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Review

Material Flow Analysis of the Wood-Based Value Chains in a Rapidly Changing Bioeconomy: A Literature Review

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Abstract: Material Flow Analysis (MFA) is a key tool in the circular bioeconomy, providing insight into the flow of materials within a system. Its use in the wood-based value chain is increasingly recognized and provides valuable information for policy making. However, to the best of our knowledge, this topic has never been systematically reviewed. To fill this gap, this study developed a systematic literature review of MFA research in the wood-based value chain. Peer-reviewed articles published between 2000 and 2024 were identified via databases such as Scopus and Google Scholar and analyzed in detail to identify and deepen different approaches to MFA with reference to its conceptualization, scope, and methodological implementation. Based on our review we categorized various MFA models based on their scale and scope, revealing significant diversity in methodological terms and data requirements. The results emphasize the existing MFA approaches often face limitations due to inconsistent data quality and lack of detailed product-level analyses. This research provides practical insights on improving data collection methods, such as standardizing input datasets and incorporating economic and social indicators, to enhance the reliability of MFA studies. It also provides guidelines for implementing MFA models aligned with circular economy principles, integrating both traditional and emerging wood products streams. These insights offer valuable directions for future research aimed at more accurately capturing the complexities of wood flows, promoting better resource management, and supporting policy formulation in the bioeconomy sector. The findings of this review underscore the importance of adopting holistic and integrated methodologies that incorporate new bio-based materials and circular economy principles, ensuring that MFA continues to be an effective tool for advancing sustainable resource management in the forest sector.

Keywords: material flow accounting; input–output analysis; forest industry; circularity; wood products; MFA

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1. Introduction

The use of Material Flow Analysis (MFA) is critical to understanding and navigating the complexities of different economic sectors. When applied to sectors characterized by multifaceted dynamics, such as the energy and commodities sectors, MFA provides invaluable insights into material flows and stocks by quantifying the inputs, outputs, and accumulation of materials within a system. It also reveals vertical linkages, such as the connections between primary (e.g., raw materials or semi-processed products) and secondary products (e.g., final products), as well as horizontal ones, like the distribution of input/output materials as well as possible trade-offs across parallel and competing value chain segments [1]. MFA is a fundamental tool to analyze the growing bioeconomy, where concepts such as efficiency and circularity are increasingly emphasized within the broader domain of the sustainability paradigm, with the final aim of promoting a sustainable circular bioeconomy [2]. This broader perspective, however, brings in more complexity because of the use of multiple inputs and the reliance on diverse supply channels and flows. For example, virgin materials could be complemented by by-products from other components of the system itself and/or recycled materials from both the system and outside [3]. The emergence of new applications for wood-based raw materials within a forest-based bioeconomy and the rapid growth and development of new bio-based materials and products is adding another layer of complexity [4,5]. MFA can be of particular interest when applied to materials, such as biomass, which can be used at different stages of the value chain and for mutually exclusive uses and aims, for example, both for energy production and as input materials for different purposes, ranging from traditional uses (e.g., in the construction and building sector) to innovative economic applications (e.g., biorefinery products such as bioplastics) [4]. This complexity requires a thorough understanding of material flows and stocks, which MFA provides by systematically assessing input and output flows within specified and bounded systems [6].

The above-reported issues have potential implications that go well beyond material flows and industrial production dynamics. Indeed, the different development trajectories of a forest bioeconomy could have different impacts on the carbon cycle in terms of climate change mitigation and adaptation potential. By using biomass as a renewable energy source to replace fossil fuels and by implementing carbon capture and storage in forests and durable wood products, a forest bioeconomy can have a relevant positive impact on the greenhouse gas balance in the atmosphere, as well as a negative impact if, for example, overharvesting and conversion of forest land to other uses are implemented [7]. The use of MFA could support informing development strategies and related policies, while also allowing impacts associated with bioeconomy development to be monitored. Nevertheless, this is challenged by data availability and quality related to traditional and, even more, new materials and products as well as their interconnections, including possible trade-offs among them. Inconsistencies in official statistics regarding wood removals, bioenergy flows, and the use of wood by-products (e.g., chips, black liquor, recycled wood, and paper products just to mention a few) highlight the urgent need for improved data collection and accuracy as a precondition to feed more reliable studies and modeling [8].

Considering these challenges and opportunities, this study aims to critically review the current state of MFA research applied to the forest-based wood sector and to evaluate its potential as a methodological tool for understanding wood value chains and their impact on climate change mitigation [9]. To achieve this, we seek to address the following research questions:

1. What are the predominant methodological approaches used in MFA studies in the wood sector?
2. How do geographical and time scales influence the findings of MFA studies?
3. What are the primary data sources utilized in MFA research, and how do they affect the reliability of results?

By systematically addressing these questions, this study will not only clarify the relevance of MFA in the context of a bioeconomy but also identify gaps and opportunities for future research, ultimately contributing to a better understanding of the wood sector’s role in climate change mitigation.

2. Materials and Methods

The literature review was conducted using a systematic approach to comply with the Preferred Reporting Items for Systematic Review and Meta-Analysis guidelines [10]. This methodology was adopted to reduce potential selection bias and to produce a literature review that is transparent and reproducible, with the overall aim of including all relevant peer-reviewed material [11]. Content analysis framework was used to critically evaluate and synthesize the findings from the selected literature [12].

2.1. Literature Collection

The search was limited to articles published in English, in peer-reviewed journals, and available in full, without geographical restrictions. It was conducted according to the workflow reported in Figure 1 and included main literature-gathering steps and sources, aimed to target different literature domains.

