WOOD2WOOD

A Wood-to-Wood Cascade Upcycling Valorisation Approach

» Deliverable 4.3

Recycled Wood Cascade Valorisation Framework

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RE	Restricted to a group specified by the consortium	
CO	Confidential, only for members of the consortium (including the European Commission Services)	

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GLOSSARY OF ACRONYMS

Acronym	Extended Definition
CDW	Construction and Demolition Waste
CHP	Combined Heat and Power
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVFP	Cascade Valorisation Framework Potential
HTC	Hydrothermal Carbonisation
H_2	Hydrogen
CH_4	Methane
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
NO_x	Nitrogen Oxides
N_2	Nitrogen
SCR	Selective Catalytic Reduction
SNT	Synthetic Natural Gas
SO_x	Sulphur Oxides
WtE	Waste-to-Energy
W2W	Wood2Wood

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EXECUTIVE SUMMARY

This deliverable addresses Task 4.3 of the W2W project, focusing on the development of a cascade valorisation framework for recycled wood from construction and demolition waste (CDW) applicable to both pure and mixed treatment processes. The study comprehensively outlines the various wood valorisation approaches currently available, alongside additional aspects that were researched and analysed for effective framework design and development.

The first section of the document offers a thorough review of all wood waste valorisation techniques, irrespective of the wood's origin. It highlights both the advantages and challenges associated with the application of each approach. Additionally, the section examines landfill and incineration practices for wood waste, emphasizing their significant adverse environmental impacts. A comparative analysis of these technologies is also included, demonstrating that the selection of the most suitable method for treating and recycling wood waste requires careful consideration of multiple parameters, which are explored in depth in the second section of the report.

The second part focuses on the framework design, detailing the various elements involved and the criteria for their selection. It outlines the methodology employed to develop a wood waste valorisation framework that is effective, scalable, and maintainable, ensuring it meets user needs and can adapt to future changes.

Finally, the last section evaluates the framework using real data from Greece, covering the period from 2010 to 2020. It discusses the main conclusions drawn from the research, addresses the challenges encountered, and outlines the strategies implemented to overcome these obstacles. The section concludes with a presentation of the future steps for ongoing research in this area.

1. INTRODUCTION

1.1. Scope of the Study

This study seeks to develop a comprehensive framework for wood valorisation, designed to facilitate the selection of appropriate valorisation technologies based on the availability and characteristics of wood feedstock. This framework will also serve as a foundational tool for evaluating all innovative wood valorisation processes and technologies developed throughout the W2W project.

The W2W wood waste cascade valorisation framework is intended to assess potential valorisation pathways for wood waste derived from construction and demolition activities (CDW) and furniture waste. By providing a systematic approach, the framework will assist decision-makers in identifying the optimal valorisation pathway across various parameters. This optimization is expected to yield multiple benefits, including reduced environmental impacts, significant cost savings, and minimized material transportation times.

In developing the framework, the characteristics of available wood feedstock were meticulously investigated to determine the most suitable valorisation pathways for waste wood. Additionally, various criteria were evaluated, including the balance of supply and demand, life cycle assessment (LCA) results, logistics optimization, and supply chain management, all aimed at maximizing recovery potential. The framework incorporates technologies for treating and upcycling both pure and mixed wood, integrating identified supplementary elements and impact variables to enhance resource recovery.

To evaluate the functionality of the framework, actual data from Greece was employed, providing a practical basis for assessment. It is important to note that the development and implementation of the framework will continue as part of the W2W project, culminating in WP15. This phase will include the validation and sustainability evaluation of the entire cascade valorisation scheme, as detailed in W2W Deliverable D15.2.

1.2. State of Art and Wood Upcycling Approaches

1.2.1. Current situation & challenges in wood recycling

The current landscape of wood recycling presents a complex interplay of opportunities and challenges as industries increasingly aim to address sustainability demands. Despite wood being one of the most recyclable natural materials, its recycling rates are notably lower than those of metals or plastics. A significant proportion of post-consumer wood waste is still disposed of in landfills in many regions, primarily due to factors such as contamination, the mixed composition of materials, and insufficient infrastructure for effectively managing diverse wood waste streams. The rising prevalence of composite wood products, including plywood and particleboard, which combine wood fibres with adhesives and other materials, exacerbates these challenges. These composites complicate recycling processes, making it difficult to retrieve pure, reusable wood (Pazzaglia and Castellani, 2023).

A major challenge in wood recycling lies in the logistical and economic barriers that hinder the widespread adoption of efficient recycling practices. The processes of collecting, sorting, and processing wood waste are labour-intensive and costly, particularly when dealing with contaminated or treated wood, which may contain hazardous chemicals such as paints, preservatives, or glues. These materials often necessitate specialized handling procedures, which can render recycling economically unfeasible. Furthermore, the absence of standardized methods for processing and classifying recycled wood complicates its integration into new products, thereby limiting market growth for recycled wood materials. The industry is also confronted with technological limitations, including the urgent need for improved sorting techniques and enhanced detection systems for hazardous substances (Garcia and Hora, 2017). Addressing these challenges is crucial for enhancing the sustainability of wood recycling and maximizing the potential of this valuable resource.

1.2.2. Technologies for treating and recycling wood

Wood waste constitutes a significant by-product across various industries, including construction, demolition, furniture manufacturing, and forestry. The effective management and recycling of this waste are essential for minimizing environmental impacts and maximizing resource recovery. A diverse array of technologies is available for the treatment and recycling of wood waste, each with its unique strengths and applications. The primary methods include mechanical recycling, which involves physically processing wood into reusable forms; remediation techniques that address contamination issues; and advanced thermal processes such as pyrolysis and gasification, which convert wood waste into energy and valuable by-products. Additionally, incineration is utilized to generate energy, albeit with associated environmental concerns, while landfilling remains a common endpoint for wood waste in areas lacking sufficient recycling infrastructure. Understanding these technologies is crucial for promoting sustainable practices in wood waste management and enhancing overall resource efficiency.

1.2.2.1 Mechanical Recycling

Mechanical recycling is a critical method for managing wood waste, providing an environmentally friendly and economically viable way to repurpose clean, untreated wood into valuable raw materials for new products. This approach is primarily cantered around the physical processing of wood waste, which involves a series of mechanical steps such as chipping, shredding, grinding, and milling to reduce the wood into smaller particles. The processed wood can then be utilized in the production of various products, including particleboards, medium density fibreboards (MDF), mulch, wood pellets, and biofuels.

Key Mechanical Recycling Processes

- **Chipping:** the first step of mechanical recycling, where large pieces of wood waste, such as logs, branches, or offcuts, are fed into a chipper machine that reduces them into smaller, uniform wood chips. This process is commonly used in the timber, landscaping, and biomass energy sectors. (Cocchi, Vargas and Tokacova 2018).
- **Shredding:** the process of breaking down wood waste into smaller, irregular pieces. Shredders are versatile and can handle various types of wood, including pallets, construction debris, and bulky wood items. They are also equipped with one or more magnetic rollers enabling the removal of the ferrous. Shredding is crucial for preparing

wood waste for further processing or direct use in applications like mulch or biomass fuel. (Cocchi, Vargas and Tokacova 2018).

- **Grinding and Milling:** Grinding and milling further reduce wood particles to finer sizes suitable for specific applications, such as the production of wood flour, sawdust, or fibres for composite boards. These processes are essential for producing uniform particles needed in industries like MDF and particleboard manufacturing.
- **Screening and Sorting:** After chipping, shredding, or grinding, the wood particles are screened and sorted to ensure uniformity in size and to remove any non-wood contaminants, such as nails, stones, or plastics. Proper screening is crucial for the quality of the final product (Cocchi, Vargas and Tokacova 2018).
- **Pelletizing:** involves compressing finely ground wood particles into dense, uniform pellets, which are commonly used as a renewable energy source in heating and power generation. Wood pellets are a popular product of mechanical recycling, particularly in regions focused on biomass energy.

Applications of Mechanically Recycled Wood

Mechanical recycling of wood waste produces various end products that serve different industries. Some of the key applications include:

- **Particleboards and MDF:** The most common use of mechanically recycled wood is in the production of particleboards and MDF. These engineered wood products are widely used in furniture manufacturing, construction, and cabinetry. By using recycled wood, manufacturers can reduce the need for virgin timber, promoting sustainable forestry practices.
- **Wood Mulch and Landscaping Materials:** Chipped and shredded wood is often used as mulch in landscaping, gardening, and erosion control. Wood mulch helps retain soil moisture, suppress weeds, and improve soil fertility. It also serves as a decorative ground cover in gardens and parks.
- **Biofuels and Biomass Energy:** Ground wood waste can be used directly as a feedstock for biomass power plants or further processed into pellets for use as a renewable energy source in heating systems. This application helps reduce reliance on fossil fuels and supports the circular economy by converting waste into energy.
- **Animal Bedding:** Shredded wood is commonly used as bedding material for livestock and pets. It provides a comfortable and absorbent base for animals and is easy to handle and dispose of, often being composted after use.
- **Composites and Wood-Plastic Products:** Fine wood particles, such as sawdust and wood flour, are used in manufacturing wood-plastic composites, which are employed in decking, fencing, and other building materials. These composites combine the benefits of wood and plastic, offering durability, moisture resistance, and aesthetic appeal.

Challenges and Limitations of Mechanical Recycling

While mechanical recycling offers numerous benefits, it also faces challenges, particularly when dealing with treated or contaminated wood waste:

- **Chemical Contaminants:** Mechanical processes struggle to handle chemically treated wood, such as painted, stained, or pressure-treated wood. During processing, these contaminants can be released into the environment or degrade the quality of the recycled product. Additional treatments, such as remediation or thermal processing, are often required to safely manage these types of wood waste.

- **Equipment Wear and Maintenance:** The mechanical nature of chipping, shredding, and grinding exposes equipment to significant wear and tear, particularly when processing dense or contaminated wood. Frequent maintenance and replacement of cutting parts can increase operational costs.
- **Particle Size Uniformity:** Consistency in particle size is crucial for producing high-quality end products, especially in MDF and particleboard manufacturing. Variations in particle size can affect the structural properties and appearance of the final product, necessitating careful screening and sorting.
- **Energy Consumption:** Mechanical recycling processes, particularly grinding and pelletizing, can be energy intensive. The energy required to operate large chippers, grinders, and pellet mills must be balanced against the environmental and economic benefits of recycling.

Mechanical recycling remains a foundational technology in the management of wood waste, offering a straightforward and cost-effective approach to converting clean, untreated wood into valuable products. Through processes such as chipping, shredding, grinding, and pelletizing, mechanical recycling supports the circular economy by reducing waste, conserving natural resources, and providing sustainable materials for various industries. However, its limitations in handling contaminated wood highlight the need for integrated waste management strategies that combine mechanical recycling with advanced technologies like remediation, pyrolysis, and gasification. As innovations in equipment and processing techniques continue to evolve, mechanical recycling will play an increasingly important role in sustainable wood waste management.

