Review

CASCADE USE OF WOOD WASTE IN MEDIUM-DENSITY FIBERBOARD PRODUCTION: RECYCLING, ADHESIVE SYSTEMS AND CIRCULAR ECONOMY PERSPECTIVES

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ABSTRACT

This review examines the cascade use of wood waste with a specific focus on medium-density fiberboard (MDF) as a wood-based biocomposite within the circular economy. MDF is widely used in furniture, interior and construction-related applications, generating increasing amounts of production residues and post-consumer waste. Although much of this material is still directed to energy recovery, its reintegration into material cycles can extend product life cycles, reduce the demand for primary lignocellulosic raw materials and improve resource efficiency. The paper discusses the structure of MDF as a system of wood fibers and thermosetting adhesive networks, emphasizing the influence of fiber morphology, residual resin and adhesive chemistry on recyclability. Particular attention is given to hydrothermal recycling technologies, recovered fiber quality and the technological limitations of incorporating recycled fibers into new MDF panels. The role of conventional synthetic adhesives and emerging bio-based or formaldehyde-free systems is analyzed in relation to material performance and compatibility with cascade recycling. Key life cycle assessment trends, including biogenic carbon storage, end-of-life scenarios and methodological challenges, are also summarized. The review highlights the significant but conditional potential of MDF for cascade use.

Keywords: *cascade use; MDF; recycled wood fibers; wood waste; adhesive systems; circular economy*

INTRODUCTION

The transition from a linear to a circular economy places wood-based materials in a strategic position due to the renewable nature of lignocellulosic biomass, its capacity to store biogenic carbon, and its potential to participate in successive material cycles [1,2]. Among these materials, medium-density fiberboard (MDF) is particularly relevant because of its widespread use in furniture and interior applications and the growing volume of post-consumer waste [3]. Despite this, a substantial share of waste MDF is still directed to energy recovery, although the European regulatory framework prioritizes material recycling over incineration [4].

As a biocomposite composed of lignocellulosic fibers and a thermosetting adhesive network, MDF combines favourable performance with the potential for reintegration into material cycles. However, this potential is conditioned by the chemical nature of the adhesive system

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and by structural changes occurring during use and recycling, which influence the ease of fiber separation and the feasibility of repeated cycles [5, 6].

Cascade use, understood as the sequential utilisation of wood in applications with decreasing added value before final energy recovery [7], is central to the circular bioeconomy, Figure 1. Material recycling prolongs biogenic carbon storage and reduces pressure on primary resources [1]. Advances in hydrothermal technologies have improved the degradation of thermosetting resins and the recovery of fibers [3], creating opportunities for the production of MDF that incorporates recycled material.

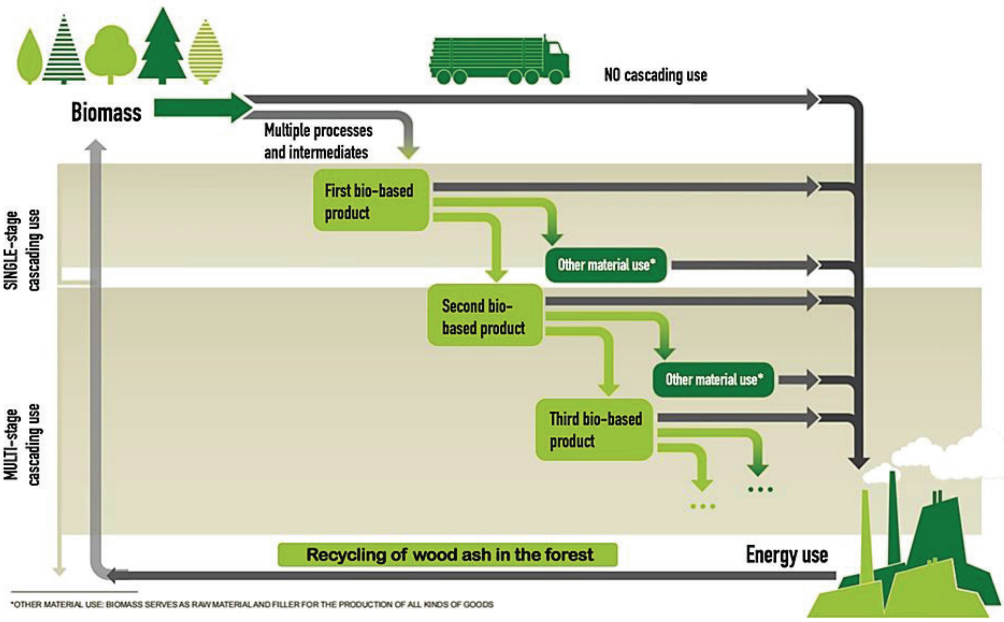

Figure 1. Cascade use of wood biomass before final energy recovery [8].

