Resources, Conservation and Recycling

Material flow analysis of forest biomass in Portugal to support a circular bioeconomy

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Highlights

- MFA for paper, panels, sawmill and energy (pellets, charcoal and power plants).
- Assessment of cascade factor, MCI, recovery rate, recycled input rate.
- Only 25% of consumed forest biomass was incorporated in final products.
- Panels sector had the highest CF and paper sector the highest MCI.
- Cascade factor and MCI are complementary indicators of circularity.

Abstract

A comprehensive understanding of how resources are utilized is required to support a circular bioeconomy. This article presents the first systematic assessment of forest biomass flows and stocks in Portugal and analyzes circularity and resource efficiency through a comprehensive set of indicators, while providing recommendations for their use and improvement in different contexts. A Material Flow Analysis was developed for 2015, including paper, wood panels, furniture, carpentry, packaging, other woodwork, and energy (firewood, pellets, charcoal, electricity, heat), addressing uncertainty. Material flow analysis indicators (e.g., domestic material consumption) and circularity/resource efficiency indicators (cascade factor, material circularity indicator, recycled input, recovery rate) were assessed. In 2015, 49% of forest biomass was used for energy and 51% for material production. The wood sector in Portugal is heterogeneous regarding circularity. Paper and wood packaging were the most recycled products (highest material circularity indicator: 0.49 and recovery rate: 54%), while the panels sector used the most industrial residues (highest cascade factor: 3.78). The indicators analyzed provided a complementary assessment of circularity, giving both system wide (cascade factor) and sector- (cascade factor, recycled input rate, recovery rate) or product-based (material circularity indicator) views. Cascade factor permits an analysis of the whole system and of separate sectors, and an assessment of post-consumer and industrial residues, and both material and energy use. Material circularity indicator considers closed- and open-loop recycling of post-consumer residues, being complementary to the cascade factor. Indicators providing complementary perspectives are important to capture multiple types of resource use and valorization within the bioeconomy system.

Keywords: Material flow analysis (MFA), Circular economy, Cascade factor (CF), Material Circularity Indicator (MCI), wood

1. Introduction

Circular bioeconomy is a recent concept defined as the intersection of bioeconomy and circular economy (Carus & Dammer, 2018). It includes the use of biomass in a sustainable way and the valorization of biomass resources efficiently within the production chain. In addition, it incentivizes the utilization of residues and post-consumption wastes and the use of circularity concepts, such as cascading, to optimize the lifespan of biomass use (Stegmann et al., 2020).

Forest biomass (trees, including trunk, bark, branches, needles, leaves, roots) is the main source of biomass not competing with food supply in Continental Europe (Hetemäki et al., 2017) and an important sector in the bioeconomy strategy (European Commission, 2018). High demand for forest biomass as a material and energy source has led to an increasing competition between industries and the need to improve circularity/resource efficiency. A comprehensive understanding of the whole forest-based system and of how forest biomass is being used is key to support a circular bioeconomy and can be performed following a material flow analysis (MFA) perspective.

MFA is defined as "a systematic assessment of material transfers and stocks within a system defined in space and time" (Brunner & Rechberger, 2004) and is used to understand systems and subsystems in a holistic and integrated way (Lenglet et al., 2017). An MFA of forest biomass allows for a comprehensive assessment of the whole forest-based sector, while differencing all sub-sectors involved, and can assist decision making in identifying potential changes in flows and sectors. MFA has been applied to assess forest biomass flows at various scales – global (Bais et al., 2015), continental (Mantau, 2012), national (Hashimoto et al., 2004; Lenglet et al., 2017; Mehr et al., 2018; Parobek et al., 2014) levels – and considering specific sectors (Van Ewijk et al., 2017). Only a few of these studies included an uncertainty analysis (Bais et al., 2015; Mehr et al., 2018; Van Ewijk et al., 2017); however, this is an important aspect, since it allows for transparency in relation to data availability, one of the limiting aspects of performing a successful MFA.

Few studies have assessed resource efficiency using indicators in MFA studies of wood. The notable exceptions are Mantau (2015), which assessed the cascade factor of the European wood sector, and Van Ewijk et al. (2017), which assessed the recovery rate and recycling input rate of the global paper and pulp sector. However, these studies tend to focus on a limited selection of indicators, which only analyze a component of the system, not allowing for a complete view. Furthermore, other indicators could be useful in an MFA context to assess circularity, such as the material circularity indicator (Ellen Macarthur Foundation, 2015). The circularity/resource efficiency can be evaluated through several perspectives requiring a variety of indicators to make sure that the entire system is being analyzed.

To the best of our knowledge, no MFA has been performed to analyze the forest biomass sector in Portugal. The exploration of forest biomass is a key component of the Portuguese economy, since the forest based industries represent 4.7% of the gross domestic product in 2017 and 10.2% of the total exports of the country, in 2018 (Direção-Geral das Atividades Económicas, 2019). Additionally, the bioeconomy represented 7% of the gross value added in 2017 and the circular economy 4.2%, both above the European Union average (Leitão et al., 2020). Moreover, about 35% of the Portuguese territory is covered by forest area (Direção-Geral das Atividades Económicas, 2017). An MFA can facilitate process optimization, cascade use, assessment of recycling metrics, and improve the management and sustainability of forest biomass resources.

The main objective of this study is to perform a systematic analysis of forest biomass flows and stocks in Portugal as well as analyze circularity and resource efficiency to support a circular bioeconomy. A systematic MFA for forest biomass addresses flows and stocks connected to the forest biomass system and the interactions between its sectors, which supports the implementation of circular bioeconomy strategies. Furthermore, a number of indicators are assessed (cascade factor (CF), material circularity indicator (MCI), recycled input rate (RIR) and recovery rate (RR)), to provide information on resource availability (e.g., virgin material, industrial residues, post-consumer residues), current state of the forest biomass system, and possible improvements towards promoting circularity in those sectors. A discussion and comparison of these indicators is performed and recommendations of how they can be used and improved to analyze circularity and resource efficiency in different contexts are provided. The analysis considers the entire life cycle of forest biomass from the extraction to the post-consumption of its products, including wood panels, pulp and paper, furniture, carpentry, wood packaging, and energy, and addressing uncertainty of those flows.