1.2.2.2. Remediation

Remediation plays a crucial role in managing contaminated wood waste, which includes wood treated with preservatives, paints, heavy metals, or other hazardous chemicals. Such contamination can pose significant environmental and health risks, making the proper treatment of this type of wood waste essential before it can be safely reused, recycled, or disposed of. Remediation technologies employ a range of physical, chemical, and biological processes to remove or neutralize contaminants, ensuring that treated wood does not release harmful substances into the environment during subsequent use or disposal.

Key Remediation Processes for Contaminated Wood

- **Physical Remediation:** involves the use of physical processes to separate, isolate, or remove contaminants from wood. These methods are generally the first step in treating contaminated wood and are often used in conjunction with chemical or biological treatments to enhance overall effectiveness (Xing, et al. 2020).
- **Chemical Remediation:** involves the use of chemical agents to break down, neutralize, or extract hazardous substances from contaminated wood. These methods are effective for treating deeply embedded contaminants, including heavy metals, preservatives, and organic pollutants (da Costa, et al. 2022).

- **Biological Remediation (Bioremediation):** leverages the natural abilities of microorganisms, fungi, or plants to break down or absorb contaminants in wood waste. This approach is environmentally friendly and can be highly effective for certain types of contaminants, particularly organic compounds.
- **Advanced Remediation Techniques:** A combination of multiple treatment methods or utilization of innovative technologies to enhance the effectiveness of contaminant removal. These methods are particularly useful for dealing with complex or highly contaminated wood waste (Xing, et al. 2020).

Applications of Remediated Wood

Once treated, remediated wood can be safely reused or disposed of, reducing the environmental impact and recovering valuable materials (McMahon, et al. 2008). Key applications of remediated wood include:

- **Reuse in Construction and Manufacturing:** Wood that has been effectively remediated can be reused in construction, furniture manufacturing, or as a raw material for engineered wood products like particleboard and MDF. Reusing remediated wood helps reduce the demand for virgin timber and promotes sustainable resource management.
- **Energy Recovery:** Remediated wood that meets safety standards can be used as a fuel source in biomass power plants or converted into biochar, pellets, or syngas through processes like pyrolysis and gasification. Using remediated wood for energy recovery prevents waste and reduces greenhouse gas emissions compared to traditional fossil fuels.
- **Soil Amendments and Composting:** In cases where contaminants have been effectively neutralized, remediated wood can be chipped and used as mulch or a component in composting operations. This application not only helps improve soil quality but also contributes to waste reduction.
- **Safe Disposal in Landfills:** For heavily contaminated wood that cannot be fully remediated, stabilization processes can reduce the mobility of hazardous substances, allowing the wood to be safely disposed of in landfills that meet environmental protection standards. This approach minimizes the risk of leaching and environmental contamination.

Challenges and Limitations of Remediation

Despite the benefits, remediation of contaminated wood faces several challenges:

- **Complexity and Cost:** Remediation processes are often complex, requiring specialized equipment, skilled operators, and careful monitoring. The cost of remediation can be high, especially for heavily contaminated wood, which may require multiple treatment steps or advanced technologies.
- **Time-Consuming:** Some remediation methods, particularly biological processes, can be slow, taking weeks or months to achieve desired contaminant reductions. This time requirement can be a barrier in situations where quick treatment is needed to manage large volumes of wood waste.
- **Incomplete Contaminant Removal:** Not all remediation methods are effective for all contaminants. For example, physical washing may remove surface-level pollutants but fail to address deep-seated chemical treatments. Additionally, some methods may leave behind residual contaminants that still pose environmental risks.

- **Secondary Waste Generation:** Some remediation processes, such as chemical treatments and thermal desorption, generate secondary waste streams that require further management. These wastes, which may include contaminated water, air emissions, or chemical residues, can complicate the overall treatment process and increase costs.
- **Environmental and Health Risks:** Handling and treating contaminated wood poses risks to workers and the environment, especially when dealing with volatile chemicals or toxic metals. Proper safety measures, protective equipment, and environmental controls are essential to prevent exposure and contamination during remediation.

Remediation is a vital component of sustainable wood waste management, especially for treated and contaminated wood that cannot be directly recycled or disposed of. By employing a range of physical, chemical, and biological technologies, remediation can effectively neutralize hazardous substances, enabling wood to be safely reused, recycled, or disposed of. However, the complexity, cost, and challenges associated with remediation highlight the need for careful planning and the integration of advanced technologies to optimize treatment outcomes. As the push for greener waste management solutions grows, innovations in remediation techniques will play an increasingly important role in managing the environmental impacts of contaminated wood waste.

1.2.2.3. Thermochemical treatment processes

Hydrothermal Carbonization (HTC)

Hydrothermal Carbonization (HTC) is a thermochemical process that converts wet biomass, such as wood waste, into a carbon-rich solid product known as hydrochar. This process occurs under relatively mild temperature conditions in the presence of water, making it an efficient method for handling high-moisture feedstocks. HTC is particularly advantageous for biomass that is difficult to dry, such as wood waste, and is seen as a promising technology for producing hydrochar and other valuable products.

Process Overview

Unlike other thermochemical processes, HTC can handle biomass with high moisture content (50-90%) without requiring pre-drying. The reactor is heated to temperatures between 180-250°C, and pressures range from 10-40 bar. The process typically takes place over 1 to 12 hours, depending on the desired product characteristics. Under these conditions, water acts as both a solvent and reactant. The heat and pressure cause the biomass to undergo hydrolysis, decarboxylation, dehydration, and polymerization reactions, leading to the formation of a carbon-rich solid, along with liquid and gaseous by-products. After the reaction is complete, the reactor is cooled, and the pressure is gradually released. The resulting mixture consists of hydrochar, process water, and small amounts of gases. HTC reactors are coupled with solid-liquid separation unit for recovery of the hydrochar, process-water treatment and gas recovery unit (Alves, et al. 2021).

Advantages of HTC:

- **Handling of Wet Biomass:** suitable for wet biomass, such as wood waste with high moisture content, without requiring energy-intensive drying processes.
- **Energy Efficiency:** operation at relatively low temperatures and pressures, leading to lower energy consumption compared to other thermochemical processes.
- Challenges and Limitations of HTC:

- **Process Water Management:** The process water generated during HTC contains organic acids and other solubilized compounds, which require treatment before disposal.
- **High initial capital investment and complex operation:** The need for high-pressure reactors and the associated safety systems makes HTC more complex and costly to implement than some other biomass conversion technologies.

Hydrothermal Carbonisation (HTC) is a valuable process for converting wood waste into useful products, particularly when dealing with high-moisture biomass. It offers several advantages, including energy efficiency, versatility in product applications, and reduced emissions. However, the process also presents challenges, such as high capital costs, process water management, and scale-up difficulties.

Torrefaction

Torrefaction pertains to a thermal pretreatment of biomass where raw biomass is heated in an inert atmosphere at temperatures of 200–300 °C. This process removes moisture and volatiles, resulting in a product with enhanced energy density, better grindability, and improved storage properties. The primary product of torrefaction is a solid material known as torrefied wood or bio-coal, which can be used as a high-quality fuel or feedstock for further processing (Chen, et al. 2015).

Advantages of Torrefaction

- **Carbon Sequestration:** Through the production of biochar, pyrolysis captures carbon from wood waste in a stable form that can be stored in soils, reducing the overall carbon footprint and helping mitigate climate change.
- **Waste volume reduction:** Wood waste is densified through torrefaction resulting in reduced volume and more cost-effective transport.
- **Enhanced product quality:** Torrefied wood waste (biochar) has increased energy density and improved grindability compared to untreated wood waste.

Challenges and limitations of Torrefaction

- **High initial capital and operational costs:** Torrefaction reactors require significant capital investment and advanced process control technologies.
- **Handling of gaseous by-products:** The release of VOCs and non-condensable gases during torrefaction of contaminated wood waste can pose environmental concerns if not properly managed.

Torrefaction of wood waste is a promising technology for improving the energy properties of treated biomass. The process enhances the energy density, grindability, and storage characteristics of wood waste, making it suitable for various applications, including co-firing in power plants and use as a feedstock for gasification. However, technology also presents challenges, including high energy and capital costs, emission management, and product variability.

Pyrolysis

Pyrolysis is an advanced thermochemical process that decomposes wood waste in the absence of oxygen, breaking down the organic materials into three primary products: biochar (solid), bio-oil (liquid), and syngas (gaseous). This versatile technology can handle a wide range of wood waste, including contaminated, mixed, or treated wood that is unsuitable for other recycling methods. By converting wood into valuable by-products, pyrolysis provides significant environmental and economic benefits, making it a key technology in sustainable wood waste management. The process not only generates renewable energy sources but also contributes to carbon sequestration through the production of biochar, enhancing soil health and reducing greenhouse gas emissions (Khodaei, et al. 2022).

Process Overview for Wood Waste

Pyrolysis processes vary in terms of operating conditions, products generated, and their applications. The main types of pyrolysis used for wood waste include slow pyrolysis, fast pyrolysis, and flash pyrolysis, each optimized for different outputs and uses.

- **Slow Pyrolysis:** operates at moderate temperatures (around 400–600°C) with long residence times, typically minutes to hours. This method focuses on maximizing the production of biochar, a stable, carbon-rich product used as a soil amendment and carbon sequestration tool (Khodaei, et al. 2022).
- **Fast Pyrolysis:** operates at higher temperatures (450–600°C) with very short residence times (typically less than 2 seconds), maximizing the production of bio-oil, a liquid biofuel that can be used as a renewable energy source or refined into valuable chemicals.
- **Flash Pyrolysis:** an extreme form of fast pyrolysis, operating at very high temperatures (up to 1,000°C) with residence times measured in milliseconds. This method aims to maximize the production of syngas, a versatile energy carrier that can be used for power generation, heating, or as a feedstock for chemical synthesis.

Advantages of Pyrolysis

Pyrolysis offers several environmental advantages over traditional wood disposal methods, such as incineration or landfilling:

- **Carbon Sequestration:** Through the production of biochar, pyrolysis captures carbon from wood waste in a stable form that can be stored in soils, reducing the overall carbon footprint and helping mitigate climate change.
- **Reduced Emissions:** Compared to direct combustion, pyrolysis generates significantly fewer pollutants, such as particulate matter, sulphur oxides, and nitrogen oxides. This makes pyrolysis a cleaner option for energy recovery from wood waste.
- **Handling of Contaminated Wood:** Pyrolysis can process treated and contaminated wood without releasing hazardous chemicals into the environment. Contaminants are often sequestered in the biochar or broken down during the high-temperature process, allowing safer handling and disposal.
- **Waste Volume Minimization:** By converting wood waste into valuable products, pyrolysis reduces the volume of waste destined for landfills, contributing to more sustainable waste management practices.

