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UTILISATION AND QUANTIFICATION OF WOOD BY-PRODUCTS FROM PRIMARY WOOD PROCESSING

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ABSTRACT

Successful implementation of wood utilisation in various industry sectors is a driving force for building a sustainable society. Knowing the volume of by-products is essential for assessing the industry's contribution to the circular economy based on the level of application of wood cascading principles. The study deals with the analysis of actual wood use patterns in Slovakia with a focus on wood by-product management. The obtained data are the basis for calculating a cascading coefficient to evaluate the use of wood in the whole chain of its processing and utilisation. Results confirm that the most important producer of wood by-products is the sawmilling industry, consuming approximately 40% of the total volume of industrial wood. The value of the cascading coefficient in the Slovak Republic calculated with the inclusion of sources and products for energy use based on 2020 data determined on the basis of a questionnaire survey was 1.33.

Keywords: cascade coefficient; harvested wood products; by-products; sawnwood.

INTRODUCTION

Renewable resources, considered an inevitable part of the issue of the circular economy, are increasingly recognized as a key factor in environmental protection, sustainable development, and economic prosperity – the circular economy emphasizes reusing sources and waste streams to create value-added products. The forest-based sector and all linked businesses played a significant in the circular economy. These sectors focus on producing and using sustainable wood and wood products. Improved utilisation of available wood waste into added-value goods produces profits for all supply chain participants (Parobek and Paluš 2024). The industry's strength, competitiveness, effectiveness, attractiveness to investors, and many other factors influence the economic growth of each country. New problems have increased in recent decades, such as transformation and adaptation to new demands from the forest-based sector, which has been characterised by globalisation, an increasingly competitive economic environment, and new technologies and innovations. Thus, wood consumption must be assumed and coordinated with the need for conventional and modern products. Many studies (Buongiorno *et al.*, 2011; Mantau *et al.*, 2010; Raunikar *et al.*, 2010) predicted an increase in wood demand in the European Union (EU), owing primarily to the rise in renewable energy use.

On the source side, forestry companies supply different wood assortments, namely sawlogs, veneer logs, pulpwood, and other industrial wood to the forest-based industries. Simultaneously, the industry generates significant volumes of wood residue (30-50% of the volume of processed wood), which can be used for industrial applications as additional resources. Furthermore, the industry is the leading consumer of these residues and other solid-wood products (Ministerial Conference on the Protection of Forests in Europe - FOREST EUROPE, 2020). From this perspective, it is critical to prioritise outputs with higher added value, which create jobs and contribute to a better carbon balance (resource efficiency). Wood products and derived residues have the potential to mitigate climate change in terms of their ability to store carbon and substitute for fossil-based materials (Howard *et al.,* 2021). The efficient cascade use of wood enables the recycling and reuse of wood waste from the production process several times. In addition to the production of primary semi-finished products such as sawn wood, veneer, wood panels, paper, and paperboard, the forest-based industries also produce a significant proportion of by-products, in particular trimmings, edgings, sawdust, shavings, bark, but also black liquor resulting from pulp production.

