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Material Recycling of Particleboard and Fibreboard – a Literature Review

Recikliranje materijala od iverica i ploča vlaknatica – pregled literature

REVIEW PAPER
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ABSTRACT • *The demand for sustainable products and production methods is driving renewed interest in wood as a renewable and environmentally friendly raw material. The recycling of wood-based materials, such as particleboard and fibreboard, is crucial in meeting this demand while conserving natural resources. This article reviews advances in the technology of wood-based material recycling, analysing the literature from the turn of the millennium to the present day, with a focus on pulping processes and their effects on physical and mechanical properties. The review identifies several established and emerging processes, including mechanical, thermohydrolytic and innovative ohmic heating processes, and notes that apart from the established processes, no other processes have been successfully scaled up to industrial application. A particular challenge remains in the processing of materials bonded with urea-formaldehyde resins, where recycling has a significant impact on particle geometry and adhesive residues, affecting product quality. Promising improvements in mechanical properties have been observed with resistive heating, suggesting potential for this technique in future recycling applications. Overall, this review highlights the need for scalable, efficient recycling solutions to meet industry sustainability goals.*

KEYWORDS: *fibreboard; literature review; particleboard; recycling*

SAŽETAK • *Zahtjev za održivim proizvodima i procesima potiče ponovno zanimanje za drvo kao obnovljivu i ekološki prihvatljivu sirovinu. Recikliranje materijala na bazi drva, poput iverice i ploča vlaknatica, imperativ je za zadovoljavanje potražnje drva uz očuvanje prirodnih resursa. Članak donosi pregled napretka u tehnologiji recikliranja materijala na bazi drva analiziranjem literature od prijelaza tisućljeća do danas, s naglaskom na procesima proizvodnje pulpe i njihovu utjecaju na fizička i mehanička svojstva drvnih čestica. U radu je identificirano nekoliko ustaljenih i novih procesa, uključujući mehaničke, termohidrolitičke i inovativne omske procese zagrijavanja, te se naglašava da osim ustaljenih procesa nijedan drugi proces nema industrijsku primjenu. Poseban je izazov obrada materijala lijepljenih urea-formaldehidnim smolama, pri čemu recikliranje ima važan utjecaj na geometriju čestica i ostatke ljepila, što utječe na kvalitetu proizvoda. Obećavajuća poboljšanja mehaničkih svojstava uočena su pri omskom zagrijavanju, što pokazuje da ta tehnika ima potencijala u budućim metodama recikliranja. Općenito, u ovom se radu ističe potreba za učinkovitim rješenjima recikliranja kako bi se postigli industrijski ciljevi održivosti.*

KLJUČNE RIJEČI: *ploča vlaknatica; pregled literature; iverica; recikliranje*

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1 INTRODUCTION
1. UVOD

The accumulation of medium-density fibreboard (MDF) and chipboard waste poses significant environmental and economic challenges. These wood-based materials, widely used in furniture and construction, contain adhesives and resins that complicate recycling efforts and can lead to harmful emissions when improperly disposed of. The growing volume of this waste, coupled with its resistance to conventi onal recycling methods, has created an urgent need for innovative solutions.

The amount of waste wood in Germany in 2020 was about 16.2 million m³, of which only about 15 % was recycled (Mantau, 2023). The remaining 85 % of waste wood will be used for energy production. This current low recycling rates represent a significant loss of wood chips and fibres that could be reused in new products. A key element of the Circular Economy Act, which came into force in 2015, is to increase the recycling of waste. While the German law does not specify a recycling rate, the European Union's circular economy package includes a target to recycle at least 65 % of municipal waste by 2035 and at least 70 % of construction and demolition waste and packaging waste by 2030. In Germany, a total of 7.8 million tons of waste wood from these three sectors was generated in 2016, which is around 70 % of the total volume (Flamme *et al.,* 2020). This means that there is still a large gap to the planned recycling rates. Wood-based materials in which the wood fibres have been glued pose a particular challenge for the recycling of waste wood. Particleboard and fibreboard are widely used furniture materials whose increasing demand and relatively short life cycles lead to increased waste generation and disposal problems (Zimmer *et al.,* 2023). This article provides an overview of recycling technologies for these wood-based materials, identifies challenges and discusses possible solutions.

Therefore, this article reviews scientific publications on particleboard and fibreboard recycling that have been published since the papers "On the Recycling of Chipboard and MDF Panels" Parts 1 & 2 by Franke and Roffael were published (1998a and 1998b). The first part of Franke and Roffael's work (Franke and Roffael, 1998a) investigated the hydrolysis resistance of cured urea formaldehyde (UF) resins in particleboard and medium density fibreboard (MDF) under the influence of steam hydrolysis, while the second part (Franke and Roffael, 1998b) compared formaldehyde emissions from UF-bonded particleboard and MDF panels with fresh pine flakes during and after various hydrolysis processes.