Challenges and Limitations of Pyrolysis

Despite its benefits, pyrolysis faces several challenges that need to be addressed to optimize its application for wood waste management:

- **High Capital Investment:** Pyrolysis systems require significant upfront capital investment in equipment, infrastructure, and safety measures. This high cost can be a barrier to adoption, particularly for smaller operations or municipalities.
- **Operational Complexity:** Pyrolysis requires precise control of temperature, residence time, and feedstock properties to achieve optimal product yields. This operational complexity necessitates skilled operators and advanced monitoring systems, increasing operational costs.
- **Feedstock Preparation:** To ensure efficient pyrolysis, wood waste must be properly prepared, often requiring drying and size reduction. High moisture content can reduce process efficiency and lower the quality of bio-oil and syngas.
- **Product Quality Variability:** The quality and composition of biochar, bio-oil, and syngas can vary depending on the type of wood waste and pyrolysis conditions. This variability can affect the marketability of the products and necessitate further processing or refining.
- **Handling of By-Products:** Although pyrolysis is a relatively clean process, it can still produce by-products such as tars, particulates, and acidic components in bio-oil that require careful handling and disposal.

Pyrolysis stands out as a highly versatile and environmentally beneficial technology for managing wood waste, converting it into valuable products that contribute to energy production, carbon sequestration, and pollution remediation. Its ability to process a wide range of wood types, including contaminated and mixed wood, makes it an attractive option for both industrial and municipal waste management. However, the challenges associated with high capital costs, operational complexity, and product variability highlight the need for ongoing research, technological innovation, and supportive policy frameworks to fully unlock the potential of pyrolysis in sustainable wood waste management. As the demand for renewable energy and carbon management solutions grows, pyrolysis is expected to play an increasingly critical role in the transition towards a circular and sustainable economy (Khodaei, et al. 2022).

Gasification

Gasification is an advanced thermochemical process that converts organic materials, such as wood waste, into a valuable product known as syngas. This process occurs in an oxygen-limited environment, where the organic material undergoes partial oxidation at elevated temperatures, typically ranging from 700°C to 1,400°C. Unlike combustion, which requires complete oxidation, gasification allows for the breakdown of the biomass into a mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and smaller quantities of other gases like carbon dioxide (CO_2) and nitrogen (N_2). The resulting syngas, or synthesis gas, is a versatile energy carrier that can be used for a variety of applications.

Process Overview

Gasification consists of several stages:

- **Drying:** Wood waste often contains significant moisture, particularly fresh or untreated waste. During the drying stage, heat is applied to evaporate water from the biomass, reducing its moisture content to a manageable level. Although gasification can handle wood waste with relatively high moisture content (up to 60%), excess moisture can reduce overall process efficiency.

- **Pyrolysis:** After drying, the biomass undergoes pyrolysis, where it is heated in the absence of oxygen. In this phase, the solid biomass decomposes into volatile gases, tar, and solid char. The gas and tar can be further processed, while the char is primarily composed of carbon and ash.
- **Partial Oxidation:** In this critical phase, a controlled amount of oxygen, steam, or air is introduced to allow the gasification reactions to occur. Partial oxidation creates an environment that promotes the breakdown of carbon-based molecules into CO, H_2, and other gases rather than fully oxidizing them into CO_2. The heat generated from these reactions sustains the high temperature necessary for gasification.
- **Reduction:** The gases produced during oxidation undergo further reactions in a reduction zone, where carbon dioxide and water vapor react with the remaining solid carbon (char) to produce additional CO and H_2 through reactions like the water-gas shift reaction and Boudouard reaction.

Advantages of Gasification

Gasification offers several benefits, especially in the context of waste management and renewable energy:

- **Wide Feedstock Flexibility:** Gasification can process a broad range of wood wastes, including those with high moisture content or impurities, such as bark, sawdust, wood chips, and other residues from forestry and agricultural activities. This flexibility makes it a highly adaptable technology for different biomass sources.
- **Efficient Energy Recovery:** Compared to traditional combustion methods, gasification is more efficient at converting biomass into usable energy, since syngas can be tailored for specific uses. For example, syngas can be conditioned and cleaned to improve its quality for high-efficiency applications like fuel cells.
- **Lower Emissions:** Gasification systems produce fewer harmful emissions than direct combustion. The controlled environment of partial oxidation helps reduce the production of pollutants like nitrogen oxides (NO_x) and sulfur oxides (SO_x). Additionally, gasification systems are equipped with filtration and gas cleaning units to remove particulates, tars, and other contaminants from the syngas before it is utilized.

Challenges and Tar Formation

Despite its advantages, gasification is a complex process that requires careful control to optimize performance and reduce challenges like tar formation. Tar, a mixture of heavy hydrocarbons, is a byproduct of incomplete gasification and can condense at lower temperatures, causing operational issues such as clogging in downstream equipment. To address this, advanced gasification systems often incorporate:

- **Tar Removal Technologies:** These include cyclones, scrubbers, and catalytic tar reformers, which help break down tars into lighter gases that can be utilized as fuel or safely disposed of.
- **Process Control:** Maintaining precise temperature, pressure, and air or steam input is critical to minimizing tar formation and ensuring consistent syngas quality. Automated systems and real-time monitoring are often employed to keep these parameters within optimal ranges.

Gasification represents a promising technology for converting wood waste into syngas, offering a highly efficient pathway for energy recovery. Its ability to handle diverse feedstocks, including those with high moisture content, makes it an appealing choice for waste management, renewable energy generation, and the production of valuable chemical feedstocks. However, its complexity requires careful system design, monitoring, and control to optimize efficiency, minimize tar formation, and ensure reliable operation.

Thermochemical Process treatment Products Application

The three main outputs of the thermochemical processes described above—biochar, bio-oil, and syngas—have diverse and valuable applications across various industries, contributing to the circular economy and environmental sustainability (Khodaei, et al. 2022).

- **Biochar:**
    - Soil Amendment: Biochar is highly valued for its ability to improve soil health by enhancing water retention, nutrient availability, and microbial activity. It also helps in reducing soil acidity and sequestering carbon, making it a powerful tool for mitigating climate change.
    - Pollution Remediation: Due to its high surface area and adsorption capacity, biochar is used in environmental remediation to remove pollutants from soil and water, including heavy metals, pesticides, and organic contaminants.
    - Carbon Sequestration: Biochar is one of the most effective ways to sequester carbon in a stable form that remains locked in the soil for centuries, helping offset carbon emissions from other sources.
- **Bio-Oil:**
    - Renewable Fuel: Bio-oil can be used directly as a low-grade fuel for boilers and furnaces or upgraded to higher-quality liquid fuels through hydro-processing and refining. It provides a renewable alternative to petroleum-based fuels, contributing to energy security and reduced greenhouse gas emissions.
    - Chemical Feedstock: Bio-oil contains valuable chemicals, such as phenols, acids, and ketones, which can be extracted and refined into high-value products like resins, adhesives, and pharmaceuticals.
    - Energy Storage: Bio-oil's potential as an energy carrier makes it suitable for use in combined heat and power (CHP) systems, where it can be combusted to generate both electricity and heat, increasing overall energy efficiency.
- **Syngas:**
    - Heating and Combined Heat and Power (CHP): In addition to generating electricity, syngas can be burned to provide direct heating or used in CHP systems, where the waste heat from electricity generation is captured and utilized, increasing overall system efficiency
    - Chemical Synthesis: Syngas is a critical feedstock in the production of chemicals such as methanol, ammonia, and synthetic natural gas (SNG). These chemicals are foundational for producing plastics, fertilizers, and other industrial products.
    - Hydrogen Production: With growing interest in hydrogen as a clean energy carrier, syngas can be further processed to produce pure hydrogen, which can be used in fuel cells or as a zero-emission fuel for transportation.

1.2.3. Incineration and Landfilling

Incineration

Incineration is a conventional thermal treatment process that involves burning wood waste in the presence of excess oxygen to convert it into heat, ash, and gaseous byproducts. This process is widely employed in waste-to-energy (WtE) plants, where the primary goal is to reduce the volume of waste while recovering energy in the form of heat or electricity. Incineration is particularly effective for rapidly reducing the bulk of biomass materials like wood waste, often achieving a volume reduction of up to 90%, making it an efficient solution for waste management.

Process Overview

The incineration process typically occurs in several stages:

- **Drying:** Like gasification, the initial stage of incineration involves drying the wood waste by evaporating its moisture content. This is essential to improve combustion efficiency, as dry biomass burns more readily and produces more heat.
- **Combustion:** Once dried, the wood waste is exposed to high temperatures, generally between 800°C and 1,200°C, in the presence of excess oxygen. In this phase, the organic matter undergoes complete oxidation, resulting in the release of heat and the production of flue gases such as carbon dioxide (CO_2) and water vapor. Combustion is a highly exothermic process, and the energy released can be harnessed to produce steam, which is then used to drive turbines for electricity generation or to provide district heating.
- **Post-Combustion:** In the final stages, any remaining combustible material is further oxidized to ensure that all organic components are completely converted into gaseous byproducts. The process results in the production of ash, which includes both fly ash (fine particulates carried with the flue gases) and bottom ash (the residue left at the bottom of the furnace).

Applications of Incineration

Incineration has several practical applications in waste management and energy recovery:

- **Electricity Generation:** The heat generated from burning wood waste can be used to produce steam, which drives turbines in a waste-to-energy plant. This converts the chemical energy of biomass into electricity, providing a renewable energy source.
- **Heating:** Incinerators can also serve as a source of thermal energy for district heating systems, where the heat produced is distributed to local buildings for space heating and water heating purposes. This makes incineration a useful option in areas where both waste management and heating demands coincide.
- **Volume Reduction:** One of the primary benefits of incineration is its ability to significantly reduce the volume of waste, making it easier and more cost-effective to manage the remaining material, particularly in regions with limited landfill space.

Advantages of Incineration

Incineration offers several key advantages in terms of waste management and energy recovery:

- **Significant Volume Reduction:** By reducing waste volume by up to 90%, incineration decreases the demand for landfill space, helping to extend the life of existing landfills and reduce the environmental impact of waste disposal.
- **Energy Recovery:** The heat produced during incineration can be efficiently converted into usable forms of energy, such as electricity and heat, contributing to renewable energy generation and lowering dependence on fossil fuels.
- **Destruction of Hazardous Materials:** Incineration is effective at destroying harmful pathogens, toxic organic compounds, and other hazardous materials present in wood waste. This makes it a suitable option for treating contaminated or treated wood that may contain chemicals like paints, pesticides, or preservatives.