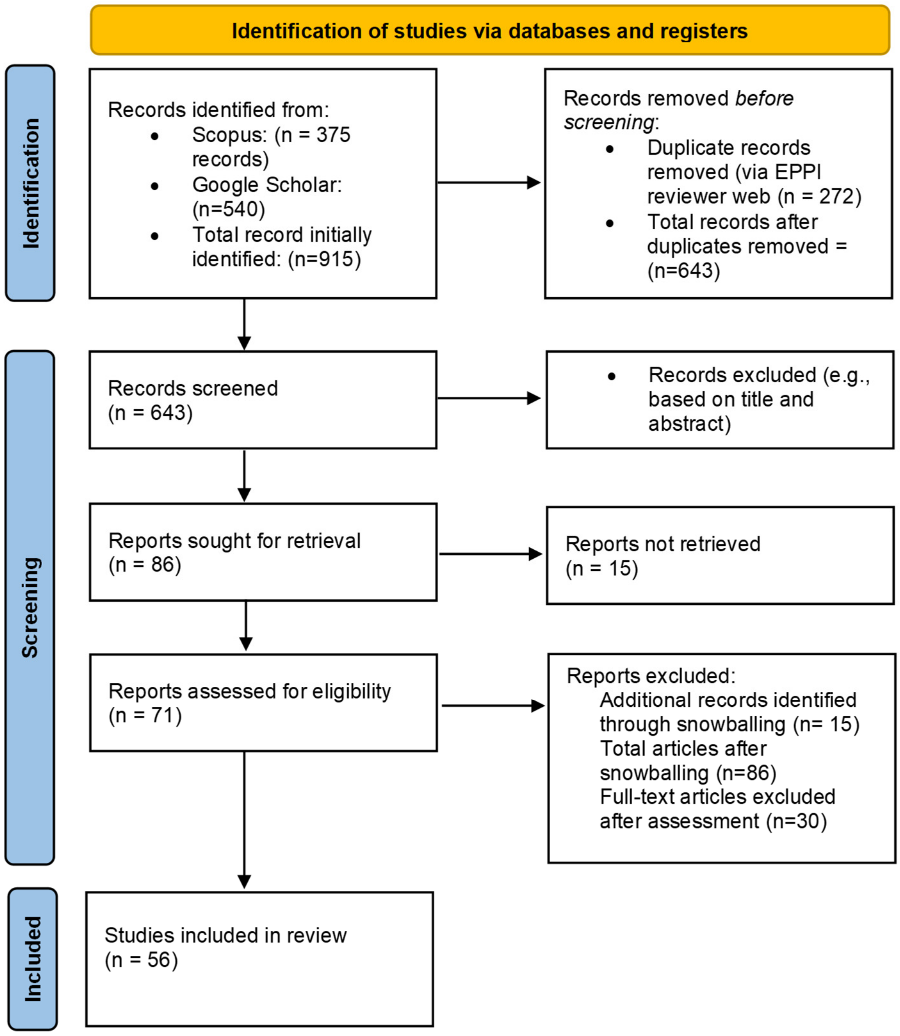

Figure 1. Literature review workflow.

As a first step, the bibliographic database Scopus was used to search for available scientific literature published from January 2000 to January 2024. The search string developed for this aim was [TITLE-ABS-KEY (wood OR wood-based products OR wood product) AND (material flow analysis OR MFA OR wood value chain)]. Keywords like "material flow analysis" and "mass flow analysis" were used to cover multiple terminology/wording in use with regard to MFA, while "wood value chain" was selected to indicate the specific scope of the review centered on wood products and associated value chains. The total number of retrieved papers was 375.

In addition, the Google Scholar search engine was used at a second stage to dig into grey literature and identify additional inputs to consider. This second step was adopted because MFA is an approach that is largely referred to and implemented beyond academic and scientific literature and—to the extent possible—we wanted to embody also these contributions within our review. To this aim, different keywords were selected as shown in Table 1 to encompass relevant practical aspects related to MFA implementation.

Table 1. Keywords used in the literature review on MFA via Google Scholar.

Article title, Abstract, Keywords: mass flow analysis OR wood flow analysis OR wood value chain OR material flow analysis OR paper flow analysis
AND
Article title, Abstract, Keywords: wood resource balance OR wood balance OR spatial and temporal resource flows OR physical input-output table OR economic modelling OR dynamic modelling economic-wide material flow accounting OR dynamic stock modelling OR sankey diagram
AND
Article title OR keywords: Raw material OR Wood processing residues OR Wood utilization OR Natural resources OR Forest resources OR Forest product OR Forest sector modelling OR Wood based products OR Natural resources.

Publish or Perish software version 8.12.4612 [13] was used to extract citations from Google Scholar. By using a search string consisting of the keywords reported in Table 1 a total of 540 papers were identified via Google Scholar.

The combined search via Scopus and Google Scholar thus resulted in a total number of 915 papers.

Prior to the screening process, the collected papers were processed via the EPPI reviewer web version 6.15.1 [14] to identify and remove duplicate articles. In total 272 duplicates were detected, finally resulting in 643 papers to be screened for inclusion/exclusion.

2.2. Article Screening and Eligibility Criteria

Articles were further refined via a two-stage screening process to narrow down the selection based on alignment with the research objectives.

First, an abstracts-based screening allowed the selection of articles that specifically refer to MFA or related terms, and their application to wood products (in a broad sense) within the abstract. This step included publications related to wood-based products, paper products, etc., and those that explicitly discussed the modeling approaches used in MFA studies. Moreover, review articles were excluded from the search to focus on primary research studies that provide original findings.

A total of 86 papers were selected. Abstracts referring to potentially ambiguous subjects, such as product substitution, recycled wood, renewable energy, final consumption, and cascading use were also included for further detailed evaluation.

The selected articles were then subjected to a full-text evaluation, which included conference papers and excluded articles not available in full text through academic subscription or authorized dissemination by the authors. This narrowed the selection to 71 papers. To further enrich the review, additional literature was sought by examining relevant references within the selected articles, via a snowball approach, thus leading to the inclusion of 15 more articles. These additional articles were also screened according to the previous criteria. In total, 86 articles were initially compiled. Of these, 30 articles did not meet the criteria and were excluded, resulting in a final selection of 56 articles (see Table S1 within Supplementary Materials).

The combination of a search through Scopus and Google Scholar, along with the snowball sampling technique, ensured a comprehensive and robust review of the literature. This multifaceted approach helped mitigate selection bias and provided a thorough understanding of MFA in the wood sector.

Based on full-text reading as well as an in-parallel assessment of already existing review studies, we identified a set of descriptors to be used as a framework for organizing and discussing the results of our own review. The four main descriptors we identified include the following:

- Geographical scale (Section 3.1);
- Time scale (Section 3.2);

- Methodological approaches used in the construction of the MFA for wood-based products, related to the predominant use of the MFA (Section 3.3);
- MFA data sources (Section 3.4).

Building on previous studies such as ref. [15], we performed an Extensive text analysis [12] of the 56 shortlisted papers using the above-mentioned four descriptors to frame results as well as for describing and comparatively analyzing our findings.

3. Results

An overall growing trend in the number of articles published on the topic was observed within the targeted period, showing a steady increase from 2000 to 2015, with some fluctuations in the subsequent years. The number of articles increased significantly in 2015, following moderate activity in 2014. By 2023, a total of 12 new articles were published, indicating a renewed interest or research focus in recent years, following some fluctuations in research interest on wood-based MFA studies between 2015 and 2020. The cumulative number of articles (represented by the red line in Figure 2) shows a consistent increase over time, reflecting sustained and growing scholarly attention to this field. This cumulative growth is particularly notable from 2015 onwards, despite some fluctuations in yearly publications.