Current statistical data do not include the volumes of by-products generated in the primary processing. In the conditions of the Slovak Republic, the most important producers of wood-based by-products are the sawmill industry (with about 40 % share in the total volume of processed wood) and the pulp and paper industry (energy-rich by-product - black liquor) (Moravčík *et al.,* 2023). The quantification of these resources in volume terms is a requirement for knowing the actual wood flows, as these are significant volumes of wood that, after primary processing, are returned as a resource for industrial processing or energy production. Knowing the volumes of these by-products is also essential for assessing the contribution of the sector to the circular economy through the value of the cascading principle. According to Haberl and Geissler (2000), wood cascading increases the efficient use of biomass, which can be achieved by integrated optimization of biomass utilisation in the industry. The novel cascading concept can help optimize wood use along the processing chain and utilisation (Parobek and Paluš, 2016). Cascading can be characterised as a recycling chain in which wood is reused, and the product at the end of its life cycle is suitable for energy generation (Brunet-Navarro *et al.,* 2018). Wood cascading is a systematic effort to obtain biomass for higher-value products (Keegan *et al.,* 2013). Mair and Stern (2017) specified that actively integrating cascading principles into the circular economy can strengthen both concepts in multiple ways. This concept, for example, could be used to communicate with members of a general audience and with specific reference to wood and other bio-based resources, cascading can be considered to represent a concept that forms a connection between circular economy and the bio-economy, fostering an inclusive, circular bio-economic vision in the future (Mair and Stern, 2017). As described by Sirkin and ten Houten (1994), cascading of renewable resources is an approach to improve the efficiency of source utilisation by a sequential re-utilisation of the same unit of a resource for multiple high-grade material applications followed by a final use for energy purposes (Höglmeier *et al.,* 2017). In that way, primary inputs have increasing positive effects due to substituting limited materials with renewable resources (Gustavsson and Sathre, 2011). Wood cascading occurs when biomass is processed into a final product, which is reused at least once as a material or product in the production process or used for energy production. Keegan *et al.,* (2013) distinguish between single and multi-stage use of resources. Moreover, Fraanje (1997) highlighted that appropriate secondary sources of the best possible quality should be applied to maximize the effects of cascading.

The cascade coefficient expresses how efficiently wood is used for different purposes before it reaches the end of its life cycle (Mantau *et al.*, 2010; Parobek *et al.*, 2014). Increasing the value of the cascade coefficient can be achieved by preferential reuse of wood-based by-products to produce products with higher added value. The least appropriate use of wood is for energy production, directly linked to releasing carbon dioxide into the atmosphere. According to the principles of wood cascading, the burning of wood should be the last stage of the wood life cycle. The above approach also allows for the creation of higher added value in the wood products and promotes employment growth. The system and rate of utilisation of wood by-products vary considerably between European Union (EU) countries (Mantau, 2012).

The study aims to calculate the cascade coefficient and evaluate the use of wood resources in the Slovak forest-based industry based on a questionnaire survey—results aimed at quantifying the production of essential semi-finished products, by-products, and processed energy wood. Subsequently, the findings were approximated for the conditions at the national level, and the values of the cascade coefficient were calculated. The conclusions are intended to serve as background material for adopting measures related to optimizing the current use of wood and wood by-products following principles of bioeconomy and cascade wood utilisation.

MATERIALS AND METHODS

The wood balance and resource balance were constructed to define wood material flows. While wood balance is mainly oriented to estimate domestic consumption regardless of the further use of wood, wood resource balance is used to determine and quantify the main resources and uses of raw wood material and wood residues. Domestic roundwood production and imports represent the major resource categories, while domestic roundwood consumption and exports represent the primary uses. The resource side is supplemented by recycled material and stock decreases, while the use side is enhanced by stock increases. The availability of the data is a critical factor in the construction of the wood balance. Data were obtained from the FAOSTAT database (FAOSTAT, 2024) and forestry reports in Slovakia (MARD SK, 2023). To create a state of wood balance, the resources must match the uses. The wood resource balance provides an in-depth examination of wood and wood product flows while focusing on the various uses within the sector.

Empirical research based on accessible data is applied to obtain absent data. Under current conditions, wood resource balance statistics can be constructed using a combination of official information and empirically collected data. Official statistics provide data for highly concentrated industries such as pulp and paper. On the other hand, data on wood products, by-wood products and waste flows in the sawmill industry are not available. As the records on the volume of produced wood residues and their consequent use either as a material or energy source are not generally available. That is why, the analysis was accompanied by the determination and quantification of wood residues patterns using a questionnaire survey among the companies operating in the sawmilling and wood-based panel industry in Slovakia. Evaluation of the use of raw wood resources in the wood processing industry is aimed at quantifying the production of (i) basic semi-finished products (sawnwood, veneers, plywood, panels), (ii) by-products (sawdust, bark, chips, peeling residues, etc.) and (iii) processed energy wood (pellets, briquettes, split firewood).