Although the achievable substitution levels vary, the literature consistently indicates that MDF can incorporate recycled fibers without compromising performance under appropriate technological conditions [9, 10]. This confirms the real, yet conditional, potential of MDF to participate in cascade material flows.

In parallel, bio-based and formaldehyde-free adhesive systems are being developed to improve compatibility with fiber recovery and reduce environmental impacts [11-13]. Although these systems may require optimisation in terms of moisture resistance or processing parameters, they represent a promising direction for enhancing the circularity of MDF.

Environmental profiling through life cycle assessment (LCA) further highlights the importance of cascade use. MDF functions as a carbon store, and the choice of adhesive system, energy mix, and end-of-life scenario exerts a substantial influence on the carbon footprint and overall environmental impacts [14, 15]. At the same time, LCA results are highly sensitive to methodological assumptions, underscoring the need for harmonised approaches.

Despite the increasing number of studies on MDF recycling, hydrothermal fiber recovery, recycled fiber reintegration, adhesive systems and environmental assessment, the available knowledge remains fragmented [3, 7, 16]. Most studies address these aspects separately, while the combined influence of adhesive chemistry, recovered fiber quality, panel performance and life cycle considerations on the real cascade potential of MDF remains insufficiently integrated.

Therefore, the present review aims to provide a critical analysis of MDF as a biocomposite in the context of cascade use. The main contribution of the review is the integrated consideration of three interrelated aspects: recycling technologies and recovered fiber quality, adhesive systems and their compatibility with repeated processing, and environmental assessment through LCA. The review is based on scientific publications, standards and policy documents related to MDF recycling, cascade use of wood biomass, adhesive systems and environmental assessment of wood-based composites. This integrated perspective is used to identify the main technological limitations, environmental implications and future development pathways for MDF in the circular bioeconomy.

1 MDF AS A BIOCOMPOSITE AND ITS POSITION IN CASCADE FLOWS

MDF panels occupy a major position within the cascade flows of wood biomass due to their wide application, large production volume, and their nature as a biocomposite composed of lignocellulosic fibers and thermosetting adhesives [3, 5]. The increasing quantities of post-consumer MDF waste make them an important resource for expanding circular material streams [7, 17]. At the same time, the chemical structure of the adhesive system and the morphology of the fibers impose significant constraints on the potential for multiple recycling cycles.

1.1 MDF as a System of Wood Fibers and an Adhesive Polymer Network

MDF represents a typical lignocellulosic biocomposite in which the wood fibers form the dispersed phase, while the cured thermosetting resin creates a three-dimensional polymer matrix that provides internal cohesion and mechanical stability [6, 18]. The fibers themselves are a natural composite of cellulose, hemicelluloses, and lignin, and the ratio between these components determines the behaviour of the fiber mat and the properties of the final product [3, 19].

The quality of MDF is closely related to fiber morphology and adhesive distribution, which become especially important when recycled fibers are incorporated. During recycling, changes in fiber length, fines content and residual resin influence the ability of the recovered material to form new bonds [5, 17].

The main adhesive systems used in MDF production are urea-formaldehyde (UF) and melamine-urea-formaldehyde (MUF) resins. Optimised formaldehyde-to-urea (F:U) molar ratios allow a balance between strength and emissions, while the cured resin forms an infusible polymer network that fills the voids between the fibers [20, 21]. In parallel, bio-based adhesives derived from sugars, proteins, tannins, and lignin are being developed. These systems show potential for partial or complete substitution of formaldehyde-based resins and offer improved compatibility with hydrothermal fiber separation [12, 22, 23].

1.2 MDF in Cascade Flows: Potential and Limitations

MDF panels have considerable potential for reintegration within cascade material cycles. Hydrothermal treatment enables the recovery of fibers, and under appropriate conditions MDF produced with UF resins with a low formaldehyde-to-urea molar ratio can be recycled in such a way that up to 100% recycled fibers can be reintegrated without significant deterioration of properties [6]. Other studies show that boards containing 20–24% recycled fibers maintain the required physico-mechanical properties and exhibit reduced formaldehyde emissions [9]. These findings confirm the real, although conditional, potential for repeated reintegration [10, 24].

