D7.1 – Preliminary LCA and LCC report

Funded by
the European Union

Document control sheet

Project	New Wave – Building a sustainable & circular economy through innovative, biobased manufacturing lines
Call identifier	Horizon-CL4-2021-TWINTRANSITION-01-05: Manufacturing technologies for bio-based materials
Grant Agreement N°	101058369
Coordinator	BTG Biomass Technology Group BV
Work package N°	7
Work package title	Sustainability and LCA + LCC
Work package leader	Blue Synergy SL
Document title	D7.1 Preliminary LCA and LCC report
Lead Beneficiary	Blue Synergy
Dissemination level	PU
Authors	Sebastian Ospina (Blue Synergy)
Contributors	Blue Synergy, All
Reviewer(s)	German Cavero (Blue Synergy), BTG Biomass Technology Group BV
Issue date	30/09/2024

Executive Summary

The NewWave project is a pioneering initiative aimed at developing and commercializing bio-based chemicals and materials through innovative thermochemical fractionation (TCF) technology. By utilizing biomass residues and renewable feedstocks, the project seeks to replace fossil-based products with sustainable alternatives in particular the construction industry. Central to the project is the conversion of biomass into raw materials used in wood panels (bio-resins), polyols & PUR's, furan-based chemicals, and modified wood (formulations), all of which offer significant environmental benefits while maintaining high performance standards. The thermochemical fractionation process is the core technology used to convert biomass into valuable bio-based products. Bio-oil produced from pyrolysis is fractionated into lignin and sugar-rich streams, which are then processed into the earlier mentioned products. Lignin, a key output, is used to replace up to 25% of phenol in traditional phenol-formaldehyde resins, with the goal of increasing this substitution to 100% in the future. Additionally, formaldehyde will eventually be replaced with Hydroxymethylfurfural (HMF), creating fully bio-based resins suitable for use in engineered wood panels like Medium-Density Fiberboard (MDF). The sugar-rich fraction is converted into furan-based chemicals via HMF. Bio-polyols are produced from the sugars by hydrotreatment and are used to produce bio-based polyurethane foams, adhesives, and coatings, offering an environmentally friendly alternative to petrochemical-based products. In addition, modified wood products are created through a impregnation process, using agents derived from Fast Pyrolysis Bio-Oil (FPBO) to enhance the durability and resistance of wood, thus providing a sustainable alternative to traditional toxic wood treatments. The project also incorporates advanced water treatment technologies, combining anaerobic and aerobic processes to treat wastewater generated during production. This system not only purifies the water for reuse but also generates biogas for energy recovery, further enhancing the sustainability of the overall process. In the next stages of the project, several key methodologies will be applied to comprehensively assess the environmental and economic performance of these processes. **Life Cycle Assessment (LCA)** will be performed to quantify the environmental impacts of each process, including greenhouse gas emissions, energy use, water consumption, and waste generation, from cradle to grave. This methodology will help to identify environmental hotspots and ensure that transitioning from fossil-based to bio-based products delivers significant sustainability benefits. Alongside LCA, **Life Cycle Costing (LCC)** will be conducted to evaluate the total costs associated with each process, such as capital investment, operational costs, and end-of-life management. By performing both LCA and LCC, the project aims to obtain a holistic view of environmental and economic sustainability, ensuring that the developed technologies are viable for commercial-scale application. **Scale-up simulations** will also be performed to model the transition from lab-scale to industrial-scale production. These simulations are crucial for assessing the feasibility of scaling up processes, identifying potential bottlenecks, and optimizing energy and material flows. The **hotspot identification** methodology will be integrated into the LCA and LCC analyses to pinpoint stages of production with disproportionately high environmental or economic impacts. Mitigation strategies—such as improving energy efficiency, optimizing feedstock use, and refining process design—will be developed to address these hotspots and enhance the overall sustainability of the project. The NewWave project promises considerable environmental benefits, including reductions in greenhouse gas emissions by replacing fossil-based chemicals with bio-based alternatives, valorizing biomass residues to promote a circular economy, and increasing energy efficiency through biogas recovery. Economically, the project aims to offer cost-effective solutions by utilizing low-cost biomass feedstocks, while also tapping into new market opportunities driven by the growing demand for sustainable materials.

In the coming phases, the project will focus on completing data collection across all processes and manufacturing lines, performing scale-up simulations to validate the feasibility of industrial-scale production, and conducting comprehensive LCA and LCC analyses to quantify both environmental and economic impacts. In addition, efforts will be directed toward identifying and mitigating environmental and economic hotspots, with the aim of optimizing sustainability and cost-efficiency. Overall, the NewWave project is well-positioned to lead the shift toward a sustainable bio-based economy, offering innovative solutions that reduce environmental impacts and create significant market opportunities, ensuring the long-term sustainability of these green technologies.

Content of Deliverable

List of figures

List of Tables

1. Introduction

In recent years, the quest for sustainable industrial processes has intensified, driven by growing environmental concerns and the imperative to reduce human impacts on the planet. The NewWave project aims to address these concerns by developing innovative, biobased manufacturing lines that contribute to building a sustainable and circular economy. This initiative seeks to replace toxic, fossil-based chemicals with environmentally friendly alternatives derived from biomass residues and end-of-life products.

The innovative approach of NewWave is to apply thermo-chemical fractionation (TCF) to unlock and fractionate residual biomass. TCF combines fast pyrolysis of the biomass with subsequent fast pyrolysis oil separation, keeping the key chemical functionalities in separate, depolymerized fractions. The pyrolysis oil and lignin- and sugar-fraction are used in the manufacturing lines producing engineered wood panels, furan base-chemicals, polyols and polyurethanes, and modified/engineered wood as given below (Figure. 1).

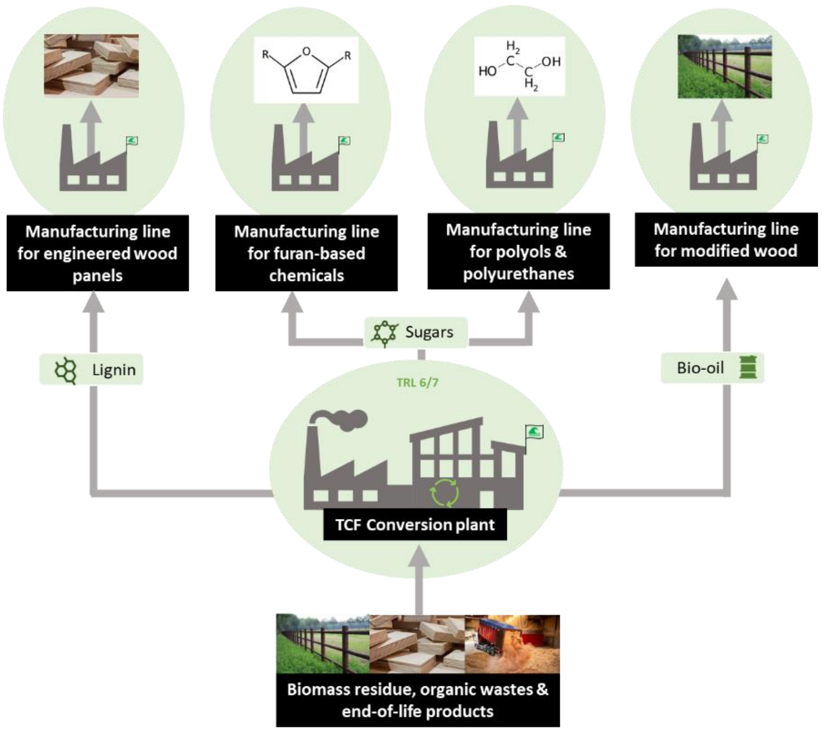


Figure. 1. NewWave manufacturing lines

Despite the clear benefits of these biobased materials, their production is not without environmental and economic challenges. These include the consumption of resources, generation of waste, and the use of chemicals in the production process. Economically, the costs associated with raw materials, energy, labor, and technology can influence the feasibility and sustainability of production. Identifying and addressing the hotspots—stages or aspects of the production process with significant environmental impacts and economic costs—is essential for enhancing the overall sustainability of these processes.

This report aims to explore these hotspots through an integrated Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approach. LCA provides a framework for assessing the environmental impacts of production from cradle to grave, encompassing raw material extraction, production, distribution, use, and disposal. LCC complements this analysis by evaluating the economic aspects, offering a comprehensive view of the costs associated with each stage of the life cycle. By combining these methodologies, the report seeks to identify areas where improvements can lead to more environmentally sustainable and economically viable production.