Until around the turn of the millennium, the processes for recycling wood composites were divided into mechanical, thermohydrolytic and chemical processes. Apart from mechanical processes for crushing materials into chips and reusing them in chipboard, only a few other processes have become established industrially. Mechanically crushed chips have a number of disadvantages. Typically, the structure of the wood particles is severely damaged; in addition, the chips have a lower water retention value and the wettability with binding agents is poorer than with fresh chips or chips obtained by thermo-hydrolytic digestion (Franke, 1999). The Pfleiderer process, the WKI process and the Formaplan process are among the few industrially realisable processes for the thermo-hydrolytic digestion of particleboard.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Based on the work of Franke and Roffael (1998a and 1998b), the scientific literature on particleboard and medium density fibreboard (MDF) was searched, analysed and compiled into a literature review using three research methods in literature databases.

Method 1: Analysis of literature referencing the work of Franke and Roffael (1998a and 1998b) by examining sources citing these two articles in literature databases.

Method 2: Evaluation of an existing literature review on the production of wood composites from recycled wood (Nguyen *et al*., 2023). The literature on particleboard and MDF was extracted from the literature review, clustered, analysed and used as a reference for further literature searches. The literature was summarised in the results chapter.

Method 3: Keyword search in scientific databases:

- Google Scholar
- ResearchGate
- Science Direct
- Web of Science

The following keywords were used:

- Fibre recycling
- Furniture waste
- Waste MDF
- Wood waste sorting technologies
- Wood materials sorting technologies

The literature was first categorised by subject into particleboard recycling processes and MDF recycling processes. The literature was then subdivided into categories such as the type of wood used, the delignification process and the glue that may be broken down or opened up by the process. Tables at the beginning of each chapter provide an overview for ease of reference. The text describes the respective processes and studies, as well as the physical and mechanical properties investigated. A table in the results section provides an overview of the physical and mechanical property results.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Recycling processes for particleboards and their physical and mechanical properties
3.1. Procesi recikliranja ploča iverica i njihova fizička i mehanička svojstva

3.1.1 Tabular overview
3.1.1. Tablični pregled

The methods for recycling chipboard can be summarised as follows (Table 1). The various digestion processes mentioned here are explained in more detail.

3.1.2 Thermal hydrolysis
3.1.2. Toplinska hidroliza

With the Conti-Recycling process according to Kirchner and Kharazipour (2002), the residence time could be reduced by 5-7 minutes as an alternative to the established Pfleiderer process with a residence time of about 10 minutes. Particleboard waste with UF resin binder is pulped at a steam pressure of 2-6 bar and temperatures between 120-180 °C and continuously conveyed by screw conveyors through five successive spirals to an outlet which ends in a vibrating channel for material sorting and screening. The process is also suitable for recycling MDF (Kirchner and Kharazipour, 2002). In investigations on the shift of the molar ratio of formaldehyde to urea in the resin of hydrolysis residues by Roffael and Kraft (2004), chipboard waste was thermohydrolytically pulped in an autoclave at 100 °C, 110 °C, 120 °C and 130 °C; a liquor ratio of particleboard:water of 1:5 and a pulping time of 60 minutes. It was found that the molar ratio of formaldehyde:urea (F : U) in the hydrolysis residues increased significantly with higher pulping temperatures, indicating more extensive adhesive degradation.

Lykidis and Grigoriou (2008) tested four different thermohydrolytic (steam) treatments under different pressure-temperature-duration-conditions. Furthermore, a second recycling cycle was tested. It was observed that the recovered particles showed higher amounts of k < 1 mm compared to the original reference material, which likely indicates that the recycling process involves a slight reduction in wood particle size. Except for the modulus of elasticity in static bending, all mechanical properties of the tested recycled panels decreased compared to the reference panels. A reduction in particle size was also noted, with the suspicion that this could negatively affect bending strength. Regarding hygroscopic properties, water absorption and thickness swelling increased. An increase in bulk density was also observed. The quality was further deteriorated by the second recycling process. Using higher temperatures leads to thermal decomposition of the wood components, resulting in a significant deterioration of the mechanical properties of the recycled panels. The degradation in quality can be significantly reduced by using milder hydrolysis temperatures. It is recommended to use blends of fresh and recycled wood particles to avoid significant degradation in the quality of the produced panels while still meeting applicable specifications. In further investiga-

Table 1 Overview of the literature focusing on the recycling of waste wood into chipboards. The literature was categorised based on the origin of the waste wood, the pulping process, and the adhesive (UF – urea formaldehyde; PF – phenol formaldehyde) suitable for the digestion process
Tablica 1. Pregled literature o recikliranju otpadnog drva u ivericu. Literatura je kategorizirana na temelju podrijetla otpadnog drva, procesa proizvodnje pulpe i ljepila (UF – urea formaldehid; PF – fenol formaldehid) prikladnoga za proces digestije.