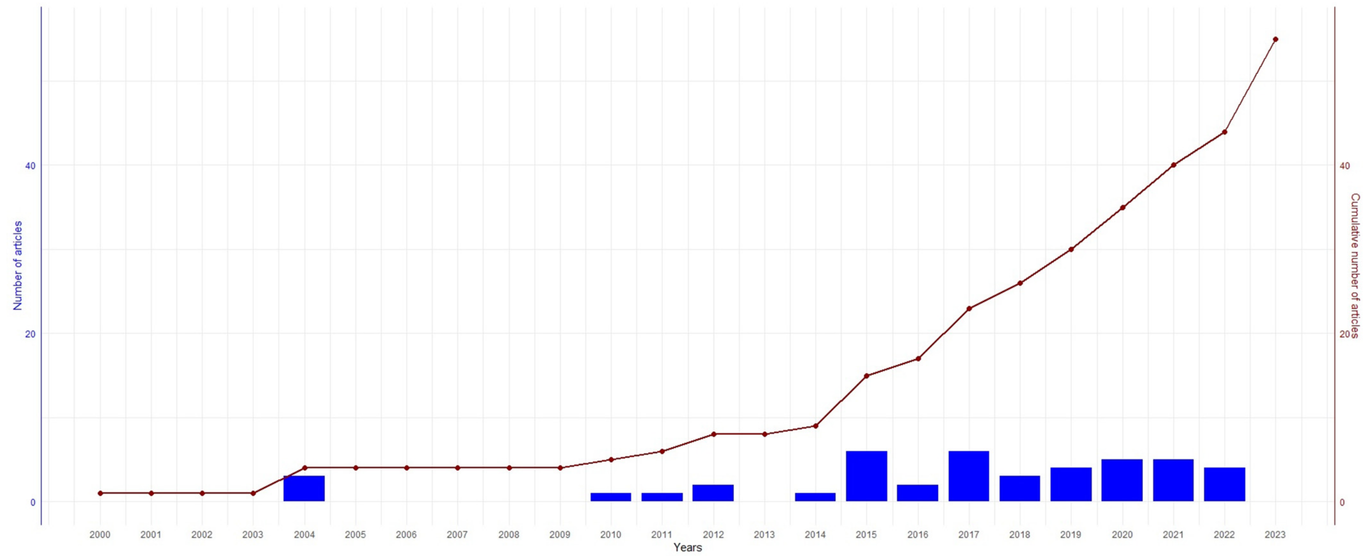

Figure 2. Number of articles published on a yearly basis (bars) and as a total (line) between 2000 and 2023 (data for 2023 are incomplete and therefore not included in the figure).

3.1. Geographical Scale

MFA for wood-based products is conducted at various scales, ranging from the microscale (e.g., product level) to different degrees of macroscale, i.e., from sub-national to global (e.g., global, regional, national, sub-national).

At the microscale, MFA tracks material flows within specific wood-based products or processes, such as the production and life cycle of a wooden chair [16], or within industries or sectors, such as wood processing or furniture manufacturing. This level of analysis helps identify opportunities for material efficiency, supply chain bottlenecks, and environmental impacts within a specific industry [9,17].

At the macroscale, MFA analyses the entire flow of wood-based materials at sub-national, national, regional (i.e., across two or more countries within the same region, e.g., Europe), or global levels, covering stages from harvesting and production to consumption, recycling, and disposal [4,18]. This high-level perspective informs policy decisions, sustainable resource management strategies, and the implementation of the cascading use of the wood principle [19,20].

The choice of the scale for a wood-based MFA study depends on the specific research questions, the availability of data, and the required level of detail to address the problem at hand [21].

Macroscale MFA analyses largely prevail, representing about 95% of all studies considered, while product-level evaluations cover the remaining proportion (5.3%). Approximately 68% of the studies analyzed in this survey are national-level evaluations. followed by regional-level evaluations (14.3%), sub-national-level evaluations (8.9%), and global-level evaluations (3.5%) (Figure 3).

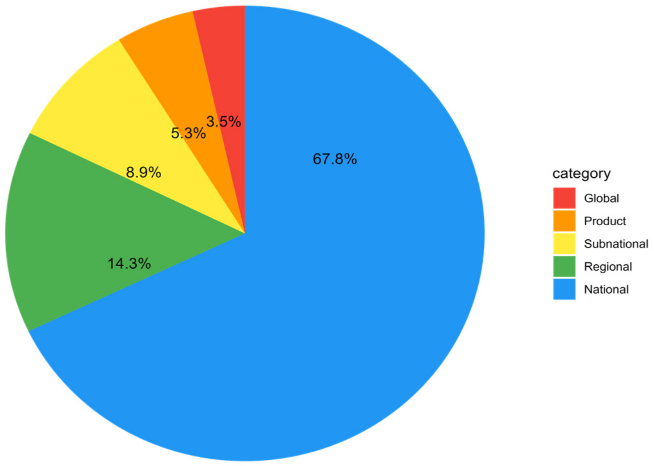

Figure 3. Reviewed MFA studies according to their geographical scale.

3.2. Time Scale

Existing literature includes both spot and dynamic approaches to MFA. Spot MFA focuses on evaluating product and material flows within a single period, providing a snapshot of material stocks and flows at a specific point in time (e.g., year) [4]. This approach is useful for assessing the current state of material efficiency and identifying immediate hotspots or inefficiencies. In contrast, dynamic MFA extends the assessment over several years or different points in time, considering the variable lifespan of products and materials and capturing temporal changes and trends. These two different time perspectives on MFA are given almost the same emphasis within the analyzed literature. Indeed, about 45% of the studies use dynamic MFA, highlighting its importance for investigating temporal changes as well as medium and long-term impacts on material systems. The remaining proportion uses spot MFA, underlining its value in providing a detailed assessment of material use, and immediate assessment of material uses and efficiency. Some studies integrate both past data and future forecasts, illustrating the practical application of dynamic MFA. This approach not only frames past trends but also provides insights into future developments based on current data and scenarios

The time dimension allows for a more comprehensive understanding of the evolution and sustainability of material flows, capturing medium and sometimes long-term trends, and allowing some forecasts on potential future scenarios [4]. As for the former aspect, the temporal focus of MFA studies can range from short-term analyses, which are useful for immediate assessment, to long-term evaluation, which captures medium to long-term trends and impacts. Moreover, MFA studies can be part of routine assessments, regularly updated/repeated over time, or produced on an ad hoc and often one-shot basis, depending on specific research needs or emerging issues. As for time orientation, we can further distinguish between past-oriented (ex post assessment) and future-oriented (forecasting) studies that provide different perspectives and use different approaches to MFA.

According to ref. [22], past-oriented MFA (ex post assessment) is based on past data, emphasizing the importance of ex post assessments in understanding historical material trends and their implications. This perspective focuses on analyzing historical data to evaluate past material flow and stocks. By examining historical trends, past-oriented MFA offers insights into the evolution of material systems, identifies long-term patterns, and assesses the effectiveness of previously adopted material management practices. This approach aligns closely with spot MFA, which provides a snapshot at a specific point in time but can also utilize historical data to inform the current assessment.

On the other hand, future-oriented MFA (forecasting and scenarios analysis) focuses on projecting future trends, highlighting the value of scenarios-based forecasts for anticipating future material flows and potential sustainability challenges. This approach involves projecting future material flows based on different scenarios and assumptions. Future-oriented MFA is crucial for strategic planning and policymaking, as it helps anticipate potential challenges and opportunities in material management. By simulating various future scenarios, this perspective allows for the exploration of potential developments and supports informed decision making for long-term sustainability. Within the literature gathered for this study, past-oriented studies were three times more frequent than future-oriented ones (24 studies vs. 8 studies).