A questionnaire survey in 2023-2024 was conducted for two main product groups: sawn timber products (sawn timber, by-products) and wood-based panels (veneers, plywood, agglomerated materials, and by-products) to determine the state of production of semi-finished timber products and by-products of mechanical wood processing in 2020. The mentioned analysed period is to minimize turbulences due to market changes and results represent the latest possible data obtained by a combined primary and secondary research method. The number of contacted companies was 177. The number of respondents was 57, i.e., a 32.2% return rate. Of these, the number of respondents producing wood-based panels was five, representing almost 100% coverage of their production in the Slovak Republic. Consequently, expert analysis of the collected data and quantification of the volumes of inputs to production and production (including by-products according to their type) were carried out. On the other side of wood resource balance, the use of the production, namely own consumption, sale, industrial processing and use for energy were analysed. Finally, the calculation of the cascade coefficient in harvested wood products (HWPs) was estimated. Most of the main production inputs (logs) and products (sawn timber, bulk materials) were reported in m3 in the questionnaires. Other production inputs and by-products were reported by respondents in different units of measurement (spatial meter, tonnes, atrotons). All data were converted into m3 as part of the data evaluation using various methods (as available and feasible), in particular, forest product conversion factors (FAO, 2020), available domestic tables, conversion factors, and estimation according to the predominant wood species of the material, its assumed moisture content and wood volume tables. Conversion factors were used to determine the need for a roundwood equivalent. The primary conversion factors for deciding the roundwood equivalent for each HWP are given in Table 1. The first column shows the volume of roundwood needed to produce 1 m3 of different HWPs. The production from chemical processing is converted from tons to log equivalent.

Tab. 1 Coefficients for determining roundwood requirments for the production of individual HWPs.

Harvested wood products (HWP)	Requirement of roundwood per $1m^3$/t of product	Product volume of $1m^3$ roundwood
Coniferous Sawnwood	1.80	0.56
Nonconiferous Sawnwood	1.70	0.59
Particalwood	1.40	0.71
Plywood	2.90	0.34
Veener	2.20	0.45
Mechanical pulp	2.50	0.40
Chemical pulp	4.50	0.22
Semi-chemical pulp	2.90	0.34
Recycled Paper	3.40	0.29

Source: UNECE/FAO (2020)

The wood resources balance in Slovakia was calculated for the whole sector of the primary use of roundwood. The relevance of the real wood resource results depended directly on the quality and availability of data on wood production and use in the individual sectors. Official statistics are available for highly concentrated sectors such as the pulp and paper industry. However, some manufacturing industries, such as the sawmill industry, are poorly concentrated, and access to input data is quite limited.

The interlink between available data through a questionnaire survey and information from official databases is a sufficient information base for assessing cascading in the Slovak Republic. The cascade analysis describes wood flows to identify and quantify the use of wood material and waste. Cascading can be defined as the efficient use of residues and recycled materials to expand the overall biomass availability in a given system.

To evaluate the cascade use of wood in the forest-based industry in Slovakia, it was necessary to determine cascade coefficients according to their type of use. The cascade coefficient is a figure that tells us how often the wastes or by-products in the balance of wood resources get from the use side to the resource side and are reused either as input material for energy generation or for further industrial production. The higher the cascade coefficient, the higher the rate of use and recycling, and the contribution to the green economy increases (Bais-Moleman *et al.,* 2018). To calculate the cascade coefficients, the following formula was used:

$$C = RW + IR \tag{1}$$

Where:
C – cascade,
RW – recovered post-consumer materials (wood, paper, furniture, waste, etc...),
IR – industrial residues.

$$CF = 1 + \frac{C}{WR_{forests}} \tag{2}$$

Where:
CF – cascading factor,
$WR_{forests}$ – wood resources from forest (industrial roundwood).