Despite this potential, MDF panels remain among the most challenging wood-based composites to recycle. Conventional UF and MUF resins form a stable three-dimensional network that hinders fiber separation. A substantial portion of the cured resin remains permanently attached to the recycled fibers and limits the possibilities for multiple recycling cycles [5, 6]. This necessitates the development of adhesive systems compatible with repeated degradation and reuse.

Bio-based adhesives, including lignin-based and protein-based systems, show potential for improving circularity because they allow easier fiber separation and result in lower emissions [1, 11, 23]. Innovative materials such as Bioblocks, produced from MDF residues, citric acid, and polyols, demonstrate additional opportunities for creating low-emission biocomposites based on recycled fibers [24].

1.3 Physical and Mechanical Properties of MDF

The performance of MDF is governed by the interaction between fiber morphology, adhesive distribution, mat structure and hot-pressing conditions [6, 25, 26]. In conventional MDF, wood fibers provide the reinforcing phase, while the cured adhesive network ensures internal cohesion and dimensional stability. Therefore, any change in fiber quality, resin penetration or density distribution directly affects the physical and mechanical properties of the panel. This relationship is particularly important in the context of cascade use, because recycled fibers usually differ from primary fibers in length, surface chemistry, fines content and the amount of residual adhesive [6, 17].

According to the commonly applied classification, the density of MDF generally falls within the range of 500–900 $kg \cdot m^{-3}$. Within this interval, density remains one of the most important structural factors influencing panel performance. Higher compression usually improves modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond strength (IB), but this effect depends strongly on uniform mat formation and effective adhesive bonding [13, 26]. The vertical density profile is also essential: denser surface layers contribute mainly to bending strength and stiffness, whereas the core layer has a decisive influence on internal bond strength [26, 27]. For this reason, recycled fibers with a high proportion of fines or residual resin may disturb mat consolidation and reduce bonding efficiency, even when the target density is achieved.

The main performance indicators for MDF include modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), thickness swelling (TS), water absorption (WA), moisture content, surface soundness and formaldehyde emission. These properties are commonly evaluated according to the relevant European standards for wood-based panels and are used to assess whether panels containing recycled fibers can meet the requirements for their intended applications [6, 25]. MOR and MOE reflect the bending strength and stiffness of the panel, while IB is highly sensitive to adhesion quality, fiber morphology and core-layer consolidation [26, 28]. WA and TS characterize moisture resistance and dimensional stability, which are particularly important when recycled fibers or modified adhesive systems are used.

In recycled MDF systems, maintaining acceptable physical and mechanical properties is more challenging because hydrothermal treatment and repeated processing can shorten fibers, increase the fine fraction and modify the fiber surface [6, 16]. Residual cured resin may partially contribute to bonding, but it can also mask active hydroxyl groups and reduce the interaction with newly added adhesive [5, 17]. As a result, the successful incorporation of recycled fibers requires a balance between fiber quality, adhesive type and dosage, pressing parameters and the target performance class of the final board. This makes the optimization of MDF properties a key prerequisite for effective cascade recycling [16].

2 ADHESIVE SYSTEMS AND THEIR INFLUENCE ON THE RECYCLABILITY OF MDF PANELS

2.1 Types of Adhesive Systems and their Role in Recyclability

Adhesive systems fundamentally determine both the performance properties and the recyclability of MDF within cascade material flows. They influence internal cohesion, moisture resistance, formaldehyde emission, durability and the ability of the panel to be disintegrated during recycling. In general, adhesive systems used or proposed for MDF can be divided into two main groups: conventional synthetic resins, such as UF, MUF, PF and pMDI, and bio-based or formaldehyde-free systems developed to reduce environmental impacts and improve compatibility with circular-economy models [16, 20, 22, 29], Figure 2.