Wood-composite *Kompozitno drvo*	**References** *Literatura*	**Waste wood origin** *Podrijetlo drvnog otpada*	**Digestion process** *Proces digestije*	**Adhesive** *Ljepilo*
Particleboard *iverica*	Franke and Roffael, 1998a	Particleboard / *iverica*	Thermal hydrolysis *toplinska hidroliza*	UF
	Kirchner and Kharazipour, 2002	Particleboard / *iverica*	Thermal hydrolysis *toplinska hidroliza*	UF
	Lykidis and Grigoriou, 2008	Particleboard / *iverica*	Thermal hydrolysis *toplinska hidroliza*	UF
	Zamarian *et al.*, 2017	MDF, Particleboard, Plywood, Construction and demolition wood *MDF, iverica, furnirska ploča, konstrukcijsko drvo*	Mechanical processes *mehanički procesi*	UF
	Laskowska and Mamiński, 2018	Plywood / *furnirska ploča*	Mechanical processes *mehanički procesi*	UF, PF
	Iždinský *et al.*, 2020	MDF, Particleboard, Paletts, HDF *MDF, iverica, palete, HDF*	Mechanical processes *mehanički procesi*	Unknown *nepoznato*
	Lubke *et al.*, 2020	Plywood / *furnirska ploča*	Thermohydrolysis *termohidroliza*	UF

tions by Lykidis and Grigoriou (2011) using thermohydrolysis, partial agglomeration of the recovered chip material was addressed, which is attributed to incomplete hydrolysis of the UF resin under the parameters used. Using new hydrolysis parameters (150 °C/10 min), the issue could largely be resolved. Under the aforementioned parameters, better results were achieved in terms of shear strength, surface strength, bending modulus of elasticity, and hygroscopic properties compared to experiments by Lykidis and Grigoriou (2008).

3.1.3 Mechanical processes
3.1.3. Mehanički procesi

Zamarian *et al.* (2017) and Azambuja (2018) applied a purely mechanical shredding method in laboratory tests to produce particleboard from a mixture of furniture waste and construction and demolition wood (MDF, particleboard, plywood and timber). The material was pre-crushed in a crusher and then treated in two passes in a special shredder. The addition of recycled chip material resulted in a reduction in water absorption and thickness swelling after 2 and 24 hours. Residual paraffin emulsions and adhesive residues from the manufacture of the original panels are thought to affect resistance. There is also an increase in bulk density due to the adhesive residues (Zamarian *et al,* 2017; Azambuja, 2018). Azambuja (2018) found that the aspect ratio of particles from particleboard and plywood panels had statistically lower average values compared to fresh reference particles and particles from wood. Regarding shear strength, the panels of all treatments made with particles from furniture waste showed equal or better values compared to the reference panels. For flexural strength, only the 10 % furniture waste treatment met the minimum requirements of the standard (Zamarian *et al.,* 2017). Since significantly better results were obtained for shear strength than for bending strength up to a certain proportion of recycled chips, it is recommended to mix the particles up to 50 % in the core layer of the particleboard, as less bending stress occurs in the core layer and the stress here affects the shear strength more (Azambuja, 2018).

Laskowska and Mamiński (2018) investigated the properties of particleboards made from post-industrial UF and PF bonded plywood. A purely mechanical method using a wood shredder was used. Initially, as observed in the studies by Zamarian *et al.* (2017) and Azambuja (2018), an increase in bulk density was observed, which, in the case of plywood, is influenced by the adhering residual adhesive and the compaction effect during veneer pressing. As a result of the increase in bulk density, it was observed that pressing times could be reduced by 3 to 6 % when using recycled material. A review of the literature by Humphrey and Bolton (1989) confirms this phenomenon and describes how the core layer becomes less compact at high bulk densities, leading to an acceleration of heat transfer. Similar to the studies by Zamarian *et al.* (2017) and Azambuja (2018), a decrease in flexural strength and a reduction in thickness swelling were also observed. Furthermore, the type of original binder (UF or PF) was found to have no effect on the comminution process and the properties of the particles produced.

