Unveiling the flows of key residual streams of the forestry sector towards valorization

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Introduction

Forestry is a vital sector that delivers a wide range of benefits including provisioning services (e.g., wood for construction and energy), regulating services (e.g., local and global climate mitigation, hydrological regulation and soil protection) and cultural services (e.g., recreational and health benefits) (Winkel et al., 2022). Also, forest-based industry boosts the EU economy and employment, creates economic opportunities to rural areas and strengthens the transition towards low-carbon bioeconomy. More specifically, in the EU, forest-based industries account for approximately 7% of the EU manufacturing GDP and provide nearly 3.5 million jobs across over 400 thousand companies (European Commission, 2025). According to the European Climate Law, forests, which cover 39% of the EU's land area, are considered an important resource for reaching carbon removal targets and carbon neutrality (Bottaro et al., 2024). The countries with the largest forest areas are Sweden (27,980 thousand ha), Finland (22,409 thousand ha) and Spain (18,576 thousand ha). The stocks of timber in the EU's forests are estimated at 28.6 billion m^3 (over bark) in 2022, with Germany accounting for the largest share (13.2%), followed by Sweden (12.6%), and France (11.8%) (EUROSTAT, 2024). An increasing interest is placed in the cascading use of woody biomass, as reflected in the Circular Economy Action Plan and the specific guidance on cascading use of woody biomass aiming to sustainability, resource efficiency, circularity, and broadening of existing market by introducing new wood-based products and subsidiarity (European Commission, 2018). At the same time, forestry activities generate significant amounts of by-products/residues, such as wood chips, sawdust, bark, and branches. The main goal of this study is to provide a quantitative estimation of forestry by-products and an overview of the different valorization routes within the European bio-based industry.

Materials and methods

The residual streams, which are created throughout the forest-based sector activities, constitute an important resource that can be sustainably valorized. The first step towards this strategy is to perform a detailed mapping of the available streams and current uses followed by the quantification of each stream. This task is performed under a material flow analysis (MFA) approach which is used to systematically quantify the flows and stocks of materials within a defined system. MFA helps simplify intricate systems while securing a basis for rational decision-making. The interpretation of results, with emphasis on the management of resources, the environment and waste, serves as a basis for other important assessment tools such as Life Cycle Assessment. The visualization of MFA results is performed through Sankey diagrams. Data collection is a critical parameter for the robustness and credibility of the analysis. The most important data sources utilized are subsequently summarized:

- The *FAOSTAT database* provides information retrieved from the Joint Questionnaire of Forest Sector (JFSQ), which is the collaborative initiative of FAO, Eurostat, International Tropical Timber Organization and the United Nations Economic Commission for Europe (UNECE).
- The *Wood Resource Balance* (WRB) sheets have been developed by JRC to provide an overview of sources and uses of woody biomass, while it also highlights data gaps and inconsistencies.
- The conversion factors and input/output coefficients for the processing of the retrieved data are sourced from the recently updated study (2022) "*Forest Product Conversion Factors*" conducted by FAO, ITTO and UNECE
- The World *Integrated Trade Solution* (WITS), which is an open database provided by the World Bank, offers information on trade and tariffs. The information is compiled by several international organizations, namely UN COMTRADE, UNCTAD TRAINS and WTO IDB/CTS.
- The *JRC database* for bio-based industries in EU27 implemented in the EC Data portal of agro-economics Modelling (DataM) and in the EC Knowledge Centre for Bioeconomy.
- Data gaps are covered by peer-reviewed scientific literature and relevant reports from established associations (e.g. Confederation of European Paper Industries (CEPI)).

A "bottom-up" approach is adopted in the MFA implementation. This is a widely accepted strategy which entails data collection from individual components and subsequently inferences for the larger system. The spatial system boundary of the analysis is EU-27. The analysis focuses on residual biomass streams (bark, sawdust, woodchips, fiber

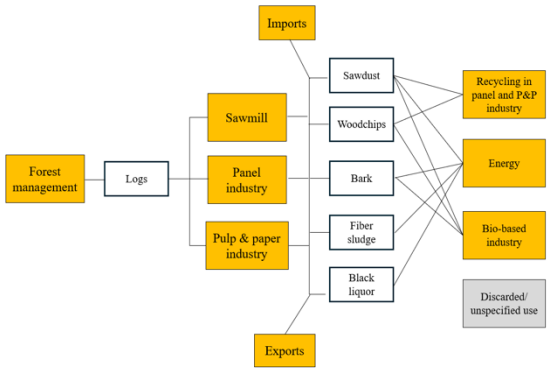

Figure 1: Outline of the value chain under assessment

sludge and black liquor), which are generated in the most dominant industries of the forestry sector, including sawmills, panel industry and pulp and paper mills. The value chain of residual forestry biomass under assessment is presented in Figure 1.

Results

The current study provides a comprehensive assessment of the production, utilization and valorisation routes of by-products generated within the forestry sector in the EU. It was found that woody by-products, comprising woodchips, bark and sawdust, constitute part of a robust market with defined uses. More specifically, approximately 24% of the woody by-products are used as raw materials in panel production and another 25% are utilized in the pulp and paper industry. Additionally, an estimated 38% of the total wood by-products are directed towards energy generation. Currently, the generated black liquor and fiber sludge are mainly used for energy generation purposes. An emerging destination is the valorization of the generated by-products in the bio-based industry aiming mainly for the production of agrochemicals (including bio-fertilizers), bioplastics and biocomposites. However, these routes of valorization are under development and only 3% of the totally generated by-products is currently utilized in this context. The results are summarized in the Sankey diagram presented in Figure 2.

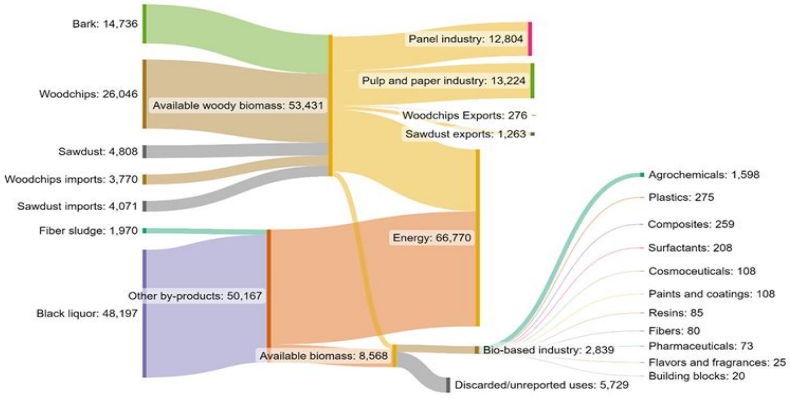

Figure 2: MFA developed for the forestry by-products value chain; the quantities are expressed in kt dry matter/y.

Conclusions

Based on the findings of the MFA, it can be observed that a substantial volume of forestry residues are used for energy generation. A noteworthy reuse amount was estimated in the cases of panel production and pulp and paper mills, constituting a positive finding for the circularity of the sector. However, the quantity of residual biomass used to produce added value products in the bio-based industry is limited. Therefore, this analysis highlights the need for the enhancement of forestry by-products upcycling, and in parallel their potential as valuable resources for sustainable, bio-based product development within a circular economy context.

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