Figure 2. Main groups of bio-based adhesives for wood-based composites. Reproduced with permission from Elsevier [30]

Among synthetic systems, UF resins remain dominant due to their low cost, high reactivity and favourable adhesion to wood fibers. Their relatively high sensitivity to hydrolysis can facilitate hydrothermal defibration, but it can also lead to chemical changes in the residual resin and affect the bonding ability of recovered fibers. MUF and PF resins provide improved durability and moisture resistance, which is beneficial during use, but their higher hydrolytic stability makes fiber recovery more difficult. pMDI adhesives offer excellent strength and water resistance; however, the highly stable isocyanate network is less compatible with conventional hydrothermal recycling and may require more severe treatment conditions [22, 31].

Bio-based adhesives, including lignin, lignosulfonates, tannins, proteins and polysaccharides, are increasingly considered as alternatives for circular wood-based panel production [12, 32]. Their potential lies not only in reducing formaldehyde emissions and dependence on fossil resources, but also in improving compatibility with fiber recovery and repeated material use. However, their practical application in MDF still depends on achieving sufficient bonding strength, moisture resistance and stable processing behavior under industrial conditions [1, 13, 23].

2.2 Polymer Network Formation and Adhesion Mechanisms

The formation of the polymer network and the type of adhesion mechanisms between the adhesive and wood fibers determine the strength, durability, and recyclability of MDF. The degree of crosslinking and the chemical resistance of the bonding system directly influence panel behaviour under moisture, temperature, and mechanical stress [22,33]. More stable networks ensure high service performance but significantly hinder hydrolytic defibration during recycling.

Formaldehyde-based resins (UF, MUF, PF) form a three-dimensional thermoset network that is insoluble and dimensionally stable [20, 34]. Adhesion is achieved through penetration into fiber pores and polar interactions between resin functional groups and the hydroxyl groups of cellulose and lignin [16, 33]. PF resins create an especially stable bond due to their aromatic structure and the potential for partial covalent bonding with lignin [22]. This high stability explains why formaldehyde resins provide good strength but simultaneously hinder hydrolytic degradation, which is critical for MDF recycling [5].

Isocyanate adhesives (pMDI) form a highly crosslinked and chemically resistant structure that bonds covalently with wood polymers [22, 33]. Their low viscosity before curing ensures deep penetration and effective mechanical interlocking, resulting in high strength and moisture resistance [31]. However, this stability makes pMDI the most difficult system to recycle, as the network is practically non-hydrolysable and prevents fiber separation.

In bio-based adhesive systems, bonding is mainly achieved through hydrogen bonding, ionic interactions, mechanical interlocking and, in some formulations, ester or other chemically reactive linkages [22, 33]. Compared with highly crosslinked synthetic networks, these systems may offer better compatibility with hydrothermal defibration, although their performance depends strongly on formulation, curing conditions and moisture resistance [12, 35].

2.3 Hydrothermal Behaviour and Comparative Recyclability

Hydrothermal resistance is a critical factor for both the long-term durability of MDF and its potential for cascade recycling. Hydrolysis of the adhesive network facilitates resin removal but may also cause hemicellulose degradation and fiber shortening, reducing the quality of recycled fibers [7, 36]. Hydrolysis resistance depends on chemical structure and crosslink density: UF resins are the most sensitive, MUF and PF show moderate resistance, while pMDI and certain biopolymer networks exhibit high stability [31, 37]. UF-bonded MDF defibrates most easily, because the network hydrolyses at relatively low temperatures. MDF produced with low molar ratio UF resins can be recycled under mild conditions (approximately 95°C), with fibers retaining mechanical properties and showing no increase in emissions [6]. Hydrothermal treatment below 100 °C can remove up to two thirds of the UF resin, while steam explosion can remove more than 80 % with limited fiber damage [7, 38]. MUF and PF resins are significantly more resistant, which limits their suitability for hydrothermal recycling [25].

pMDI-bonded MDF cannot be defibrated under standard hydrothermal conditions, because the isocyanate network is non-hydrolysable [5]. Fiber recovery requires aggressive thermochemical treatments that damage the lignocellulosic structure [7], which makes pMDI incompatible with cascade recycling.

Bio-based adhesives contain more hydrolysable linkages, for example ester bonds, which facilitate defibration and make them compatible with repeated recycling [22]. Systems such as CLIPboard allow multiple recycling cycles under steam treatment, although mechanical properties gradually decline [12]. Lignin, lignosulfonate, saccharide and protein-based adhesives promote fiber separation but require precise control of manufacturing parameters [32].