Iždinský *et al.* (2020) also used mechanical crushing in their investigations to produce UF resin-bonded laboratory particleboards for property determination from a mixture of material waste, fir wood pallets, old furniture and defective particleboards. All materials were processed with a ring flaker and then ground into particles in a mill. Reduced thickness swelling was observed after 2 and 24 hours of immersion in water, particularly for UF-bonded particleboard. The *MOR*, *MOE* and internal bond IB of the particleboards were negatively affected by increasing amounts of recycled material. The results are in agreement with those of Zamarian *et al.* (2017), Azambuja (2018) and Laskowska and Mamiński (2018).

3.1.4 Thermohydrolysis
3.1.4. Termohidroliza

Lubke *et al.* (2020) soaked pieces of chipboard for 30 minutes to absorb moisture and allow the samples to swell. A Pallmann drum chipper with longitudinal slots was used for shredding. The bending strength of the recycled particleboard decreased by 13 % and the shear strength by 34 %, while the modulus of elasticity in static bending showed a slight increase of 1.3 %. Comparing the results with those of other studies, it should be noted that Lykidis and Grigoriou (2008; 2011) obtained similar results under hydrothermal conditions. They also found that after the second hydrothermal treatment under pressure (167 °C, 20 min), the Young's modulus increased by 20.7 %. The researchers suggest that the thermohydrolytic treatment increases the elasticity of the chips, which can lead to a reduction in the long-term deflection of the panels. Multiple recycling of the panels further degrades the aforementioned properties, as also described by Lykidis and Grigoriou (2011).

3.2 Recycling processes for MDF and their physical and mechanical properties
3.2. Procesi recikliranja MDF ploča i njihova fizička i mehanička svojstva

3.2.1 Tabular overview
3.2.1. Tablični pregled

The methods for recycling MDF can be summarised as follows (Table 2). The various digestion processes mentioned here are explained in more detail.

3.2.2 Thermomechanical and thermohydrolytic pulping processes
3.2.2. Termomehanički i termohidrolitički procesi proizvodnje pulpe

Krzysik *et al.* (1997) used a thermomechanical pulping process for the production of MDF, specifically processing chips from construction and demolition wood (species: spruce, pine, fir) and paper. The chips were fibrillated on a Sprout-Bauer refiner at a steam temperature of 77 °C and a disc gap of 0.3 mm for ½ minute. The bending strength of the test boards decreased with increasing board thickness, with only 6 mm thick boards meeting the standard. However, the bending modulus largely complied with or exceeded the standard. The authors specifically referenced the ANSI A208.2 standard for MDF, which was the prevalent guideline for MDF properties in North America at the time of their research. Similarly, the internal bond strength decreased with increasing board thickness, with none meeting the standard. Thickness swelling did not meet the requirements for any thickness. However, it was observed that the fibres could be easily wetted with all adhesives, indicating the potential for the production of MDF from these waste materials. With regard to the influence of parameters on hydrolysis, it should be noted that the degradation of cured UF resins depends on their chemical structure and degree of cross-linking (Elbert, 1995; Fleischer and Marutzky, 2000). This includes the fact that UF resins with a high F:U molar ratio have a higher resistance to hydrolysis than those with a low F:U molar ratio (Lubis *et al.,* 2018a). As adhering residual resin remains a core issue in recycling, Lubis *et al.* (2018b) focused on resin removal from recycled fibres and found that hydrolysis time has less influence on cured UF resins than temperature or molar ratio. Under hydrolysis (neutral and alkaline pulping), residual resins are not completely removed as they remain in the cell walls of the fibres (approximately 23-59 %). Acid or chemical pulping, on the other hand, can remove resins much better (more than 74 %).

Buschalsky and Mai (2021) used MDF with a relatively low F:U molar ratio (1.11) for recycling. UF-bonded MDF was thermohydrolytically pulped in an autoclave with water at 95 °C for 20-30 min and

Table 2 Overview of literature focusing on recycling of waste wood into MDF. The literature has been categorised according to the origin of the waste wood, the pulping process and the adhesives suitable for the pulping process.
Tablica 2. Pregled literature o recikliranju otpadnog drva u MDF ploču. Literatura je kategorizirana na temelju podrijetla otpadnog drva, procesa proizvodnje pulpe i ljepila (UF – urea formaldehid; PF – fenol formaldehid) prikladnoga za proces proizvodnje pulpe.