2. Materials and methods

2.1. Material flow analysis of forest biomass

An MFA of forest biomass flows in Portugal in 2015 (the most recent year for which the most complete statistical data was available) was performed. Figure 1 presents the full MFA model, including the system boundary, the processes included in the analysis, the forest biomass product chain and the interactions between sectors. The primary input flows considered correspond to above-ground forest biomass, such as logs and forest residues.

The MFA model is developed from a set of input data relating to processes, stocks and flows (raw materials, products, industrial residues, post-consumer products, imports and exports) and is divided in three main parts: (i) industrial processing, (ii) product use, and (iii) post-consumption. It includes primary to tertiary transformations and forestry products from sawn wood, carpentry, furniture, packaging, and other wood products, wood panels, wood chips and sawdust, industrial and forest residues, pulp and paper, as well as energy generation. Products (wood panels, paper, carpentry, furniture, packaging, and other woodwork) are used for a certain period of time and are discarded when they reach the end-of-life. Three destinations were considered for post-consumer products: recycling, energy recovery and landfilling. Energy generation includes the following pathways: electricity generation from forest residues in dedicated plants, electricity and heat generation in cogeneration plants, incineration of post-consumer products, firewood, charcoal production and pellet production. The analysis of forest biomass production, i.e. the biomass stock in the forest, was excluded and only the resources extracted in 2015 were analyzed. Each flow and stock in Figure 1 is described in Table S.1 and the sawmill subsystem is shown in more detail in Fig. S.1, both in the Supplementary Material (SM). STAN (O. Cencic & Rechberger, 2008) was the software selected to perform and analyze the MFA model.

The reference unit used is cubic meter of wood fiber equivalent (m^3(f)). This unit is commonly used in MFAs of forest biomass (Lenglet et al., 2017; Mantau, 2012). The volume of wood fiber equivalent corresponds to the volume of wood fiber content in the product when the fiber is in its saturation point (Lenglet et al., 2017). For each product, a conversion factor (which represents the amount of m^3(f) contained in one m^3 or tonne (t) of product), based on Lenglet et al. (2017) and Weimar (2011), was applied. Selecting m^3 or t of wood for the reference unit could have led to double counting or consistency issues (Lenglet et al., 2017), particularly for products like panels or paper that include other materials in their composition besides wood, which would be accounted for as wood (Lenglet et al., 2017).

2.2. Data collection and assumptions for estimating wood flows

The approach chosen for collecting information was top-down, complemented by a bottom-up approach. In most cases, the final products flows were calculated from data on forest biomass consumption for each of the sectors (top-down approach). In others, the consumption of virgin resources was calculated based on the flows of final products of the system (bottom-up approach). The use of these complementary approaches was implemented due to lack of information and to solve data inconsistencies in the construction of the MFA model. The main data sources for the inputs, outputs and trade of materials and products are shown in Table S.2 of the SM. Imports, exports, and some inputs and outputs (e.g. F2.15, F4.10) were converted from statistical data to the reference unit using conversion factors from Lenglet et al. (2017) and Weimar (2011) (Tables S.3 and S.4, SM).

Bark (F2.05 and F2.13) was accounted for as an industrial residue, which was mainly directed to energy recovery (dedicated plants) and, in some cases, used internally to generate energy for the processes (as in wood panel production). However, statistical data on roundwood flows by sector were provided under bark (FAO, 2019; ICNF, 2017). Therefore, a volume ratio (m^3 of wood/(m^3 of wood + bark)) of 0.88 (UNECE/FAO Timber Branch, 2010) was applied to these flows.

The residues generated in each process, excluding bark, were calculated by subtracting the main output (final product flow) from the input of raw material. In general, energy recovery was considered the destination of these residues. Some industries used these residues internally for heat generation for the process. In the case of the paper and wood panels sector, process residues (resulting from transformation processes) were used for cogeneration. The exception was F2.09 (residues from production of furniture, carpentry, packaging and others), which was also recycled as chips and sawdust to produce wood panels.

Due to lack of data on some processes, some assumptions were made to ensure that the MFA model was complete. The main assumptions regarding panels, pellets, furniture and other woodwork are presented in Section 5 of the SM.