Overall, comparative studies indicate that the recyclability of MDF is closely related to the hydrolytic stability of the adhesive network. UF-bonded MDF shows the highest compatibility with hydrothermal recycling, whereas MUF and PF systems are more limited due to their higher resistance to hydrolysis. pMDI-bonded panels are the least suitable for conventional hydrothermal defibration. Bio-based and hybrid systems, particularly lignosulfonate-based formulations, represent a promising direction for improving MDF circularity, but their practical application requires further optimization of water resistance, curing behavior and panel performance [6, 9 ,12 ,32].

3 RECYCLING TECHNOLOGIES AND FIBER QUALITY

3.1 Technological Basis of MDF Production and Implications for Recycling

Dry-process MDF production includes raw-material preparation, thermomechanical defibration, drying, resin application, mat formation and hot pressing [25, 26]. These operations determine the initial fiber morphology, resin distribution, density profile and degree of adhesive curing, all of which influence both panel performance and subsequent recyclability [26, 39].

In the context of cascade use, these technological characteristics are important mainly because they affect the ease of re-defibration and the quality of recovered fibers. Fiber morphology, matrix composition and crosslinking degree determine how efficiently the cured panel can be disintegrated, how much residual resin remains on the fiber surface, and whether the recovered material can be reintegrated into new MDF without substantial loss of performance.

3.2 Hydrothermal Recycling Technologies and Their Effect on Fiber Morphology

Hydrothermal recycling relies on the hydrolytic cleavage of bonds between fibers and the cured resin, using heat and water or steam to degrade the UF matrix and release the fibrous material. Process intensity is governed by the combined severity factor, which integrates temperature and time [38]. Under mild conditions (95°C, 20–30 min), recycled fibers retain approximately 30 % of the original resin but can be reintegrated without significant loss of performance [6]. More intensive treatments, such as steam explosion at 180°C and 1 MPa for 15 min, remove more than 80 % of the resin and enable effective defibration [7, 40]. Mechanical refining following hydrothermal treatment further improves fiber separation [38].

The degree to which fiber morphology is preserved depends on process severity. Mild conditions maintain longer fibers and lower fines content, while aggressive treatments cause fiber shortening and fines formation. These changes impose practical limits on the proportion of recycled fibers that can be incorporated into new MDF without compromising panel quality.

3.3 Properties of Recycled Fibers, Reintegration Potential and Technological Limitations

Recycled fibers differ markedly from primary fibers in length, morphology and chemical composition. They are shorter, contain more fines and retain residual resin, which hinders uniform resin distribution and reduces the mechanical properties of newly produced panels [16, 17, 36]. The residual resin forms a rigid surface film that masks hydroxyl groups and limits the formation of new adhesive bonds [41, 42]. Fiber shortening and fines generation are the main causes of strength deterioration during reprocessing [3, 43, 37]. Hydrolysis also increases the proportion of hydrophilic groups, which may raise thickness swelling [6, 44].

The quality of recycled fibers depends on hydrothermal intensity, defibration degree, fines content and residual resin amount. Under optimised conditions, fibers with characteristics close to primary fibers can be obtained, enabling effective cascade use [11, 16]. Substitution levels range from low (up to 20–25 %), where properties remain within standard limits [9, 45], to medium (25–40 %), where internal bond strength begins to decline [46]. At high substitution levels (above 40 % and up to 100 %), performance depends strongly on the defibration method. Although many studies report strength reduction above 20 % recycled fibers [7], hydrothermal recycling at 95 °C has demonstrated that up to 100 % recycled fibers can be used without significant deterioration [6].

The adhesive system is a main factor for successful reintegration. In UF-bonded MDF, residual resin may both support bonding and hinder adhesion by masking hydroxyl groups [6]. For hydrothermally recycled fibers, a minimum of about 12 % UF resin is recommended [9]. Hybrid systems combining UF with bio-based components show strong potential: the addition of kraft lignin improves mechanical properties and reduces formaldehyde emissions in panels containing 10–30 % recycled fibers [16, 37].

4 ENVIRONMENTAL PROFILE AND LCA TRENDS

4.1 LCA Framework: Functional Unit, System Boundaries and Biogenic Carbon

The functional unit provides the reference basis for comparing MDF production scenarios. For MDF and wood-residue-based biocomposites, the dominant choice is 1 m^3 of finished product, enabling consistent comparison between boards made from primary fibers, varying proportions of recycled fibers, or exclusively from wood residues [15, 47, 48].