Wood is a versatile material and can be used in various manufacturing processes, so it was necessary to identify on both sides of the balance whether these were finished products or products that enter the input side of the balance for reuse. This analysis allowed the calculation of a cascade coefficient, which takes into account the reuse of wood entering from the use side and returning to the source side and vice versa. The cascade coefficient is defined as the total wood use, including wood waste, recycled wood, and wood from forests, divided by wood used from forests. However, such a cascade technique did not overvalue or undervalue the final balance; it only expanded the range of items or product groups included in the study. Thus, the final balance accounted for by-product flows, as well as indirect wood flows.

RESULTS AND DISCUSSION

Wood balance presents a global view of the resources and primary uses of roundwood in Slovakia (Tab. 2). The volume of domestic consumption (9.59 mil. m^3) was deducted from the roundwood production and foreign trade. Export amounted to 2.29 mil. m^3 and import 1.99 mil. m^3 million. Based on a simple calculation, domestic consumption was set at 7.3 mil. m^3.

Tab. 2 Wood Balance in the Slovak Republic.

Wood resources		Use of wood	
Roundwood production	7 448 000		
Roundwood import	1 999 850	Roundwood export	2 290 000
Recycled paper	141 113		
		Domestic consumption	7 298 963
Total resources	9 588 963	Total uses	9 588 963

Detailed identification of wood by-products used in Slovakia was done by designing the wood resource balance. Based on the answers of 57 respondents from the operations in the sawmilling and panel industry, the survey results represented 50% of the total sawnwood production in terms of volumes reported.

The primary input for sawmills is dominated by coniferous logs (Fig. 1), and naturally, the main product is sawnwood (Fig. 2). Coniferous (79.4%) and non-coniferous (14.0%) logs are the main production inputs. Other inputs (almost 6%) consisted of sawnwood and veneer for the associated production activities of sawmills; offcuts, logging residues, sawdust, and wood chips are used mainly for the energy for internal use or the production of pellets and wood briquettes. Over 52% of final sawmill production was sawnwood. Other products represented by pallets, crates, floors, roofs, fences, furniture parts, handles, facing, etc. accounted for 5.8%. The rest of the production (42.1%) consisted of by-products, part of which was used to produce energy pellets, briquettes and split firewood.

According to the survey data, the production volume was converted to the whole country production of sawnowood using a coefficient of 2.031. The coefficient results from the share of the sawnwood output in the SR recorded in the JFSQ (Joint Forest Sector Questionnaire) 2020 (e.g. 1.5 mil. m3) and the share of production according to the survey (0.75 mil. m3).