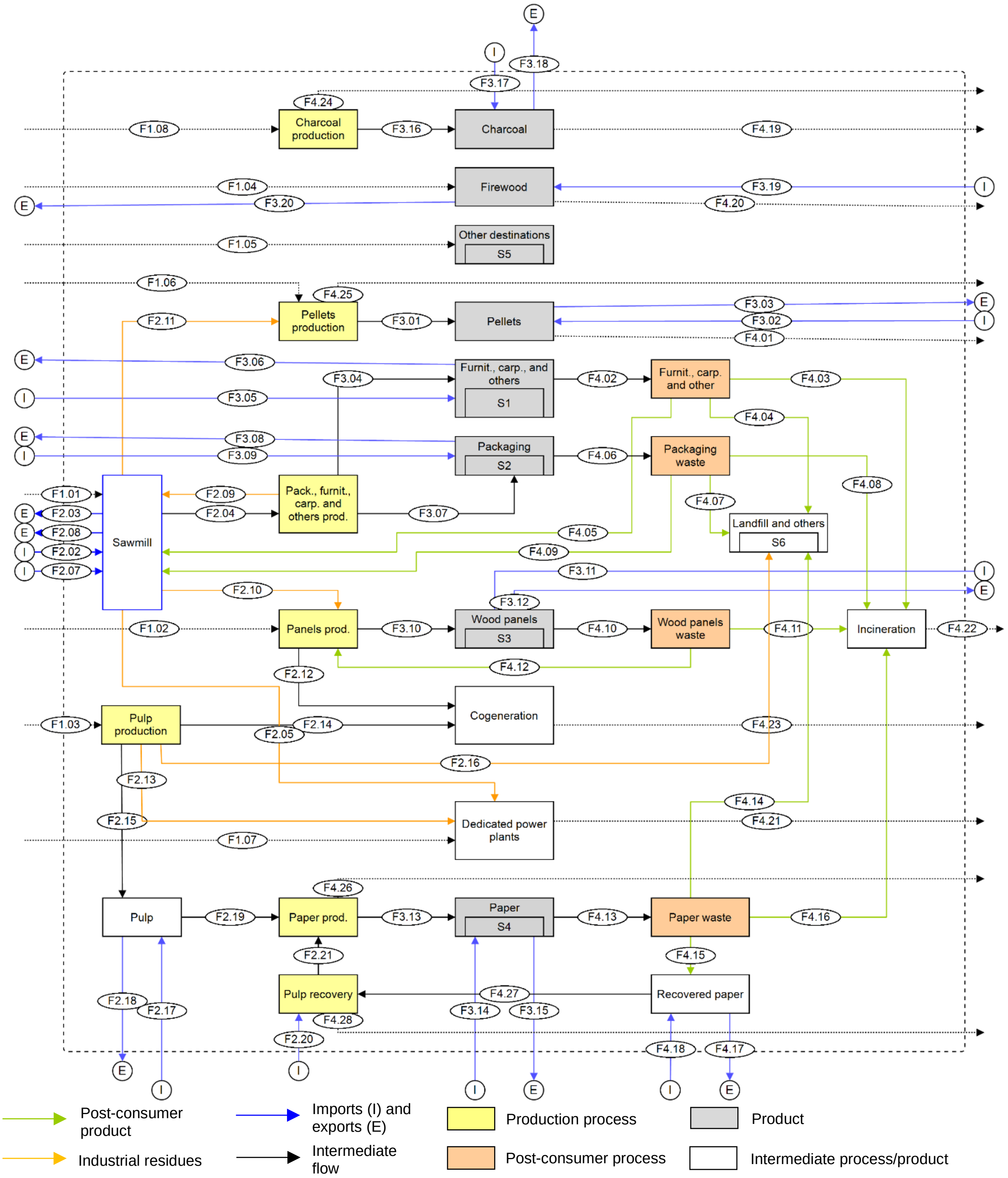

Figure 1. MFA model overview of forest biomass flows (F) and stocks (S). The description of each flow can be found in Table S.1 (SM). Pack., furnit., carp. and others prod.: Packaging, furniture, carpentry, and other woodwork production; Prod: production; Furnit., carp. and others: Furniture, carpentry, and other woodwork.

Final products can either be kept in stock (where they can be reused) or consumed and disposed of in the same year. In general, new products are added to stock annually and part of the older stock is discarded (net addition to stock). Products in stock included furniture, carpentry, other woodwork, packaging, panels and paper (S1-S6 in Fig.1). To calculate the addition to stock in 2015, the quantities discarded annually were estimated based on normal and Weibull distributions, depending on the products. For furniture, carpentry and other woodwork, a normal distribution was used, considering an average life span of 35 years, based on Brunet-Navarro et al. (2017), whereas for panels, the assumed life span was 25 years. In the case of packaging, a normal distribution was used considering an average service life of 3 years. For paper, a cumulative Weibull distribution was considered, based on Pivnenko et al. (2016). The parameters for both normal and Weibull distributions are presented in Tables S.6 and S.7 (SM).

Once the product reaches its end-of-life, it is either recycled, incinerated or landfilled. For paper, statistical data on the amount of recycled paper was available (FAO, 2019; ICNF, 2017), and it was assumed that 37.5% was sent to landfill (or other destinations) and 62.5% to incineration, with the exception of post-consumption sanitary/household paper, which was considered to be 100% landfilled or had other destinations (e.g. anaerobic digestion). For post-consumer wood panels, 10% were assumed to be recycled and incorporated into new panels and the remainder incinerated (Brunet-Navarro et al., 2017), 87% of wood packaging were recycled (Agência Portuguesa do Ambiente (APA), 2019). For the remaining products from sawnwood, a recycling rate of 30% was applied (Brunet-Navarro et al., 2017). Given the unavailability of data for the remainder post-consumption treatments, we considered that 20% was landfilled and 80% incinerated (i.e. 3% of post-consumption packaging was sent to landfill and 10% to incineration; 14% of furniture, carpentry and other woodwork was landfilled and 56% incinerated).

In addition to industrial production, part of the forest biomass was used for energy purposes, namely in dedicated power plants, cogeneration plants and for the production of pellets, charcoal and firewood. Biomass consumption in cogeneration and dedicated plants is shown in Tables S.8 and S.9 (SM). Cogeneration plants generated energy both for internal use and electricity for the grid. However, given the available data, it was not possible to allocate the biomass flows to each of these uses and only one aggregated flow was considered (F4.23). Both paper and panel industries generated energy in cogeneration plants. While, for panels, it was considered that all industrial waste could be recovered in cogeneration plants, in the paper sector, dedicated plants were also used to recover energy from various industrial residues, such as bark, black liquor and others (e.g. sludge and ash). Forest residues were also used for electricity generation in dedicated power plants and for charcoal production. Pellets (a mix of chips, sawdust and roundwood compressed into a final product) and firewood were both considered biomass for energy.

2.2.1. Uncertainty characterization

Uncertainty analysis of input data was performed following the approach described by Laner et al. (2016). This method, built according to the pedigree scheme, includes five indicators that are scored from 1 (good quality of data) to 4 (poor data quality) (Laner et al., 2016): (i) reliability, which assesses the documentation of data and its availability; (ii) completeness, which evaluates how complete the information is; (iii) temporal and geographical correlation, which relate to the possibility of mismatch between the year and location of the data available and those of the assessment; (iv) other correlations, which assesses other possible uncertainties not accounted for in the previous indicators. In addition, all indicators, except for reliability, are evaluated towards their levels of sensitivity, from high to low, depending on the influence of the indicator in the study.

Input data is considered to be normally distributed and the final value of uncertainty corresponds to the aggregation of the coefficients of variation (CV, standard deviation divided by mean) obtained for each indicator, represented in Eq.1 (Van Eygen et al., 2017). The uncertainty characterization of each flow is documented in Table S.10 in the SM.

$$CV_{total} = \sqrt{CV^2_{reliability} + CV^2_{completness} + CV^2_{geogr.corr.} + CV^2_{temp.corr.} + CV^2_{other\ corr.}} \quad \text{(Eq.1)}$$

Where,
CV_{total} is the total coefficient of variation (uncertainty);
$CV_{reliability}$ is the coefficient of variation of reliability;
$CV_{completeness}$ is the coefficient of variation of completeness;
$CV_{geographical\ correlation}$ is the coefficient of variation of geographical correlation;
$CV_{temporal\ correlation}$ is the coefficient of variation of temporal correlation;
$CV_{other\ correlations}$ is the coefficient of variation of other correlations.