The scope of this report includes a detailed analysis of the production processes within the NewWave project, highlighting environmental and economic hotspots. The objectives are to conduct a holistic assessment of the production processes using LCA and LCC methodologies, identify key areas for improvement, and propose strategies to mitigate environmental impacts while optimizing economic outcomes.

2. Theoretical background

2.1. General Process Overview

The **NewWave project** is centered around innovative **Thermochemical Fractionation (TCF)** technology to convert biomass into raw materials used to produced bio-based chemicals and materials such as polyols, furan-based chemicals, bio-resins, and modified wood. This process employs a circular approach where multiple biomass streams are valorized, maximizing resource efficiency and sustainability. The overall (simplified) process, as depicted in Figure 2, illustrates the interconnected steps of pyrolysis, fractionation (TFC), and downstream processing that contribute to the production of high-value chemicals and materials, highlighting the integration of various units such as water treatment, polyols & PUR's production (ML1), furan-based chemicals synthesis (ML2), bio-resins manufacturing (ML3), and modified wood production (ML4).

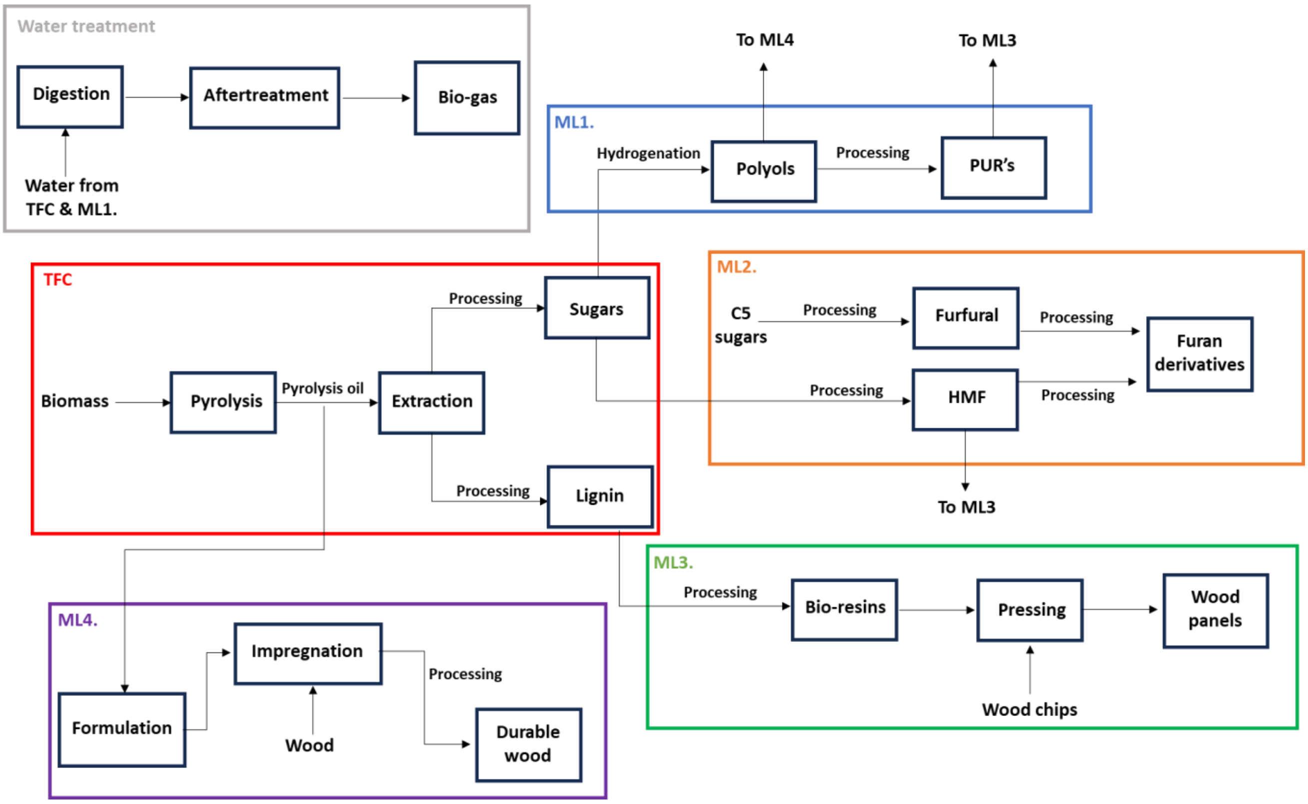


Figure 2: General process overview

2.1.1. Thermochemical Fractionation (TCF)

The core of the process begins with **Thermochemical Fractionation (TCF)**, where biomass (BM) undergoes **pyrolysis** in the presence of sand as a heat transfer medium and natural gas. Pyrolysis occurs without the use of catalysts, relying on the sand to facilitate heat transfer. During pyrolysis, the biomass is thermally decomposed to produce bio-oil, non-condensable gases, and char. The non-condensable gases, along with the char, are combusted to provide energy for the system, resulting in minimal external energy input and potentially an excess of energy for other processes.

The bio-oil produced is separated into two main fractions: **lignin** and **sugar streams**, through **fractionation**. The lignin is subsequently processed, while the sugar stream undergoes further processing in downstream reactions to produce high-value chemicals such as **polyols** and **furfural derivatives**.

2.1.2. Polyols Production (ML1 - WP3)

The sugar-rich fraction derived from the bio-oil is first processed into a **sugar syrup**, which is then hydrogenated to create polyols. The resulting polyols are key intermediates for various polymer applications, such as the production of **polyurethane foams** and adhesives. The process includes prepolymer synthesis and the formulation of **rigid and flexible foams**, which are widely used in construction, automotive, and furniture industries.

Further steps in the process involve hybrid PU-Epoxy system blends, as well as the curing of PU adhesives, producing materials with enhanced durability and mechanical properties.

2.1.3. Furan-Based Chemicals (ML2/WP4)

Parallel to polyols production, the process also focuses on producing **furan-based chemicals** which are derived from the sugar-rich stream. The sugar stream is first converted into **HMF**, a platform chemical, through catalytic processes. Also Furfural will be used as starting material. The furan derivatives targeted are valuable green solvents and chemical intermediates, with applications in pharmaceuticals, agrochemicals, and polymer production. The use of these bio-based chemicals provides a sustainable alternative to petroleum-based counterparts, promoting a reduction in environmental impact.

2.1.4. Bio-resins and Engineered Wood (ML3/WP5)

Another major stream from the TCF process is focused on the production of **bio-resins and engineered wood products**. The lignin separated during fractionation is processed into bio-based resins, which replace traditional phenol in phenol-formaldehyde resins. The process uses the lignin-rich stream as the core ingredient in **bio-based phenol-formaldehyde resins**, while future plans include replacing formaldehyde with HMF, further enhancing the environmental benefits of the resins.

The production of engineered wood begins with **debarking and chipping** of wood feedstock, followed by **defibration** and **blending** with bio-resins to create composite materials like **medium-density fiberboard (MDF)**. After blending, the wood fibers are formed into mats, which are then subjected to hot pressing and curing to form the final MDF product. This material is a sustainable alternative to traditional wood products and is used in furniture, construction, and other industries requiring high-performance materials.

2.1.5. Modified Wood (ML4/WP6)

In the modified wood line, biomass residues or lower-grade timber undergo a bio-based modification process. Initially, the wood is **debarked**, followed by **screening** to ensure uniform size. The wood is then impregnated with bio-based agents derived from pyrolysis bio-oil, which enhances the wood's resistance to environmental factors such as decay and pests.

After impregnation, the wood is subjected to **low-temperature drying** and **high-temperature steam curing**, which stabilizes the bio-based agents within the wood matrix. The final product is a modified wood that offers enhanced durability and sustainability, serving as a substitute for chemically treated wood products in construction and outdoor applications.

2.1.6. Water Treatment (WP2)

The water treatment system is an integral part of the process, ensuring that effluents generated during biomass conversion and chemical production are sustainably managed. The water treatment involves a combination of **activated sludge reactors**, **sludge dewatering**, and anaerobic sludge reactor. These processes treat wastewater, ensuring that effluents meet environmental standards before being discharged or reused in the system. Sludge generated in the process is further treated and dewatered, minimizing waste and allowing for efficient resource recovery.

