhesives to join wood products and give greater dimensions of wood available, and other non-wood materials to improve the performance of the product.

The woodworking sector is the world's largest user of adhesives, with 70% of the world's volume being used in woodworking products. About 80% of woodworking products require some sort of adhesive. The majority of additives used in woodworking are not bio-based (Sandberg, 2016). Currently, an estimated 9% of the total adhesive production in the EU is bio-based (Spekreijse et al., 2019). While glues made from animal proteins used to be common in the woodworking sector, currently synthetic adhesives are now the most common. Many synthetic adhesives use formaldehyde, a toxic substance and known carcinogen. However, there are also various other bio-based adhesives available, such as adhesives from animal collagen, dairy proteins, gluten proteins, starch crops, cellulose, and lignin (Ülker, 2016).

Most of the preservatives used for the impregnation of wood are fossil-based, of which some are known as probable carcinogens. Common preservatives used in woodworking in the past, such as chromated copper arsenate (CCA), pentachlorophenol (penta) and creosote, are now partially banned or restricted in their use in the EU due to their toxicity to humans (Western Wood Preservers Institute, 2023). There are also many bio-based alternatives available. Natural preservatives such as wax, shellac and drying oils can be used, as well as varnishes, lacquers and paints from a vegetable oil basis. Additionally, woodworking products can be chemically modified using furfurylation methods, in which the wood is impregnated with a mix of furfuryl alcohol and catalysts. Furfuryl alcohol is commonly produced from agricultural waste. The same woodworking wood can also be thermally modified using heat and vegetable oils (van Dam & van den Oever, 2019).

Environmental sustainability

To make sure woodworking products are produced sustainably, certifications could be required, or the environmental impact can be assessed. Many buyers of woodworking products ask for sustainable forest management certifications, namely the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). Both certifications aim at creating and implementing sustainable forest policies to save and protect forests against destruction (Michal, et al., 2019).

A case study will be performed within the ALIGNED project, in which an LCA will be applied to woodworking products. The case study takes many different factors into account, such as the combined use of hardwood and softwood, and different bonding techniques.

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3.2 Case study

Introduction to the company and case study

Foreco Dalfsen is a family-owned firm founded in 1983 with 120 employees that produces and trades timber products. They are leaders in sustainable wood protection and specialized in wood treatment (e.g., creosote treatment to regular pressure treatment, wood acetylation, and thermal modification). More information can be found on the Foreco website: 'https://www.foreco.nl/'.

The woodworking industry is characterised by many small and medium sized enterprises (SMEs), including Foreco. These SMEs produce a wide range of wood products derived from various wood species. All these products require separate LCAs, which comes at a high economic cost (Foreco, 2022). Challenges arise when performing an LCA on forestry-based products, including uncertainties in the supply chain, complex interactions with the environment, material conversion, resource use and the quantification of the emissions released (Sahoo, 2019). The woodworking sector is dealing with an increased market demand for LCAs and increased regulatory pressure, which can lead to organisational and financial difficulties.

Foreco has a wood stock that consists of about 15,000 m^3 of wood and 60,000 m^2 of terrain. Foreco's product portfolio includes various products, including 'NobelWood', 'WaxedWood', 'SafeWood', 'SoundWood and 'Cloeziana'. Within the ALIGNED project, it was decided to focus on sheet piles. Generally, wooden sheet piles are made out of tropical hardwood. Tropical hardwoods have natural oils that make them more resistant to insects, rot, mould, water and weather. Additionally, tropical hardwoods are non-toxic, strong, low-maintenance and durable. However, the sourcing of tropical woods presents its own challenges, including biodiversity losses, a lower growth rate, certifications, fraudulent labelling, transportation and its associated emissions, etc. Therefore, in order to reduce the use of tropical hardwood and still have its benefits, Foreco has created a product called 'TwinWood'. TwinWood is created using a combination of softwood and hardwood, which are connected through a finger joint. In the WP3 case study, pure tropical hardwood (Azobé) will be compared with TwinWood.

Product: Sheet pile TwinWood

The Azobé sheet pile is a sheet pile product made out of 100% Azobé, a type of tropical hardwood. The production is comparable to other wooden sheet piles. The sheet pile has a thickness of 50 mm, the width of the planks is 245 mm.

The TwinWood sheet pile is a composite sheet pile of Central European softwood (pine), and Azobé, tropical hardwood. The pine and Azobé are glued with a finger joint (15 mm), so that a large part of the hardwood can be replaced by softwood. TwinWood consists of 80% pine and 20% Azobé. The production is comparable to other wooden sheet piles and has the same proportions as the Azobé sheet pile product

TwinWood can be applied as sheet piling, scaffolding pole, and bollards. The smart combination of hard- and softwood guarantees a high constructive strength and long service life. This makes TwinWood a perfect choice for application in water.

The part of TwinWood that remains under the water level is softwood, pine. The upper part is hardwood. Since the softwood is not in contact with oxygen, as it remains under the water level, it will not degrade. Hardwood is applied at the water level and above as wood products are more vulnerable for decay above water. Hardwood is very durable and will have a long service live even in these tough conditions. By connecting the two types of timber with a strong finger joint, a sustainable and strong product is created.

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Other improvements when it comes to sustainability of the TwinWood product could be through the optimization of energy consumption, the use of bio-based alternatives to adhesives and packaging materials.

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4. Textiles sector

4.1 Sector overview

The textile sector covers a wide range of activities, which includes the transformation of both natural and synthetic fibres into fabrics and yarns; and the production of various products such as bed linens, industrial filters, and clothes (European Commission, 2023). Natural fibres are derived from animals and plants. Examples of commonly used natural fibres are cotton, flax and wool. Synthetic fibres are man-made and do not occur naturally, this includes fibres such as nylon, polyester, and acrylics, which are fossil-based (Jhanji Dhir, 2022). While these natural fibres are bio-based, there are also various man-made bio-based fibres on the market, for example, fibres from bioplastics that are derived from natural oils (Henkel, 2021).

Textile consumption

In recent years, the share of natural fibres in textile production has decreased significantly. This is partly due to the exponential growth of polyester production. Between 2008 and 2018, synthetic fibre production rose from 41 to 72 million tonnes per year (Townsend, 2019). As shown in Figure 4, in 2021, 64% of global fibre production was synthetic, 28% plant-based, 6% man-made cellulosic and 2% was animal-based. The plant-based, animal-based, and man-made cellulosic fibres (MMCF) are bio-based, as they are manufactured from renewable raw materials. Of all bio-based fibres, the most commonly used is cotton. Cotton accounted for about 78% of global plant-based fibre production and 61% of bio-based fibre production by weight (Textile Exchange, 2022). As can be seen in Figure 5, European households consume large amounts of textiles, with an average textile consumption of 15 kg per person per year, of which 6 kg consists of clothes. This amounts to an estimated total consumption of 6.6 million tonnes of textile products per year in Europe (European Environment Agency, 2022). European households spend on average 600 euros on clothing a year, as well as 150 euros for footwear and 70 euros for household textiles (Waterkamp, 2022).