Wood-composite *Kompozitno drvo*	**References** *Literatura*	**Waste wood origin** *Podrijetlo drvnog otpada*	**Digestion process** *Proces digestije*	**Adhesive** *Ljepilo*
Medium density fibreboard *srednje gusta vlaknatica*	Krzysik *et al.,* 1997	Construction demolition wood / *konstrukcijsko drvo od rušenja*	Thermo-mechanical *termomehanički*	varying / *promjenjivo*
	Franke and Roffael, 1998a	MDF	Thermohydrolysis *termohidroliza*	UF
	Kirchner and Kharazipour, 2002	MDF	Thermohydrolysis *termohidroliza*	UF
	Buschalsky and Mai, 2021	MDF	Thermohydrolysis *termohidroliza*	UF
	Savov *et al.,* 2023	MDF	Thermohydrolysis *termohidroliza*	UF
	Mantanis *et al.,* 2004	MDF	Thermo-hydrolytic-mechanical *termohidrolitičko-mehanički*	UF
	Ihnát *et al.,* 2018	MDF, Chipboard, OSB	Thermo-hydrolytic-mechanical *termohidrolitičko-mehanički*	UF, MUF
	Lubke *et al.,* 2020	Chipboard	Thermo-hydrolytic-mechanical *termohidrolitičko-mehanički*	UF
	Wan *et al.,* 2014	MDF, Chipboard, OSB	Steam explosion *parna eksplozija*	UF, PF
	Dix *et al.,* 2001	MDF	Chemical decomposition *kemijska dekompozicija*	UF, MUF, PF, pMDI
	Ateş *et al.,* 2023	MDF	Chemical decomposition *kemijska dekompozicija*	UF
	Moezzipour *et al.,* 2018	MDF	Ohmic heating *omsko zagrijavanje*	UF
	Elias and Bartlett, 2018	MDF	Micro-release-process *process mikrootpuštanja*	UF
	Ateş *et al.,* 2023	MDF	Microwave-process *mikrovalni proces*	UF

processed into test panels. The disintegration process required significantly lower temperatures and was significantly shorter than in previous studies. Nitrogen content analysis showed that the recovered fibres contained approximately 30 % of the original UF. The density of the test boards was higher than the target density and the density of the reference boards. Thickness swelling was reduced by 50 % after the first recycling, by 25 % after the second recycling for 10 mm boards and by 40 % for 16 mm boards compared to the reference. Internal bond strength was identical to the reference after the first recycling and increased by 64.5 % for 10 mm MDF after the second recycling, which the scientists attributed to a slight reduction in fibre length that can occur during recycling, resulting in increased surface area and better adhesion (Back, 1987). However, there is a reduction in flexural strength with fibre shortening (Myers, 1983). In addition, a high proportion of fines contributes to a reduction in the modulus of elasticity (Dix *et al.,* 2001).

Ateş *et al.* (2023) used the WKI method and found that some fibres were extremely thick. In addition, the investigations showed a decrease in flexural strength and an increase in thickness swelling. The main reason for this is the presence of glue and paraffin residues on the recycled fibres. These microscopic residues can remain on the surface of the recycled fibres and even reduce the bonding ability of the fibres by binding to the -OH groups in the fibres, which could also affect the decrease in internal bond strength described in previous works (Zeng *et al.,* 2018). A significant increase in recycled fine fibres was also observed. There was also some decrease in fibre fractions with lengths greater than 1.24 mm, which can be classified as coarse fibres.

3.2.3 Thermohydrolytic-thermomechanical pulping processes

3.2.3. Termohidrolitičko-termomehanički procesi proizvodnje pulpe

Mantanis *et al*. (2004) attempted to industrialise a thermohydrolytic-thermomechanical pulping process for MDF with the aim of increasing the proportion of recycled fibre in production to over 20 %. MDF was pre-shredded into chips using a hammer mill and mixed with fresh wood chips at a ratio of 3:1. Impurities were removed by metal detection, screening and washing. The refining time in the refiner was 3-3 1/2 minutes at a pressure of 8.2 mbar with a fibre throughput of 5.0 t/h. It was found that the process could be used in production lines with single stage presses for E2 class MDF products. At 25 % waste, an internal bond strength of 0.60 N/mm² was achieved, which was more than half that of the reference boards. The addition of an unknown additive at 10 % resulted in an almost complete improvement. Similar behaviour was observed for flexural strength. Thickness swelling could be reduced by using waste boards. It is reported that even at a substitution level of 25 %, and without changing the press cycle and productivity, the new process resulted in "recycled" MDF boards with properties far exceeding European standards.

In studies by Roffael *et al.* (2010), MDF waste was pre-crushed and subjected to thermo-hydrolytic treatment at 170 °C for 5 minutes, followed by fibrillation in the refiner. Changes in the morphology of TMP (thermomechanically pulped fibres) from used particleboard and fibreboard to TMP from virgin wood were observed. Recycled TMP had a shorter fibre length and a higher fine fraction within the recovered fibres. TMP from wood can be replaced up to 30 % by TMP from used chipboard and fibreboard in the production of UF resin-bonded MDF without significant impairment of the mechanical-technological properties of the boards produced.