2.2. *Thermochemical fractionation*

Thermochemical Fractionation (TCF) is a critical process in the NewWave project, designed to convert biomass residues into raw materials for the production of bio-based chemicals and materials, thereby promoting circularity and resource efficiency. The process begins with the thermal decomposition of biomass in a pyrolysis unit, followed by fractionation, where bio-oil is separated into valuable chemical streams.

2.2.1. Overview of the TCF Process

In the TCF process, **pyrolysis** is the first step. Biomass is thermally decomposed in the absence of oxygen to produce three main outputs: **bio-oil**, **non-condensable gases**, and **char**. The pyrolysis reaction takes place in a **rotating cone reactor**, a specialized type of pyrolysis reactor designed to ensure efficient heat transfer and uniform thermal decomposition of the biomass.

2.2.1.1. The Rotating Cone Reactor

The **rotating cone reactor** is central to the TCF process, known for its high thermal efficiency and ability to handle diverse biomass feedstocks. The reactor is a conical chamber where biomass is introduced from the top, along with sand, which acts as an inert heat transfer medium. The sand is preheated and brought into contact with the biomass as it moves through the rotating cone. This ensures rapid heat transfer to the biomass particles, initiating pyrolysis at temperatures between **400°C and 600°C**.

The conical design promotes the **constant movement** of biomass particles, ensuring that they are evenly distributed and exposed to heat. This movement prevents the formation of hot spots and ensures that pyrolysis occurs uniformly across the biomass. The geometry of the cone also facilitates the quick removal of volatile products (bio-oil vapors), which are swiftly condensed to avoid secondary reactions that could degrade their quality.

Another advantage of the rotating cone reactor is its ability to operate at **atmospheric pressure**, simplifying the system's design and operational demands. It also ensures high **thermal efficiency**, as the non-condensable gases and char produced during pyrolysis are combusted to provide the heat required for the process. This **energy recovery** mechanism reduces external energy inputs, making the reactor highly efficient and self-sustaining.

2.2.1.2. Process Description

The TCF process consists of several key stages:

1. **Pyrolysis**:
    1. Biomass is fed into the rotating cone reactor, where it is rapidly heated in an oxygen-free environment, decomposing into **bio-oil**, **non-condensable gases**, and **char**. The rotating cone reactor’s design ensures that the biomass particles are in constant motion, allowing for uniform heating and fast thermal decomposition.
    2. The pyrolysis vapors produced are quickly swept from the reaction zone and condensed into bio-oil. The char and non-condensable gases are combusted to provide energy for the process.
2. **Fractionation**:
    1. The bio-oil is then processed in a fractionation unit, where it is separated into two primary streams: a **sugar-rich fraction** and a **lignin-rich fraction**. This separation is achieved through an extraction process that isolates these components based on their chemical characteristics.
    2. The **sugar fraction** is further processed into bio-based chemicals, such as HMF and furan derivatives and also polyols, which are used in the production of polyurethane materials. The **lignin fraction** is converted into bio-resins, which are valuable for producing bio-based phenol-formaldehyde resins used in engineered wood products.
3. **Energy Recovery**:

1. The combustion of the **non-condensable gases** and **char** generated during pyrolysis is a crucial part of the energy recovery strategy in the TCF process. The heat generated from this combustion is used to sustain the pyrolysis reaction, ensuring that the process is energy-efficient and minimizes external energy requirements.

2.3. Polyols and Polyurethanes

Polyols and **polyurethanes** are essential components in a wide range of industrial applications, such as foams, adhesives, coatings, and sealants. The NewWave project aims to develop **bio-polyols**, sustainable alternatives to conventional petrochemical-derived polyols, through the **thermochemical fractionation (TCF)** of biomass. These bio-polyols are used to create bio-based polyurethanes with reduced environmental impact.

2.3.1. Production of Polyols and Polyurethanes

The production of bio-polyols starts with the **hydrotreatment** of the **sugar-rich fraction** derived from **bio-oil** obtained via **pyrolysis**. Using a special catalyst, the sugar-rich fraction undergoes hydrogenation, leading to the formation of bio-polyols, which are the key intermediates in polyurethane production. These bio-polyols, including both short-chain (e.g., mono ethylene glycol, MEG) and long-chain polyols, are used to produce **polyurethane foams, adhesives, and coatings**.

Table 1: Process description for Polyols and Polyurethanes production

Process Stage	**Description**
Sugar-Rich Fraction	The sugar-rich fraction, obtained through fractionation of bio-oil, serves as the feedstock for bio-polyol production.
Hydrotreatment	Using hydrogen and a special catalyst, the sugar-rich fraction is hydrogenated to produce bio-polyols.
Polyol Separation	The bio-polyols are separated and purified through distillation and fractionation.
Polyurethane Synthesis	Bio-polyols are reacted with isocyanates to form **polyurethane foams** and **adhesives** for various applications.

2.4. Furan Based Chemicals

The NewWave project focuses on the sustainable production of **furan-based chemicals**. These chemicals, derived from the **sugar-rich fraction** obtained during the thermochemical fractionation (TCF) of biomass, serve as greener alternatives to traditional fossil-based solvents. Their applications span across industries such as pharmaceuticals, agrochemicals, and polymers.

2.4.1. Production of Furan-Based Chemicals

The production process for furan-based chemicals begins with the **fractionation** of bio-oil, which yields a **sugar-rich fraction**. This fraction is then converted into **HMF**, a key intermediate, through a dehydration process. Furfural will also be tested as the raw material.

Table 2: Production process description for furan derivatives

Process Stage	**Description**
Sugar Fraction from Bio-Oil	The sugar-rich fraction, obtained through the fractionation of bio-oil, serves as the primary feedstock for furan chemical production.
HMF & Furfural Production	Pyrolytic sugars are dehydrated to produce **HMF** through a catalytic dehydration process. Furfural is produced by the dehydration of C5-sugars.
Processing	HMF and also Furfural are processed to produce different furan derivatives.
Final Products	The final bio-based products are green solvents for applications in pharmaceuticals, resins, and agrochemicals.

2.5. Engineered Wood Panels

The production of **Medium-Density Fiberboard (MDF)** using bio-resins is a critical aspect of the NewWave project. By replacing fossil-based phenol-formaldehyde resins with **lignin-based bio-resins**, the project aims to create a more sustainable alternative while maintaining high performance. This section outlines the production process, the integration of bio-resins, and energy/material outputs.

2.5.1. Production of Bio-Resins

The bio-resins used in engineered wood panel production are derived from the **lignin fraction** of bio-oil, which is obtained during the **Thermochemical Fractionation (TCF)** process. Initially, the bio-resin formulation includes **25% lignin** as a replacement for phenol in traditional phenol-formaldehyde resins. The goal is to incrementally increase the lignin content, ultimately reaching **100% lignin** substitution for phenol, and to eventually replace **formaldehyde** with **Hydroxymethylfurfural (HMF)**.

Lignin's molecular structure allows it to function as a partial phenol substitute, reducing the use of fossil-derived chemicals while contributing to the overall sustainability of the MDF production process.

2.5.1.1. Process Flow for Engineered Wood Panels

The following table summarizes the key stages of the MDF production process, which includes the utilization of bio-resins made with lignin.

Table 3: MDF production process

Process Stage	**Description**
Debarking and Chipping	Wood biomass is debarked and chipped into small pieces to prepare it for further processing.
Defibration	The wood chips are broken down into fibers that are mixed with bio-resins to create MDF.
Blending with Bio-Resin	Wood fibers are blended with bio-resin containing **25% lignin**, with the goal to increase lignin content over time.
Mat Formation	The blended material is formed into mats, which are prepped for hot pressing.
Hot Pressing & Curing	The mats are hot-pressed and cured to solidify the resin and create the final MDF panels.
Final Product	The finished MDF panels have mechanical properties comparable to conventional products, with enhanced sustainability.

2.5.1.2. Transition to 100% Lignin Substitution and Formaldehyde Replacement

As the project advances, the goal is to fully replace fossil-based **phenol** with **lignin**, thereby eliminating the reliance on fossil-derived chemicals. This transition will result in increased use of lignin-based bio-resins in MDF production, ensuring that the process is fully integrated into the circular economy.

Additionally, the replacement of **formaldehyde** with **HMF** will further enhance the sustainability of the bio-resins. HMF is a renewable, non-toxic alternative that will improve the environmental and health profile of the final MDF product. The gradual increase in lignin substitution, combined with future formaldehyde replacement, will position bio-resins as a fully sustainable alternative to traditional resins, significantly reducing the environmental impact of engineered wood panel production.