Additionally, net addition to stock, 19 flows (e.g., F4.19-F4.26), and respective CVs were calculated using STAN, based on the mass balance principle. Furthermore, data reconciliation as implemented in STAN was performed to avoid error propagation (Oliver Cencic, 2016), which could alter the flows.

2.3. Indicators

Typical MFA indicators, such as domestic extraction (DE), direct material input (DMI), domestic material consumption (DMC), physical trade balance (PTB), net addition to stock (NAS), and domestic processed output (DPO) (Eurostat, 2001), were selected for the analysis of the MFA results (described in Section 2.3.1). Furthermore, multiple indicators assessing different aspects of circularity were also selected for analysis: cascade factor, material circularity indicator, recovery rate and recycling input rate (described in Sections 2.3.2-2.3.4). Table 1 presents the notation of the indicators.

Table 1. Indicators.

Symbol	Description
B^i	Virgin forest biomass input per sector *i* (m^3(f))
CF	Cascade factor (dimensionless)
C^{pn}	Cascade factor in wood panels (dimensionless)
C^{pp}	Cascade factor for pulps and paper (dimensionless)
C^t	Total cascade factor (dimensionless)
DE	Domestic extraction (Mm^3 (f))
DMC	Domestic material consumption (Mm^3 (f))
DMI	Direct material input (Mm^3 (f))
DPO	Domestic processed output (Mm^3 (f))
i	Sector (*t*: total; *pp*: pulp and paper; *pn*: panels)
j	Origin of residues (*p*: industrial process; *f*: post-consumer product)
k	Destination of residues (*p*: industrial process; *v*: energy recovery)
1	How are residues valorised (*m*: material; *e*: energy)
MCI	Material circularity indicator (dimensionless)
NAS	Net addition to stock (Mm^3 (f))

PTB	Physical trade balance (Mm^3 (f))
$R^i_{f,p,m}$	Post-consumer product (*f*) used in industrial processes (p) as material (m) (m^3(f))
$R^i_{f,v,e}$	Post-consumer product (*f*) for energy (v, e) (m^3(f))
$R^i_{p,p,e}$	Industrial residues (p) used in industrial processes (p) for energy (e) (m^3(f))
$R^i_{p,p,m}$	Industrial residues (p) used in industrial processes (p) as material (m) (m^3(f))
RIR	Recycled input rate (%)
RR	Recovery rate (%)

2.3.1. MFA indicators

DE corresponds to the amount of forest biomass extracted in Portugal annually and reflects the quantity of endogenous forest biomass consumed. DMI measures the direct input of all solid materials that have economic value, i.e. the amount of forest biomass extracted, and the associated imports (Eq. 2). DMI translates the total forest biomass balance for product processing.

DMI = DE + Imports (Eq. 2)

DMC is the balance between domestic extraction of raw materials, imports and exports of raw materials and goods (Eq. 3), distinguishing between what was consumed in Portugal and in other countries (exported). PTB is defined as the difference between imports and exports.

DMC = DE + Imports – Exports =DE + PTB (Eq. 3)

NAS measures the physical growth of the economy (EASAC, 2016). It translates the difference between what is added to stock each year and the quantity of material discarded in that year. DPO is the quantity of materials used in the country, before flowing into the environment (Eurostat, 2001), and includes emissions to air and water, wastes deposited in landfills and dissipative flows (Eq. 4).

DPO = emissions + waste + dissipative flows (Eq. 4)

2.3.2. Recovery rate and recycled input rate

Recycling is one way of reducing the consumption of virgin wood fiber. The recovery rate (RR) corresponds to the ratio between the amount of recycled products and the amount of products produced in the country in a given year (Eq. 5).

RR= Recycled products / production in Portugal (Eq.5)

The indicator recycled input rate (RIR) was suggested as an alternative to RR (Van Ewijk et al., 2017). RIR is the ratio between the input of recycled products and the total fiber input (Eq.6) (Van Ewijk et al., 2017). Total fiber input corresponds to the total input of virgin biomass in the sector plus recycled biomass. Both RR and RIR were calculated for the following products: paper, panels and sawnwood chain products.

RIR = Input of recycled products / Total input of fiber (Eq.6)

2.3.3. Cascade factor

Cascade use can be applied to improve efficiency and reduce environmental impacts associated with biomass extraction (Fehrenbach et al., 2017). Cascade use can be assessed through a product or a sector perspective (Mantau, 2015). A product cascade occurs when the material, e.g. forest biomass, is processed into a final product and, at the end of the product life, is used at least once more either for material or energy purposes. A sector cascade occurs when industrial residues and recycled materials are processed within a specific industrial sector and assesses the utilization of the biomass for multiple products. The latter is the cascade assessed in this study.

The cascade factor (CF) was calculated for the entire system (total CF) and for the panels and paper industries, for 2015 (Equations 7-10, adapted from Mantau, 2015). The analysis considers the residues of industrial processes (cascade in wood residues, Equation 7), recycled post-consumer products (cascade in recycled products, Equation 8), both of the above (cascade in products, Equation 9), and the whole system (total CF, Equation 10).

Cascade in wood residues: $(B^{i} + \boldsymbol{R^{i}_{p,p,m}}) / B^{i}$ (Eq.7)

Cascade in recycled products: $(B^{t} + \boldsymbol{R^{i}_{f,p,m}}) / B^{t}$ (Eq.8)

Cascade in products: $(B^{i} + \boldsymbol{R^{i}_{p,p,m}} + \boldsymbol{R^{i}_{f,p,m}}) / B^{i}$ (Eq.9)

Total CF: $(B^{t} + \boldsymbol{R^{i}_{p,p,m}} + \boldsymbol{R^{i}_{f,p,m}} + \boldsymbol{R^{t}_{f,v,e}} + \boldsymbol{R^{t}_{p,p,e}}) / B^{t}$ (Eq.10)

The CF is always greater than or equal to 1: (i) it is equal to 1 when virgin raw material (no transformations, B^{i}) is used once over its useful life; (ii) it is greater than 1 when (part) of the virgin raw material is used at least once (as material or source of energy). This means that the more industrial residues and recycled products are used, the higher the CF.