System boundaries define which life cycle stages are included. The most common configuration is cradle-to-gate, covering raw material extraction, fiber preparation, adhesive production, and all manufacturing processes up to the factory gate [47, 49]. This boundary setting is particularly effective for identifying production hotspots such as energy-intensive refining and resin synthesis. For carbon footprint assessments or cascade-use evaluations, boundaries are extended to cradle-to-grave, incorporating the use phase and end-of-life pathways including recycling, energy recovery, or landfilling [14, 50]. Methodological standards such as PAS 2050, the GHG Protocol, and ISO 14067 differ in their treatment of biogenic carbon and storage, which can lead to substantial variation in reported results [15]. Clear boundary definition is therefore essential for comparability across MDF systems.

Wood-based products act as temporary carbon stores, retaining biogenic CO_2 absorbed during tree growth. MDF can store over 1000 kg CO_2 eq·m^{-3}, which under certain methodological assumptions may yield a negative cradle-to-gate carbon footprint [14, 15, 50]. However, standards differ in how this storage is accounted for: PAS 2050 and the GHG Protocol allow deduction of stored CO_2, whereas ISO 14067 requires separate reporting. As a result, the same MDF system may range from –667.75 to +816.92 kg CO_2 eq·m^{-3}, illustrating how methodological choices can even reverse the sign of the carbon footprint [15]. Incorporating cascade cycles adds further complexity. Multiple material-use cycles prior to final energy recovery extend carbon storage duration and reduce demand for primary resources, thereby lowering overall greenhouse gas emissions [34, 51]. Yet quantitative modelling of cascade chains remains limited by data gaps and inconsistent methodological approaches [52].

4.2 Environmental Indicators and Scenario Comparison

Environmental assessment of MDF relies on LCIA methods such as CML-IA, Environmental Footprint 3.1, ReCiPe, and CED, each emphasizing different impact mechanisms [34, 47]. MDF is particularly sensitive to methodological choice due to biogenic carbon accounting, cascade use, and the diversity of end-of-life pathways. Among all indicators, Global Warming Potential (GWP) is the most influential. UF resins and electricity consumption are the dominant contributors to climate impacts, reflecting the importance of adhesive systems and the energy profile of production [47, 48].

Cumulative Energy Demand (CED) is another important indicator, with fiber preparation and hot pressing representing the most energy-intensive stages. In secondary composites, fossil resource use and high electricity consumption become the main contributors [49]. The energy mix strongly influences results, and transitions toward renewable energy significantly improve the environmental profile. Beyond climate and energy impacts, UF resins and electricity also contribute substantially to acidification, eutrophication, toxicity, and water use [47]. Wood preparation alone accounts for more than 90% of impacts on human health, ecosystems, and resource depletion [50]. For secondary composites, categories such as Freshwater Eutrophication and Mineral Resource Use are particularly relevant due to energy-intensive processing [49].

Conventional LCIA methods do not include explicit circularity indicators, yet research highlights the importance of indicators such as service life, number of cascade cycles, and duration of carbon storage [52, 53]. Therefore, circularity assessment requires complementing standard LCIA categories with metrics related to life cycle extension, reuse, and recycling [10].

Scenario comparison further illustrates how adhesive systems, recycled fiber content, and end-of-life pathways shape the environmental profile of MDF. The baseline scenario considers MDF produced with UF resins and primary fibers, where UF resins and electricity dominate climate and resource impacts, and fiber preparation is the main hotspot [47, 50].

A second scenario introduces MDF with partially recycled fibers while retaining UF resins. Recycled fibers can be incorporated without compromising performance, and reductions in formaldehyde emissions are observed [9]. LCA results show reduced burdens from primary fiber extraction and resin production, but also increased energy and water requirements [5].

A third scenario examines MDF produced with bio-based or formaldehyde-free adhesives in combination with recycled fibers. Adhesives based on lignin, proteins, or modified UF resins reduce dependence on fossil resources, although the environmental benefits depend on the energy efficiency of adhesive synthesis [16]. Finally, end-of-life pathways strongly influence overall performance. Reintegration of MDF waste into new panels provides the greatest environmental benefits, while landfilling is the least favourable option [14]. Multiple material-use cycles prior to final energy recovery represent the most sustainable pathway, extending carbon storage and reducing demand for primary resources [34, 53].