2.6. Modified Woods

Modified woods play a crucial role in sustainable construction, offering improved durability, resistance to decay, and enhanced mechanical properties compared to untreated wood. The NewWave project aims to produce modified wood products using **bio-based agents** derived from **Fast Pyrolysis Bio-Oil (FPBO)**, thus replacing toxic chemicals traditionally used in wood treatment processes, such as creosote. This bio-based approach contributes to both environmental sustainability and the circular economy.

2.6.1.1. Wood Modification Process

The modification of wood in the NewWave project involves several key steps, beginning with the selection of appropriate wood species and culminating in the production of modified wood that is suitable for various construction and outdoor applications. The bio-based agents used in this process are derived from FPBO and other natural additives, ensuring deep penetration into the wood fibers and enhancing the wood's overall properties.

Table 4: Modified woods production process

Process Stage	Description
Raw Material Selection	The process begins with the selection of wood species, such as **radiata pine**, based on desired properties and availability.
Impregnation with Bio-Based Agents	Wood is impregnated with bio-based agents under vacuum pressure to ensure deep penetration of the agents into the wood structure.
Drying	After impregnation, the wood is dried under controlled conditions to remove excess moisture and stabilize the bio-based agents within the wood.
Curing	The impregnated wood undergoes heat treatment, ensuring the bio-based agents chemically bond with the wood fibers, enhancing durability and resistance.
Finishing	Finally, the modified wood is sanded, trimmed, and coated (if required) to achieve the desired surface quality.

2.7. Water Treatments

The wastewater generated in the NewWave project, particularly from the **Thermochemical Fractionation (TCF)** and the production lines, requires specialized treatment methods to convert organic matter into biogas and purify the water for reuse or discharge. The project employs a combination of **anaerobic** and **aerobic post-treatment** processes to achieve high levels of contaminant removal, focusing on the biological degradation of organic pollutants.

2.7.1. Wastewater Treatment Process

The selected treatment train consists of an **anaerobic process** using an **anaerobic sludge reactor** followed by an **aerobic post-treatment** for further removal of residual pollutants. This combination allows for the effective breakdown of organic matter and the generation of biogas, which can be used for energy recovery.

Table 5: Water treatment process description

Process Stage	Description
Anaerobic Treatment	Wastewater is treated anaerobically, converting organic compounds into biogas through microbial activity.
Aerobic Post-Treatment	The anaerobic effluent is further treated aerobically to remove residual chemical oxygen demand (COD) and other pollutants.
Effluent Reuse or Discharge	The treated effluent can either be discharged into the environment or reused in the TCF.

3. Methodology

3.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle. This includes all stages from raw material extraction, production, and use to disposal or recycling. The primary objective of LCA is to provide a comprehensive understanding of the environmental burdens associated with a product or process, enabling more informed and sustainable decision-making.

LCA is crucial for identifying opportunities to improve environmental performance, reducing resource consumption, minimizing waste, and lowering emissions. It helps businesses, policymakers, and researchers develop strategies to enhance sustainability and mitigate negative environmental impacts.

The development of LCA began in the 1960s and 1970s, with initial studies focusing on energy consumption and resource use. Over the years, LCA methodologies have evolved to include a broader range of environmental impacts and more sophisticated analytical tools. The International Organization for Standardization (ISO) has established key standards for LCA, notably ISO 14040 and ISO 14044, which provide guidelines and requirements for conducting LCA studies. These standards ensure consistency, transparency, and reliability in LCA practices.

3.1.1. Phases of LCA

Goal and Scope Definition: This initial phase involves clearly defining the objectives of the LCA study, the product or process to be assessed, and the boundaries of the analysis. The goal and scope definition sets the framework for the study, specifying the functional unit (e.g., one kilogram of product), system boundaries (e.g., cradle-to-gate or cradle-to-grave), and the environmental impact categories to be considered (e.g., global warming potential, resource depletion).

Life Cycle Inventory (LCI) Analysis: LCI analysis involves collecting and quantifying data on all inputs and outputs associated with the product or process within the defined system boundaries. This includes raw materials, energy use, emissions to air, water, and soil, and waste generation. The data collected during LCI forms the basis for assessing environmental impacts in subsequent phases.

Life Cycle Impact Assessment (LCIA): LCIA evaluates the potential environmental impacts based on the inventory data collected in the LCI phase. This involves categorizing and quantifying the contributions of different inputs and outputs to various impact categories, such as climate change, acidification, eutrophication, and human toxicity. LCIA methodologies, such as ReCiPe and CML, provide standardized approaches for impact assessment.

Interpretation of Results: The final phase involves analyzing and interpreting the results of the LCI and LCIA to draw conclusions and make recommendations. This phase includes identifying significant environmental impacts, evaluating the robustness of the results, and exploring options for improvement. Sensitivity analysis and uncertainty analysis are often conducted to assess the reliability and robustness of the findings.

3.1.2. Methodologies and Tools

3.1.2.1. Common Methodologies:

- **ReCiPe:** A widely used LCIA methodology that provides a comprehensive approach to assessing environmental impacts across multiple categories. ReCiPe includes both midpoint indicators (e.g., climate change) and endpoint indicators (e.g., human health).
- **CML (Centrum voor Milieukunde Leiden):** Another established LCIA methodology developed by the University of Leiden, focusing on midpoint indicators. CML provides a set of characterization factors for assessing various environmental impacts.

Software Tools:

- **SimaPro:** A leading LCA software tool used by researchers and practitioners worldwide. SimaPro supports comprehensive LCA studies, offering extensive databases and robust analytical capabilities for impact assessment and interpretation.

3.1.3. Applications and Benefits

Use in Environmental Decision-Making: LCA is a valuable tool for environmental decision-making in various contexts, including product design, policy development, and corporate sustainability. It helps identify hotspots in the life cycle of products or processes where environmental improvements can be made, guiding the development of more sustainable practices and technologies.

Case Studies from the NewWave Project: The NewWave project has employed LCA to assess the environmental impacts of its biobased manufacturing lines, including the production of bio-polyols, engineered wood panels, and modified wood and furan-based chemicals. These LCA studies have provided critical insights into the environmental performance of the project's innovations, identifying opportunities for reducing resource use and emissions, and enhancing the overall sustainability of the products developed.

3.1.4. Challenges and Solutions

Data Availability and Quality Issues: One of the primary challenges in conducting LCA is the availability and quality of data. Accurate and comprehensive data on raw materials, energy use, emissions, and waste generation is essential for reliable LCA results. However, such data can be difficult to obtain, especially for complex supply chains or emerging technologies.

3.1.4.1. Solutions for Improving LCA Accuracy:

- **Data Standardization:** Developing standardized data collection protocols and databases can improve data quality and consistency, enhancing the reliability of LCA studies.
- **Collaborative Data Sharing:** Encouraging collaboration and data sharing among industries, researchers, and policymakers can help fill data gaps and improve the robustness of LCA.
- **Advanced Modeling Techniques:** Utilizing advanced modeling techniques and sensitivity analysis can help address uncertainties and improve the accuracy of LCA results.
- **Continuous Improvement:** Regularly updating LCA databases and methodologies to reflect new scientific knowledge and technological advancements ensures that LCA remains a relevant and effective tool for environmental assessment.

3.2. *Life Cycle Costing*

Life Cycle Costing (LCC) is an economic analysis method used to evaluate the total cost of ownership of a product, process, or system over its entire life cycle. This includes initial costs, operation and maintenance costs, and end-of-life disposal costs. LCC is essential for understanding the true cost implications of a product or system, allowing stakeholders to make informed decisions that consider both upfront and long-term financial impacts. By accounting for all costs associated with a product’s life cycle, LCC promotes more sustainable and cost-effective decision-making.

LCC has evolved from basic cost analysis methods used in the mid-20th century to more sophisticated models that integrate environmental and social costs. The International Organization for Standardization (ISO) developed standards for LCC, notably ISO 15686-5, which provides guidelines for conducting life cycle cost analysis in the context of building and construction. These standards ensure consistency, transparency, and comparability in LCC studies, enhancing their credibility and utility.

3.2.1. Phases of LCC

Goal and Scope Definition: The first phase of LCC involves defining the objectives and scope of the analysis. This includes specifying the product or system to be evaluated, the time horizon (e.g., 10 years, 50 years), and the costs to be considered (e.g., acquisition, operation, maintenance, disposal). Defining the goal and scope ensures that the LCC study is focused and relevant, aligning with the decision-making needs of stakeholders.