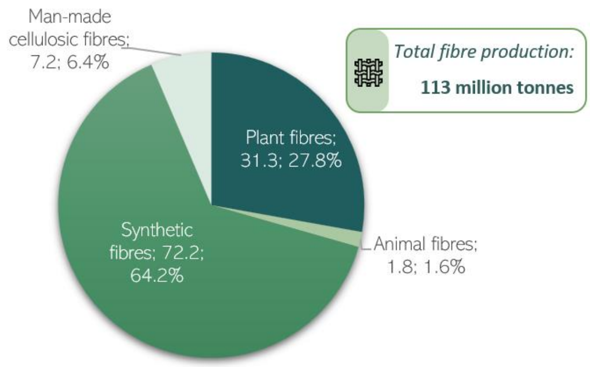

Figure 4, Global fibre production in 2021 (million tonnes), data from Textile Exchange.

Figure 5, Overview textiles consumption, own image.

On average, clothes are discarded after being worn seven times (Nizzoli, 2022). Between 2000 and 2015, it is estimated that clothing production doubled, while in the same period the number of times a garment is worn decreased by 36% (Harmsen & Bos, 2020). The increasing consumption of textiles, as well as the declining clothing utilization rate, are largely due to the 'fast fashion' phenomenon. Fast fashion has led to a quicker turnaround of new styles with more collections offered per year. Fast fashion goods often have lower prices and inferior quality

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(Ellen MacArthur Foundation, 2017). The fast fashion industry is dependent on cheap synthetic fibres which has caused a spike in the demand for fibres such as polyester and polyamide (Ethical Consumer, 2021).

Textile production

The EU textiles and clothing sector plays a big role in the European manufacturing industry. The EU textiles and clothing sector employs 1.7 million people and has an annual turnover of over 166 billion euros (European Commission, 2023). In 2019, there were about 160,000 companies in the sector, which are mostly small businesses. Of the EU textile workforce, 90% is employed in companies with less than 50 employees. The EU produced 6.9 billion tonnes of finished textile products in 2020, as well as intermediate products for textiles, such as fibres, yarns and fabrics. The textile and clothing sector is very globalised, with the global market accounting for 38% of EU turnover. Between 2010 and 2019, EU textile and clothing exports increased by 58% and imports by 43%.

Figure 6, Overview textiles sector, own image.

The biggest producers within the EU textile sector are Italy, France, Germany, Spain and Portugal. These five countries together represent about three-quarters of the EU production. While Southern European countries contribute more to clothing production, Northern European countries contribute more to textile production, especially technical textiles (European Commission, 2023). Technical textiles are used in different sectors and are primarily used for their technical performance and functional properties, rather than aesthetics (Expafol, 2022).

The textile sector is also quite labour-intensive. Worldwide, the textile sector is the third largest employer, after food and construction. Most of the textile production takes place in Asia, where lower costs of production have been known to come at the expense of the workers' safety and health (European Environment Agency, 2022). In 2013, a garment factory in Dhaka (Bangladesh) collapsed, resulting in the deaths of 1132 people. This event served as a wake-up call for the global fashion industry to operate in a more sustainable manner, which does not only focus on the environment but also on social impacts (AllThings.Bio, 2023).

Environmental sustainability

The consumption of textiles has been identified as the fourth largest impact on the environment, after food, housing and mobility. Textile consumption inflicts the third largest pressure on water and land use and is a major driver of greenhouse gas emissions and resource depletion (Waterkamp, 2022).

Both the production and consumption of textiles can have significant impacts on the environment. These impacts range from the production phase to its end-of-life phase. During production, the cultivation of natural fibres such as cotton requires substantial use of land and water, fertilizers and pesticides. The production of synthetic fibres has its own environmental impact, for example, regarding high energy use and the chemical feedstocks used. The manufacturing process of textiles requires large amounts of energy and water and might use a variety of chemicals. The distribution and retail of textiles can lead to transport emissions and

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generation of packaging waste. The maintenance and use of textiles can lead to the release of microfibres and chemicals into wastewater and to significant amounts of textile waste (European Environment Agency, 2023). Fibres from textiles have traditionally been difficult to recycle. It is estimated that less than one percent of textiles worldwide are being recycled into new textiles. Another 12% of textile waste is downcycled into lower-value applications, such as insulation materials or mattress stuffing. However, the far majority of textile waste ends up in landfills or is incinerated (Ellen McArthur Foundation, 2017).

Especially natural/bio-based fibres have shown to be difficult to recycle, as traditional mechanical recycling methods lead to major reductions in fibre length, resulting in fibres that are too short to be spun into a yarn with proper strength. The increasing use of mixed fabrics has also made the recycling more difficult, as many different types of fibres are used that need to be sorted and separated.

As such, one of the major challenges of the textile sector is the need to be less wasteful and use less resources. To contribute to more sustainable operations, the recycling of textiles as well as the use of renewable raw materials should be considered. As such, the use of natural and other bio-based fibres and their recycling processes are important (AllThings.Bio, 2023).

Several sustainability practices can be applied to minimize the environmental impacts in the textile sector. The EU has launched its strategy for sustainable and circular textiles, which includes the promotion of more durable, repairable, and recyclable clothes, that are to a great extent made from recycled fibres, are free of hazardous substances, and respect social rights and the environment (European Commission, 2023). Additionally, there are various sustainability certifications and standards available for textiles, such as Recycled Claim Standard (RCS), Organic Content Standard (OCS), Global Organic Textile Standard (GOTS), OEKO-TEX and the EU Ecolabel These standards range from environmental impacts, organic content, recycling, animal welfare, and fair labour practices within the textile sector.

LCA has been employed extensively in the assessment of (bio-based) textiles and clothing, including on cotton, jute and kenaf (La Rosa & Grammatikos, 2019); man-made cellulosic fibres (Schulz & Suresh, 2017) and bio-based polyester fibres (Ivanovic et al., 2021).The importance of both bio-based fibres and innovative recycling processes that tackle the problem of recycling fabrics of mixed fibres, will be highlighted through a case study within ALIGNED. In the case study, an LCA will be applied to an innovative recycling process of work clothing, made from a mixed polyester-cotton fabric.

4.2 Case study

Introduction to the company and the case study

UTEXBEL is a textile group that was founded in 1929 in Ronse, Belgium. UTEXBEL is fully vertically integrated, as it covers the entire textile supply chain from fibre to finished fabric. UTEXBEL develops, produces and commercializes yarns and fabrics with certain functionalities according to customer specifications. These specifications contribute to the safety, health and comfort of the end user. UTEXBEL is a market leader in public procurement, industrial protective workwear, leisure wear and technical textiles. Almost half of the company's activities is fabrics for public tenders (45%), followed by protective wear (40%), fashion (10%) and for technical applications (5%). The company has three spinning mills in Belgium, in Ronse, Kluisbergen, and Mouscron, as well as one in Morocco. Additionally, UTEXBEL has 2 weaving mills, one in Ronse (Belgium) and one in Baiseux (France). More information can be found on the UTEXBEL website: https://utexbel.com/.