2.3.4. Material Circularity Indicator

To explore and improve circularity within products and industries, the Ellen MacArthur Foundation developed the Material Circularity Indicator (MCI). This indicator measures the circularity of material flows of a product or a company, taking into account the lifespan of the product when compared to the industry average (Ellen Macarthur Foundation, 2015). The main parameters are the quantity of product collected for recycling and reuse, and the efficiency of the recycling process. The lifespan of the products, which indicates how long a product is used in comparison with the industry average, was considered according to Table S.7 (SM). The recycling efficiencies of the various products were either calculated from the MFA results (for paper) or a default value (80%) was considered when data was lacking (wood panels, sawnwood chain). Product reuse was not considered due to unavailability of data. The calculation of the indicator is performed using an excel spreadsheet (Ellen Macarthur Foundation, 2020). The MCI varies between 0 and 1, with 0 representing a linear system (that uses only virgin feedstock and no recycling) and 1 a fully circular system.

3. Results and discussion

3.1. MFA of forest biomass in Portugal

The MFA of forest biomass in Portugal for 2015 is shown in Figure 2. Results are given in Mm^3(f) with the corresponding standard deviation. Domestic extraction (DE) was 14.9±2% Mm^3 (f). Additionally, 7.1±2% Mm^3(f) of forest biomass were imported, leading to a direct material input (DMI) of 22.0±3% Mm^3(f). Exports were 10.5±2% Mm^3(f), resulting in a domestic material consumption

(DMC) of 11.5±3% Mm^3(f). Portugal was a net exporter of wood-based products (the physical trade balance (PTB) was -3.4±5% Mm^3(f)), producing almost the same volume of products for foreign markets as for the national market. Although the amount of biomass extracted in the country would have been enough to supply domestic consumption (DE>DMC), the exported goods required the import of biomass to balance demand. The net addition to stock (NAS) was positive for panels and packaging, but negative for the other sectors: paper and furniture, carpentry and other woodwork. This means that there were more post-consumer products of paper, furniture, carpentry and other woodwork leaving stock than new products entering it; while for panels and packaging, consumption in 2015 surpassed the amount of end-of-life products. The paper industry, although the highest consumer of biomass, had the lowest NAS, because 5% of the paper produced was sanitary and packaging paper, which was assumed to be discarded in the same year of production. The domestic processed output (DPO) was 11.3±5% Mm^3(f) in 2015, representing 98.5% of the DMC. This high percentage means that the amount of biomass discarded after consumption in 2015, corresponds to almost all the biomass used for production in that year.

In 2015, 18.0±8% Mm^3(f) of forest biomass was consumed in Portugal. From this, 49% were directly used for energy and 51% for material production, of which about half (25%) was incorporated into final products (the remaining were residues of the industrial process). These numbers reveal that the lifespan of most biomass resources used in Portugal is low. One tenth of forest biomass consumed were forest residues used in dedicated power plants and charcoal production. The consumption of forest residues was not provided in the official statistics; however, the value calculated is in accordance with Ferreira et al. (2017), which estimated an availability of forest residues of 2 Mt per year (about 1.8 Mm^3(f)). The estimated amount of roundwood used in 2015 was 16.2±8% Mm^3(f); however, the reported amount was 15.4 Mm^3(f) (ICNF, 2017), which leaves a deficit of 0.84 Mm^3(f) (5%) unreported, albeit within the uncertainty range.

Roundwood consumed by the paper industry was 9.7±14% Mm^3(f), with about 60% of the forest biomass incorporated in pulp (5.8±2% Mm^3(f)) and the remainder used as cogeneration fuel (through energy recovery of industrial residues). Cogeneration fuel in the paper industry accounted for 65% of the total forest biomass sent to cogeneration plants.

The panel sector consumed 3±5% Mm^3(f) of forest biomass (73% industrial residues, including chips and sawdust, and 27% roundwood), of which 1.7±2% Mm^3(f) were incorporated in the products and the remainder was used as cogeneration fuel for internal consumption or electricity generation to the national grid. Approximately 13% of the total amount of roundwood consumed was used for production of furniture, carpentry, other woodwork, packaging and chips (Fig. S.2, SM). Charcoal and dedicated power plants consumed 1.8±8% Mm^3(f) of forest residues, 94% of which was used in the latter. Pellets production used 2.6±14% Mm^3(f) of forest biomass, distributed between roundwood (86%) and chips (14%), which is consistent with the values reported in Quinteiro et al. (2019) for two pellet plants in Portugal (83% roundwood and 17% residues).

In 2015, 2.1±6% Mm^3(f) (54%) of post-consumer wood products were recycled (more than 80% were recycled paper). Incineration was the destination of 1.0±26% Mm^3(f) of post-consumer products, the majority coming from post-consumer wood panels. Lastly, landfill disposal accounted for 0.7±196% Mm^3(f), mostly from products from the sawnwood chain and pulp production.

3.1.1. Uncertainty analysis

The uncertainty range of the flows depends on the quality of data, which varies with the life stage of each product. Data uncertainty for roundwood flows is low (±2% to ±15%) and is mainly due to the addition of bark to the original flows (i.e. undetailed and undescribed data). At the production stage, the uncertainty increased, due to uncertainty in production efficiencies and generation of residues (±2% to ±655%). Towards the end of the product life cycle, the uncertainty increased further because of low availability of data about post-consumer products and their destination (uncertainties from ±2% to ±329%). Whilst data for recycling was generally available, resulting in lower uncertainty (±2% to ±20%), data about landfill disposal (±75% to ±655%) and incineration (±23% to ±175%) was much scarcer, increasing the uncertainty. Import and export data were well defined resulting in low uncertainty. Uncertainty ranges for NAS were calculated in STAN, resulting in uncertainties of ±20% for paper production, ±30% for panels, ±724% for wood packaging and ±2405% for furniture, carpentry and other woodwork. In all cases, the high uncertainty is associated with the flows with low magnitude (< 414 Mm^3(f)). Furthermore, data reconciliation was performed for 17 flows due to the existence of more equations than unknowns. Notwithstanding, no significant changes were observed.