Data Collection and Cost Modeling: This phase involves gathering data on all relevant costs over the life cycle of the product or system. Data sources can include historical cost records, market surveys, expert estimates, and technical specifications. Cost modeling involves developing a structured framework to quantify these costs, often using present value techniques to account for the time value of money. Key cost categories typically include capital costs, operating costs, maintenance costs, and end-of-life costs.

Interpretation of Results: In the final phase, the results of the LCC analysis are interpreted to inform decision-making. This includes comparing different scenarios, identifying cost drivers, and assessing the financial implications of various options. Sensitivity analysis and uncertainty analysis are often conducted to evaluate the robustness of the results and identify areas where more precise data or additional research is needed.

3.2.2. Methodologies

3.2.2.1. Common Methodologies:

- **Net Present Value (NPV):** A method that calculates the present value of all future cash flows associated with a product or system, discounted at a specified rate. NPV helps to compare the financial viability of different options over the same time horizon.
- **Internal Rate of Return (IRR):** A metric that identifies the discount rate at which the net present value of future cash flows is zero. IRR is used to evaluate the profitability of investments.
- **Payback Period:** The time required for the cumulative cash flows from a product or system to equal the initial investment. This method helps assess the risk and return of investments.

3.2.3. Applications and Benefits

Use in Economic Decision-Making: LCC is widely used in various sectors to support economic decision-making. It helps stakeholders assess the long-term financial viability of investments, optimize resource allocation, and identify cost-saving opportunities. By providing a holistic view of costs over the entire life cycle, LCC enables more sustainable and cost-effective choices.

Case Studies from the NewWave Project: The NewWave project has applied LCC to evaluate the economic performance of its biobased manufacturing lines, including the production of bio-polyols, engineered wood panels, modified wood and furan-based chemicals. These LCC studies have provided valuable insights into the total costs of ownership, highlighting areas where cost efficiencies can be achieved and supporting the economic viability of sustainable alternatives.

3.2.4. Challenges and Solutions

Data Availability and Quality Issues: One of the main challenges in LCC is obtaining accurate and comprehensive data. Cost data can be difficult to collect, especially for new or innovative technologies, and there can be significant variability in cost estimates due to market fluctuations and other factors.

3.2.4.1. Solutions for Improving LCC Accuracy:

- **Data Standardization:** Developing standardized data collection protocols and cost databases can improve the quality and consistency of LCC studies.
- **Collaborative Data Sharing:** Encouraging collaboration and data sharing among industries, researchers, and policymakers can help fill data gaps and enhance the robustness of LCC.
- **Advanced Cost Modeling Techniques:** Utilizing advanced cost modeling techniques and sensitivity analysis can address uncertainties and improve the accuracy of LCC results.
- **Continuous Improvement:** Regularly updating cost databases and methodologies to reflect new information and technological advancements ensures that LCC remains a relevant and effective tool for economic assessment.

3.3. Environmental and Economic Hotspots

Understanding the concept of hotspots is crucial in the sustainability assessment of industrial processes. Hotspots are defined as stages or aspects of a process that have significant environmental or economic impacts. Identifying these hotspots is the first step toward mitigating negative consequences and enhancing the overall sustainability of the process.

3.3.1. Environmental Hotspots

Environmental hotspots in the production process are those stages in the life cycle that contribute most significantly to the product's total environmental impact. These impacts can be diverse, including greenhouse gas emissions, water usage, energy consumption, pollution, and depletion of natural resources. Identifying environmental hotspots requires a comprehensive analysis of the entire life cycle of the product, from raw material extraction through to production, use, and disposal. This analysis helps in pinpointing areas where interventions can yield the most significant environmental benefits.

3.3.2. Economic Hotspots

Economic hotspots, on the other hand, are identified by analysing the cost implications throughout the product's life cycle. This includes the costs associated with raw materials, energy, labour, maintenance, waste management, and any other expenses incurred during the production, use, and end-of-life phases. Economic hotspots are critical for understanding where the most significant cost drivers lie and where cost reduction efforts can be most effectively applied.

3.3.3. Integrating Environmental and Economic Assessments

The integration of environmental and economic assessments provides a holistic view of a product's sustainability. It allows for the identification of trade-offs or synergies between environmental and economic objectives. For example, a process modification that reduces energy consumption (an environmental benefit) may also lower operating costs (an economic benefit), addressing both environmental and economic hotspots simultaneously. Conversely, a strategy that reduces costs by using cheaper but more environmentally harmful materials would highlight a trade-off between economic gains and environmental impacts.

The goal of identifying environmental and economic hotspots is not merely to document these impacts but to inform strategies for improvement. By understanding where the greatest impacts occur, decision-makers can prioritize interventions, invest in research and development, and implement changes that lead to more sustainable and economically viable production processes.

This understanding of environmental and economic hotspots lays the groundwork for the application of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies in the subsequent analysis of rhamnolipid production.

3.4. Goal and Scope Definition, Data Collection, and Inventory Analysis

3.4.1. Goal and Scope Definition

The goal of the combined Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) study is to evaluate both the environmental and economic impacts of the manufacturing lines developed within the NewWave project. The analysis aims to identify environmental and economic hotspots across the life cycle of each product, helping to guide decision-making towards more sustainable and cost-effective production practices.

Scope:

- **System Boundaries:** The system boundaries for this combined LCA-LCC analysis are defined as cradle-to-gate for the products and cradle-to-grave for waste, effluents, and emissions generated. This approach encompasses all stages from raw material extraction, production, and transportation to the point where the product is ready for delivery (cradle-to-gate), as well as the complete lifecycle of waste, emissions, and effluents until their final disposal or emission to the environment (cradle-to-grave).

- **Functional Units:** Each manufacturing line has its own functional unit corresponding to the main product being produced. For example:
  - Bio-polyol production: 1 kg of bio-polyol.
  - Medium Density Fiberboard (MDF) production: 1 m^3 of MDF.
  - Modified/engineered wood production: 1 m^2 of modified wood.
  - Furan based chemicals: 1 kg of 2-MeTHF

These functional units ensure consistency in comparing environmental impacts and costs across different products and processes.

4. Preliminary results – Potential economic and environmental benefits and Hotspot identification

4.1. Thermochemical fractionation

4.1.1. Potential Environmental and Economic Benefits of TCF

The TCF process presents significant environmental and economic benefits, especially in the context of transitioning to a bio-based circular economy. The integration of pyrolysis and fractionation allows for the valorization of biomass residues and organic wastes, which otherwise would be discarded or treated through less sustainable methods.

4.1.1.1. Environmental Benefits:

1. **Reduction in Waste**: TCF effectively transforms biomass residues into valuable bio-based products, thus reducing the amount of organic waste that would typically go to landfills or be incinerated.
2. **Carbon Footprint Reduction**: By replacing fossil-based chemicals with bio-based alternatives, TCF helps reduce the overall carbon emissions associated with the production of chemicals, resins, and materials. Moreover, the energy self-sufficiency of the applied pyrolysis technology, which burns non-condensable gases and char, contributes to a reduction in external energy needs, further lowering greenhouse gas emissions.
3. **Sustainable Resource Use**: The ability to process diverse biomass types enables more sustainable and local resource use, reducing dependence on non-renewable materials. This flexibility also promotes the utilization of locally available biomass, minimizing the transportation-related environmental impacts.
4. **Energy Recovery**: The system's energy efficiency, achieved by burning the by-products of pyrolysis, ensures that less external energy is required to sustain the process, making TCF a low-energy-demanding process compared to conventional fossil-based systems.

4.1.1.2. Economic Benefits:

1. **Cost Efficiency**: The ability to produce bio-oil, polyols, resins, and other bio-based products from relatively low-cost biomass residues offers significant economic advantages. By tapping into underutilized resources (such as agricultural or forestry waste), TCF reduces the dependency on expensive fossil-based inputs.
2. **Value Addition**: TCF adds value to low-value biomass, creating raw materials for high-demand products such as bio-based resins, polyols, and furan derivatives. These products have growing markets, particularly in industries aiming to lower their carbon footprint or meet sustainability targets.
3. **Scalability**: The flexibility of the rotating cone reactor has already been demonstrated on a commercial scale, the addition of an extraction unit has not.

4.1.2. Challenges and Hotspots at Industrial Scale

While TCF offers many advantages, several challenges and potential hotspots could arise as the process is scaled to an industrial level. These challenges span both environmental and economic domains and will need to be addressed to ensure the long-term sustainability and viability of TCF.