3.3. Methodological Approaches

MFA has evolved into a critical tool for understanding and managing the flow and stock of materials in various systems, defined in both space and time. Initially conceptualized by ref. [23], MFA builds on the idea of social metabolism, which extends the biological concept of metabolism to human societies. The authors in ref. [23] were among the first to lay the foundation for the MFA with their seminal work, *Metabolism of the Anthroposphere*. They conceptualized MFA as a systematic method for assessing material flows and stocks within a defined system, focusing on the interaction between human activities and natural systems. This foundational framework was applied in various contexts; for example, ref. [24] used the MFA described by refs. [23,25] to analyze the timber chain and assess the role of wood in future resource planning.

Building on this foundation, ref. [25] expanded the scope of MFA to encompass more complex systems and interactions. They emphasized the need for a comprehensive methodology that could account for various material flows across different sectors. This expanded framework was later used by ref. [26], who applied the MFA described by ref. [27] to quantify wood in non-residential building structures in Quebec, Canada, utilizing a top-down approach.

The concept of social metabolism was introduced by ref. [28] who framed MFA as a tool to understand the material and energy exchanges between society and the environment, with a particular emphasis on the socio-economic dimensions of these flows. This concept and the associated approach were later utilized by ref. [29] to quantify and model wood flows in Turkey, highlighting the socio-economic impacts on material use and waste generation.

Ref. [30] refined the concept of MFA further by introducing the Material Input per Service Unit. This approach focused on quantifying the material inputs required to provide specific services, linking material flows directly to economic activities. The authors in ref. [31] applied this framework to assess the circularity of products, showing how MFA can facilitate sustainable resource management and promote circular economy principles.

Ref. [4] made significant contributions to the practical application of MFA with their *Practical Handbook of Material Flow Analysis.* Their work provided detailed guidelines for conducting MFA, emphasizing the importance of transparency and reproducibility in the analysis process. These guidelines and approaches have been widely adopted in various studies. For example, they were adopted by ref. [32] to assess wood flow, circularity, and the cascade use of wood in Denmark. Similarly, ref. [33] applied this framework in Sweden, integrating MFA with LCA to evaluate the environmental impact of process chains developed for wood-based butanediol (BDO) production from wood residues. Other notable applications include ref. [17], who used this methodology in the Orchid City wood-value chain in the Netherlands, and ref. [18], who employed it in Portugal. The versatility and applicability of the approach by ref. [4] are further demonstrated by its use in many geographical contexts. For instance, ref. [34] applied the methodology in Norway, ref. [35] in France, and ref. [36] in Finland, where it was combined with LCA and simulation modeling. The authors in ref. [37] used it for a comprehensive MFA in Spain, and ref. [38] applied it in Germany to develop a predictive model for the recovery of timber.

The development of a broad set of applications has made MFA an essential tool for understanding and managing material flows in various contexts and at different scales, from single economic sectors to entire economies. To this aim, MFA encompasses a range of methodological approaches, each providing specific perspectives and tools for understanding and quantifying material flows within different contexts. These approaches can be broadly categorized into several main groups (Figure 4). Within this framework, Material Flow Accounting (MFAc) represents a core MFA component regardless of the methodological approach adopted; therefore, we first provide an outlook of different ways to deal with it. This includes providing methodological options for Input–Output Analysis (IOA) as this represents a key part of MFAc.

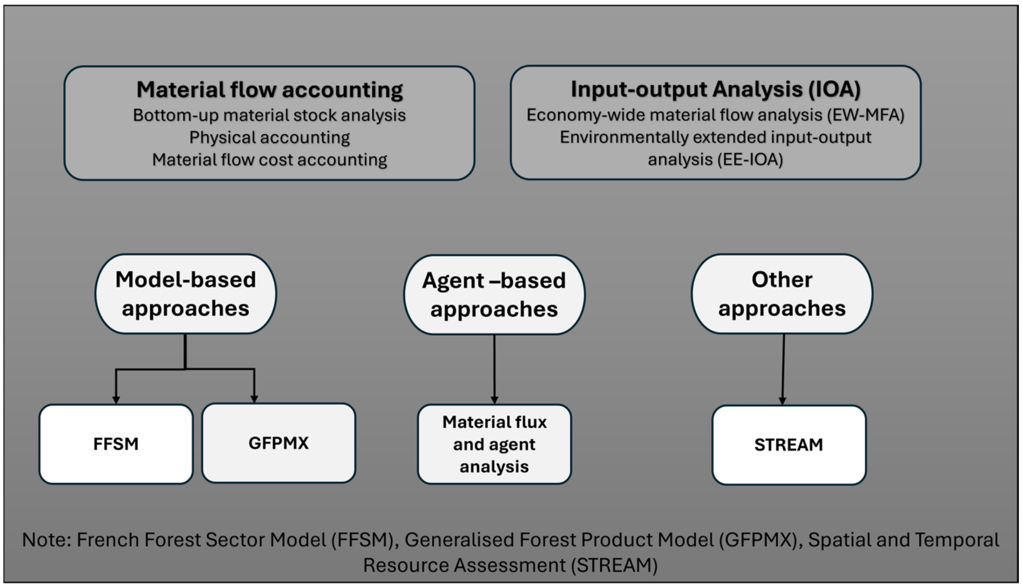

Figure 4. Categorization of methodological approaches used for MFA.

Ref. [39] model emphasizes stock dynamics, allowing for the prediction of material flow based on existing stocks and inflows. By employing extrapolation methods such as linear and logistic models, the model enables forecasting of future trends in material use and waste generation. For example, ref. [40] applied this model in Austria to predict resource demand and waste within the sector, highlighting its versatility in different regional contexts. Additionally, ref. [41] showcase inflow-driven dynamic stock modeling, which further refines this framework by focusing on how material inflows contribute to stock accumulation.

The application scope of Müller's model, initially centered on housing in the Netherlands, has been expanded in subsequent studies to encompass a broader range of sectors and geographical contexts [24,39]. For instance, ref. [42] adopted the model for use in Switzerland, integrating it with LCA to know the environmental impact of wood-based products and resource demand forecasts. Similarly ref. [43] applied the model to Switzerland, further demonstrating its utility across different national settings.

Advances in dynamic MFA have also focused on refining data treatment methodologies, improving the handling of data uncertainty and spatial distribution of material flows. These enhancements have increased the model's predictive accuracy and broadened its applicability. Furthermore, integration with other models, such as economy-wide material flow analysis, has enabled a more comprehensive understanding of material flows across entire economies, rather than limiting the analysis of a specific sector.

3.3.1. Material Flow Accounting

MFAc as an MFA core component is the foundation of the broader field of industrial ecology, building on the concept of social metabolism [44]. It focuses on the systematic accounting of material inputs, outputs, and stocks within a defined system. Over time, various approaches have been developed to enhance its accuracy and applicability across different contexts.