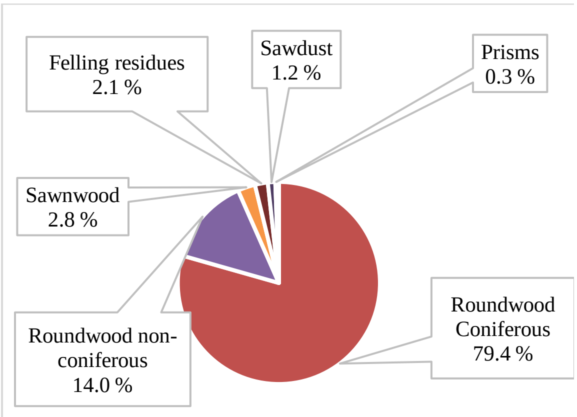

Fig. 1 Structure of inputs to sawmills

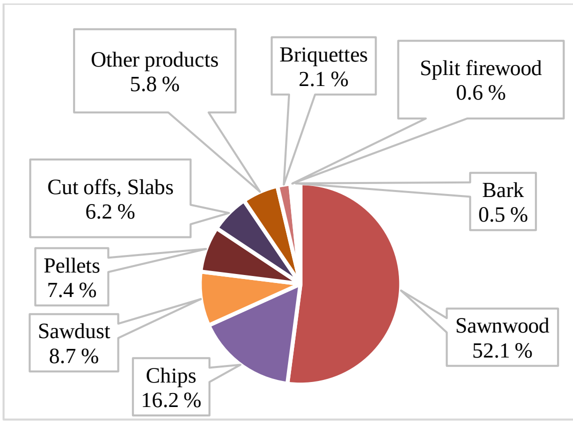

Fig. 2 Structure of outputs from sawmills

The share of coniferous roundwood as input raw material in the wood-based panel production plants was 35.8% and that of broadleaved 5.4%. Recycled wood had a significantly high share of 29.0%, sawdust and shavings 14.4%, and wood chips 10.7%. The lowest share was 4.8% for cuttings. According to the survey, up to 98.4% of the final products were produced in wood-based materials from the volume of production inputs, namely, veneers, plywood, and agglomerated materials. By-products (peeling residues, peeling core, bark, wood chips, and wood dust) accounted for only 1.6 % of the total volume of production inputs. The production volumes of wood-based materials in the plants participating in the survey were converted to production in the whole country by a factor of 0.725. The value of the coefficient was derived from the share of wood-based materials production according to the UNECE (1.05 mil. m^3) and the share of production according to the survey (1.45 mil. m^3).

The total volume of by-products in 2020 was 1.25 mil. m^3. Out of this, 61.2% was used for energy production and 38.8% was used for further industrial utilisation (Fig. 3). Among the most produced were chips (477,000 m^3) and sawdust (255,000 m^3).

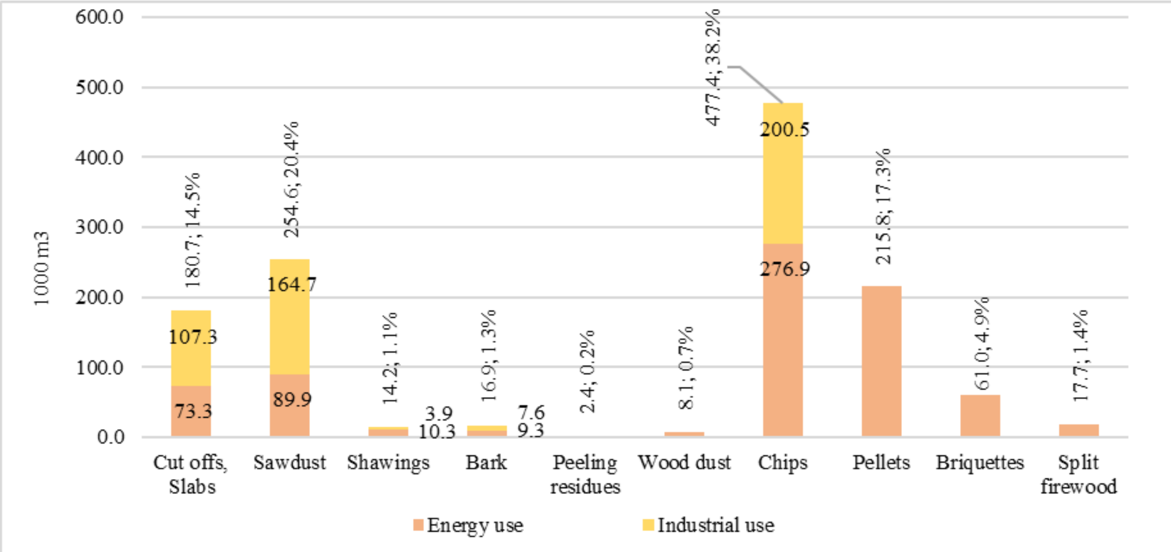

Fig. 3 Structure of by-products use by sectors.

Fig. 4 shows the production of by-products broken down according to their use for energy (37.7%), in industrial use (38.8%) and for energy purposes through processed energy wood such as pellets, briquettes, and split firewood (23.5%).