4.1.2.1. Environmental Challenges and Hotspots:

1. **Feedstock Variability**:
    1. **Challenge**: Biomass feedstocks vary widely in composition depending on their source, which can lead to inconsistencies in the yield and quality of bio-oil and other outputs. This variability can also affect the reactor's performance and energy efficiency.

    2. **Mitigation Strategy**: Standardizing the feedstock specifications, pretreating biomass before pyrolysis, or developing more robust reactor designs that can handle diverse feedstocks will be critical in overcoming this challenge. Additionally, local sourcing strategies could minimize transportation and variability in feedstock quality.
2. **Emissions Control**:
    1. **Challenge**: While TCF reduces emissions compared to fossil-based processes, the combustion of non-condensable gases and char could still lead to the release of pollutants, including particulate matter and CO_2.
    2. **Mitigation Strategy**: Installing advanced emissions control systems, such as filters or scrubbers, and using carbon capture technologies to sequester CO_2 from combustion streams could minimize the environmental impact at industrial scales.

4.1.2.2. Economic Challenges and Hotspots:

1. **Capital Expenditure**:
    1. **Challenge**: The applied pyrolysis technology (rotating cone) has already been demonstrated on a commercial scale, the addition of an extraction unit has not. The infrastructure for fractionation at industrial levels may require specialized materials and costs.
    2. **Mitigation Strategy**: Reducing capital costs can be achieved by optimizing fractionation design for cost-effective materials and improving efficiency to lower operational expenditures. Partnering with industrial stakeholders to share infrastructure costs may also help mitigate this economic barrier.
2. **Market Competitiveness of Bio-Based Products**:
    1. **Challenge**: The bio-based products derived from TCF raw materials, such as resins and polyols, must compete with well-established, often cheaper, fossil-based alternatives. Ensuring market penetration and competitive pricing will be a challenge.
    2. **Mitigation Strategy**: Supporting policies and incentives for bio-based products can help create a favorable market environment. Additionally, demonstrating superior performance and sustainability credentials (e.g., lower carbon footprint, non-toxicity) for TCF-derived products can attract industries seeking to meet sustainability goals.
3. **Supply Chain and Logistics**:
    1. **Challenge**: Ensuring a steady and cost-effective supply of biomass feedstock can be difficult, particularly if feedstocks are seasonal or geographically dispersed. Transportation of large biomass quantities to centralized processing plants can introduce significant costs and carbon emissions.
    2. **Mitigation Strategy**: Developing local and decentralized biomass sourcing strategies, where processing occurs close to the biomass source, can reduce transportation costs and emissions. This approach can also ensure a more stable and predictable supply of feedstock.

4.2. *Polyols and Polyurethanes*

4.2.1. Potential Environmental and Economic Benefits and Challenges

The transition to bio-based polyols and polyurethanes offers substantial environmental and economic benefits but also presents challenges that must be overcome to ensure successful industrial-scale adoption.

4.2.1.1. Environmental Benefits

1. **Reduced Carbon Footprint**:
    1. Bio-polyols are derived from renewable biomass, leading to a significant reduction in carbon emissions compared to fossil-derived polyols. The utilization of biochar and syngas by-products also contributes to overall energy efficiency.

2. **Sustainable Resource Use**:
    1. The production process valorizes low-value biomass residues, reducing the need for landfilling or incineration and promoting the circular economy.
3. **Lower Toxicity**:
    1. Bio-based polyols and their resulting polyurethanes exhibit lower toxicity, improving indoor air quality and reducing environmental pollution.

4.2.1.2. Economic Benefits

1. **Cost-Effective Raw Materials**:
    1. The use of low-cost biomass residues in the production of bio-polyols can lower the overall cost of polyol and polyurethane production in the long term.
2. **Market Demand for Green Materials**:
    1. The growing demand for sustainable and eco-friendly products, particularly in the construction and automotive industries, offers significant market opportunities for bio-polyols and bio-based polyurethanes.

4.2.2. Challenges and Industrial Hotspots

While bio-based polyols and polyurethanes offer numerous advantages, several challenges and potential hotspots exist at the industrial level.

4.2.2.1. Environmental Hotspots and Challenges

1. **Feedstock Variability**:
    1. **Challenge**: Variations in biomass composition can affect the efficiency and consistency of bio-polyol production, leading to fluctuating yields and product quality.
    2. **Mitigation**: Standardizing biomass feedstock specifications and pre-treatment processes will help ensure consistent quality.
2. **Energy-Intensive Hydrotreatment**:
    1. **Challenge**: The hydrotreatment stage requires significant energy input, which can increase the overall carbon footprint of the process.
    2. **Mitigation**: Optimizing the energy recovery systems and using renewable energy sources can reduce the energy demand of hydrotreatment.

4.2.2.2. Economic Hotspots and Challenges

1. **Production Costs**:
    1. **Challenge**: The cost of bio-polyol production, particularly at smaller scales, may initially be higher than traditional petrochemical polyols, which could limit market penetration.
    2. **Mitigation**: Scaling up production and improving process efficiencies through technology improvements will help reduce production costs.
2. **Catalyst Stability and Efficiency**:
    1. **Challenge**: Catalysts used in the hydrotreatment process can degrade over time, reducing their efficiency and necessitating frequent replacement.
    2. **Mitigation**: Research into advanced catalysts with longer lifespans and higher stability will be key to reducing catalyst-related costs.

4.3. Furan based chemicals

4.3.1. Potential Environmental and Economic Benefits and Challenges

The transition to furan-based chemicals presents significant environmental and economic benefits, but also comes with challenges at the industrial scale.

4.3.1.1. Environmental Benefits

1. **Reduction in Fossil-Based Chemical Use**:

    1. Furan-based chemicals, replace petroleum-derived solvents, reducing dependence on fossil fuels and lowering greenhouse gas emissions.
2. **Biodegradability**:
    1. These bio-based solvents are more biodegradable than their petroleum counterparts, leading to lower environmental toxicity and pollution.
3. **Valorization of Biomass**:
    1. Utilizing pyrolytic sugars from biomass residues ensures that the feedstock is renewable and sustainable, contributing to a circular economy.

4.3.1.2. Economic Benefits

1. **Cost Savings on Feedstock**:
    1. The use of biomass residues, which are often lower in cost compared to petroleum-based raw materials, provides a long-term economic advantage.
2. **High Market Demand for Green Solvents**:
    1. As industries move toward sustainability, there is growing demand for bio-based solvents. This opens up market opportunities, particularly in sectors like pharmaceuticals and agrochemicals.

4.3.2. Challenges and Industrial Hotspots

Scaling up the production of furan-based chemicals to an industrial level presents several challenges, particularly regarding feedstock variability, energy consumption, and market competitiveness.

4.3.2.1. Environmental Hotspots and Challenges

1. **Feedstock Variability**:
    1. **Challenge**: The sugar content in biomass varies significantly, affecting the efficiency of furan derivative production.
    2. **Mitigation**: Developing standardized feedstock specifications and pre-treatment techniques can help minimize variability and ensure consistent yields.
2. **Energy-Intensive processing**:
    1. **Challenge**: Further processing, which is energy-intensive, can increase the overall carbon footprint of furan-based chemical production if not optimized.
    2. **Mitigation**: The use of renewable energy sources for the process and improving energy recovery systems will be crucial for reducing the energy footprint.

4.3.2.2. Economic Hotspots and Challenges

1. **Production Costs**:
    1. **Challenge**: While furan-based chemicals have environmental benefits, their production costs may initially be higher than fossil-based alternatives.
    2. **Mitigation**: Economies of scale and technological improvements will be key to lowering production costs. Incentives for green chemicals will also make these products more competitive.

4.4. Engineered Wood Panels

4.4.1. Potential Environmental and Economic Benefits and Challenges

The transition to **bio-resins** for **engineered wood panels** provides both environmental and economic advantages, but it also presents challenges that need to be addressed to ensure successful industrial-scale implementation. This section discusses the potential benefits, challenges, and theoretical hotspots that could arise as the project scales up.

4.4.1.1. Environmental Benefits

1. **Reduction in Fossil-Based Chemical Use**:

    1. By replacing phenol with lignin and formaldehyde with HMF, the reliance on fossil-based chemicals is significantly reduced, leading to lower overall carbon emissions from the resin production process.
2. **Lower Toxicity**:
    1. The eventual replacement of **formaldehyde** with **HMF** creates a safer working environment for employees and reduces toxic emissions during the life cycle of MDF products. Formaldehyde, a known carcinogen, is a major environmental and health concern in conventional resin systems.
3. **Waste Valorization**:
    1. The integration of lignin, a product of biomass fractionation, into the resin system helps valorize what would otherwise be waste material, contributing to a more circular approach and reducing the environmental impact of disposal or incineration.