For example, ref. [45] applied the MFAc approach alongside LCA at the regional level in the European Union to analyze the environmental impacts of the wood-based value chain. This integration of MFAc and LCA provided a comprehensive understanding of material flows and their environmental consequences, offering valuable insights for sustainable resource management. Similarly, ref. [46] utilized MFAc in Northern Italy to assess the environmental impacts generated by the three subsystems of the forest-based bioenergy value chain, i.e., forestry, logistics, and conversion. By implementing a multi-method framework of environmental accounting, this study offered critical insights into material and energy flows within the bioenergy sector. The authors in ref. [47] used the standard of Material and Energy Flow Accounting (MEFA) [48] throughout their study of global wood flow analysis from 1990 to 2010. This approach provided a detailed examination of wood flow across different regions and time periods, demonstrating the utility of MEFA in understanding global material flow and its implications for resource management.

These examples demonstrate the versatility and relevance of MFAc, especially when combined with methodologies like LCA, in providing detailed analyses of material flows and their environmental impacts across various sectors and regions. Below are descriptions of additional approaches that enhance MFAc's core capabilities in various contexts:

Bottom-up material stock analysis (MSA) is characterized by a focus on detailed, granular examination, beginning with the end product and tracing back to the input materials and their associated flows. This methodology focuses on analyzing individual stocks and material at a detailed site or project level to estimate total material stocks and flows [49]. Essential data parameters for a bottom-up MSA include detailed information on the composition, quantity, and location of materials within a product, building, or infrastructure, tracking the different types and quantities of materials used [50]. For instance, ref. [51] applied a bottom-up modeling approach in France to analyze the wood fuel and supply chain. Their study defined two segments within this supply chain: forest harvesting and processing. This detailed examination allowed for a comprehensive understanding of material flow and efficiency within the wood fuel sector. Additionally, research has utilized this approach to examine material flows in 13 cities in China, providing an in-depth analysis of material use [52]. Similarly, studies in Finland have examined the use of wood in construction projects, providing information on the dynamics of material flows within the construction industry [53]. The granularity of this approach lies not in introducing a new methodology but in the detailed level of data analysis it employs, allowing for precise estimation and a deeper understanding of material efficiency and flows.

Physical accounting covers those material and energy flows that run through a system (e.g., a country) within a given period of time, as well as all material assets of that system. Seifert work on the entropy law provides the foundation of modern material and energy flow accounts, linking thermodynamics systems and highlighting the importance of tracking matter alongside energy in a Closed thermodynamics system [54]. His concept of maintaining separate accounts for matter and energy laid the groundwork for national material and energy accounts, which evolved into tools such as National Resource Accounts (NRA), Material and Energy Balances (MEB), and ultimately MFA, all of which provide a structured way to understand and optimize resource use.

MFA, in particular, extends beyond traditional physical accounting by emphasizing circularity within the bioeconomy, focusing on maximizing resource efficiency and minimizing waste. MFA can be incorporated within the broader framework of Environmental Management Accounting (EMA), which combines both physical and monetary environmental data to support internal decision making [55]. EMA includes information on the use, flows, and destinies of energy, water, and materials, as well as the financial aspects of environmental cost and savings. By operating through a material flow and mass balance assessment, MFA forms the core of physical environmental accounting within EMA, providing a crucial foundation for evaluating resource use within a sustainable, circular bioeconomy.

Several studies have illustrated the practical application of MFA within physical accounting frameworks across different regions and sectors. For instance, ref. [56] applied a physical accounting approach to assess material flows within the Slovakia wood industry by combining official data with survey results to examine production, consumption, and recycling activities in 2011. The authors in ref. [57] used this approach to quantify biomass flows in Austria, explicitly quantifying internal flows to refine the assessment of national biomass use. Similarly, ref. [58] applied physical accounting to study wood-based materials in Brazil, while ref. [59] applied it to the European Union. Research has also integrated MFA with LCA to enhance the understanding of resource use and environmental impacts. Studies like ref. [60] focused on the wood industry in 2013, used to assess raw wood flow in Slovakia, analyzing wood and waste usage, while ref. [61] used the approach in Germany. Furthermore, ref. [62] modeled the land footprint of EU consumption through the physical accounting approach and LCA.

Material Flow Cost Accounting (MFCA). Within the EMA framework, MFCA is a specialized method that traces the flows and stocks of materials within a system, quantifies these material flows in physical units (e.g., mass, volume), and evaluates the costs associated with material flows and energy uses, thus allocating them to the corresponding product and service outputs [63]. MFCA, built on the mass balance approach advocated by the European Commission, is particularly effective for managing complex resource and waste stream [64].

For example, a study by the European Commission employed MFCA across EU countries, utilizing an online survey of 90 companies to track material flows and improve both environmental and financial performance [65]. The concept of MFCA originated from the environmental management project at the textile company Kunert in Southern Germany during the late 1980s and early 1990s [66]. It was then formalized in the ISO 14051 standard [67]. MCFA is considered an attractive decision-support tool for resource, waste, and environmental management, reflecting a linear relationship where reducing product-related waste leads to decreased input flows [68]. Widely utilized, especially in Japan, MFCA is known by various names, including resource efficiency accounting, flow cost accounting, and material-flow oriented activity-based costing [69].

3.3.2. Input–Output Analysis

IOA is an approach that examines the interdependencies and relationships between different sectors and industries in an economy [70]. It quantifies the flows of materials, energy, and waste between different processes or economic sectors [71]. This allows a detailed accounting of material inputs, processing, and outputs within a defined system [70]. The input–output framework is used to track how materials move through a production or consumption system, from extraction to final disposal or recycling [71]. IOA is a powerful tool for examining the interdependencies between different sectors of an economy through the lens of material flows. It provides a structured framework for understanding how materials move between industries and are transformed into products and services.

Input–output tables serve as fundamental data sources for various MFAc methodologies offering detailed information on material inputs and outputs across different sectors. These tables enable analysis of economic transactions and material flows within an economy, forming the basis of IOA.

An example of this is the use of input–output tables to illustrate the flow of goods and services between producers and consumers, showing how industries interact with final consumers through sales and purchases. In some studies in Germany [72,73], physical input–output tables were used to map material flows across sectors and end-use categories, with a focus on wood-based products, particularly in construction and waste management.

Two main different approaches to IOA can be adopted: Economy-Wide Material Flow Analysis (EW-MFA) and Environmentally Extended Input–Output Analysis (EE-IOA). They are shortly presented below.

Economy-Wide Material Flow Analysis (EW-MFA). This approach applies the principles of IOA on a macroscale, normally a single country, providing a comprehensive view of material flows across entire economies [74]. The key differentiator of EW-MFA is its focus on capturing material flows across whole economies, rather than specific sectors or smaller areas. The primary purpose of EW-MFA is to describe the physical interaction of the national economy with the natural environment and the rest of the world economy in terms of material flows. It achieves this by capturing the mass balances with an economy, where total inputs (resource extraction plus imports) must equal total outputs (domestic consumption, export, accumulation, and waste) [44].

EW-MFA is a statistical accounting framework that systematically records material flows into and out of an economy. This approach allows for the compilation of data that track the movement of material from natural resources into the economy, through processes of extraction, trade, consumption, and disposal, providing a detailed and comprehensive picture of material use and resource efficiency [74].