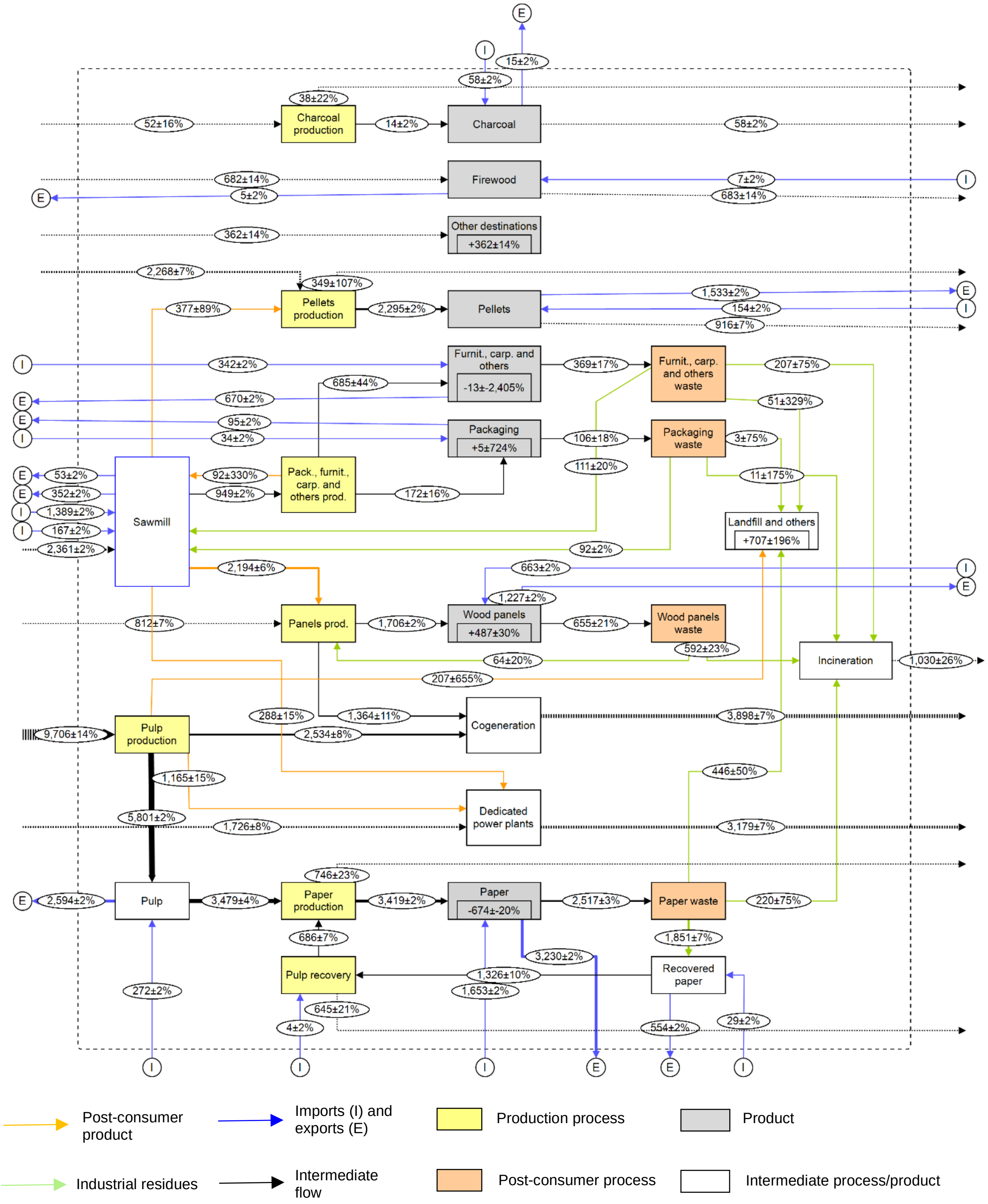

Figure 2. Material flow analysis of forest biomass in Portugal, in 2015 (all flows and stocks are in Mm^3 (f)) of forest biomass). Pack., furnit., carp. and others prod.: Packaging, furniture, carpentry, and other woodwork production; Prod: production; Furnit., carp. and others: Furniture, carpentry, and other woodwork.

3.1. Recovery rate and recycling input rate

The total recovery rate (RR) in 2015 indicates that the equivalent of 27% of wood-based products produced in 2015 was recycled that year. The recycled input rate (RIR) revealed that only 7% of the total fibre input to the various sectors was recovered and recycled fibre. The RR for paper in 2015 was 39%, i.e. the amount of recycled paper in 2015 corresponded to 39% of the paper produced in that year (F4.27/F3.13). The RIR for paper was 6%, i.e., from the total fibre input to this sector only 6% was recovered and recycled fibre (F2.21/(F1.03+F2.17+F2.20+ F2.21)). However, in the Portuguese pulp and paper sector, biomass consumed may be higher than the amount needed strictly for paper production, as energy generation to the grid is common in most industries and has specific economic incentives. As RIR is sensitive to forest biomass input and it was not possible to differentiate between how much biomass was used to produce paper and how much was consumed solely for the purpose of generating electricity for sale, the value of the fibre input may be overestimated, which leads to a possibly underestimated RIR.

The RR for panels was 4% (F4.12/F3.10) and the RIR was 8%, meaning that from the total input of biomass (F1.02+F2.10+F4.12), only 8% was recycled fibre, part coming from panel recycling (F4.12) and the rest from sawmill industry (recycling of packaging, furniture, carpentry and other woodwork, corresponding to 7.7% of F2.10). The low values are due to the industry high production but low post-consumption recycling. In the sawnwood chain, the combined RR for furniture, carpentry and other woodwork was 16% (F4.05/F3.4), while for packaging it was 54% (F4.09/F3.07). In these two cases, there is no input of recycled products, leading to a null RIR; however, the RR is considerable, particularly for packaging, because post consumption products are used and transformed in different sectors (open-loop recycling), which shows the importance of considering both indicators.

The sectors with the highest RR (wood packaging: 54%; paper: 39%) were the ones that diverted the highest share of post-consumption waste to recycling (87% and 84%, respectively). Although there is still room for improvement on this indicator in all sectors, even with 100% recycling of post-consumption waste, RR would not surpass 62% for wood packaging, 54% for furniture and other woodwork, 43% for paper, and 27% for panels. The main reason is that a high share of production was exported and, therefore, not recycled within the country. This means that the RR indicator does not convey the effective recycling potential within the system boundary. To circumvent this, we suggest calculating RR considering only the domestic consumption (of biomass input to the production of products consumed in the country), instead of total production. From this perspective, RR would be 83% for packaging and 72% for paper, which shows the influence of exports in these sectors and that most of post-consumption materials in Portugal were actually recovered and recycled into wood-based material production. The RR for furniture, carpentry and other woodwork would double (31%). For panels, RR would increase only to 6%, because the quantity exported was not significant when compared with domestic consumption. The total RR of the system would be 46%.