Challenges and Environmental Considerations

While incineration is an effective waste management solution, it also presents several challenges, particularly in terms of environmental impact. The combustion process generates emissions, which include:

- **Carbon Dioxide (CO_2):** As with any combustion process, incineration releases CO_2, a major greenhouse gas, contributing to global warming. However, since wood waste is considered a renewable biomass, the carbon released is part of the natural carbon cycle, provided the biomass is sustainably sourced.
- **Particulates and Pollutants:** Incineration can produce fine particulate matter, nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and other pollutants. These emissions must be carefully managed to comply with environmental regulations.

Air Pollution Control Systems

Modern incineration facilities are equipped with advanced air pollution control technologies to mitigate the environmental impact of emissions. These systems include:

- **Electrostatic Precipitators (ESPs):** ESPs are used to capture fine particulate matter from flue gases. They electrically charge the particles and collect them on plates, preventing them from being released into the atmosphere.
- **Scrubbers:** Wet scrubbers or dry scrubbers are employed to neutralize acidic gases like sulfur dioxide (SO_2) and hydrogen chloride (HCl) by passing the flue gas through a spray of alkaline solution, effectively reducing harmful gas emissions.
- **Selective Catalytic Reduction (SCR):** This technology helps reduce nitrogen oxides (NO_x) emissions by using a catalyst to convert NO_x into nitrogen and water vapor, which are harmless.

Ash Management

The combustion process also produces ash, which is divided into two types:

- **Bottom Ash:** This is the residual solid material left after the wood waste has been completely burned. Bottom ash typically contains non-combustible materials, such as metals and minerals, and may also include small amounts of toxic substances, depending on the composition of the wood waste.
- **Fly Ash:** Fly ash consists of fine particulates that are carried with the flue gases and can contain trace amounts of heavy metals and toxic compounds. Due to its potential toxicity,

fly ash must be handled and disposed of with care, often requiring treatment before being sent to landfills.

Both types of ash may contain hazardous elements like heavy metals, depending on the wood waste source. For example, treated wood or wood containing preservatives and coatings can produce ash with higher levels of toxic elements, necessitating proper handling, testing, and disposal according to environmental regulations.

Incineration is a widely used method for reducing the volume of wood waste and recovering energy in the form of heat and electricity. Its ability to handle large quantities of biomass and significantly reduce waste makes it an essential tool in modern waste management systems. However, the process generates emissions, including CO_2, particulates, and other pollutants, which must be carefully managed using advanced air pollution control systems. Furthermore, the ash produced during incineration can contain toxic elements, requiring appropriate disposal or further treatment. Despite these challenges, incineration remains a key technology for converting wood waste into valuable energy while minimizing the environmental impact of waste disposal.

Landfilling

Landfilling is the practice of disposing of waste materials, including wood waste, by burying them in designated landfill sites. While this method is traditionally one of the most common waste disposal options, it is widely considered the least favourable due to its significant environmental drawbacks. Landfilling wood waste contributes to a variety of environmental issues, including groundwater contamination, greenhouse gas emissions, and the permanent loss of resources that could otherwise be recovered or recycled. Despite these challenges, landfilling remains an option for wood waste that cannot be treated or processed economically, although its use is increasingly restricted by regulations promoting more sustainable waste management practices.

Environmental Impacts of Landfilling

Landfilling wood waste has several detrimental effects on the environment:

- **Groundwater Contamination:** One of the most serious concerns with landfills is the potential for groundwater contamination. As wood waste decomposes, it can release leachate, a liquid that forms when water percolates through the waste material. Leachate can contain organic compounds, heavy metals, and other pollutants, which, if not properly managed, can seep into the soil and contaminate nearby groundwater sources. Modern landfills are often lined with protective layers and equipped with leachate collection systems, but older or poorly managed landfills pose a greater risk to water quality.
- **Methane Emissions:** When organic materials like wood waste are buried in landfills, they break down anaerobically (in the absence of oxygen), producing methane (CH_4) as a byproduct. Methane is a potent greenhouse gas, with a global warming potential approximately 25 times greater than carbon dioxide (CO_2) over a 100-year period. Although many modern landfills are equipped with gas collection systems to capture methane for energy production, significant amounts of methane can still escape into the atmosphere, contributing to climate change.
- **Loss of Resources:** Landfilling wood waste results in the permanent loss of valuable materials that could otherwise be recycled or converted into energy. Wood waste can be processed for uses such as bioenergy production, composting, or as raw material for new

wood-based products. By sending wood waste to landfills, these opportunities for resource recovery are missed, contributing to the depletion of natural resources and increasing the demand for virgin materials.

- **Land Use and Space Requirements:** Landfills require large areas of land, which can be a limited and valuable resource, particularly in densely populated regions. As landfills fill up, new sites must be found, which often leads to public opposition due to concerns over environmental impact, health risks, and property values. In addition, the long-term maintenance of landfills—such as monitoring for methane leaks and groundwater contamination—requires ongoing management and financial resources.

Wood Waste in Landfills

Not all types of wood waste are equally suited for alternative treatment methods, and some may still end up in landfills. Examples of wood waste that may be landfilled include:

- **Contaminated or Treated Wood:** Wood waste that has been treated with chemicals, such as pressure-treated lumber or wood coated with paints, stains, or varnishes, may be difficult to recycle or process in a sustainable way. The chemical treatments used in these products can pose environmental and health hazards during recycling or energy recovery, making landfilling a more viable, albeit less desirable, option.
- **Mixed Waste Streams:** In some cases, wood waste is mixed with other types of waste, such as construction and demolition debris. If it is not economically feasible to separate the wood from other materials for recycling or energy recovery, the entire waste stream may be landfilled.

Regulatory Shifts and Sustainable Waste Management

Recognizing the environmental and economic drawbacks of landfilling, many countries and regions have enacted regulations aimed at reducing reliance on this disposal method and promoting more sustainable waste management practices. Key regulatory measures include:

- **Landfill Bans and Restrictions:** In some areas, governments have introduced restrictions or outright bans on the landfilling of certain types of organic waste, including wood waste. These policies encourage the diversion of wood waste to more sustainable alternatives, such as recycling, composting, or energy recovery through incineration or gasification.
- **Landfill Taxes:** Many jurisdictions impose taxes on the disposal of waste in landfills, making landfilling a more expensive option compared to recycling or other forms of waste management. The goal of these taxes is to incentivize waste generators and processors to explore alternative, more sustainable methods of waste disposal.

Alternatives to Landfilling

To reduce the environmental impact of wood waste disposal, several alternatives to landfilling have gained prominence, including:

- **Recycling and Reuse:** Wood waste can be recycled into products such as wood chips, mulch, particleboard, or compost. In the construction industry, wood waste from demolition can often be reclaimed and repurposed for other projects. Recycling and reusing wood not only conserve natural resources but also reduce the volume of waste sent to landfills.

- **Energy Recovery:** Incineration or gasification of wood waste can convert the material into useful forms of energy, such as electricity, heat, or syngas. This provides a dual benefit of reducing landfill volume while recovering valuable energy from organic materials.
- **Composting:** Untreated wood waste can be broken down in composting facilities to produce nutrient-rich compost or soil amendments. This process keeps organic waste out of landfills and contributes to soil health and agricultural productivity.

Landfilling wood waste, though still practiced in some cases, is increasingly recognized as an unsustainable and environmentally harmful method of waste disposal. It contributes to groundwater contamination, methane emissions, and the loss of valuable resources, making it a less favourable option compared to alternatives like recycling, composting, and energy recovery. Regulations that restrict the landfilling of wood waste, combined with economic incentives like landfill taxes, are driving a shift toward more sustainable waste management practices. By promoting resource recovery and reducing landfill dependence, these efforts contribute to a more environmentally responsible approach to managing wood waste.

1.2.4. Comparative Analysis of Technologies

The treatment of contaminated wood waste is a critical aspect of sustainable waste management, as it directly impacts resource recovery and environmental protection. Various approaches exist for addressing wood waste, with thermochemical processes, mechanical methods, and biochemical methods each offering distinct advantages and challenges.

Mechanical methods of treating wood waste, such as shredding, chipping, and grinding, focus primarily on physical alteration rather than chemical transformation. These methods are generally less energy-intensive and can effectively process clean wood waste into smaller, manageable pieces for further applications like landscaping mulch or wood pellets. However, mechanical methods may not adequately address contaminated wood waste, as they do not alter the chemical composition or remove harmful substances. This limitation can lead to environmental concerns if treated waste is improperly reused.

Biochemical methods, including composting and anaerobic digestion, offer another alternative for wood waste treatment. These methods utilize microorganisms to break down organic materials, resulting in the production of biogas and nutrient-rich compost. While biochemical processes are particularly effective for clean wood waste and can contribute to soil enrichment, they typically require longer processing times and are less effective for contaminated materials due to the potential inhibition of microbial activity by harmful substances.

Nevertheless, thermochemical processes—including hydrothermal carbonization (HTC), torrefaction, pyrolysis, gasification, and incineration—have gained prominence for their ability to convert wood waste into valuable products while minimizing ecological harm. These thermochemical processes exhibit significant variability in their operational conditions, which can greatly influence their effectiveness and efficiency. Factors such as temperature, pressure, heating rate, and the presence or absence of oxygen are pivotal in determining the types and characteristics of the products generated. For instance, the operational temperature can dictate not only the yield of desired products but also the composition and toxicity of by-products formed. Higher temperatures may enhance conversion efficiency, enabling a more complete breakdown of organic materials; however, they can also lead to the generation of complex by-products that necessitate careful management and additional processing steps. Furthermore, pressure and heating rate play crucial roles in modulating reaction kinetics, thereby affecting the overall productivity of each method.

Figure 1 illustrates a categorization of these thermochemical processes based on their operational temperature ranges and oxygen requirements, highlighting the diverse pathways and outcomes associated with each method. This comparative analysis underscores the importance of selecting the appropriate treatment method based on the specific characteristics of the wood waste in question. Each approach has unique implications for resource recovery and environmental impact, emphasizing the need for an integrated strategy that combines mechanical, biochemical, and thermochemical methods. Ultimately, a nuanced understanding of these variables is essential for developing more efficient and sustainable waste management practices, allowing for optimal resource recovery while minimizing ecological harm.