For instance, as illustrated in Table S1 in the Supplementary Materials, ref. [75] carried out an investigation of wood flow patterns in the EU-27 using EW-MFA in conjunction with official databases for the period 2002–2011. This study exemplifies the use of EW-MFA to clarify the dynamics of material flows within specific geographical areas, thus facilitating informed decision-making processes for sustainable resource management and policy formulation. Similarly, ref. [76] utilized the EW-MFA methodology to analyze material flows in Slovakia and the Czech Republic, providing insight into regional material use and resource management. The authors in ref. [77] applied the EW-MFA framework in Switzerland, examining the country's material efficiency and circularity. Ref. [78] used EW-MFA to study material flows in Germany, highlighting the importance of MFA in understanding national resource use and waste generation.

EM-MFA has evolved through several stages of standardization. It became the first standardized analysis in the Eurostat methodological guide following pilot studies such as those by ref. [79]. Further standardization was achieved through the Eurostat compilation guide [80] and within the OECD work program on material flows (2004–2008). The standardization process culminated in the OECD Guide to Material Flow and Resource Productivity [6].

Environmentally Extended Input–Output Analysis (EE-IOA). Building on the traditional IOA framework, EE-IOA incorporates environmental impacts such as energy use and emissions into the analysis of material flows [81]. The use of input–output tables in this approach provides a deeper understanding of the exchange of goods and services between different sectors and final consumers, while incorporating environmental aspects such as material flows, energy consumption, and pollutant emissions [82]. By integrating economic and environmental data through EE-IOA, researchers and policymakers can effectively assess the environmental impacts of economic activities and consumption patterns [81]. EE-IOA can also be considered a type of EW-MFA if the analysis is conducted at a macro-economic level, capturing the overall material flows within an economy.

By following LCA principles, ref. [81] demonstrates how EE-IOA distinguishes between foreground and background systems, providing insights that support sustainable policy development. This integration allows researchers and policymakers to identify key consumption-based drivers of environmental impacts and address these through informed decision making.

3.3.3. Model-Based Approaches

Model-based approaches offer a dynamic framework for analyzing material flows and sectoral interactions over time, going beyond the static nature of traditional IOA. While IOA provides a snapshot of economic and environmental interdependencies at a single point in time, model-based approaches, such as agent-based modeling and system dynamics, enable the simulation of material flows over time, capturing the evolving interactions and feedback loops within a complex system. These dynamic simulations allow for the prediction of future scenarios and the assessment of policy impacts on global or sectoral material flows. Rather than being seen as alternatives, IOA and model-based approaches are complementary. Together, they provide a more comprehensive analysis of material consumption and resource use, facilitating a deeper understanding of the both static and dynamic aspects of economic and environmental systems.

There are different cases of model-based approaches used within specific tools designed for the forest-wood sector: two examples are provided below.

Generalized Forest Product Model (GFPMX) was specifically designed to model material flows within the forest sector and forest-based industries. In doing so, it helps to understand supply chain dynamics and the impact of different policies on forest product markets. The GFPMX model is a global forest products model designed to forecast the consumption, production, import, export, and price of various forest products such as fuelwood, industrial roundwood, sawnwood, and others for each country and year [83]. Building on the spider web theorem, and assuming that markets take time to adjust to shocks, the model has been used to assess, for example, the impact of the COVID-19 recession on the global forest sector.

French Forest Sector Model. The French Forest Sector Model (FFSM) is a recursive bio-economic model designed to analyze the interaction between the economic and biological dynamics of the French forest sector. The model was developed by refs. [84,85] based on two key modules: an inventory-based forest dynamic module (FD) and a partial equilibrium market module (MK). The FD module tracks the stock and growth of forest resources, while the MK modules model the economic behavior of the forest sector, focusing on the supply and demand for raw wood and processed products. At each annual step, the MK modules calculate the market equilibrium, determining the harvest level for that year. This back-and-forth between the economic and biological modules ensures that the model captures both the economic drivers and biological dynamics of the forest sector. This makes the FFSM a comprehensive tool for assessing the sustainability of resource management and the long-term viability of the forest sector under different policy scenarios. Bio-economic models like FFSM have been applied in various regions to support decision making, emphasizing the importance of integrated approaches for sustainable forest management and policy development.

The FFSM has proven useful in evaluating the impact of various climate policies, such as those promoting energy wood consumption or incentivizing carbon sequestration. For example, ref. [9] used the FFSM to assess wood flows in France between 2009 and 2020. The authors in ref. [86] utilized the methodology of ref. [9] and applied the cascade approach to wood flow analysis introduced by ref. [59] to evaluate primary wood processing, further demonstrating the value of integrated bio-economic models in supporting decision making and policy development for sustainable forest management.

3.3.4. Agent-Based Approaches

To capture the complexity and dynamics of material flows, agent-based and system-dynamic approaches are used. These methods provide dynamic insights by simulating interactions and feedback loops within complex systems.

Material flow and agent analysis. Material flow analysis, as defined by ref. [87], is a quantitative technique used to monitor the movement and accumulation of materials within a given system, such as a geographical area, an industry, or a product life cycle. This approach considers material flows in terms of agents (e.g., industries, sectors) and their interactions. It allows detailed analysis of specific components within a system, such as the behavior of individual firms or the impact of regulatory changes. It provides a comprehensive view of resource use and waste production within the system under study. Agent analysis, also known as Structural Agent Analysis, is a complementary MFA approach that examines the influence of different actors or 'agents' in shaping material flows [88]. It assesses how the actions, decisions, and interactions of different agents (e.g., producers, consumers, policymakers) affect the patterns of material consumption and handling within the system. For example, ref. [87] applied this methodology in Switzerland for analyzing the wood-based value chain, demonstrating how MFA can offer insights into sector-specific resource management. Similarly, ref. [89] conducted a study across Slovakia, Italy, and Austria from 2008 to 2014, using MFA along with a Strength, Weaknesses, Opportunities, and Threats (SWOT) analysis to evaluate the environmental impacts of the wood value chain. Combining MFA and SWOT analysis, as exemplified by ref. [89], offers a holistic perspective by integrating environmental and organizational factors, thus providing a robust framework for evaluating both material flows and strategic factors impacting sustainability.

The dynamic MFA model can also be integrated with the Stock and Flow adaptation model discussed in the context of climate change adaptation strategies. Originally introduced by ref. [90], it distinguishes between two types of adaptation: stock adaptation and flow adaptation. Stock adaptation refers to long-term, capital-intensive investments aimed at reducing the long-term impact of climate change, such as the development of resilient infrastructure. Flow adaptation, on the other hand, involves short-term, flexible measures that can be adjusted as needed, often requiring less upfront investment but offering temporary solutions. The balance between these two adaptation strategies is crucial for effective climate policy. For example, ref. [91] applied this approach in Switzerland to the entire wood supply chain. Emphasizing the importance of strategic investment in both stock and flow adaptations to ensure long-term sustainability and resilience.