Ihnat *et al.* (2018) recycled a mixture of particleboard, MDF, and OSB into fibre. In addition to the usual UF bonded particleboard and MDF, Melamine-Urea-Formaldehyde Resin (MUF) bonded particleboard, MDF and OSB were also used. The MUF bonded samples were first treated in boiling water at 180 °C to induce swelling. Adhesive bridges were then broken by pressing and the samples were re-comminuted using a Palmann drum chipper. Finally, the material was fibrillated on a Sprout-Waldron refiner and refined on a Valley-Hollander. UF bonded particleboard was boiled for 30 minutes to a moisture content of 40 % and MDF for 3 minutes to a moisture content of 45 %. The same process technology was then used as for the MUF bonded wood materials, except for the pressing step. The fibres obtained were then characterised and not processed into laboratory boards. Chipboard waste with UF bonding has a high proportion of long fibres, while that from MUF-bonded chipboard and OSB has a high proportion of fine fibres, due to the greater brittleness of the MUF-wetted chips. Fibres obtained from MUF-based MDF waste are suitable for MDF production immediately after processing.

Lubis *et al.* (2018b) produced recycled fibres from MDF waste using a thermohydrolytic-mechanical treatment (steam treatment: 30 min at 180 °C and 600 kPa) for laboratory boards with different recycled fibre content. After steam treatment, the fibres were comminuted in two batches using a hammer mill (1500 rpm) and a refiner (atmospheric pressure; 1000 rpm; plate gap 1 mm). The shorter fibre lengths and higher fine fraction within the recycled fibres compared to virgin fibres observed by Roffael *et al.* (2010) were confirmed. The highest internal bond strength occurred at 10 % recycled fibre content, regardless of pulping method and wood species, after which the internal bond strength decreased. Mechanical properties, including flexural strength and modulus, showed a similar trend with increasing recycled fibre content. Thickness swelling and water absorption decreased with increasing recycled fibre content. It is recommended that 10 % recycled fibre can be substituted for fresh fibre without compromising properties.

Lubke *et al.* (2020) used a thermohydrolytic mechanical pulping process to produce fibres for MDF from particleboard waste. The waste was first shredded and then boiled in water for 30 minutes to achieve a moisture content of at least 40 %. A Sprout-Waldron disc refiner was then used to process the chips into fibres in a single pass through the refiner's grinding heads. Several recycling processes were carried out and thermomechanical pulping, targeting a 13°SR-24°SR range, was found to be suitable for the production of fibreboard from recycled chips. The °SR, or Schopper-Riegler number, is a measure of the drainage rate of pulp suspension and indicates the degree of pulp refining. It directly relates to the fibre properties and their suitability for MDF production. A higher °SR value indicates a slower drainage rate and typically corresponds to more refined fibres with better bonding potential, which is crucial for achieving the desired strength properties in the final MDF product. The final stages of cascade utilisation in this material stream demonstrated that the properties met the lowest levels required by the applicable standards.

Following Savov *et al.* (2023), thermal hydrolysis was carried out in an autoclave using saturated steam as the heat transfer medium. In contrast to previous studies, MDF was used in samples with dimensions similar to those of wood chips. The influence of the hydrolysis process parameters, namely process time and temperature, on the properties of the recycled MDF wood fibre was investigated. Hydrolysis temperatures of 121 °C and 134 °C were used, with three durations for each temperature - 30, 45 and 60 minutes. After hydrolysis, the resulting fibre fraction was refined using a hammer mill. The fractional and elemental composition of the recycled fibres obtained was evaluated. Consistent with the findings of Roffael *et al.* (2010) and Lubis *et al.* (2018b), the recycled MDF fibres had a similar fibre morphology and fractional composition to the fresh fibres but were shorter in length.

3.2.4 Steam explosion and chemical digestion processes
3.2.4. Parna eksplozija i procesi kemijske digestije

Wan *et al.* (2014) used a steam explosion process to produce and evaluate fibres for the production of MDF from waste particleboard, MDF (UF-bonded) and OSB (PF-bonded). The recycled material was first impregnated with 0.5 % butane tetracarboxylic acid in the expectation of complete dissolution of the chips and fibres. According to the literature, water vapour at 235 °C acts on a vessel. The pressure difference between the pressure vessel and the atmosphere creates an explosion effect at the outlet of the pressure vessel, which breaks the material back into fibres. It has been found that recycled fibres from the steam explosion process are 30 % shorter than virgin industrial fibres. When particleboard is used as the raw material for recycled fibres, the fibre length increases compared to MDF fibres, but remains shorter than industrial fibres. The length of fibres from OSB, on the other hand, exceeds that of industrial fibres. According to the report, particleboard and OSB have a high potential for fibre production by steam explosion.