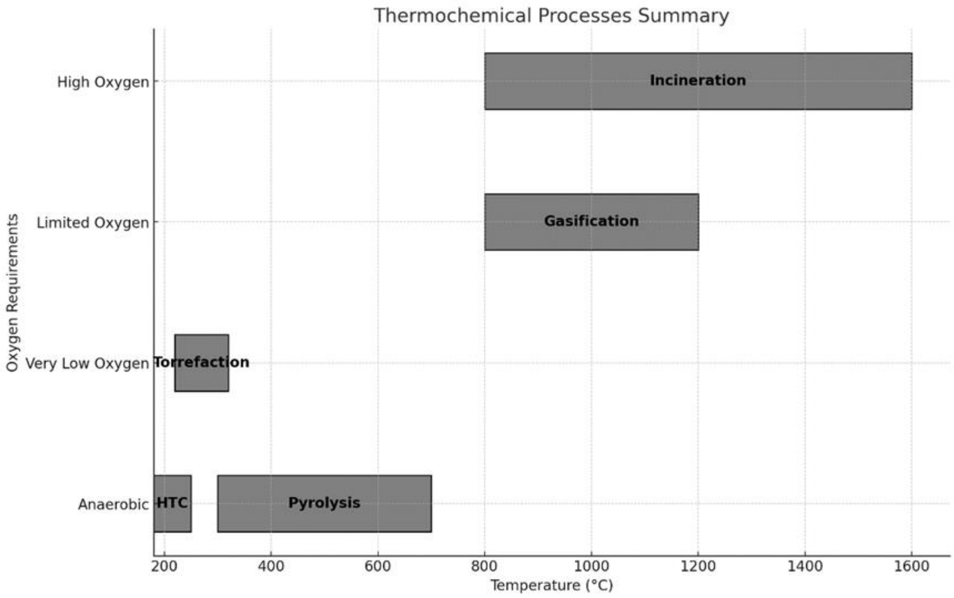

Figure 1: Thermochemical processes summary based on temperature range and oxygen requirements

1.2.5. Selection Criteria for Technologies

Choosing the right technology for treating and recycling wood waste depends on a range of factors, including the type and contamination level of the wood, environmental impact, economic viability, and regulatory requirements. When selecting the most appropriate technology for wood waste management, several critical criteria must be considered to ensure effective and sustainable outcomes.

Wood Type and Contamination Level are paramount in determining the suitable processing method. Pure, untreated wood is ideal for mechanical recycling, as it can be efficiently transformed into new products without extensive treatment. In contrast, wood that has been treated, coated, or contaminated necessitates advanced processing techniques such as pyrolysis, gasification, or remediation. These methods are designed to handle the complexities associated with altered wood, particularly when it comes to the degradation of hazardous substances. For heavily contaminated wood, specialized incineration or secure landfilling may be required to mitigate risks to human health and the environment, thus necessitating a nuanced approach to technology selection based on the specific characteristics of the wood in question.

The **Environmental Impact** of each technology is a crucial factor in the decision-making process. Technologies that prioritize minimal emissions and effective waste management are increasingly preferred, given the global emphasis on sustainability. Pyrolysis and gasification stand out for their ability to convert wood waste into valuable products while maintaining low emissions. These processes not only reduce the environmental footprint of wood waste disposal but also contribute to the circular economy by generating renewable fuels and chemicals. Conversely, methods such as incineration and landfilling often result in higher environmental costs, prompting regulatory bodies to favor more sustainable alternatives that align with contemporary environmental goals.

Economic Viability is another significant consideration, as the cost of treatment can vary widely across different technologies. Mechanical recycling generally represents the least expensive option, but its applicability is limited to clean wood waste. In contrast, pyrolysis and gasification may require considerable initial investment; however, they offer long-term economic benefits through the production and sale of renewable products. The economic implications of remediation can fluctuate based on the level of contamination, while landfilling may seem cost-effective initially, it often incurs long-term environmental and regulatory costs that can outweigh short-term savings.

Regulatory Compliance is critical in the selection process, as adherence to environmental laws influences technology choice significantly. Technologies that effectively minimize emissions, manage hazardous waste, and promote resource recovery are typically favoured in regulatory frameworks. Increasingly stringent regulations discourage practices like uncontrolled incineration and landfilling, steering stakeholders toward more sustainable and compliant solutions that align with evolving environmental standards.

The **Resource Recovery Potential** of each technology is also a key objective in wood waste management. Effective resource recovery maximizes the value derived from wood waste, and technologies such as pyrolysis and gasification excel in this regard. They can convert waste into marketable products, thus fostering economic growth while supporting environmental sustainability. Mechanical recycling further enhances resource recovery by transforming wood into new materials, adhering to circular economy principles.

Finally, **Operational Complexity** is an important factor that varies significantly among technologies. Mechanical recycling is relatively straightforward, requiring minimal technical expertise, which can facilitate widespread implementation. On the other hand, pyrolysis and gasification demand advanced operational controls and specialized technical knowledge, making them more complex to manage. While incineration may appear simpler, it necessitates robust emission control systems, presenting additional operational challenges. Therefore, a careful evaluation of operational requirements is essential to ensure the successful implementation of the chosen technology.

In summary, the selection of appropriate technology for wood waste management must consider multiple interrelated criteria, including wood type and contamination level, environmental impact, economic viability, regulatory compliance, resource recovery potential, and operational complexity. A comprehensive understanding of these factors will enable stakeholders to make informed decisions that promote sustainable practices in wood waste management.

Overall, while mechanical recycling remains an effective and cost-efficient solution for clean wood waste, advanced thermal processes such as pyrolysis and gasification present significant environmental and economic benefits, particularly in the treatment of contaminated wood. These methods not only facilitate the recovery of energy and valuable materials from otherwise discarded wood but also reduce the environmental footprint associated with traditional disposal methods. Furthermore, remediation processes are critical for managing treated and hazardous wood, ensuring compliance with safety and environmental standards, thus mitigating risks to human health and ecosystems. By integrating these innovative technologies, we can enhance the effectiveness of wood waste management strategies and promote a more sustainable and circular economy.

To fully harness the potential of wood waste management, it is essential to establish a comprehensive and harmonized framework for selecting appropriate treatment technologies. This framework should consider a range of interrelated factors, including wood composition and classification, separation technologies, supply chain management, sustainability considerations, and financial implications. By addressing these critical elements, stakeholders can ensure that all relevant aspects are integrated into the decision-making process. Facilitating the adoption of innovative, low-impact technologies not only drives the transition toward more sustainable and resource-efficient practices but also enhances the recovery of valuable materials while minimizing environmental impact. Ultimately, this approach contributes to the development of a resilient circular economy, enabling stakeholders to navigate the complexities of wood waste management more effectively and fostering collaboration and innovation across the industry.

2. METHODOLOGY

2.1. GENERAL ASPECTS OF THE INVOLVED METHODOLOGY

Developing a comprehensive wood valorisation framework entails several crucial steps to ensure its effectiveness, sustainability, and adaptability. Our main objective was to create a framework that remains flexible in the face of evolving market conditions, regulatory landscapes, and technological innovations, thereby ensuring long-term success in wood waste management. To achieve this, we adopted a structured approach in the design and development of the framework, aimed at maximizing resource recovery, promoting sustainable practices, and involving all relevant stakeholders (see Figure 2).

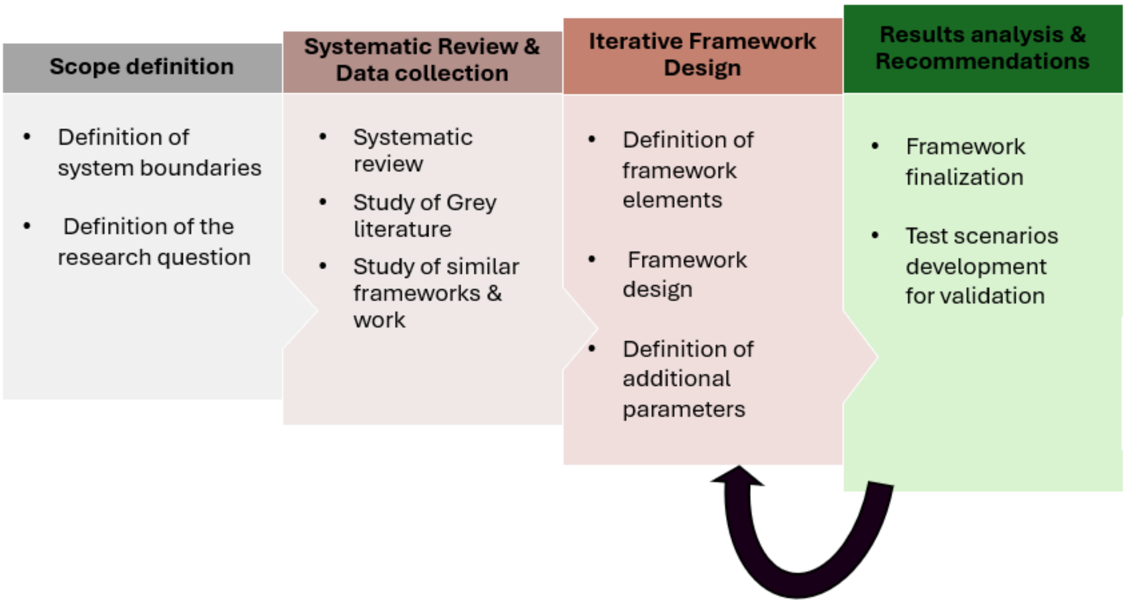

Figure 2: Framework development methodology

Initially, the scope of the study was carefully defined to ensure clarity and focus throughout the research process, guiding both the design of the study and the interpretation of results. Clear system boundaries were established, encompassing technological and regional constraints, as well as existing legislation and policies. These boundaries facilitated a comprehensive understanding of the main objectives and expected impacts of the framework, allowing for a concentrated examination of relevant factors and aspects.

To facilitate the necessary data collection and evaluation of potential valorisation pathways for wood waste derived from construction and demolition waste (CDW) and furniture waste, a systematic review was conducted focusing on wood waste cascade valorisation technologies. This review included a thorough analysis of both scientific and grey literature, as well as existing frameworks and related works.

Furthermore, data pertaining to wood characterization and classification schemes, alongside policy options currently available in the European Union as outlined in W2W Deliverable D4.2, were collected. This information constitutes a vital component of the framework, providing a structured approach to maximize the value and utility of wood resources.

Subsequently, the essential components of the framework were identified by breaking down its structure, thereby enhancing comprehension and application within the research environment. The key elements recognized included the specifications and classifications of various types of wood feedstock, available classification methods, wood sorting and separation techniques, and all associated wood valorisation processes. Additional factors, such as the supply and demand for recycled wood, recycling costs, Life Cycle Assessment (LCA), and Life Cycle Calculations (LCC), were evaluated to determine the optimal valorisation path for each type of waste wood and to establish a comprehensive framework for effective wood upcycling.

Following this, all identified elements were structured and organized in a logical and coherent manner to facilitate understanding and implementation. This approach aims to create a comprehensive framework that promotes continuous improvement in wood waste management practices.

Finally, the framework was tested using data collected from Greece, a country deemed sufficiently representative for this purpose, particularly since many partners involved in the W2W project, including the leader of Use Case 1, are based there. It is noteworthy that all data and insights gathered during the framework validation were utilized to refine its components and implement necessary adjustments based on the validation results. This iterative method included repeated cycles of testing and feedback, ensuring that the framework remains robust, relevant, effective, and suitable for real-world application.