Additionally, the Material Input Stock and Output framework, used by ref. [92], employs an inflow-oriented modeling approach to monitor material flows and stock across the economy from 1990 to 2019 in four specific countries. This model was integrated with the circular economy monitoring framework proposed by ref. [93] to assess the circularity performance of the national socio-economic system.

These models, including system dynamics and stock and flow adaptation, collectively enhance our ability to understand and manage material flows and resources, both in response to environmental challenges and in anticipation of future demands. By integrating such models with broader environmental and economic frameworks, a more comprehensive analysis of material consumption and resource use can be achieved, contributing to more effective sustainability and climate mitigation strategies.

3.3.5. Other Approaches

In addition to the above-described approaches, there are several other approaches that provide complementary tools and data sources for conducting MFA.

Spatial and Temporal Resource Assessment (STREAM) emphasizes the spatial and temporal dimensions of material flows, often used for regional or local assessments. This approach helps to understand the geographical distribution and temporal changes in material flows. The methodology known as STREAM has proven to be a valuable tool for conducting MFA on wood-based products. STREAM provides a structured approach to systematically track and quantify material flows and stocks within a specific system, such as the value chain of wood-based products [94]. When applied to wood-based products, STREAM involves the delineation of different stages in the product life cycle, including harvesting of raw wood materials, manufacturing, distribution, use, and end-of-life management [9,21,95]. This comprehensive methodology provides an in-depth understanding of material flows and stock changes related to wood-based products [16].

The critical component of the STREAM methodology is the use of Physical Supply and Use Tables (PSUT). These tables are an extension of the monetary supply and use tables utilized in national accounting and are a key resource for analyzing wood-related production, trade, and consumption at the product and industry levels within an economy, as shown in the Danish context. The PSUT, which are part of the Environmental-Economic Accounts or Green National Accounts, provide data for 2016 and 2018, capturing the magnitude (in tonnes) and nature of material and commodities flowing within the economy and between the economy and nature [96]. These tables cover the entire economy, detailing imports, domestic production across 117 industry groups, and around 1800 physical products and exports. Input from natural resource extraction and flows of residuals to the environment, such as emission and solid waste, are also included.

The PSUT are especially relevant for analyzing wood flows because they are coded to correspond with the European goods classification system, the Combined Nomenclature (CN). This allows for direct correspondence to products in Chapter 44 (Wood and Articles of Wood; Wood Charcoal) and Chapter 94 (Miscellaneous Manufactured Articles, including Furniture and prefabricated buildings). The PSUT's structure includes a wood product sub-grouping, primarily consisting of products from these chapters, making it an invaluable tool for understanding material flows within the wood-based product industry.

Examples of studies that have applied the STREAM method in the forest-wood sector include refs. [97,98], which used PSUT to provide an integral view of material flow for the wood and paper industry in the Netherlands. The authors in ref. [32] examined Danish wood flows in 2018, utilizing the PSUT to monitor the circulation of wood resources in the bioeconomy and assess their circular and cascading use. These studies demonstrate how STREAM, supported by the detailed data in PSUT, effectively captures material flows and provides insights into the sustainability of resource use, particularly within the wood-based product industry.

3.4. Data Sources

An examination of the data sources used in MFA research on wood-based products reveals considerable diversity. Major statistical databases such as COMTRADE, FAOSTAT, EUROSTAT, and others are identified as the primary sources of data in MFA research, with 53.4% of studies using these repositories. Scientific publications provide valuable information in 20% of the studies, demonstrating the rigorous methodological standards inherent in academic discussions (Figure 5). Grey literature, which includes reports, working papers, government documents, white papers, conference proceedings, and more, enhances the diversity of data used in MFA research, with 8.3% of studies relying on this type of information. Another 18.3% of studies use a variety of data collection methods, such as surveys and expert judgments.

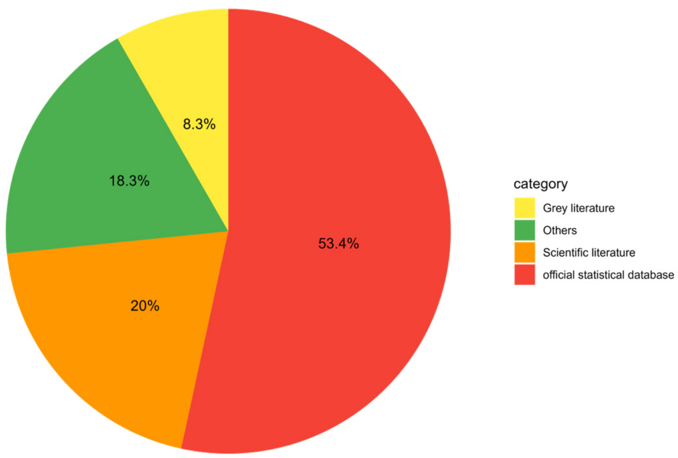

Figure 5. Different data sources used in wood-based MFA studies.

4. Discussion

The growing interest in the MFA of wood and wood-based products over time can be attributed to the recognition of wood as a key renewable resource for a sustainable bioeconomy [99] as well as to the growing concerns associated with an increasing demand by different sectors/uses and associated impacts on forest resources as well as potential trade-offs. In such a perspective, it is evident that the MFA framework is well suited for material recovery and flow assessment purposes, to promote efficient resource use as well as a circular approach. Within the existing literature, there is a strong emphasis on national-level assessments using MFA, a dimension that has attracted considerable attention from academics. Researchers from Austria and Germany have emerged as prolific contributors to MFA applications in the wood value chain [38,40,57,72,100,101].

Although less common, product-level MFA has relevant potential, especially for emerging and innovative products that are being developed and marketed within the bioeconomy framework. Fundamental to product-level MFA is the availability of comprehensive and reliable data sources, which are essential to accurately represent material flows and facilitate sustainability assessments.

A critical facet prevalent in wood-based MFA studies relates to the underlying methodological frameworks, which often rely on assumptions in key areas. However, the applicability of such assumptions to real-world scenarios remains questionable, particularly in cases where different end products are mistakenly assigned identical conversion factors. For example, studies may assume a uniform wood-to-product conversion factor for both high-quality lumber and lower-grade pulpwood, despite the fact that these products differ significantly in terms of processing efficiency and material losses. This oversimplification can lead to inaccurate estimates of resource use and waste generation, affecting the reliability of material flow assessments.

Due to the variety of methodological approaches described in Section 3.4, which sometimes produces inconsistent results, there is a need for standardized approaches to wood flow analysis [101]. This interest is particularly notable in the building and construction sector, where wood products are increasingly being used, requiring a method to quantify material use and assess its impacts [26]. This might become even more relevant when considering the carbon stocking potentialities of these products as durable carbon pools, for example, within the framework of the proposed Carbon Removals Certification Regulation drafted by the European Commission.