UTEXBEL has an annual production of 7,000 tonnes of spun yarns, 11 million meters of fabric (approximately 17 million m^2) and 5% of the annual turnover is invested in research and development.

UTEXBEL is OEKO-TEX STeP certified, which means that there are various sustainability objectives that are anchored into the daily policy. These objectives include producing textiles locally, developing yarns and fabrics with a smaller environmental impact, to invest in more resource-efficient (i.e., energy and water) machinery, and the investment in solar panels and water treatment facilities.

Furthermore, UTEXBEL is a socially committed family business that takes care of its staff, purchases ethically and produces in Europe. In addition, UTEXBEL is committed to further reducing the impact on the environment and surroundings.

UTEXBEL has an extensive and steadily growing collection (for sportswear and workwear, corporate fashion, and protective wear) in organic and/or fairtrade cotton, BCI-cotton and recycled PES. Used, end-of-life garments are collected from laundries, taken apart, shredded and used as new material in their spinning process for the weaving of new workwear fabrics, and thus closing the loop. More specifically, garment recycling happens at external partners. After the used garments are collected, they are disassembled at a sheltered workplace. Here, the hard parts and coloured accents are removed which yield pure textile material. This material is shredded into fibres and serves as input for the spinning mill at UTEXBEL. The fact that the value chain is integrated from fibre to fabric enables easier communication between the involved departments (i.e., spinning, weaving, dyeing), thereby creating optimized integrated solutions.

Product: Dr. Green

Within the framework of the ALIGNED project, the focus is on the product called Dr. Green, a recycled product from used end-of-life hospital garments. To produce the Dr. Green product, white hospital garments are collected from an industrial launderer, after which the hard and coloured parts are removed from the garments in a social workplace. The fibres can then be recovered from the disassembled garments using mechanical operations, such as shredding and carding. These recovered fibres are then blended with virgin fibres and industrial waste, after which the fibres can be spun, weaved and finished to produce new garments. A part of the cotton fraction is reduced to dust during the mechanical operations. Additionally, losses of 10 to 20% can occur during the removal of hard and coloured parts, depending on the complexity of the garments.

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The hospital garments consist of a blend of polyester (67%) and cotton (33%) and are washed between 50 and 100 times during their lifetime. The standard number of wash cycles for a garment is 50 times, however, for hospital wear, the washing frequency can be twice as high due to a higher risk of staining and contamination.

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5. Pulp and Paper sector

5.1 Sector overview

Europe is the world's second-largest producer of pulp and paper, manufacturing yearly 37 million tonnes of pulp and 100 million tonnes of paper articles, which represents about a quarter of the world's production (The Confederation of European Paper Industries, 2021).

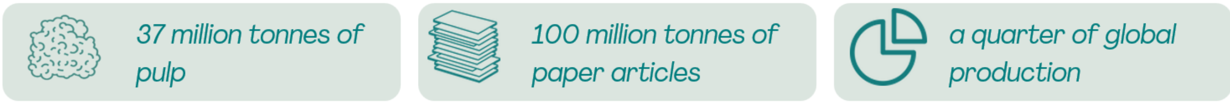

Figure 7, Statistics EU pulp and paper production, own image.

The pulp and paper sector is the EU's second-largest forest-based sector, after woodworking. Paper is produced using pulp, a soft and moist material that is made of cellulose. The pulp can be obtained using chemicals or by grinding the raw material and mixing it with water. The pulp can be combined with water and chemicals; and is then flattened, dried and cut into sheets and rolls, creating paper. Paper is used for various purposes, including writing, printing, packaging, and sanitary functions (World Paper Mill, 2019).

About 93% of raw materials used for pulp and paper production come from trees, with one tree being able to produce 8000 sheets of paper (Jiang et al., 2021). The most commonly used feedstocks for the pulp and paper sector are recycled paper and wood fibres, as well as alternative fibres, which originate from cellulose-containing crops and plants, such as cotton, bamboo, linen, bagasse, and bast fibres. As such, the industry is already largely bio-based, as its main raw materials are wood and alternative fibres from cellulose-containing crops and plants. However, 12% of the sector's inputs consist of non-fibrous materials, such as starches, clays and calcium carbonate, which are used as coatings and fillers. There are also various chemicals used in the production processes, and many paper articles contain ink or other additives and fillers (The Confederation of European Paper Industries, 2021).

Figure 8, Facts about paper production and recycling, own image.

One of the main feedstocks used in the sector are recycled fibres. The recycling rate of paper in Europe is quite high and reached 71.4% in 2021 (European Paper Recycling Council, 2022). Recycled fibres account for about half of the raw materials used for paper products in Europe (Finnish Forest Industries, 2021). In 2020, paper fibres were recycled 3.8 times on average in Europe, while the global average was 2.4 times (Two Sides, 2021).

EU production

As shown in Figure 9, there were 1820 pulp and paper companies active in the EU in 2020, employing around 160,000 people. In the same year the EU pulp and paper sector had a turnover

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of 74 billion euros. As such, the pulp and paper sector had a share of about 0.45% of the EU's GDP. The manufacturing of paperboard and paper articles had a turnover of 104 billion euros in the same year. Around 16,400 manufacturers of paperboard and paper articles were active in the EU in 2020, employing almost half a million people (Eurostat, 2023). Together, the production of pulp and paper as well as paper articles accounts for 1.2% of the EU's GDP. The sector is dominated by large enterprises such as Stora Enso, UPM, SCA and Smurfit Kappa (The Confederation of European Paper Industries, 2021).