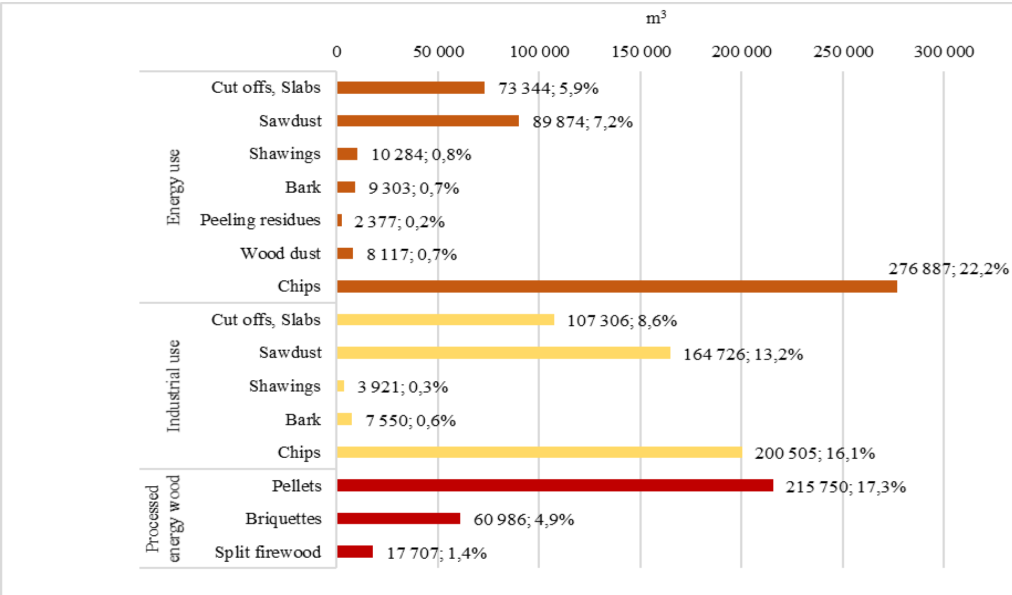

Fig. 4 Structure of by-products use by products.

A cascade coefficient can express the indirect wood flows. It describes the reuse of wood generated on the use side and returned to the resource side. The coefficient is calculated as the ratio of total wood supplies e.g. 9.536 mil. m^3 in 2020 (woody biomass from forest, recycled material, by-products and processed energy wood) and the volume of domestic consumption of roundwood e.g. 7.158 mil. m^3 in 2020. The value of the calculated cascade coefficient was 1.332 (Table 3). A better alternative to calculating the cascade coefficient is to remove processed energy wood from the source side and produced fuel wood from the use side. This approach captures the desired increase in the use of by-products for further industrial processing, namely for producing wood-based panels, pulp and paper. This also extends the carbon fixation time of wood products and delays the end of the life cycle of wood through its combustion with carbon emissions to the atmosphere. In this case, the share of total resources in 2020 (woody biomass from forests, recycled material and by-products used for further industrial processing) would be 7.254 mil. m^3 and the domestic consumption of raw wood in 2020, excluding fuel wood, will be 6.629 mil. m^3. The value of the cascade coefficient calculated this way is 1.094.

Tab. 3 Calculation of the value of the cascade coefficient including resources and by-products for the industry and energy sector.

Wood biomass from the forests	Coniferous logs	2 726 670	2 726 670
	Non-coniferous logs	1 386 620	1 386 620
	Pulpwood and other industrial roundwood	2 515 830	2 515 830
	Fuelwood	528 730	528 730
Recycled material	Recycled wood and paper	141 113	
By-products	Cut-offs, slabs, edge boards	180 650	
	Sawdust	254 600	
	Shavings	14 205	
	Bark	16 853	
	Peeling residues, wood cores	2 377	
	Wood dust	8 117	
	Chips	477 392	
	Black liquor	988 467	
Processed energy wood	Pellets	215 750	
	Briquets	60 986	
	Split firewood	17 707	
Total		*9 536 067*	*7 157 850*
Cascade coefficient		1.332	

Explanatory notes:
1. Consumption of raw timber in the SR in 2020, excluding post-harvest residues, was 7.158 million m^3 (Green Report 2020).
2. The volume of recycled wood and paper that entered as a source of production was 0.141 million m^3 (processed from sources for 2020 published in the Pulp and Paper Industry Report of the SR in 2021)
3. Volume of by-products (0.954 million m^3) returning back into industrial production or energy production as a resource after primary processing (NFC, questionnaire survey 2022)
4. Black Liguer (processed from 2020 sources published in the Pulp and Paper Industry Report 2021).
5. The volume of processed energy wood (pellets, briquettes and chipped wood) in 2020 was 0.294 million m^3 (NFC, questionnaire survey 2022).