According to Dix *et al.* (2001), urea resin bonded MDF coated with paper was digested in a sodium hydroxide solution (10 % NaOH based on atro MDF) at 200 °C for 2 hours. The digestion process resulted in an increase in bending and transverse tensile strength when 30 % recycled fibre content was used. At 50 % recycled fibre content, the changes in properties are small. Thickness swelling is significantly reduced when the chemically recovered fibres are used, so that the test panels meet the requirements of EN 622-5 even without the use of hydrophobing agents. In a study by Ateş *et al.* (2023), acid hydrolysis was used to recycle MDF using formic acid and phosphoric acid. The MDF samples to be recycled were heated and mixed in a 25 % acid solution. The acid hydrolysis treatment resulted in deformation of the boards during hot pressing and damage to the fibres. Acid hydrolysis severely damages the fibres and should not be used for the recycling of wood-based materials.

In addition, chemical treatment of MDF waste with sodium sulphite and sodium hydroxide reactivated the cured resin, eventually leading to low resin content in recycled MDF (Nakos *et al.,* 2001).

3.2.5 Ohmic heating and micro-releasing processes
3.2.5. Omsko zagrijavanje i procesi mikrootpuštanja

A new ohmic heating process was developed specifically for MDF recycling by Moezzipour *et al.* (2018). For a typical thermo-hydrolytic-mechanical reference recycling process, shredded MDF waste from industry was steamed in a laboratory autoclave at 105 °C for 150 min at 4 bar pressure. The steamed waste was then defibred in a refiner. To recycle MDF waste using an electrical process, shredded MDF waste was soaked in warm water for 30 minutes and then poured into a chamber containing salt water (electrolyte). Finally, an electric current was passed through the mixture, releasing the fibres from the MDF waste.

In terms of the previously described change in fibre geometry due to thermohydrolytic digestion, the fibres from the ohmic heating process were longer and similar to the standard fibres from Iranian MDF mills, as less fibre degradation occurs in the electrical heating process due to the removal of pressure and the long heating time in the autoclave without a refining stage in the electrical heating process. In addition, the lignin and hemicellulose content was found to be lower than that of the reference fibres, especially in thermohydrolysis pulps. No degradation of cellulose was observed. The thickness swelling of the recycled thermohydrolysis treated MDF was higher than that of the reference. Recycled MDF from the electric heating process had lower swelling than that from thermohydrolysis.

The *MOR* of the panels produced using the electrical heating method exceeded the EN standard, while the panels produced using the thermohydrolytic method did not meet the requirements. It is very clear that the modulus of elasticity of the recycled fibre panels produced by the electrical heating method was higher than that of the panels produced by the thermohydrolytic method. Even the *MOE* values of the MDF boards produced exceeded the requirements of the relevant standard specifications (EN310). The internal bonding (IB) of the recycled boards from the thermohydrolytic treatment was lower than that of the reference.

Elias and Bartlett (2018) report on the micro-release process, which works in a similar way to the ohmic heating process: The MDF waste is shredded and separated, immersed in 98 °C water for 5 minutes, which triggers microwaves that cause the fibres to swell. Finally, the recycled fibres can be used as raw material to replace part of the virgin fibres and produce recycled MDF. The samples separated for recycling by the micro-separation method were kept in boiling distilled water for 5 minutes before swelling for 5 minutes at medium wave frequency in an industrial microwave oven. Complete defibration was performed manually. The microwave process had no effect on fibre shortening. These trials in an industrial plant successfully demonstrated that the addition of up to 20 % recycled material can be achieved without adverse effects.

3.3 Changes in physical and mechanical properties of recycled particle and fibre boards

3.3. Promjene fizičkih i mehaničkih svojstava recikliranih ploča iverica i vlaknatica

The recycling of particleboard and fibreboard usually results in a deterioration of the physical and mechanical properties of the new wood-based materials produced from it compared to the original material. Some processes also report improvements in these properties for individual characteristics. Various sources provide information on whether and how the physical and mechanical properties of recycled boards change. Tables 3 and 4 give an overview of the changed physical and mechanical properties of particle- and fibreboard according to the studies of the authors mentioned.