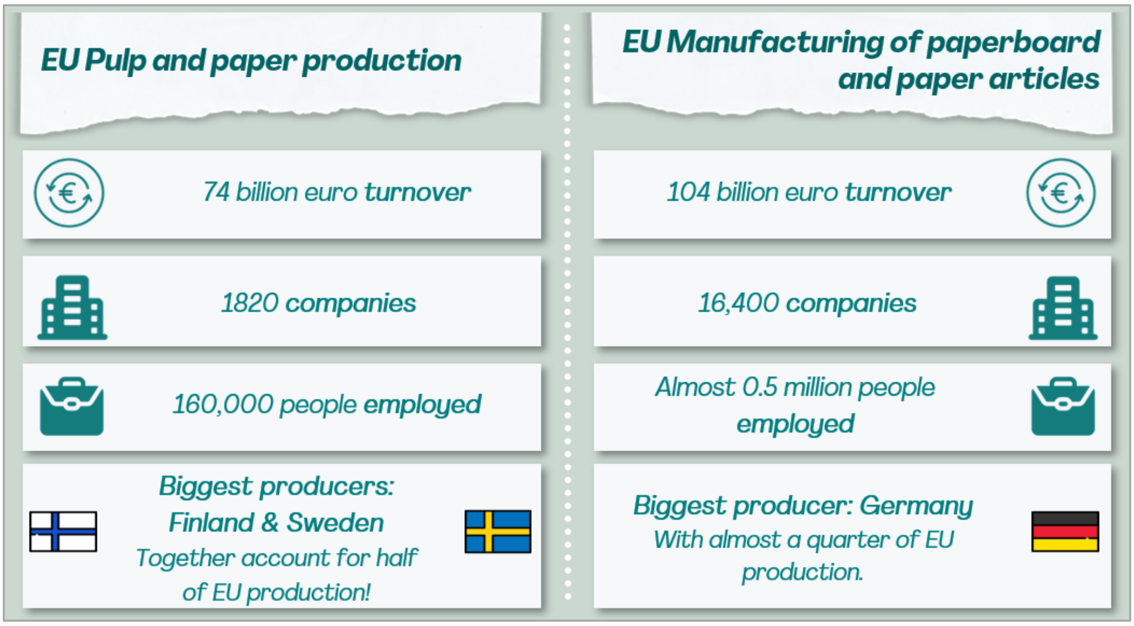

Figure 9, Overview EU pulp and paper manufacturing industries, own image.

The biggest producers of pulp in the EU are Sweden and Finland, which together produced about half of Europe's total pulp production in 2021. Germany is the EU's biggest producer of paper and paperboard, as it produced almost a quarter of the EU's total production in 2021.

Environmental Sustainability

Globally, an estimated 40% of harvested wood is used to manufacture paper. The production of pulp and paper has been linked with cases of deforestation and forest degradation, which has various social, economic and environmental impacts. In the paper production process, various chemicals are used sodium sulphide and bleaching agents; which can lead to large amounts of toxic wastewater being released into the environment and the release of harmful gases into the atmosphere (Jiang et al., 2021). The sector is one of the largest greenhouse gas emitters among the manufacturing industries, due to its high energy use and fuel combustion. However, the pulp and paper sector is also the largest industrial consumer of renewable energy in the EU, as 60% of the sector's energy needs was covered by biomass in 2020, mostly through the combustion of lignin, a by-product from the pulping process (AFRY, 2022).

Various practices focus on the environmental sustainability of the forests resources destinated to the production of pulp and paper products. This includes EU policies and regulations such as the European Green Deal, the European Packaging and Packaging Waste Directive, Forest Law Enforcement, Governance and Trade (FLEGT) and the EU Timber Regulation (EUTR); as well as sustainability standards such as Cradle to Cradle (C2C) and the EU Ecolabel. For premium and niche markets, specific ISO standards could also be involved, such as ISO 14001 for environmental management.

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Besides the legal requirements, such as the EU's policies against illegal harvesting, many buyers ask for sustainable forest management certifications. Sustainable forest management is of high importance to the EU pulp and paper sector, since the sector relies on the long-term stability of European forests and their resilience to climate change, as this affects the overall quality and quantity of wood production (European Confederation of Woodworking Industries, 2021). The two main sustainable forest management certifications are the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). Both certifications aim at creating and implementing sustainable forest policies to save and protect forests against destruction. The certifications both rest on the same three pillars: the social, economic and environmental impacts of wood production (Michal, et al., 2019).

Pulping by-products

The main source of fibres for pulp and paper products are forestry products, mainly logs from trees, also known as roundwood. The roundwood consists of bark, cellulose fibres, hemicellulose, lignin and extractives. The bark protects the fibres of the log, which are held together by the lignin. The pulping process aims at extracting these fibres by removing the lignin. Pulp mills have different chemical and mechanical processes to extract these fibres (Casey, 2017). In mechanical pulping, fibres are mechanically removed, usually by grinding the material. In chemical pulping, the lignin which is holding the fibres together is broken down and dissolved using certain chemicals (Olson, 2013). The pulp can then be mixed with water and chemicals, flattened, dried and cut into sheets and rolls to create paper. The paper can be further processed to create paper articles such as cardboard, toilet paper, and graphic paper such as newspapers (World Paper Mill, 2019). The used paper products can be recycled by re-pulping and de-inking the recovered fibres to create new paper products. The pulping process also gives various by-products, such as black liquor, crude sulphate turpentine, tall oil and lignin. The main purpose of pulping is the separation of as much lignin as possible, as it reduces the quality of the paper. Currently, about 98% of the lignin produced in the pulp and paper sector is used for combustion heating or power generation, while less than 2% is used for other applications (Yao, et al., 2022). Lignin can be extracted and used for applications such as in asphalt, or used as vanillin, a binder, dispersant, dye, adhesive or bio-oil. Lignin is, after cellulose, the most abundant biopolymer on earth, which makes the valorisation of lignin a great opportunity to be used in different applications.

The traditional pulp and paper facilities are shifting towards multi-output biorefineries, where bioenergy, biomaterials and bio-based chemicals are simultaneously produced. These biorefineries produce a range of emerging bio-based products such as man-made cellulosic fibres, biodiesel, bio-naphtha, lignosulphonate and tall oil products. The share of emerging bio-based products as a part of the EU's pulp and paper sector's turnover is currently around 3% but is expected to be substantially larger in the future (Lombard, 2021). This makes it important to assess the possible extraction methods and applications of pulping by-products, such as lignin. Lignin has been traditionally difficult to valorise in other pathways than energy recovery (Wenger, et al. 2020), and therefore new technologies that allow to use this abundant feedstock are of high importance for the green transition. As such, the case study will be focussed on the valorisation of lignin.

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5.2 Case study

Introduction to the company and the case study

The pulp sector is rapidly transforming towards biorefining to diversify the production primarily from cellulosic pulp to other value-added products, due to a declining trend in the demand for paper and an increased demand for bio-based products. Lignin is a family of polymers extracted from biomass with more or less a preserved structure from "native lignin". It is one of the most abundant non-fossil fuel based organic polymers which can potentially be refined to substitute conventional fossil fuel-based materials (Moretti et al., 2021). Conventionally, lignin is a by-product of pulp production. The type of lignin obtained from conventional pulp production is mostly referred to in the literature and the market as "technical lignin", this includes "kraft lignin" from the sulphate/kraft pulping process and "sulfonated lignin" from the sulphite pulping process. Technical lignin is in an irreversible condensed form that can either be valorised as on-site energy recovery or low value applications such as bitumen. However, technologies are emerging to extract lignin in high valued, functional, and stable form.

Bloom Biorenewables Ltd. is a company that considers themselves a "lignin first" biorefinery, where they focus on extraction, de-polymerization and valorisation of lignin. Lignin is valorised using Aldehyde Assisted Fraction (AAF) biorefinery which produces a functionalized lignin with well-defined properties and chemical structure. Using AAF technology, the company manages to separate and stabilize lignin polymers and hemi-cellulose derived sugars from lignocellulosic biomass. Stabilized structures of lignin and hemicellulose are then valorised to be used for diverse end uses, such as cosmetics, textiles, bioplastics, food additives, biofuels, etc. AAF also enables the efficient recovery of the cellulose. More information can be found on the Bloom website: https://www.bloombiorenewables.com/.