In recent years, using wood for energy production has become increasingly important. Wood is increasingly used as a fuel in both internal and external energy production facilities, and it also serves as an important source of heat in households. These same wood species and wood residues can also be used to produce a variety of wood products, thus acting as substitutes. As stated by Mantau (2015), industrial by-products, including those derived from sawmilling and panel production and black liqueur from pulp milling, collectively constitute 38.6% of the total wood flows in Europe.

Market conditions for roundwood producers are strongly influenced by the availability of wood resources, legislative frameworks, voluntary international agreements and global initiatives for sustainable forest management. On the other hand, by-products receive less attention in political strategies, and a clear target for their use needs to be present. The EU's Circular Economy Strategy is the first to identify the purpose of explicitly by-product uses. To some extent, by-products play a role as a renewable source in the EU's Bioeconomy Strategy (European Commission, 2018).

These factors directly influence the supply of renewable wood resources. At the same time, policies that prefer the use of renewable raw materials stimulate the demand for energy wood. Wood, traditionally used for wood production, is now also increasingly in energy demand, leading to price increases.

As previously stated, the primary distinction between the wood balance and the wood resource balance is the integration of wood waste into the calculations, which increases the total resources to 12 million m^3. The results of this analysis can be compared with those of Mantau (2010), who estimated the total wood resource potential in the Slovak Republic, including imports, at 14.8 million m^3. The discrepancies between these estimates can be attributed primarily to the disparate values of wood waste reported in the questionnaires and different developments in wood production in particular periods. In our investigation, for instance, the production of black liquor was found to be 0.8 million m^3 lower, and the output of sawn timber and pulpwood was approximately 1 million m^3 lower than the figures reported by Mantau (2010).

Due to the constraints posed by market structure, the utilisation patterns of by-products could play at least as significant a role in climate change mitigation as wood construction.

CONCLUSION

The study confirmed that the wood resource balance approach used to identify and quantify wood material flows represents a significant tool for the evaluation of wood products' contribution to climate change mitigation. For determining domestic wood consumption and thus the wood cascade coefficient value calculation, the volumes of foreign wood trade are significant variables as exports account for almost 31% of domestic production, and imports account for more than 27% of domestic consumption.

Due to the availability of statistical data on by-product production and utilisation, a sampling-based market survey was used to collect such data and define the main use patterns. Findings show that almost 50% of all products from the sawmills enter by-product streams and are further available for utilisation either as a material or energy source. Over 60% of by-products, dominated by chips, are used for energy production. Finally, the wood cascade coefficient indicating the repeated use of wood was 1.33.

The value of the cascade coefficient without considering fuel wood volumes was 1.09. Such calculation allows a better expression of the desirability of increasing the use of by-products for further industrial processing, especially for products with a longer lifetime. This would thereby extend the carbon fixation time in the HWP and delay the end of the life cycle of wood through its combustion, which is associated with carbon emissions to the atmosphere.

The results focused on the approximation of by-product production for the conditions of the whole Slovak Republic and the calculation of cascade coefficient values. Available timber resources, legislation, voluntary international agreements, and global sustainable forestry initiatives and policies heavily regulate current market conditions for the forest-based sector. For this reason, wood flows and the value of the cascade coefficient can alternate every year. However, the study can serve as background material and measures for optimising the current use of wood and wood by-products by principles of the circular bioeconomy and cascade wood utilisation.

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