2.2. Identification of Main Framework Components and Selection Criteria

Identifying the most appropriate techniques for the treatment and reuse of wood waste requires a nuanced approach that carefully balances environmental, economic, and regulatory considerations. Drawing from the critical factors and criteria outlined in Section 1.2.5 of this report, we have discerned three primary elements that form the cornerstone of an effective framework: wood classification schemes, separation and sorting technologies, and wood valorisation processes.

These components are essential for developing a robust strategy for wood waste management. Wood classification schemes facilitate the systematic categorization of various wood types based on their inherent characteristics and potential for reuse, allowing for more tailored treatment approaches. Separation and sorting technologies are vital for efficiently processing mixed wood waste streams, ensuring that different types of wood can be directed to the most suitable recycling or treatment processes. Lastly, an in-depth understanding and application of diverse wood valorisation processes enables the maximization of resource recovery, fostering sustainable practices that align with contemporary environmental goals.

Collectively, these elements form a comprehensive framework that addresses the multifaceted challenges inherent in wood waste management. By integrating these components, the framework facilitates informed decision-making and promotes best practices within the field, ultimately contributing to more sustainable and effective wood waste management solutions.

2.2.1. Wood Classification Schemes

Considering the absence of harmonized European legislation on wood waste classification, one of the objectives of the W2W project is to define a classification system. The European Waste Catalogue only classifies wood waste as hazardous or non-hazardous (Eurostat 2010), which is inadequate for optimizing recycling efforts. Some references (Vis, Mantau, and Allen 2016) examine the source, type, and quality grade of wood waste, highlighting the importance of physical and chemical impurities such as heavy metals and polychlorinated biphenyls (PCBs).

W2W D4.2 provides detailed information on the available data on the waste wood approaches and the environmental regulations and directives that apply to waste wood classification and management in each EU country. Based on these data, the W2W project will propose a classification system for wood waste that will improve the cascade valorisation approach.

Table 1: Wood waste codes included in the European Waste Catalogue. Codes with an asterisk are hazardous wastes pursuant to Article 1(4) first indent of Directive 91/689/EEC (SEPA, 2015)

03	**Waste from wood processing and the production of panels and furniture, pulp, paper, and cardboard**	
	03 01	Waste from wood processing and the production of panels and furniture
		03 01 01 Waste bark and cork 03 01 04* Sawdust, shavings, cuttings, wood, particle board, and veneer containing hazardous substances 03 01 05 Sawdust, shavings, cuttings, wood, particle board, and veneer other than those mentioned in 03 01 04 03 01 99 Wastes not otherwise specified
	03 03	Waste from pulp, paper, and cardboard production and processing
		03 03 01 Waste bark and wood 03 03 02 Green liquor sludge (from recovery of cooking liquor) 03 03 05 De-inking sludges from paper recycling 03 03 07 Mechanically separated rejects from pulping of waste paper and cardboard 03 03 08 Waste from sorting of paper and cardboard destined for recycling 03 03 10 Fibre rejects, fibre-, filler-, and coating-sludges from mechanical separation 03 03 11 Sludges from on-site effluent treatment other than those mentioned in 03 03 10 03 03 99 Waste not otherwise specified
15	**Waste packaging; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified**	
	15 01	Packaging (including separately collected municipal packaging waste)
		15 01 03 Wooden packaging
17	**Construction and demolition wastes (including excavated soil from contaminated sites)**	
	17 02	Wood, glass, and plastic
		17 02 01 Wood 17 02 04* Glass, plastic, and wood containing or contaminated with hazardous substances
19	**Waste from waste management facilities, off-site wastewater treatment plants and the preparation of water intended for human consumption and water for industrial use**	
	19 12	Waste from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified
		19 12 06* Wood containing hazardous substances 19 12 07 Wood other than that mentioned in 19 12 06
20	**Municipal waste (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions**	
	20 01	Separately collected fractions (except 15 01)
		20 01 37* Wood containing hazardous substances 20 01 38 Wood other than that mentioned in 20 01 37

Wood waste can be classified into four categories—untreated wood, coated wood, wood with halogenated compounds, and wood with hazardous compounds—based on factors such as contamination level, chemical treatment, and potential environmental hazards. Understanding these classifications is crucial for selecting appropriate treatment and upcycling solutions.

In particular:

- Untreated Wood: This category includes clean, untreated wood, such as offcuts, sawdust, and shavings from woodworking and construction. Wood waste contains no chemical treatments, coatings, or hazardous substances, making it ideal for direct reuse or recycling via mechanical processes. It is recycled and reused into products such as mulch, animal bedding, and particleboard. Because of its low contamination level, untreated wood is frequently the least expensive and environmentally friendly to process.

- Coated Wood: Coated wood, include wood that has been painted, stained, or treated with preservatives such as creosote, CCA (chromated copper arsenate), or other chemicals. This class presents a moderate environmental risk due to the potential release of hazardous substances during processing. Remediation, pyrolysis, and gasification are all treatment options for this class of wood waste, and they can neutralize contaminants or convert the wood into useful byproducts. However, these processes are more complicated and expensive than processing untreated wood.
- Wood with halogenated compounds: Wood with halogenated compounds refers to highly contaminated wood, including demolition debris, old railway ties, utility poles, and industrial wood. This type of wood waste often contains high levels of hazardous chemicals, heavy metals, or asbestos, posing serious environmental and health risks. Wood with halogenated compounds must be handled using specialized remediation processes such as advanced chemical treatments, thermal desorption, or controlled incineration with strict emission controls. Because of the high levels of contamination, these processes can be expensive and produce hazardous residues that must be carefully disposed of.
- Wood with hazardous compounds: This is the most perilous, containing toxic chemicals, radioactive materials, and persistent organic pollutants. This type of wood waste is determined by exceeding the thresholds established in European Regulation 1357/2014 (Eurostat 2010), which governs hazardous waste. Examples include wood from municipal landfills and hazardous waste cleanup operations. It requires highly specialized treatment, which frequently includes hazardous waste incineration, chemical stabilization, or secure landfilling in facilities designed to contain toxic substances. This class of wood is the most difficult and expensive to treat, with strict regulations governing its disposal.

2.2.2. Sorting & Separation Technologies

Sorting and separation technologies play a crucial role in the wood valorisation framework by enhancing quality, maximizing resource efficiency, supporting sustainability, driving innovation, and ensuring compliance—all of which contribute to a more effective and responsible use of wood resources. Furthermore, wood separation technologies are an essential tool for enhancing and optimising wood waste classification, and subsequently, the selection of the best valorisation strategy.

W2W project focuses on advancing the sorting of Construction and Demolition Waste (CDW) to enhance recycling efficiency and support a circular economy. A comprehensive methodology will be developed to improve the separation and sorting of materials at different levels, from individual construction sites to regional and urban scales. The approach will utilise advanced non-destructive techniques to analyse materials like wood and glass, determining the most efficient particle sizes for further processing. Robotic sorting systems, supported by technologies like NIR spectroscopy, will be implemented to optimise the separation of materials based on quality and impurities.

For the W2W project, a multi-robot composite sorting system will be developed to separate wood and glass from mixed CDW with above 95 percent accuracy. The optimum particle size will be considered the factor employed in selecting sensor equipment, and classification criteria will be constantly updated in response to the defined flows. The classification levels will be continuously generated using sustainability assessment standards and input from digital tools for production planning and supply-vs-demand, as well as the thresholds set by the W2W framework. Furthermore, to help and improve the separation of the wood into distinct classes, information about the origin, chemical composition, or even EWC codes of the wood waste can be used as input for a sorting system. Finally, Mixed reality technology will be used for human-robot collaboration (HRC) along the conveyor picking line, facilitating separation and enhancing sorting accuracy and speed. (Konstantinidis *et al.*, 2023)

2.2.3. Wood Valorisation Processes

Wood waste valorisation offers numerous pathways for maximizing the utility of wood resources, contributing to sustainability, reducing waste, and producing valuable products and energy. In this study, all wood waste valorisation processes available in bibliography were evaluated and included as the third and most important element of this framework. Each of these processes contributes to improving the wood's usability and marketability, aligning with sustainability goals, and promoting efficient resource efficiency. The primary technologies, which are described in detailed in section 1.2.2., can be divided into four major categories: mechanical recycling, remediation, pyrolysis and gasification, and incineration and landfilling, with the last group only used when there are no other alternatives for upcycling wood waste (Figure 3).

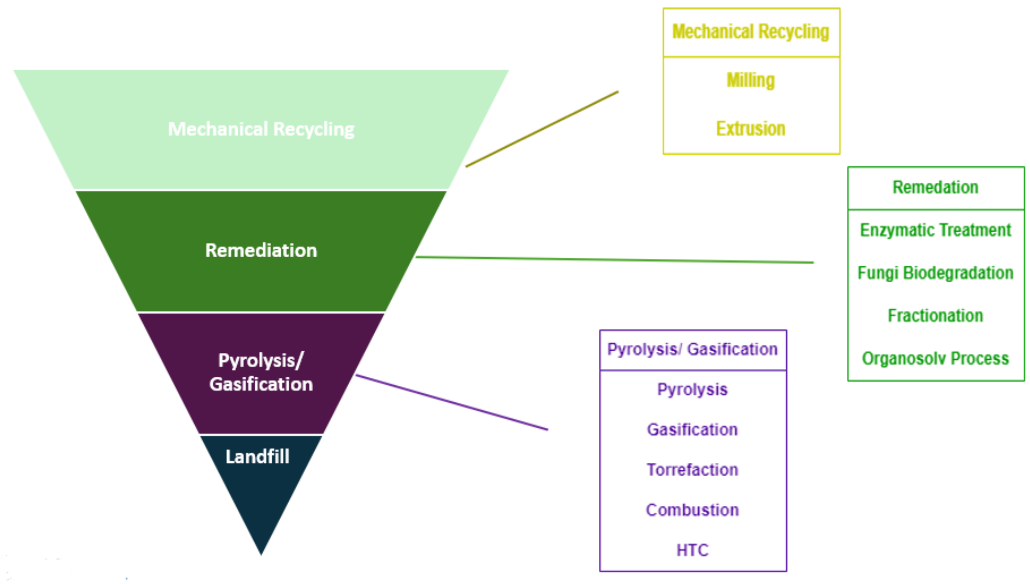

Figure 3: Primary wood valorisation processes classification

2.3. Integration of Components into the Valorisation Scheme

Each wood valorisation method possesses unique advantages that are shaped by a variety of factors, including feedstock quality, technological availability, and prevailing market conditions. The determination of the most appropriate valorisation approach is inherently context-dependent, influenced by the specific circumstances surrounding each situation. To navigate this complexity, the proposed framework serves as a comprehensive feasibility study, thoughtfully integrating all relevant factors to identify the optimal valorisation method for each specific case. This framework aims to facilitate informed decision-making by providing a structured process for evaluating different valorisation options based on the characteristics of the wood waste at hand.