RIR values were very low in all sectors, due to low incorporation of recycled wood. For the panel sector, if all post-consumption products were recycled, RIR would increase by 2.1% by each 10% of post-consumption material added to production, to a maximum RIR of 26%. For paper, the increase would be smaller, reaching a maximum RIR of 7.2%. The total RIR of the system could increase to 7%. The limited improvement potential of this indicator is compromised by the limited availability of post-consumption materials (e.g. due to a high export rate), low recycling efficiencies, as well as the low recyclability potential of some materials (e.g. due to the use of additives).

3.2. Cascade factor

The cascade factors (CF) are presented in Table 2 and detailed in Table S.11. The cascade in industrial residues (C^t in industrial residues) for the whole system (1.15±16%) was higher than for recycled products (C^t in recycled products: 1.09±8%), as more industrial residues were used for material production than recycled products. The total CF (C^t: 1.59±10%) was higher than the cascade in products (1.24±13%), because of the use of wood residues for energy, particularly industrial residues, which was not accounted for in the CF in products. The cascade in recycled products is the lowest, meaning that recycling can be improved, with potential to more utilization of post-consumption residues. Moreover, since all materials not incorporated into the final products were assumed to be used for energy, but may have other destinations, the amount of biomass for energy ($\boldsymbol{R_{p,p,e}}$) and, consequently, the total CF may be overestimated.

Sector cascades were calculated for paper and wood panels, since these are the only sectors with material cascades. The quantity of forest biomass consumed by each sector was very different: the paper sector consumed 12 times more forest biomass than the panel sector (see Table 2). In the paper sector, residues from industrial processes were considered to be used for energy generation rather than as material, so $R_{p,p,m}$ was zero, resulting in a cascade of 1 for industrial residues. The cascade in products was higher for panels (C^{pn}: 3.78±18%). A sector with a high cascade factor means that it is valorising a large share of its industrial residues and recycled products for the manufacturing of new products; therefore, applying circular economy strategies and reducing the extractions of raw materials. The paper industry shifted its industrial residues for energy, which led to a lower cascade in products (C^{pp}) (1.14±14%). On the other hand, recycling was lower in the panel than in the paper industries, due to technical issues that make panels recycling difficult. Additionally, paper recycling is actively promoted and there is a selective collection system for paper waste.

Table 2. Cascade factor for the total system (t), and pulp and paper (pp) and panel (pn) sectors.

	Total	***Pulp and paper***	***Panels***
	i=t	***i=pp***	***i=pn***
C^i in industrial residues	1.15±16%	1.00	3.49±10%
C^i in recycled products	1.09±8%	1.14±14%	1.29±21%
C^i in products	1.24±13%	1.14±14%	3.78±18%
Total C^i factor	1.59±10%	n.a.	n.a.

n.a. not applicable

3.3. Material circularity indicator

The material circularity indicator (MCI) calculated for wood-based products is shown in Table 3. The MCI for paper was divided into two groups: (1) sanitary/household paper and (2) other types of paper. This division was necessary because the sanitary paper was used linearly, i.e., produced, used and disposed of in landfill, without the possibility of recycling, and, therefore, the MCI was zero. The MCI for the other papers was 0.49±4%. The high MCI is due to high recycling rates, which result in materials that are used for longer lifespans, and high recycling efficiency (52%: F2.21/F4.27), resulting in products that are used through more than one life cycle before being disposed of or used for energy recovery. Conversely, wood panels have a high lifespan, but a low recycling rate (10%). The MCI for wood panels was 0.17±14%, indicating very low circularity. Although 73% of biomass input for panel production was wood chips, only 8% of these were recycled (i.e. originated from post-consumer panels and other products from the sawmill industry); the remainder were industrial residues, not accounted for in the MCI. The sawnwood chain products were divided into two groups according to their lifespan and recycling rates: (1) furniture, carpentry and other woodwork, and (2) packaging. Both groups only use virgin feedstock for their production. The results for the first group revealed a higher circularity (0.34±55%) than packaging (0.28±21%), because of the longer lifespan. Due to aggregation of data for wood panels and the sawnwood chain, the default value for recycling efficiencies was considered to be 80%, adding more uncertainty to the results.

Table 3. Material circularity indicator (MCI) for wood-based products in Portugal in 2015.

Product	Material circularity indicator
Sanitary paper	0
Other paper	0.49±4%
Panels	0.17±14%
Furniture, carpentry and other woodwork	0.34±55%
Packaging	0.28±21%

3.4. Discussion and comparison of indicators for the assessment of circularity

The indicators presented in Section 2.3 evaluate different aspects and provide a complementary picture of the circularity of the system. RIR and CF focus on inputs to the system, whilst RR and MCI focus on an output perspective, i.e. assess post-consumption recycling. Table 4 summarizes the main advantages and disadvantages of each indicator, based on their application to the forest sector in Portugal. While RR and RIR are both recycling-based indicators, RR provides information on the recovery of post-consumption materials relatively to material production (output) instead of material use (input). As show in Section 3.2, RR can be improved to provide a more realistic perspective of the recycling potential if a domestic consumption perspective is used. On the other hand, RIR, presents a more complete analysis of the efficiency of the use of resources in the industry by giving important information in terms of how post-consumption material is effectively used in production, and, consequently, how it substitutes raw material, accounting for the efficiency of the recycling process and production losses. However, RIR, as a production-based indicator, only accounts for closed-loop recycling, and therefore, it is mostly relevant when recycled material is used in production, providing limited information for products that have no recycled content (e.g., furniture, carpentry and packaging). Since it also ignores the use of industrial residues, RIR does not account for an important part of the system.