The pilot scale biorefinery is currently located in Marly, Switzerland. The current feedstock to produce lignin depends upon the locally sourced hardwood, particularly beechwood. The technology used is novel and emerging (TRL 4) with a plant processing of 250 litres of wet biomass, but the production will be scaled up in future. The key products produced at Bloom's bio-refinery are lignin monomers, oligomers, dimethyl glyoxylate xylose (DMGX – a bioplastic precursor), and cellulose.

The properties of extracted lignin are highly dependent on the extraction processes and biomass feedstock.

Product: AAF lignin

Extraction process: Bloom uses aldehyde assisted fraction (AAF) of lignin which produces a functionalised lignin with well-defined properties and chemical structure. The protection aldehyde prevented excessive condensation and it thus retains most of its native chemical bonds. The stable form of lignin can either be used as an alternative for several petrochemicals (e.g., phenols) or further depolymerized into monomers or oligomers that can either be directly used in the formulation of products (e.g., vanillin), or be transformed and used in the chemical market as drop-in replacements (products which have same chemical formula and properties e.g. propylsyringol (lignin monomer) to BHT (approximated as 2,6-di-tertbutylphenol).

Biomass type: The yield and distribution of lignin monomers is also dependent on the biomass type. Hardwood such as beechwood is the primary source of biomass used for lignin extraction at Bloom. However, lignin can potentially be extracted from other sources of biomass such as agricultural wastes. Bloom aims to expand and adapt the technology to refine lignocellulosic biomass from different types of feedstocks (such as, other types of hardwood, softwood and agricultural wastes).

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The case study has identified the following steps that can potentially reduce energy needs and consequently improve environmental performance: reducing processing energy, assessing the choice between different and alternative chemicals, addressing the reduction of chemical use, switching feedstocks, and the end-of-life of materials.

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6. Bio-based chemicals sector

6.1 Sector overview

The chemical industry is the fourth largest industry in the European Union (EU), and the second largest producer in the world regarding chemical sales (CEFIC, 2022; EC, 2020a). It is highly concentrated in eight countries: Germany, France, Italy, Netherlands, Spain, Switzerland, Belgium and Austria (Figure 10) (Eurostat, 2023). However, the sector has been shrinking and, by 2030, it is expected that the EU becomes drops from the second largest chemical producer to the third largest chemical producer in the world (CEFIC, 2022; EC, 2020a).

Figure 10, Overview EU chemical sector, own image.

Within the chemical sector the top largest processes in terms of energy use are steam cracking, hydrogen, aromatics, ammonia/urea, and ethyl benzene production. The largest amount of GHG emissions is released during the production of ammonia/urea, steam cracking, hydrogen, nitric acid and chlorine (Boulamanti and Moya, 2017).

Sustainability challenges and opportunities

The chemical industry faces environmental challenges including high greenhouse gas (GHG) emissions, high energy costs and dependence on other countries (Figure 11). The chemical industry is the third largest GHG emitter in the EU and 60 million tonnes (Mt) of carbon dioxide equivalent (CO_2-eq) were emitted in 2020 (EEA, 2022). Several actions, including investments and other types of support, have been taken to improve the sustainability and resilience of the sector, covering a toxic-free environment, ending pollution, climate neutrality, circularity, and digitalization (EC, 2023a; 2020). Additionally, various policies and strategies have been implemented with the same aim, including the European Green Deal (EC, 2015); the Circular Economy Action Plan (EC, 2020b), the Chemicals Strategy for Sustainability Towards a Toxic-Free Environment (EC, 2020a); the safe and sustainable-by-design framework (EC, 2020a); Transition Pathway For The Chemical Industry (EC, 2023a); and the global agreement to end plastic pollution started during the United Nations Environmental Assembly in 2022 (UNEA, 2022).

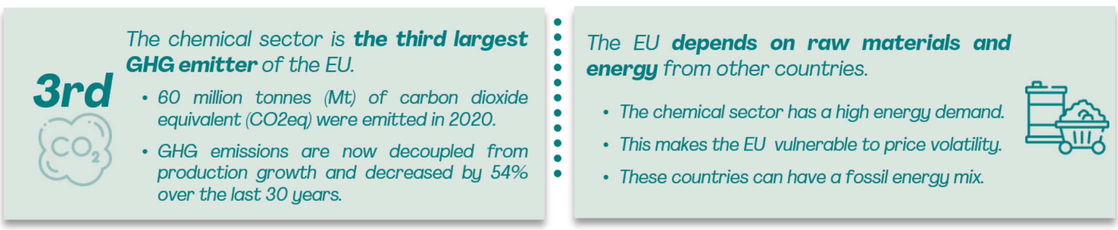

Figure 11, Sustainability facts EU chemical sector, own image.

GHG emissions are now decoupled from production growth, and decreased by 54% from 1990 to 2019, mostly due to a reduction in N_2O emissions (CEFIC, 2022). More attention has been

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given to plastics worldwide due its poor management leading to plastic and microplastics debris ending up on rivers and marine ecosystems and because of its high GHG emissions (Rosenboom et al., 2022). Recycled plastic represented 10% of the total plastic production in the EU, which amounted to 57.2 Mt in 2021. This is 20% more than 2020, and five times more than the amount of bio-based plastics produced in 2021 (PlasticsEurope, 2022).

The sustainability impacts of the chemical sector are assessed applying Product Environmental Footprint (PEF) and Life Cycle Assessment (LCA) methodologies (EC, 2019; TFS, 2022). However, specifically for bio-based chemicals, LCA results are variable and face some challenges. The sector lacks harmonized methods to measure environmental sustainability and circularity, and most of studies do not explore environmental impacts beyond GHG emissions (Ögmundarson et al., 2020; Rosenboom et al., 2022).

Energy and raw materials dependence

Due to its highly globalized value chain, the EU depends on raw materials and energy from other countries. The COVID pandemic, followed by the war in Ukraine, stressed the highly sensitive dependence of the chemicals sector with the geopolitical context (EC, 2023a). As the largest consumer of natural gas, the chemical sector in the EU is vulnerable to the volatility of prices faced in 2022 due to the war (EC, 2022). Natural gas and electricity represent 36% and 28%, respectively, of the EU chemical sector energy demand (CEFIC, 2022). Differently from the other sectors, gas is not only used as source of thermal energy or electricity, but also as a feedstock for the production of chemicals (Boulamanti and Moya, 2017).