The primary objective of the framework is to identify the optimal valorisation path for each designated wood class, as detailed in Section 2.2.3. To facilitate this, a decision tree has been developed specifically for wood waste valorisation, providing a clear and intuitive visualization of the process selection based on various classifications, as depicted in Figure 4. This decision tree serves as an invaluable resource for stakeholders, guiding them in making informed decisions regarding wood waste valorisation. By following the pathways outlined within the tree, businesses can effectively maximize the value extracted from wood waste while simultaneously ensuring adherence to regulatory requirements and alignment with market demands. This strategic approach not only fosters sustainability by promoting responsible resource utilization but also enhances overall resource efficiency within the wood industry, paving the way for more effective and environmentally conscious practices.

Crucially, wood classification plays a vital role in selecting the optimal valorisation process. Different types and sizes of wood exhibit distinct properties that influence their usability and economic value, while regional regulations and compliance requirements further impact how wood can be effectively valorised. As a result, wood classification, alongside wood sorting and separation, has been identified as one of the most critical factors in the design of the framework. These elements are positioned as the cornerstone of the framework, reflecting their significance in determining the best valorisation pathway.

To ensure that the chosen valorisation process aligns effectively with the specific characteristics of the wood, it is essential to classify wood waste based on various criteria, including type, quality, moisture content, size, source, and region. This classification allows for a more tailored approach to valorisation, optimizing resource utilization and maximizing both the economic and environmental benefits associated with wood waste valorisation. In developing the framework, four major wood classes were identified to assist in the final selection of the most suitable valorisation methods: untreated wood, coated wood, wood containing halogenated compounds, and wood with hazardous compounds. By establishing these classifications, the framework not only enhances decision-making capabilities but also aligns with best practices in the field, ultimately contributing to more sustainable and effective wood waste management strategies.

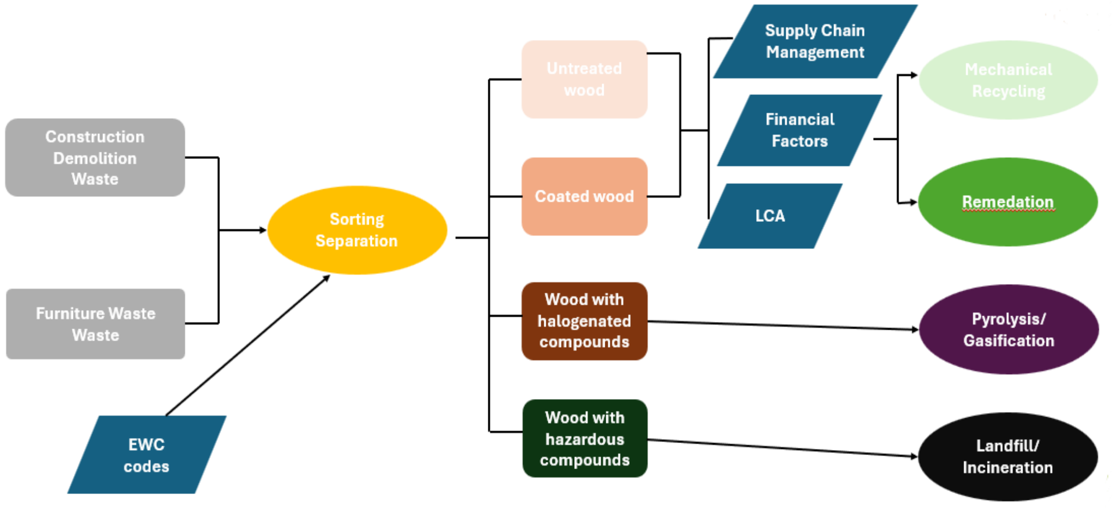

Figure 4: W2W Wood Valorisation Decision-Tree

2.4 Additional Framework Elements

Additional criteria, such as offer vs demand, logistics optimization, environmental impact, processing costs, and supply chain management, were considered for the framework development, with the goal of maximising source recovery potential and minimizing environmental impacts through the application of circular management principles and the development of structures for the circular economy and industrial symbiosis. The incorporation of the aforementioned additional elements will enable a more comprehensive approach in selecting the most appropriate approach in wood recycling, since all aspects of each available valorisation route will be taken into account.

To create a robust strategy for wood waste valorisation that not only enhances recovery potential but also aligns with the principles of circular economy and industrial symbiosis, we incorporated these criteria into our framework, in the form of the following equation that calculates the Cascade Valorisation Framework Potential (CVFP) (Ghisellini et al., 2016; Korhonen et al., 2018; Stahel, 2016):

$$CVFP = \sum_{i=A}^{B} Q_i * \frac{E_i * P_i}{Econ_i}$$

- *i = A or B depending on wood waste class*
- *Qi = Quantity of each wood class*
- *Ei = Environmental impact cost (GHG emissions of recycling processes)*
- *Pi = Processing cost for the treatment of wood waste of type i*
- *Econi = Economic benefit derived from the recycling of wood waste of type i (revenue from wood recycling)*

The developed equation establishes a correlation between the quantities of wood classes A and B, their associated environmental impacts, economic costs, and the potential economic benefits derived from various valorisation routes. The primary objective of this equation is to provide a straightforward quantification score that facilitates the comparison of alternative valorisation pathways for classes A and B.

To achieve this, the equation incorporates the negative impacts associated with recycling, such as greenhouse gas (GHG) emissions and processing costs, in the numerator. In contrast, the economic benefits of valorisation are placed in the denominator. As a result, a lower CVFP (Cost-Value-Factor-Performance) score is preferred when comparing different valorisation routes, as it signifies a more favourable balance between environmental and economic burdens relative to the economic benefits. In contrast, alternatives with higher CVFP scores indicate less optimal outcomes. By quantifying these factors, the equation provides a valuable tool for stakeholders to evaluate and select the most effective valorisation strategies for wood waste, thereby enhancing resource recovery and minimizing environmental impacts.

Overall, this equation serves as a foundational tool in our current analysis; however, we recognize the necessity of expanding this framework to incorporate broader considerations such as sustainability and social impacts. Future work will focus on investigating the interrelations among these additional dimensions and how they can be effectively integrated into our comprehensive wood valorisation framework. By conducting in-depth research on the correlation of these factors, we aim to enrich our understanding and enhance the robustness of our model. As we progress, we will ensure that the results are thoroughly validated, thus reinforcing the relevance and applicability of our framework in addressing the multifaceted challenges of wood valorisation.

3. TOWARDS FRAMEWORK EVALUATION WITH ACTUAL DATA

As Greece works to align with broader European Union environmental policies, such as the Waste Framework Directive and the Circular Economy Action Plan, further improvements can be made in recycling volumes, particularly in mechanical recycling, and reducing reliance on energy recovery for treated wood, (*EUR-LEX - 52020DC0098 - EN - EUR-LEX*, 2008).

The shift towards a circular economy is evident, with greater emphasis on reuse and recycling, but challenges remain in fully integrating these principles. Supply chain dynamics, technological advancements in sorting processes, and market demand for recycled products will all play key roles in shaping the future of wood waste management in the country. By continuing to enhance these systems, Greece can further minimize the environmental impact of wood waste disposal and move closer to achieving its sustainability goals. Wood waste management has become increasingly critical as countries like Greece seek to align with the European Union's circular economy goals and sustainability initiatives.

Validating a wood valorisation framework requires a comprehensive set of data to ensure its effectiveness, feasibility, and sustainability. Collecting and analysing these data types will lay a solid foundation to validate the wood valorisation framework. It will enable stakeholders to evaluate its efficacy, identify areas for improvement, and ensure compliance with market needs and sustainability objectives. Regular updates and continuous monitoring of these data points are required to adapt the framework to changing situations and increase its overall effectiveness.

Table 2 shows data on the quantities of wood recycled in Greece throughout a decade, reflecting all changes in local recycling practices and policy. Mechanical recycling constitutes approximately 80-90% of the wood recycling in Greece, driven by the demand for secondary wood in manufacturing, such as particleboard production. On the other hand, remediation accounts for a smaller share, roughly 10-20%, focused on reclaiming wood from surface treated wood for reuse or lower-value applications. (*Directive - 2008/98 - EN - Waste framework directive - EUR-Lex*, 2020)

Table 2: Statistics of wood waste valorisation in Greece between 2010 and 2020 (Eurostat,2023)

Year	Class & Treatment of waste wood			Total (tn)
	Untreated & Coated Wood Recycling (Mechanical & Remediation)	**Wood with Halogenated Compounds Energy recovery**	**Wood with Hazardous Compounds Landfill/Incineration**	
2010	83320	38359	206609	388288
2012	25765	10711	79824	116300
2014	13220	5496	40959	59675
2016	7262	5224	396	12882
2018	11988	8932	971	21891
2020	6526	7374	458	14358
Median	12604	8153	20965	40783

The data in the table above could potentially be used to assess the functionality of the designed framework and verify its reliability.-The primary aim for utilizing the data presented in Table 2, was to highlight that the developed framework can be efficiently utilized to guide stakeholders in selecting the appropriate wood waste valorisation route. Specifically, the developed framework considers practices and propose available routes that are already established, however the incorporation of the additional components, as described in previous chapter, will further facilitate the selection of the most proper valorisation pathway. Moreover, the additional components of the framework cannot be utilized in data from previous years, since their main ambition and functionality is to guide stakeholders' decisions in real-time. Additionally, it is worth noting that the validation of a wood valorisation framework is a dynamic and evolving process that requires involvement from a variety of stakeholders, rigorous evaluation, and flexibility to changing conditions. In the future, as part of the W2W project, and WP15, a Use Case scenario will be used for the validation of the framework, to be refined and strengthened, and to ensure it effectively promotes sustainable wood use, enhances economic value, and contributes positively to environmental conservation.

4. DISCUSSION OF FINDINGS

4.1. Primary Results

The present framework is fundamentally anchored in the decision tree presented in Section 2.3 (Figure 4) and the equation detailed in Section 2.4, with the primary objective of offering a comprehensive strategy for valorising wood waste generated from industrial and man-made operations. This framework elucidates the processing of various wood waste types, commencing with their classification and sorting based on contamination levels and recycling eligibility. By systematically categorizing wood waste, it ensures that each type is treated appropriately, thereby maximizing resource recovery and minimizing environmental impacts. In light of these findings, future work will expand upon this foundational model to incorporate sustainability and social considerations, thus fostering a more holistic approach to wood valorisation that not only addresses economic factors but also promotes positive environmental and social outcomes. This expanded perspective will be critical for developing a robust and validated wood valorisation strategy that aligns with contemporary sustainability goals.