Besides the large variety of MFA methodologies, a significant proportion of the literature highlights challenges related to data quality, poising the problem of a possible "Garbage In, Garbage Out" (GIGO) effect [102] with reference to MFA studies. Most of the studies reported data quality issues for end-use products, waste streams, fuelwood data, secondary processing products, intersectoral flows, and wood recycling. A notable challenge in MFA studies related to official data collection is the mis-estimation of certain categories, in particular the use of wood biomass for energy, where problems often arise from missing or underestimated data related to own or local informal consumption or mis-estimation (wood biomass from urban forest or/and agricultural activities considered as forest biomass). An illustrative example can be found in Europe (e.g., Italy, Sweden, and Germany), where official databases consistently underestimate fuelwood volumes, as can be seen from official statistics reporting repeated values over many successive years, indicating a widespread problem of overlooking data quality in MFA analyses shown in Figure S1 of the Supplementary Materials.

Many studies have reported difficulties in obtaining accurate data on the end use of wood-based products, which is critical for understanding the full life cycle and fate of materials. Accurate tracking of waste streams is essential for assessing the efficiency of material use and the potential for recycling and reuse, but inconsistencies and gaps in waste data often undermine the robustness of MFA. In addition, the secondary processing of wood products such as plywood and particleboard involves complex flows that are often poorly documented, leading to gaps in the MFA. Understanding how materials move between different sectors of the economy is crucial for a comprehensive MFA, but such flows are often poorly recorded. In addition, accurate data on the recycling of wood materials are needed to assess sustainability and resource efficiency, but many studies have highlighted the challenges of accurately tracking recycled wood flows. Some studies have identified a significant problem with the neglect of the waste stream due to data availability constraints and limitations of the models used. This problem is due to the fact that certain models rely on monetary values as a primary input, whereas the waste stream itself has no tangible monetary value. Therefore, the above factors represent only a part of the common constraints that require thorough investigation and effective mitigation strategies.

The conventional view of the bioenergy sector is severely lacking in relevant information, especially for novel products such as pellets, Sustainable Aviation Fuel, and other recycled products whose origins remain undisclosed. A comprehensive understanding of the bioeconomy sector is hampered by the lack of data on the recycling of final wood products and other segments such as biotextiles, bioplastics, and various products derived from innovative chemical processes, together with their associated conversion factors.

Taken together, these data quality issues represent significant barriers to achieving accurate and reliable MFA results.

As pointed out by ref. [103], the top-down approach often introduces data uncertainty at the MFA level. It is imperative to develop a detailed composition of different waste items at the material level to capture the benefits and potential improvements at the process level (especially at recycling facilities).

Further research is needed to identify the final sinks, to trace the flow of waste products to these sinks, and to analyze the actors involved in these processes. At the national level, many surveys are currently including all final products. The scope is currently limited to traditional wood-based products (paper, wood packaging, building material, furniture), leaving out green chemistry and wood–plastic composites.

Many studies are currently limited in scope and require the development of a detailed model that captures all flows, including hidden ones, while integrating each sector with economic indicators such as employment figures, turnover rates, and GDP metrics. Due to the data-intensive nature of MFA, the study of the cycle of different sectors up to the recycling stage, based on aspects such as sales, stocks, and lifetimes, can be facilitated by using historical sales data from developed countries with a time series framework. However, numerous studies reviewed in the literature have highlighted the need to establish a standardization process for datasets at both product and material levels obtained from recycling facilities through material characterization. In addition to the downstream data requirements in MFA studies, sales, and import data are emerging as key parameters for MFA, especially in the context of national-level estimations using various supplementary methods such as the time step method, distribution lag, and simple lag. It is imperative that policymakers address this issue and focus on the establishment of a national product inventory database that is regularly updated on an annual basis. The integration of concepts such as the Internet of Things and big data seems extremely promising for the development of such a database.

In summary, a major limitation of wood-based MFA is the scarcity of data and the considerable uncertainty associated with the available data, which are typical hurdles in MFA [9]. Another challenge is the complexity of adjusting to fluctuations in the global market, which can affect the wood processing sector [9]. In addition, limitations such as cut-off thresholds, data non-disclosure, and high levels of data aggregation in official production statistics can also limit analysis [78]. These limitations impede a comprehensive understanding of wood flows and have implications for several areas, including trade balances, forest management, economic policies, and climate change strategies [32].

5. Conclusions

The predominant focus of material flow accounting (MFA) models has been on national-level assessments, with Austria and Germany leading the way in research publications [38,40,57,72,100]. However, there is a noticeable lack of assessment of products at a detailed level, highlighting the need for comprehensive data and analysis to effectively address waste management issues and minimize environmental impacts. Methodologies are often based on assumptions rather than empirical evidence, leading to inaccuracies, particularly in estimating fuelwood use. There is also a lack of recognition of stock in use from previous years, inconsistencies in units of analysis, and an urgent need for more comprehensive and integrated methodologies.

The practical implications of this research are substantial. By synthesizing the distribution of data sources and evaluating methodological diversity, this study provides a roadmap for enhancing the robustness of MFA research in the wood sector. Researchers and policymakers can leverage these insights to refine data collection practices and ensure more accurate, data-driven decision making. For example, addressing gaps in data on hidden by-product streams and improving methods to track end-use recycling can directly impact the development of more sustainable resource management strategies.

Incorporating economic indicators into MFA studies could encourage cooperation among supply chain participants and accelerate the development of recycling. Future research efforts should address these shortcomings by adopting a holistic approach that integrates MFA with LCA and covers all aspects of sustainability. Life Cycle Sustainability Assessment, which combines LCA with social and economic impact assessments, is a promising method for assessing environmental, social, and economic impacts throughout the life cycle. This transformation will require a shift toward circular economy principles, emphasizing mass conservation and integrating emerging sectors of the bioeconomy, such as wood–plastic composites and green chemical products. In addition, the integration of standardized datasets and product repositories at the national level, facilitated by technologies such as the Internet of Things and big data, will be crucial for accurate and thorough assessments. Ultimately, advancing MFA in the forest sector requires a fundamental shift toward circularity, encompassing a wider range of products and considering the complex interplay of economic, technical, and socio-political factors. Integrated and forward-looking methodologies are essential to effectively address the complex challenges of sustainable resource management and to contribute to the transition toward a more resilient and environmentally sound forest sector.

This study has several limitations that should be acknowledged. First, the scope of the review is constrained by the inclusion criteria, such as language and the availability of full-text articles, which may have led to the exclusion of relevant studies. Additionally, the search was limited to Scopus and Google Scholar databases, potentially overlooking pertinent literature in less accessible sources. This reliance on assumptions in some identified studies points to a broader challenge of data availability and quality that may have influenced the analysis presented here.

Recommendations for future research and policy action include revisiting the Statistical classification of economic activities in the European Community (NACE) and the Standard International Trade Classification (SITC) classifications to better capture nuanced data and integrate social elements into MFA analyses to provide a more holistic understanding of resource use and its impacts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15122112/s1, Figure S1: Annual wood production of various countries from 2000 to 2022 (million cubic meters); Table S1: Summary of the studies analyzed in the literature review; Table S2: A summary of the methodological approaches identified through the literature review.

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