4.3 Interpretation of Results and Methodological Limitations

The interpretation of LCA results for MDF is constrained by several methodological factors. The most significant challenge is the lack of comparability between studies, arising from differences in functional units, system boundaries, allocation rules, and the LCIA methods applied [15,49,53]. The choice of allocation approach can alter the final assessment by up to a factor of two [49].

A second limitation is the lack of reliable data for end-of-life processes and the actual behaviour of long-lived wood products [51]. Insufficient transparency in EoL scenarios increases uncertainty and limits the interpretability of results.

An additional complication is the competition between material recycling and energy recovery, which depends on market conditions and renewable energy policies [14]. Although material recycling generally shows a more favourable environmental profile than incineration, results remain highly dependent on system boundaries and the quality of input data.

A further methodological challenge is the treatment of biogenic carbon. Differences between PAS 2050, the GHG Protocol, and ISO 14067 can change even the sign of the carbon footprint [15, 54]. This highlights that the assessment of climate benefits from cascade use depends not only on technological parameters but also on the chosen methodological framework.

5 CHALLENGES AND FUTURE DIRECTIONS

A comprehensive assessment of MDF within cascade material flows reveals several scientific, technological and methodological challenges that limit its recyclability and long-term circularity. These challenges arise from fiber degradation during repeated processing, the behaviour of adhesive systems under hydrothermal conditions and the methodological inconsistencies in environmental assessment. This chapter synthesises the main barriers to effective cascade use and outlines future directions for improving recycling technologies, developing more compatible adhesive systems and integrating circularity indicators into environmental evaluations.

5.1 Technological Challenges in Recycling and Fiber Quality

The main technological challenge in the cascade use of MDF is the progressive deterioration of recovered fiber quality during hydrothermal defibration and repeated processing. Fiber shortening, increased fines content, changes in surface chemistry and the presence of residual cured resin reduce bonding efficiency and limit the number of feasible recycling cycles [3, 16, 17]. Although residual adhesive may partly contribute to bonding, it can also mask hydroxyl groups and restrict the interaction between recovered fibers and newly added resin [41, 42].

These limitations show that successful cascade recycling of MDF depends not only on fiber recovery, but also on controlling the quality of the recovered material. Optimised hydrothermal and steam-explosion processes can yield fibers with characteristics close to primary fibers and allow acceptable reintegration levels [6, 9]. However, higher recycled fiber contents require adapted adhesive dosage, improved fiber morphology and optimized pressing parameters. Therefore, MDF recycling should be approached as a controlled cascade process rather than as unlimited closed-loop recycling.

5.2 Adhesive-Related and Environmental Assessment Challenges

The adhesive system is a decisive factor for both MDF performance and recyclability. UF resins are highly sensitive to hydrolysis, which facilitates recycling but leads to partial network degradation and chemical changes that affect re-bonding [6]. MUF and PF resins exhibit significantly higher hydrolysis resistance, improving durability but hindering hydrothermal defibration [25]. pMDI-bonded MDF presents the greatest challenge, as the isocyanate network is practically non-hydrolysable and requires aggressive thermochemical treatments that damage the lignocellulosic structure [5, 31], making pMDI incompatible with cascade recycling.

Bio-based adhesives offer promising alternatives but also have limitations. Lignosulfonate-based systems enable low-emission MDF production, yet water resistance remains a critical issue, particularly when industrial waste fibers are used [1, 55]. Hybrid UF-lignin systems show strong potential: the addition of 7.5 % kraft lignin improves MOR and MOE and reduces formaldehyde emissions in panels containing 10 % recycled fibers, in some cases outperforming panels made from primary fibers [16].

Environmental assessment introduces additional challenges. LCA results vary widely due to differences in functional units, system boundaries, allocation rules and LCIA methods [49, 53]. The treatment of biogenic carbon is particularly inconsistent: different standards (PAS 2050, GHG Protocol, ISO 14067) can produce values ranging from −660 to +800 kg CO_2 eq·m^{-3} for the same MDF system [15]. Further limitations include insufficient end-of-life data, unclear EoL scenarios and competition between material recycling and energy recovery [14, 51]. Conventional LCIA approaches lack explicit metrics for circularity, including cascade cycles, service life and carbon storage duration, despite their recognised importance for assessing the sustainability of wood-based materials [10, 52].