Bio-based chemical sector

Producing chemicals from biomass adds value to biomass and can also benefit from the strong knowledge and infrastructure from the production of biofuels (EC, 2021a). Two of the main challenges of the EU chemical sector are its high GHG emissions and its dependence on other countries, with fossil energy mixes. Incentivizing the bioeconomy can not only support sustainable development and innovation within the chemical sector but can also lead to GHG mitigation and autonomy. The most used feedstocks in the bio-based chemical sector are currently sugary, starchy and oily crops (Spekreijse et al., 2019), but due to land use issues, the attention has currently shifted to the valorisation of lignocellulosic crops and residues from agriculture and forestry, and of organic waste of different kinds from food, municipal solid waste, sewage, and wastewater (Jong et al., 2020). Lignin, organic wastes and CO_2 have great potential to directly replace fossil-based chemicals and to produce novel chemicals with equivalent or similar functionalities.

The challenges faced in reaching a large-scale bio-based chemical sector include that biomass should be sustainably sourced and should not cause potential competition with food production (EC, 2018; Rosenboom et al., 2022). Biomass is a limited resource and while the EU already relies on biomass imports (Spekreijse et al., 2019) some bio-based processes are still not as mature as commercial fossil ones and face several technical barriers on a commercial scale (EC, 2021a). The environmental performance of bio-based chemicals depends on a wide range of factors along the life cycle, such as the type of biomass used, the specific conversion process, and the end-of-life treatment (Rosenboom et al., 2022).

As mentioned above, one of the main feedstocks of the bio-based chemical sector are oil-based crops. A significant share of bio-based chemicals is produced using vegetable oils extracted from rapeseed, sunflower, and soy. The chemical compounds derived from natural fats and oils are also known as oleochemicals (Acme Hardesty, 2020). Oleochemicals can support the chemical sector to improve its environmental performance as they are biodegradable and can have a lower toxicity and carbon footprint than fossil-based alternatives.

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6.2 Case study

Introduction to the company and the case study

Oleon is one of the leading producers of oleochemicals since 1950. Oleon is specialised in converting natural fats and oils into a wide range of oleochemical products, such as fatty acids, glycerin, esters, dimers, technical oils, specialty oleochemicals and biodiesel. As a leading producer of oleochemicals made from renewable raw materials, their products combine high performance with biodegradability. Oleon offers oleochemical building blocks and ingredients in a large variety of markets such as: crop protection, cosmetics, lubricants, nutrition, oilfield, coatings, detergents and many more. Oleochemicals products are used in a wide range of industries as raw materials, ingredients or additives, enhancing the properties of the final product. These oleochemicals are used for their functional properties such as chemical reactivity, lubricity, stabilisation of emulsions, etc. The industry also attaches great value to the fact that most oleochemicals are completely non-toxic, and do not cause skin or eye irritation. Oleon's global commercial, finance, purchasing and HR functions are based at Ertvelde near Ghent (Belgium). Oleon has two production sites in Belgium (Ertvelde and Oelegem), one in Germany (Emmerich), one in Compiègne (France) and two in Port Klang (Malaysia). The Corporate Social Responsibility (CSR) team is composed of 6 employees split between Belgium and France. Oleon's CSR roadmap is based on 3 commitments: taking action on the natural resources and biodiversity, taking action to the climate, and taking action for a collective and inclusive project. In this third commitment they aim to involve all their stakeholders in a more sustainable economy. More information can be found on the Oleon website: https://www.oleon.com/.

Product: Hydrogenated Dimer Acids

Within the framework of the ALIGNED project, Oleon's case study focuses on *Hydrogenated Dimer Acids*. In terms of volume, HDA represents 6.6% of Oleon's activities. These products undergo different steps specific to the oleochemistry, they are derived from the dimerization of fatty acids of vegetable origin which then undergo hydrogenation of the double bonds. This product was chosen because there is a large interest within Oleon to obtain more insight into the sustainability of this product, making it easier to obtain process data. Moreover, this also increases the potential to further improve the sustainability of the process based on the LCA outcomes.

In Europe, Oleon holds 40 to 45% of the production of HDAs, in a sector that is growing rapidly, particularly thanks to their application in the bio-polyamide sector. According to estimates, this market will grow by 3.5 to 5% by 2032. From an environmental point of view, this type of product has one of the most requested Carbon Footprint Products.

ALIGNED will create decision support systems for technology development in the company cases. Previous studies performed by Oleon indicate that the feedstock used accounts for the majority of the GHG emissions allocated to their products. For that reason, the focus of this case study will be on exploring suitable alternatives for the fatty acid feedstock.

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7. Shared feedstocks between the bio-based sectors

Several feedstocks are used in multiple bio-based sectors that are covered in the ALIGNED project. The main shared feedstocks are wood and various other types of plants, such as fibre crops, starch crops, sugar crops and oil crops. The shared feedstocks between the bio-based construction, woodworking, textiles, pulp and paper, and chemicals sectors can be described as follows.