4.4.1.2. Economic Benefits

1. **Cost Savings from Biomass Utilization**:
    1. Utilizing lignin, a product of the fractionation process, to replace costly phenol in resin production offers potential savings in material costs. As lignin is abundant and renewable, its use in resins can help lower production costs over time.
2. **Market Differentiation and Demand**:
    1. The shift toward **bio-based products** aligns with growing market trends for sustainable materials, particularly in industries such as construction, where there is increasing demand for products with a lower carbon footprint. MDF panels made with bio-resins could command premium pricing and attract eco-conscious consumers.
3. **Energy Efficiency**:
    1. The energy required for MDF production can be reduced by optimizing the integration of renewable energy sources and improving the energy recovery systems within the production line. This will lower the operational costs of MDF production over time.

4.4.2. Challenges and Hotspots at Industrial Scale

Scaling up the production of MDF using **bio-resins** brings several challenges. Some of these are specific to the material properties of bio-resins, while others relate to operational efficiency at an industrial level. Several theoretical environmental and economic hotspots must be addressed to ensure the process is economically viable and environmentally sustainable.

4.4.2.1. Environmental Hotspots and Challenges

1. **Feedstock Variability**:
    1. **Challenge**: The lignin obtained from biomass varies in chemical composition depending on the type and source of biomass used. This variability can affect the performance and quality of the resulting bio-resins, particularly when aiming for a 100% phenol replacement.
    2. **Mitigation**: Developing advanced lignin pre-treatment or blending strategies will help standardize the quality of lignin entering the resin production process. Implementing quality control measures to assess lignin composition before use can minimize inconsistencies.
2. **Energy Consumption in Hot Pressing**:
    1. **Challenge**: The energy-intensive nature of the **hot pressing** stage, particularly when scaling up to industrial levels, can result in a large energy footprint. Without proper energy recovery and efficiency measures, this could diminish the overall environmental benefits.
    2. **Mitigation**: Integrating renewable energy sources such as solar or biomass-derived energy for the pressing and curing stages can offset this energy demand. Additionally, optimizing the hot pressing process to reduce cycle times and temperature requirements will help lower energy consumption.

3. **Emissions from Resin Curing**:
    1. **Challenge**: While the replacement of formaldehyde with HMF reduces harmful emissions, the curing process for bio-resins may still release volatile organic compounds (VOCs) or other emissions, depending on the lignin content and resin formulation.
    2. **Mitigation**: Employing advanced emission control systems, such as filtration and scrubbing technologies, will help capture and neutralize these emissions. Monitoring VOC levels during production and optimizing resin formulations for lower emissions can also help mitigate this hotspot.

4.4.2.2. Economic Hotspots and Challenges

1. **Cost of Lignin Pre-Treatment**:
    1. **Challenge**: To ensure lignin is compatible with resin formulations, pre-treatment steps such as drying, purification, or chemical modification may be required. These additional steps could increase production costs, particularly at an industrial scale.
    2. **Mitigation**: Streamlining the lignin extraction and pre-treatment processes, or co-locating bio-resin production facilities near lignin suppliers, could help minimize transportation and pre-treatment costs. Further research into cost-effective pre-treatment methods will also be critical.
2. **Material Substitution and Compatibility**:
    1. **Challenge**: While lignin can replace a significant portion of phenol in resins, complete substitution may alter the mechanical properties of the final MDF product. Ensuring that the bio-resins meet the required performance standards for strength and durability remains a key challenge.
    2. **Mitigation**: Ongoing R&D into resin formulation, particularly around lignin compatibility, will be crucial to achieving a balance between cost savings, environmental impact, and material performance. Collaborating with material scientists and industrial partners will help optimize these formulations for industrial application.
3. **Supply Chain and Biomass Availability**:
    1. **Challenge**: As bio-resin production scales up, ensuring a consistent and cost-effective supply of biomass (and therefore lignin) may present logistical challenges. Biomass availability may vary seasonally or geographically, impacting the reliability of lignin supply.
    2. **Mitigation**: Developing a robust supply chain with multiple biomass suppliers will ensure a consistent feedstock. Implementing biomass storage solutions and creating long-term supply contracts with biomass producers will also help stabilize the lignin supply chain.

4.5. Modified woods

4.5.1. Potential Environmental and Economic Benefits and Challenges

The use of bio-based agents for wood modification offers significant environmental and economic advantages but also presents challenges, particularly when scaling up production for industrial applications.

4.5.1.1. Environmental Benefits

1. **Reduced Use of Toxic Chemicals**:
    1. The use of bio-based agents derived from FPBO eliminates the need for harmful chemicals like creosote, thus reducing environmental pollution and health risks.
2. **Sustainable Resource Use**:
    1. Modified wood extends the lifespan of wood products, reducing the need for frequent replacements. This, in turn, conserves resources and reduces waste.
3. **Valorization of Biomass**:

    1. The bio-based agents used in wood modification are derived from biomass residues, promoting waste valorization and contributing to the circular economy.

4.5.1.2. Economic Benefits

1. **Cost Savings**:
    1. Utilizing low-cost biomass residues for producing bio-based agents reduces overall material costs, making the wood modification process more economically viable.
2. **Market Demand for Sustainable Products**:
    1. With growing demand for eco-friendly construction materials, modified wood products offer a competitive advantage in the market, especially for sustainable building projects.

4.5.2. Challenges and Industrial Hotspots

Several challenges must be addressed to ensure the industrial-scale production of modified woods remains viable, particularly in terms of process consistency, feedstock variability, and market acceptance.

4.5.2.1. Environmental Hotspots and Challenges

1. **Feedstock Variability**:
    1. **Challenge**: Variations in wood species and moisture content can affect the consistency and effectiveness of the modification process.
    2. **Mitigation**: Standardizing raw material specifications and optimizing process parameters will ensure consistent quality across different wood types.
2. **Energy-Intensive Drying and Curing**:
    1. **Challenge**: The drying and curing stages are energy-intensive, potentially increasing the overall carbon footprint of the process.
    2. **Mitigation**: Integrating renewable energy sources and optimizing the energy recovery systems during these stages will help reduce the environmental impact.

4.5.2.2. Economic Hotspots and Challenges

1. **Cost of Bio-Based Agents**:
    1. **Challenge**: Bio-based agents can be more expensive than conventional chemicals, impacting the cost-effectiveness of modified wood.
    2. **Mitigation**: Scaling up production and improving the efficiency of bio-based agent synthesis will help reduce costs.
2. **Market Acceptance**:
    1. **Challenge**: Gaining acceptance for bio-based modified wood products in markets traditionally dominated by conventional wood treatments can be challenging.
    2. **Mitigation**: Demonstrating the superior performance and environmental benefits of modified wood through pilot projects and case studies will facilitate market acceptance.

4.6. Wastewater treatments

4.6.1. Potential Environmental and Economic Benefits and Challenges

The water treatment processes offer both environmental and economic benefits but also present challenges, especially as they scale up to industrial levels.

4.6.1.1. Environmental Benefits

1. **Reduced Wastewater Discharge**:
    1. Effective treatment enables the reuse of effluent, reducing the volume of wastewater discharged into the environment and lowering the project’s water footprint.
2. **Biogas Production**:
    1. The anaerobic process generates biogas with a high methane content, which can be used for energy recovery, lowering the overall energy consumption of the process.

3. **Nutrient Recovery**:
    1. Nutrients like nitrogen and phosphorus can be recovered and reused, reducing the need for external inputs and minimizing nutrient-related pollution.

4.6.1.2. Economic Benefits

1. **Cost Savings from Biogas Utilization**:
    1. The biogas generated from the anaerobic treatment can be converted into heat and electricity through CHP units, offsetting operational energy costs.
2. **Reduced Environmental Compliance Costs**:
    1. By meeting stringent wastewater discharge limits, the project can avoid potential fines and reduce the need for expensive post-treatment technologies.

4.6.2. Challenges and Industrial Hotspots

Several environmental and economic challenges must be addressed to ensure the viability of water treatment at industrial scale.