5.3 Future Development Pathways

Future progress in the cascade use of MDF requires simultaneous improvement of recycling technologies, adhesive systems and environmental assessment methodologies. Optimising hydrothermal processes is essential for improving fiber quality. Developing milder conditions that minimise fiber shortening and fines formation, as well as combined hydrolysis-steam-explosion methods, can yield fibers with characteristics close to primary fibers and enable higher substitution levels [3].

Advances in adhesive systems are equally important. Modified UF resins, hybrid UF-lignin formulations and bio-based adhesives with controllable hydrolytic resistance can reduce environmental impacts while facilitating re-defibration and maintaining performance [11, 21]. These systems can compensate for the structural limitations of recycled fibers and support higher reintegration rates. Achieving stable properties at substitution levels above 30–40% requires improvements in fiber morphology, optimisation of adhesive dosage and adaptation of hot-pressing parameters [9].

A crucial direction is the integration of circularity indicators into LCA. Current LCIA methods do not account for cascade cycles, carbon storage duration or reuse potential, although these factors are central to evaluating the sustainability of wood-based materials [52, 53]. Developing methodologies that incorporate these parameters will enable more realistic and comparable assessments of environmental benefits.

Finally, the establishment of industrial systems for collection, sorting and pre-treatment of MDF waste is essential for practical implementation of cascade models. Automated technologies for removing coatings, contaminants and residual adhesives will improve fiber quality and reduce technological losses [5]. Overall, future development should be directed toward high-efficiency, low-emission and practically recyclable wood composites aligned with the principles of the circular bioeconomy.

CONCLUSIONS

The present review demonstrates that medium-density fiberboard has significant, but conditional, potential for cascade use within the circular bioeconomy. Its main advantage lies in the possibility of reintegrating recovered lignocellulosic fibers into new material cycles, thereby extending the service life of wood biomass, reducing demand for primary raw materials and supporting more resource-efficient wood-based panel production.

The main contribution of this review is the integrated consideration of three closely related aspects that are often discussed separately: recycling technology, adhesive chemistry and environmental assessment. The analysis shows that the recyclability of MDF cannot be evaluated only through the availability of recycling technologies. It also depends on the morphology and surface condition of recovered fibers, the amount and behavior of residual resin, the compatibility of the adhesive system with repeated processing, and the performance requirements of the final board.

Hydrothermal treatment remains the most promising approach for MDF fiber recovery, but it does not provide unlimited closed-loop recycling. Fiber shortening, increased fines content and residual cured resin restrict the number of feasible recycling cycles and may reduce physical and mechanical properties. Therefore, MDF should be considered a material with controlled cascade potential rather than a fully closed-loop product.

The adhesive system is a decisive factor in this process. UF-bonded MDF is more suitable for hydrothermal defibration, while more hydrolysis-resistant systems such as MUF, PF and pMDI improve durability but limit recyclability. Bio-based and formaldehyde-free adhesives offer promising opportunities for improving circularity, although their moisture resistance and processing behavior still require further optimization.

Finally, LCA studies confirm the environmental relevance of cascade MDF use, particularly in relation to resource efficiency, carbon storage and end-of-life scenarios. However, the results remain highly dependent on methodological assumptions. Future research should therefore combine optimized recycling processes, adhesive systems designed for recyclability, improved recovered fiber quality and harmonized LCA approaches. This integrated perspective is essential for the development of low-emission, resource-efficient and practically recyclable MDF-based composites.

ABBREVIATIONS

The manuscript contains the following abbreviations:

MDF	Medium-Density Fiberboard
UF	Urea-Formaldehyde
MUF	Melamine-Urea-Formaldehyde
pMDI	Polymeric Methylene Diphenyl Diisocyanate
MOR	Modulus of Rupture
MOE	Modulus of Elasticity
WA	Water Absorption
TS	Thickness Swelling
PF	Phenol-Formaldehyde
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
GWP	Global Warming Potential
CED	Cumulative Energy Demand
EoL	End-of-Life

AUTHOR CONTRIBUTIONS

Conceptualization, V.D. and G.I.; methodology, V.D. and G.I.; software, G.I.; validation, V.D. and G.I.; formal analysis, V.D.; investigation, V.D., G.I.; Resources, V.D. and G.I.; Data Curation, V.D. and G.I.; Writing—Original Draft Preparation, G.I.; Writing—Review and Editing, V.D; Visualization, V.D. and G.I.; Supervision, V.D. and G.I.; Project Administration, V.D. and G.I.; Funding Acquisition, V.D. and G.I.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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