7.1 Wood

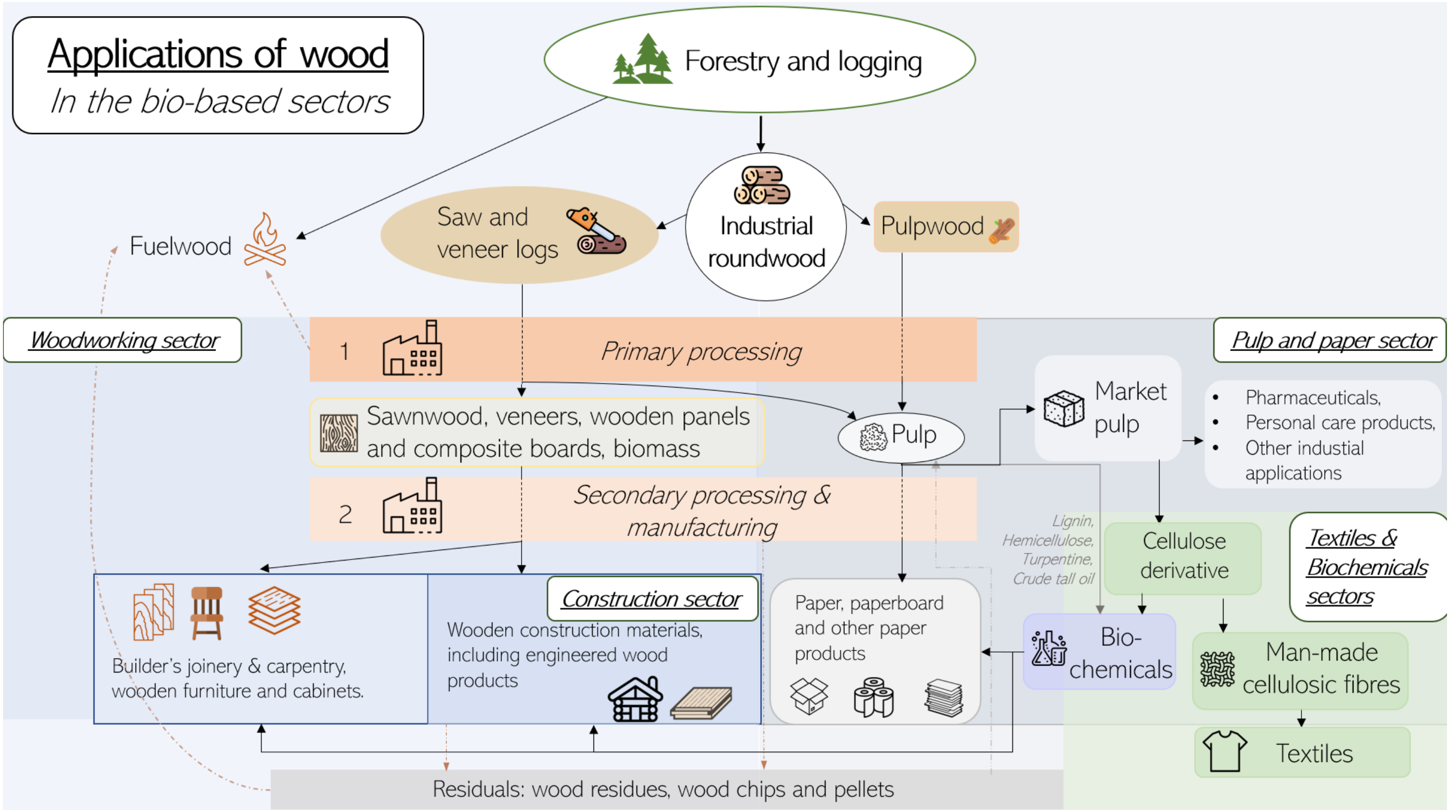

Figure 12, Overview of wood applications in ALIGNED's five bio-based sectors, own image.

Wood comes from different types and species of trees and can be used for various purposes and products. Figure 13 shows that a major share of the EU's roundwood production (all forest removals) is used as saw and veneer logs (43%), as well as 32% pulpwood and 24% fuelwood (Eurostat, 2022). As can be seen in Figure 12, the woodworking sector processes these saw and veneer logs into sawnwood, veneers, wooden panels and boards. These products can then be further processed into engineered wood products, other wooden construction materials, builder's joinery and carpentry products, as well as furniture and cabinets.

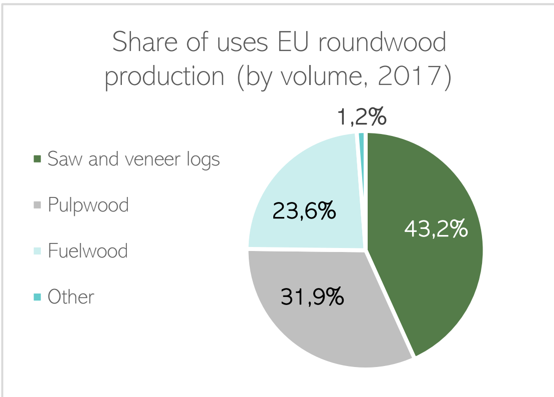

Figure 13, Use of roundwood produced in the EU. Own calculations using Eurostat data.

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Pulpwood, as well as chips and residues from sawmills, is the wood used in the pulp and paper sector. Pulpwood and residues are used to produce pulp, which can either be processed into paper and paper products or sold as market pulp. Market pulp is used for various applications such as personal hygiene products, such as diapers and menstrual products, as well as in pharmaceuticals and cellulose derivatives.

Cellulose can be derived from the market pulp. These cellulose derivatives can be used to create adhesives for the pulp and paper and woodworking sectors, or as a thickening and brightening agent for coatings in the woodworking sector. The main use of cellulose derivatives are man-made cellulosic fibres, where the cellulose is dissolved and spun to create fibres such as viscose and acetate for textiles and for other industrial sectors.

During the pulping process, where wood and other cellulosic materials are converted into pulp, the cellulose is separated from the lignin, hemicellulose and extractives. While the cellulose remains in the pulp, the other organic compounds are dissolved into black liquor. While black liquor is usually burned to generate energy, the organic compounds can also be extracted.

The extractives from block liquor can be removed to produce crude tall oil and turpentine. Crude tall oil is used in the woodworking sector for coatings, adhesives and drying oils, and can also be used to produce various other bio-based chemicals. Turpentine is mainly used as a solvent and thinner for paints and lacquers in the woodworking sector, as well as in a range of other bio-based chemicals.

Hemicellulose and lignin can be obtained and used for various applications such as bio-based chemicals. Hemicellulose can be used to produce bioethanol, which is used in various bio-based chemicals. Lastly, lignin can be used for a range of applications, including in pavement engineering, to produce the flavouring agent vanillin, or for bio-based chemicals such as dispersants, adhesives and surfactants.

Finally, post-consumer or post-industrial paper products can be recycled. Used paper products are mostly recycled into new paper products but can also be used for other purposes. Recycled paper can be used as insulation material in the construction sector and its cellulosic fibres can be used to reinforce bio-based plastics and bio-composite products.

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7.2 Non-wood feedstocks

Figure 14 gives an overview of the shared (non-wood) feedstocks between the five bio-based sectors. This includes fibre, starch, sugar and oil crops, as well as animal products, residues, by-products and other streams from the other bio-based sectors.