4.6.2.1. Environmental Hotspots and Challenges

1. **High Energy Consumption for Aeration**:
    1. **Challenge**: The aerobic post-treatment requires significant energy for aeration, potentially increasing the carbon footprint of the process.
    2. **Mitigation**: Energy recovery from biogas, combined with the use of renewable energy sources for aeration, will help reduce the process's energy demand.
2. **Sludge Handling**:
    1. **Challenge**: Both anaerobic and aerobic treatments generate sludge that requires handling, disposal, or further treatment, adding to operational complexity.
    2. **Mitigation**: Implementing efficient sludge dewatering and exploring options for sludge valorization (e.g., as fertilizer) can reduce handling costs and environmental impact.

4.6.2.2. Economic Hotspots and Challenges

1. **Capital Investment for Treatment Infrastructure**:
    1. **Challenge**: Scaling up the water treatment system, including reactors, pumps, and aeration systems, requires significant capital investment.
    2. **Mitigation**: Cost-sharing with industrial partners and government subsidies for green technologies could help lower upfront costs.
2. **Nutrient and Chemical Costs**:
    1. **Challenge**: The addition of nutrients and chemicals (such as urea, phosphoric acid, and trace elements) to maintain optimal microbial activity in the reactors can be costly.
    2. **Mitigation**: Optimization of nutrient dosing and recycling strategies will help reduce ongoing operational costs.

5. Next Steps

As the NewWave project progresses, several key actions must be undertaken to complete the comprehensive evaluation of environmental and economic sustainability across all manufacturing lines. These next steps will ensure the accuracy and effectiveness of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis and provide a solid foundation for further scaling the processes involved.

5.1. *Completion of Data Collection*

The first priority is to finalize the collection of operational data across all processes and manufacturing lines. This step is critical to establishing an accurate baseline for both LCA and LCC assessments. The focus will be on:

- **Collecting data** related to material inputs, energy consumption, emissions, and waste for each of the manufacturing lines (e.g., polyols, furan-based chemicals, bioresins, and modified wood).
- **Refining data** for any process stages where gaps or inconsistencies exist, especially regarding energy consumption, by-products, and material yields.
- **Confirming the scalability** of the data, ensuring that the figures represent both lab-scale and industrial-scale operations.

5.1.1. Scale-Up Simulations

Once the data collection is complete, the next step is to perform simulations to assess the performance of the manufacturing processes at an industrial scale. This involves:

- **Modeling and simulating the scale-up** of the Thermochemical Fractionation (TCF) process, polyols production, furan-based chemicals, and wood modification and panels to ensure that efficiencies are maintained or improved as production scales.
- **Identifying operational bottlenecks** that could emerge during scale-up and proposing solutions to overcome these barriers.
- **Validating the energy recovery systems** and other key operational components to ensure that they remain effective at higher production volumes.

5.2. *Life Cycle Assessment (LCA) and Life Cycle Costing (LCC)*

With all data collected and scale-up simulations complete, the project will proceed with detailed LCA and LCC evaluations:

- **Performing a full LCA analysis** for each manufacturing line, examining the environmental impacts at each stage of the life cycle, from raw material sourcing to production, and end-of-life treatment. This will include evaluating greenhouse gas emissions, resource depletion, water usage, and waste generation.
- **Conducting LCC evaluations**, focusing on the total cost of production, operational expenses, and end-of-life costs for each line. This will include sensitivity analyses to account for market fluctuations, feedstock prices, and technological improvements.
- **Benchmarking environmental and economic performance** against traditional, fossil-based production systems to demonstrate the potential advantages of bio-based alternatives.

5.3. *Hotspot Identification*

An integral part of the LCA and LCC analyses is the identification of environmental and economic hotspots—stages in the production process with disproportionately high impacts:

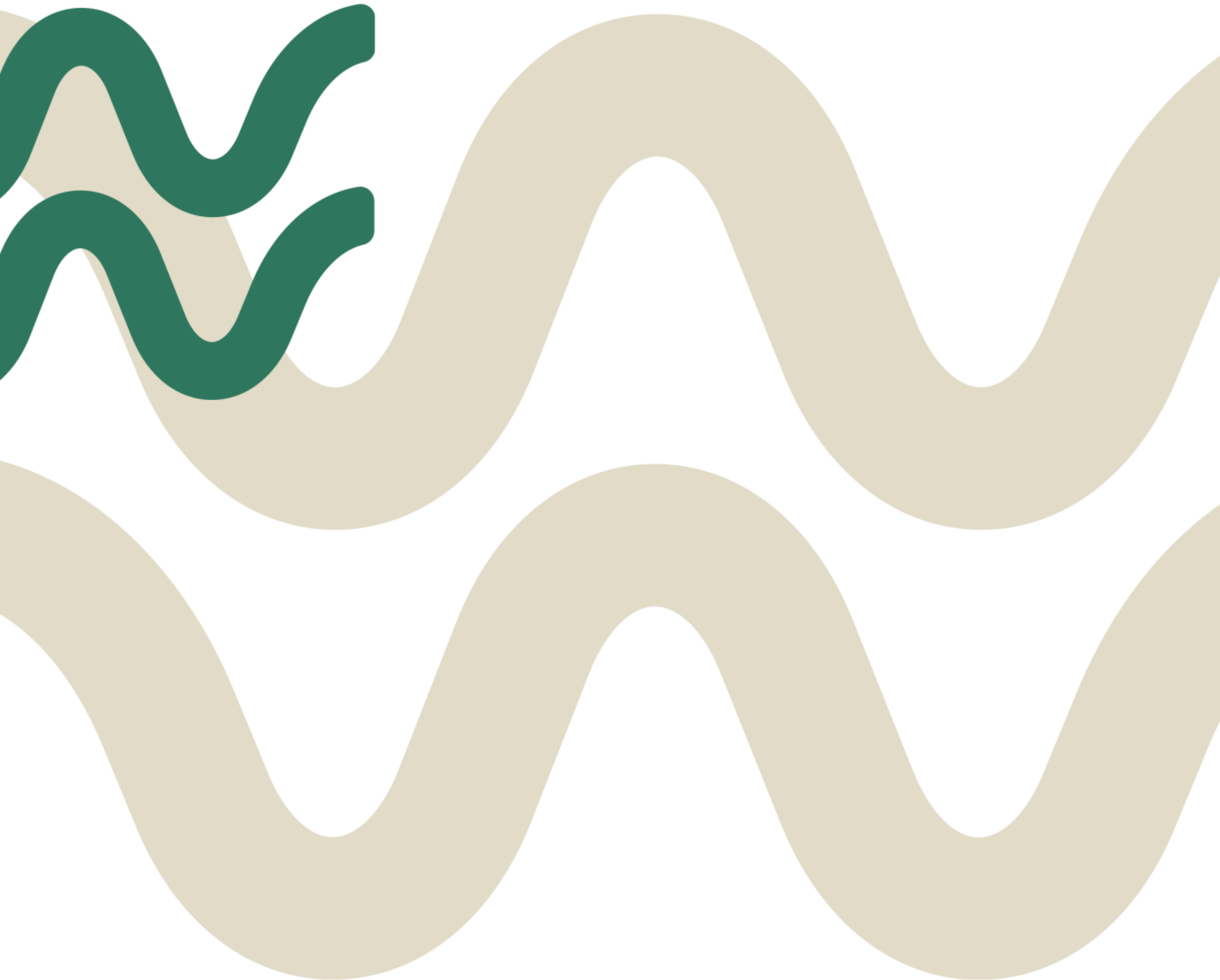
- **Identifying environmental hotspots**, such as energy-intensive stages (e.g. hydrogenation, aeration), emissions from combustion or curing, and water or nutrient requirements in water treatment.
- **Recognizing economic hotspots**, including high operational costs due to energy consumption, material variability, or supply chain challenges.
- **Mapping interdependencies** between environmental and economic hotspots to address areas where improvements in environmental performance may also result in cost savings.

5.3.1. Mitigation and Improvement Strategies

Once hotspots are identified, the final step will be to develop strategies to mitigate their impacts and improve overall process sustainability. This will involve:

- **Implementing energy efficiency measures**, particularly in processes such as curing, hot pressing, hydrogenation, and aeration. Integrating renewable energy sources or optimizing recovery systems will be key.
- **Reducing feedstock variability** by developing pre-treatment standards and improving biomass sourcing strategies to ensure consistent process yields and quality.
- **Optimizing operational costs** by researching new technologies or catalysts to reduce energy demand, extend catalyst life, and minimize material costs.
- **Exploring circular economy opportunities**, such as reusing waste streams (e.g., sludge valorization).

NewWave



Funded by
the European Union

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101058369