The CF assesses the use of all types of residual biomass and can be disaggregated into cascade of recycled products and cascade in industrial residues, allowing for a separate analysis of recycling of post-consumption products and use of industrial residues, and providing additional information in comparison with RIR. This is evident for the panels industry, for which the CF was the highest, while RIR was low, because this sector uses a large amount of industrial residues in their production. Therefore, the role of the panel industry in the valorisation of industrial residues is only captured with the CF. Notwithstanding, its calculation requires a full MFA of the system, particularly for the total CF.

Conversely to RIR and CF, the MCI focuses on recycling at the end-of-life and does not consider recycling between industrial sectors. Nevertheless, it accounts for both open- and closed-loop recycling, in opposition to both RIR and CF. If an industry does not use any recycled fibre or recycled fibre coming from its own end-of-life products, CF is one and RIR is zero, respectively; however, if its post-consumer residues are recycled by other sectors as an open-loop recycling system (e.g., furniture, carpentry, wood packaging and other woodwork), then MCI is positive. This means that RIR and CF are more focused on the industry and the use of the materials within the industry, while MCI assesses the circularity of a material that can be used through several different industries. One of the advantages of MCI is that it explicitly accounts for recycling efficiencies; however, these can be hard to assess, even when performing an MFA, because it requires data to be highly desegregated by sector.

4. Conclusions

The MFA of the wood sector in Portugal provides a comprehensive picture of how forest biomass resources are used within the country. The MFA is key to calculate and assess circularity indicators, because it provides new information about wood flows not available directly from official statistics, such as post-consumption residues (recovery rate (RR), cascade factor (CF)) and recycled input (recycled input rate (RIR), material circularity index (MCI)). Moreover, for sectors with a higher level of process disaggregation, such as the pulp and paper sector, the MFA allows for the calculation of recycling efficiencies for the assessment of the MCI.

The wood sector in Portugal is heterogeneous with regard to circularity, showing multiple types of resource use and valorization within the system. More than half of the forest biomass extracted in 2015 was used directly for material purposes and the remaining for energy. Nevertheless, only 25% of the forest biomass was incorporated into final products. Paper and wood packaging were the most recycled products within the system, but while paper was recycled back to the pulp and paper industry, post-consumer residues from wood packaging were used by other sectors (e.g., panels and pellets). In terms of circularity of industrial residues, the panels sector had the most promising results, since it used residues from several other industries in its production. Increasing recycling of post-consumer panels, wood packaging, furniture and carpentry products would reduce significantly the extraction of raw materials, particularly in the panels sector. Despite being the sector with the highest recovery rate, the pulp and paper sector was also the one that used the highest amount of virgin feedstock, both for material and energy purposes (the latter resulting mostly from the valorization of residues of the industrial process). Increasing recovery rates of paper products alone would entail limited improvements in virgin feedstock dependency, as availability of post-consumption paper is a function of paper consumption within the country, which corresponds to about half of paper production.

A discussion and comparison of the indicators for the assessment of circularity, including recommendations for improving and use of indicators in different contexts, was also presented. The indicators provided a complementary assessment of the circularity of the system, giving either a system wide view (CF) or a sector- (CF, RIR, RR) or product-based (MCI) view. CF gave the most complete assessment as it can either be applied to the whole system or to separate sectors, besides integrating both post-consumer and industrial residues, as well as both material and energy uses. In fact, the use of industrial residues in the wood sector in Portugal in 2015 was higher than the use of post-consumption residues, and these were mostly used for energy generation rather than as material. However, CF is limited for assessing sectors that use exclusively virgin material but produce products that are recycled at the end-of-life in other sectors, such as the furniture sector, because it takes an input focus. For those cases, the MCI is useful as it takes an output perspective and considers both closed- and open-loop recycling of post-consumer residues.

Table 4. Advantages and drawbacks of selected indicators to assess circularity

Indicator	What it measures	Advantages	Drawbacks
Recycling rate	Compares the end-of-life products sent to recycling (both closed loop and open loop) to total production (output perspective).	Can be adapted to production-based or consumption-based assessments, depending on the context (e.g., net exporters, net importers, no commercial trade).	Does not account for recycling efficiencies; is very dependent on the trade balance.
Recycled input rate	Share of recycled input in production (post-consumer products from the sector - closed loop - or from other sectors - open loop); Gives important information in terms of how post-consumption material is effectively used in production, and consequently how it substitutes raw material (input perspective).	Considers the efficiency of the recycling process and production losses.	Ignores industrial residues and open loop recycling of the post-consumer residues of the sector (i.e. post-consumer products that are not recycled back to the sector are not accounted for). Not relevant for products that have no recycled content (e.g., furniture, carpentry and packaging).
Cascade factor	Assesses the utilization of biomass in multiple sectors and for multiple products (input perspective). Relevant to understand the use of non-virgin material in a sector.	Accounts for both post-consumer residues as well as industrial residues, and the contribution of each one can be disaggregated; accounts for both material and energy use of the residues.	Requires a full material flow analysis to be assessed. Not relevant for products that have no recycled content (e.g., furniture, carpentry and packaging).
Material circularity indicator	Measures the circularity of the material flows of a product or a company (output perspective).	Accounts for the lifetime of the product, recycling efficiencies and open loop recycling of the post-consumer residues.	Ignores industrial residues; Recycling efficiencies may be difficult to assess.

Portugal is a net exporter of wood-based products, therefore, a high share of the post-consumption residues resulting from that production are not recycled nor treated within the country. As a result, most of the indicators do not necessarily convey the effective circularity potential within the system boundary because they are focused on production. Whilst for input-based indicators (RIR and CF), an approach based on domestic consumption is difficult to apply, RR can be adapted to assess the domestic consumption-based RR, giving a more realistic perspective of post-consumption recycling within system. From that perspective, it was found that 46% of wood-based products consumed in 2015 in Portugal were recovered for recycling.

The main outcomes of this article can be used to comprehensively understand the forest biomass system and the interactions, resource efficiency and circularity of its sectors. Besides adding empirical knowledge about the biomass sector in Portugal, this article allows for policy makers, industry, and other stakeholders to use the MFA results and indicators to analyze the individual sectors and identify potential circular bioeconomy strategies to be implemented. Furthermore, these can be further used as a basis to assess different circular bioeconomy strategies, for which other aspects should be considered, such as the physical distance between the different sectors, or the environmental impacts along the value chains.

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Appendix A. Supplementary material

Supplementary material related with this article can be found, in the online version, at doi:

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