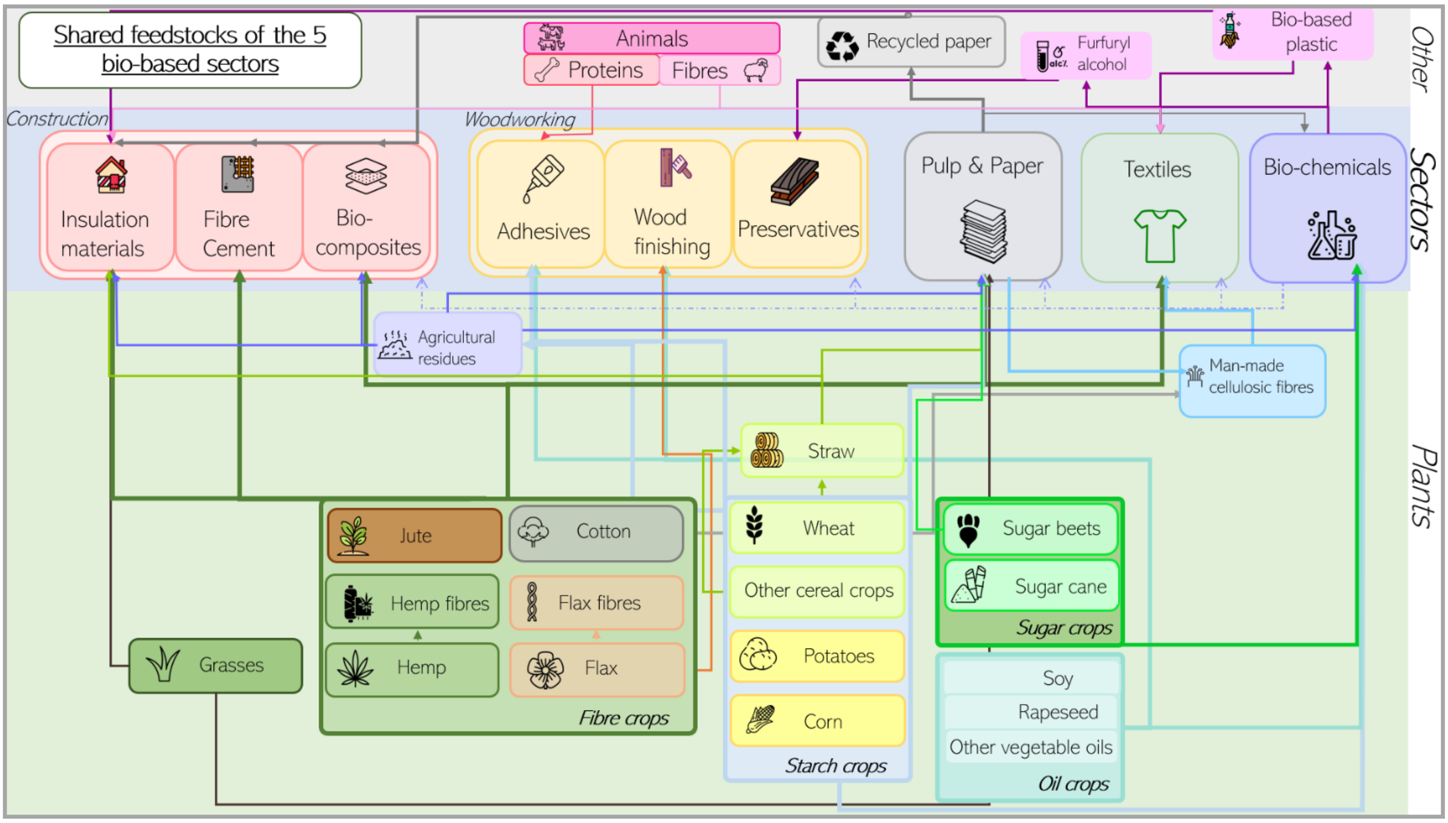

Figure 14, Overview of applications of other feedstocks in ALIGNED's five bio-based sectors, own image.

Starch

Starches are carbohydrates extracted from agricultural raw materials, mainly from potatoes, wheat and maize, but also from barley, rice and peas (CEPI, 2021). The EU produces 11 million tonnes of starch annually. Half of the starch consumed in the EU is used in food, and the other half is for non-food applications, mainly in paper production (StarchEurope, 2023).

By weight, starches are the third-largest component in paper, surpassed by cellulose fibres and minerals (Jonhed, 2006). Starch is used in paper production to thicken and bind the paper but is also used as an adhesive and as a coating. When native starch is modified using chemical, physical or enzymatic processes, it is known as modified starch. These starches are mostly used in the food industry but can be used as an adhesive during the papermaking process and as a coating (CEPI, 2021).

Starch-containing crops are also used to produce bio-based plastics. These bio-based plastics can be used to produce insulation materials, as well as bio-based synthetic fibres in the textiles sector. For example, corn is used to produce partially bio-based polyurethane, PBT polyester, and PTT polyester. Corn, sugar beet pulp, sugarcane and cassava can be used to produce poly-

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lactic acid (PLA), which is mainly used for packaging and can be used for insulation in the construction sector (van Dam & van den Oever, 2019). Bio-based composites from bio-based plastics such as PLA or PHA can be fortified using starch.

Starches are also used in the construction sector to produce adhesives (starch glues) and can be used in flame-retardant products (Tavakoli et al., 2022).

Vegetable oil

Vegetable oils are derived from plant sources, such as vegetables, seeds, nuts, cereal grains, and fruits. This includes palm, olive, corn, soybean, rapeseed, castor and sunflower oil.

Vegetable oils can be used to make a range of bio-based chemicals, such as plasticizers, biofuels, bio-lubricants, adhesives, printing inks, paints and coatings, which are used in the bio-based sectors (Karmakar et al., 2020). Oil-containing crops, such as castor, are also used to produce bioplastics, which are used as bio-synthetic fibres for the textiles sector.

Vegetable oils are widely used in the woodworking sector, as they are used as varnishes, lacquers, and paints, but also for adhesives and for thermal modification. Additionally, oil from corn can be used as a flame retardant in woodworking products. Vegetable oils can be used to make bio-based resins, which are used in the construction sector to make engineered stone products.

Sugar

Crops that are primarily cultivated for sugar production and the production of alcohol and ethanol are also known as sugar crops. The two main sugar crops are sugar beets and sugar cane (Marzo et al., 2019). The EU is the world's largest producer of beet sugar, with a production of 14.2 million tonnes in the 2020-2021 season (European Association of Sugar Manufacturers, 2022). The biggest producers of sugar beets in the EU are Spain, Belgium, France and the Netherlands (Statistics Netherlands, 2019). The global sugar market is dominated by sugar cane, which is only produced in small amounts in Europe (Rossi, 2018).

Sugar beets and sugar cane can be used to produce bio-based plastics. Bio-based plastics such as PLA can be used in the construction sector as insulation material and can be used to produce bio-synthetic fibres, used in the textiles sector. Additionally, bark from sugar cane also be used to produce bio-based fibres for the textiles sector.

The pulp from sugar beets and sugar cane waste can be used to produce paper. Beet fibres could be extracted from beet pulp, a by-product of sugar production, to produce paper. Furfuryl alcohol can be made out of agricultural waste from corn cobs and sugar cane. Furfuryl alcohol is used to impregnate wood products, in order to chemically modify the wood to increase its resistance to biological degradation and to make the product more stable (Sandberg et al., 2017).

Fibres

Crops that are primarily grown for the production of fibres are known as fibre crops. This includes cotton, and other bast fibres such as jute, kenaf, hemp and flax. Additionally, lignocellulosic agricultural waste, such as stalks, stems, straws, hulls and cobs can be used to extract cellulose fibres.

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These fibres are primarily used for textiles, where they are converted into garments, home textiles and industrial textiles. As these natural fibres have great moisture retention qualities, they can also be used as bio-based insulation materials in the construction sector. Additionally, as many of these crops, as well as agricultural waste, are high in cellulose, they can be used to make pulp and paper. Recycled cotton and cotton linter, a by-product from cotton production, have high cellulose and low lignin content and can therefore be used to produce man-made cellulosic fibres for textiles and can be used to produce paper. Grasses, such as miscanthus can also be used for insulation, as well as paper production.

Industrial hemp fibres are not only used to produce textiles and paper, they can also be used in the construction sector. Hemp fibres can reinforce concrete, also known as hempcrete and hemp can be used for insulation.

While not commonly produced in Europe, bamboo has great properties for paper production and its fibres are also used in bio-composite products.

Animal products

Animals are also used in the bio-based sectors. In the textiles sector, fibres from sheep, cashmere goats, alpacas, silk moths, and mohair goats are used. Protein from various animals can also be used to produce bio-based adhesives. These adhesives are commonly made using animal bones and hides, as well as milk, blood, and fish skins.

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