In Table 3, we summarize the major categories of wood waste processes, encompassing both recycling and disposal methods. This table serves as a reference point within the framework, highlighting the diverse approaches available for managing wood waste effectively. By outlining these processes, the framework facilitates informed decision-making for stakeholders, ensuring that the valorisation of wood waste aligns with sustainable practices and regulatory requirements.

Table 3: Wood waste treatment process summary

Process Type	Advantages	Challenges	Environmental Impact	Wood Waste Class
Mechanical Recycling	Reusable products, Low operational complexity	Equipment maintenance, Not suitable for contaminated wood	Low	Untreated Wood
Remediation	Recovery of contaminated wood, Potential high value products	High cost, Time intensive, Potential secondary waste production	Low (if remediation compounds are retrieved)	Coated Wood & Wood with halogenated compounds
Thermal treatment	CHP production, Carbon sequestration, Added value products	Complex handling of by-products	Low (if CO_2 emissions are minimized)	Coated Wood & Wood with halogenated compounds
Incineration	CHP production	GHG emissions	Medium to Major (depends on emission control technologies)	Wood with halogenated compounds & Wood with hazardous compounds
Landfilling	Low cost	GHG emissions, Groundwater contamination	Major	Wood with hazardous compounds

- **Untreated Wood:** Owing to its superior quality and low contamination, untreated wood is best suited for mechanical recycling and remediation. Mechanical recycling involves repurposing this wood to create fibreboard, particleboard, or other wood-based products.
- **Coated Wood** (Surface -treated wood suitable for recycling or remediation): Coated wood is usually undergoing mechanical recycling or remediation. Surface impurities are eliminated or treated during remediation to restore the wood's usability. Remediation is a valuable process, especially for moderately treated wood, but it faces limitations due to cost and technical complexity.

Since untreated and coated wood can be either remedied or mechanically recycled, other factors need to be considered to determine the most effective valorisation pathway. For this reason, the concept of LCA (Life Cycle Assessment) suggests that decisions about whether to mechanically recycle or remediate the waste wood are guided by sustainability assessments. The supply chain and financial considerations are also important in selecting which of the previously mentioned routes to consider taking.

- **Wood with halogenated compounds** (Contaminated wood – non-hazardous): This wood class is primarily directed towards energy recovery and is not suitable for recycling because of chemical treatments or coatings. By capturing the energy contained in the wood through procedures like pyrolysis or gasification, the need for fossil fuels is decreased.

- **Wood with hazardous compounds** (Contaminated wood –unsuitable for energy recovery): Since this class of wood is the most contaminated of wood waste, the only viable options are usually incineration or landfilling. However, the quantity of wood that is burned or dumped in landfills can be significantly reduced with better rules and sorting techniques.
  The sharp decline in landfill volumes indicates that Greece is making great strides toward minimizing the disposal of hazardous waste, which is a good trend for the environment.

4.2. Framework Initial Application Results

As countries like Greece try to align with the circular economy goals and sustainability initiatives of the European Union, wood waste management has become more and more crucial. Three main classes of waste management can be distinguished from the data on wood waste obtained from European and Greek authorities between 2010 and 2020: recycling (Mechanical & Remediation - Untreated Wood & Coated Wood), energy recovery (Wood with halogenated compounds), and landfill/incineration (Wood with hazardous compounds). This classification is based on a hierarchy of waste treatment techniques, where recycling takes precedence over landfilling and energy recovery.

The obtained statistics show a clear decrease in Greece's total amount of wood waste managed between 2010 and 2020. Particularly:

- **Recycling (Mechanical & Remediation) – Untreated and Coated Wood**: The data indicates a steady drop in recycling of wood, untreated wood and coated wood, from 83320 tons in 2010 to 6526 tons in 2020. This is a noteworthy decrease of more than 90% in a ten-year period. The overall decline in processed or available wood for recycling is reflected in the median value over the last ten years, which is 12604 tons.
- **Energy Recovery - Wood with halogenated compounds**: Wood containing halogenated compounds also exhibits a notable decline from 38359 tons in 2010 to 7374 tons in 2020. This wood is primarily treated to make it unsuitable for direct recycling but usable for energy recovery (through processes like pyrolysis and gasification). This decline in energy recovery suggests that waste sorting may improve and that energy sources may start changing. The median value of 8153 tons indicates that, while energy recovery has been a consistent approach to managing wood waste, it has been decreasing.
- **Landfill/Incineration - Wood with hazardous compounds**: Wood containing hazardous compounds is waste wood that poses a risk to human health or the environment and needs to be burned or dumped in a landfill. Data in this category indicates a sharp decline, from 206609 tons in 2010 to just 458 tons in 2020, indicating a significant improvement in the removal of wood waste from landfills.

The median value of 20965 tons for landfill/incineration highlights the decrease in the amount of wood waste disposed of in this manner.

Positive advancements in wood waste management have been observed in Greece between 2010 and 2020, as demonstrated by a discernible decrease in the overall amount of waste disposed of in landfills and an increased emphasis on recycling and energy recovery. The decrease in volume from 388,288 tons in 2010 to 14,358 tons in 2020 can be ascribed to various factors such as enhanced waste sorting, amplified recycling and reuse endeavours, and plausible reductions in wood consumption. In accordance with EU directives intended to minimize reliance on landfills and promote recycling, there has been a decrease in the amount of wood waste containing hazardous compounds being dumped in landfills. This indicates a shift towards more sustainable practices. In addition, the focus on higher-quality recycling—particularly for untreated wood through mechanical recycling—indicates a shift in the industry toward the processing of cleaner wood, where the advantages to the economy and environment are more evident. Because of its moderate contamination, coated wood is more likely to be used in remediation, which emphasizes the need for sophisticated waste management techniques.

Based on the gathered data, it is reasonable to conclude that the proposed framework can be effectively implemented in practice. The evidence indicates that its essential elements and selection criteria are not only robust but also closely align with established practices observed in various countries. This alignment underscores the framework's relevance and applicability within diverse contexts, suggesting that it can facilitate effective wood waste management strategies. By reflecting widespread industry standards and practices, the framework is poised to support stakeholders in making informed decisions that enhance sustainability and resource efficiency in wood valorisation efforts.

The framework's potential for effective application in the project's Use Cases is underscored by its alignment with the data derived from existing literature. This initial indication of suitability suggests that the framework is well-equipped to address the complexities of wood waste valorisation. By incorporating additional components such as Life Cycle Assessment (LCA), supply chain management, and financial indicators, the framework will enhance decision-making among stakeholders involved in the project. These supplementary elements will provide a more holistic understanding of the impacts and opportunities associated with different valorisation strategies, thereby facilitating informed and strategic choices that promote sustainability and resource efficiency. Ultimately, this integrated approach positions the framework as a valuable tool for optimizing wood waste management practices in various contexts.

4.3. Challenges Encountered and Strategies to Overcome them

The primary challenge we encountered while designing the W2W wood valorisation framework stemmed from issues related to wood classification and the absence of consistent, harmonized regulations. Key obstacles associated with these issues included varying wood classification standards across the European Union, regulatory uncertainty, difficulties in quality assessment, inadequate traceability, market restrictions, and concerns regarding environmental impacts.

To address these challenges, it is essential to advocate for the establishment of uniform standards and guidelines for wood classification and valorisation. Collaboration among stakeholders—including government entities, industry representatives, and researchers—can facilitate the development of a more coherent framework that supports efficient wood valorisation and promotes sustainable practices. By tackling the lack of harmonized regulation in wood waste classification, stakeholders can foster a more conducive environment for effective valorisation, thereby enhancing sustainability and advancing the circular economy.

In addition to regulatory harmonization, it is vital to evaluate the existing logistics and infrastructure for the collection, processing, and distribution of wood waste and valorised products. This evaluation should also encompass an assessment of current and future market demands for products derived from wood waste, identifying potential customers and applications. Moreover, integrating Life Cycle Assessment (LCA) into the analysis will enable a comprehensive evaluation of the overall environmental impact of wood valorisation processes and products, from extraction through to end-of-life. This integration will help ensure that the framework aligns with broader sustainability goals and policies, such as carbon neutrality and waste reduction targets.

The interrelationships among these elements should be thoroughly investigated and continually considered when determining the most effective valorisation processes for various types of wood. By accounting for these factors, the wood valorisation framework can be made more robust and adaptable, ultimately delivering significant environmental, economic, and social benefits.

4.4. Improvements & Future Steps

To refine the wood valorisation framework and ensure continuous monitoring, it is essential to adopt a systematic approach that considers a range of critical success variables. One of the key next steps and objectives of this research is to develop a strategy for the large-scale implementation of the framework, ensuring that it effectively meets the needs of the project and its stakeholders. This process will involve a detailed examination and further exploration of various additional components that will serve as the foundation for a dynamic valorisation system. Key factors such as supply and demand dynamics, logistics optimization, and supply chain management will be analysed to understand their interrelationships and their influence on selecting the most suitable valorisation approach for both pure and coated wood.

Moreover, we plan to establish iterative methods for the ongoing evaluation and refinement of the framework. By implementing these strategies and regularly assessing the various aspects within the wood valorisation framework, stakeholders can enhance efficiency, adaptability, and sustainability. This continuously evolving approach will be instrumental in addressing challenges, improving resource recovery, and fostering a circular economy model for wood waste management.

Finally, we aim to create testing scenarios to validate our framework using data from the W2W project use cases. Additionally, we will develop guidelines to facilitate the replication of this framework in other relevant fields, thereby broadening its impact and applicability. This comprehensive strategy will not only strengthen the framework itself but also contribute to the advancement of sustainable practices in wood waste management.

5. CONCLUSION

This document presents the initial version of the W2W comprehensive wood cascade valorisation framework. Following further enhancements, this framework is designed to assist decision-makers in identifying the most effective valorisation routes and ideal pathways that can lead to reduced environmental impacts, as well as significant cost savings.

The current study establishes a robust foundation for evaluating various upcycling techniques based on the availability and characteristics of wood feedstock. It will thoroughly analyse and assess the novel wood valorisation techniques and technologies developed throughout the W2W project. Moreover, by incorporating complementary elements and impact variables—such as supply chain management, logistics optimization criteria, and Life Cycle Assessment (LCA) calculations—the framework will be refined to maximize resource recovery.

In conclusion, the W2W wood valorisation framework represents a significant advancement in sustainable wood waste management. This comprehensive approach promotes the optimal utilization of wood resources, encouraging not only economic viability but also enhancing ecological integrity. By fostering the adoption of innovative technologies and practices, the framework aims to elevate the value of wood products, transforming them from raw materials into commercially viable products. This initiative ultimately supports the transition towards a more sustainable and circular economy in wood waste management.

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