All the articles dealing with the morphology of the particles state that the particle size changes as a result of recycling, which has a particular effect on the bending strength. The change in the degree of thinness, particularly in the case of chips, and the shortening of the fibre length should be mentioned here. The cause of this significant reduction in bending strength values can be explained by the effect of hydrothermal heating on the thermal degradation of wood components, in particular the reduction of lignin (Moezzipour *et al.,* 2018). Yilgor *et al.* (2001) also found that the decrease in mechanical properties was mainly due to the thermal decomposition of wood during hydrothermal treatments, which is confirmed by the work of Franke and Roffael (1998a) and Lykidis and Grigoriou (2008) on thermohydrolysis. The shortening of chips and fibres

Table 3 Overview of change in physical and mechanical properties for particleboard recycling (*IB* – internal bonding, *MOR* – modulus of rupture, *MOE* – modulus of elasticity, *TS* – thickness swelling, / – not mentioned)
Tablica 3. Pregled promjena fizičkih i mehaničkih svojstava iverice (*IB* – *čvrstoća* na raslojavanje, *MOR* – modul loma, *MOE* – modul elastičnosti, *TS* – debljinsko bubrenje, / – nije navedeno)

References *Literatura*	**Particle size** *Veličina iverja*	***IB***	***MOR***	***MOE***	***TS***
Lykidis and Grigoriou, 2008	reduction *smanjenje*	reduction *smanjen*	reduction *smanjen*	improvement *poboljšan*	increase *povećan*
Lykidis and Grigoriou, 2011	/	reduction *smanjen*	reduction *smanjen*	improvement *poboljšan*	increase *povećan*
Zamarian *et al.*, 2017	reduction *smanjenje*	improvement *poboljšan*	reduction *smanjen*	comparable *usporediv*	decrease *smanjen*
Azambuja, 2018	reduction *smanjenje*	improvement *poboljšan*	reduction *smanjen*	comparable *usporediv*	decrease *smanjen*
Iždinský *et al.*, 2020	/	reduction *smanjen*	reduction *smanjen*	reduction *smanjen*	decrease *smanjen*
Lubke *et al.*, 2020	/	reduction *smanjen*	reduction *smanjen*	improvement *poboljšan*	/

Table 4 Overview of change in physical and mechanical properties for MDF recycling (IB = internal bonding, MOR – modulus of rupture, MOE – modulus of elasticity, TS – thickness swelling, / – not mentioned)
Tablica 4. Pregled promjena fizičkih i mehaničkih svojstava ploče vlaknatice (IB – *čvrstoća* na raslojavanje, MOR – modul loma, MOE – modul elastičnosti, TS – debljinsko bubrenje, / – nije navedeno)

References *Literatura*	**Particle size** *Veličina vlakana*	**IB**	**MOR**	**MOE**	**TS**
Krzysik *et al.*, 1997	/	reduction *smanjen*	reduction *smanjen*	improvement *poboljšan*	increase *povećan*
Buschalsky and Mai, 2021	/	improvement *poboljšan*	not significant *bez značajne promjene*	not significant *bez značajne promjene*	decrease *smanjen*
Ateş *et al.*, 2023	reduction and high proportion of fines *smanjena, uz visok udio finih vlakana*	reduction *smanjen*	/	improvement *poboljšan*	decrease *smanjen*
Mantanis *et al.*, 2004	/	comparable with additive used *usporediv s upotrijebljenim aditivom*	comparable with additive used *usporediv s upotrijebljenim aditivom*	/	decrease *smanjen*
Roffael *et al.*, 2010	reduction and high proportion of fines *smanjena, uz visok udio finih vlakana*	reduction over 30 % recycled fibre content *smanjen za više od 30 % recikliranih vlakana*	reduction over 30 % recycled fibre content *smanjen za više od 30 % recikliranih vlakana*	reduction over 30 % recycled fibre content *smanjen za više od 30 % recikliranih vlakana*	reduction over 30 % recycled fibre content *smanjen za više od 30 % recikliranih vlakana*
Ihnat *et al.*, 2018	reduction depend-ing on the raw material *smanjena ovisno o vrsti sirovine*	/	/	/	/
Lubis *et al.*, 2018b	reduction and high proportion of fines *smanjena, uz visok udio finih vlakana*	reduction *smanjen*	reduction *smanjen*	reduction *smanjen*	decrease *smanjen*
Lubke and Ihnát, 2020	/	slight reduction *blago smanjen*	slight reduction *blago smanjen*	slight reduction *blago smanjen*	slight increase blago povećan
Savov *et al.*, 2023	reduction and high proportion of fines *smanjena, uz visok udio finih vlakana*	/	/	/	/
Wan *et al.*, 2014	increase *povećana*	/	/	/	/
Dix *et al.*, 2001	/	reduction over 50 % recycled fibre content *smanjen za više od 50 % recikliranih vlakana*	reduction over 50 % recycled fibre content *smanjen za više od 50 % recikliranih vlakana*	/	decrease *smanjen*
Moezzipour *et al.*, 2018	comparable *usporediva*	improvement *poboljšan*	improvement *poboljšan*	improvement *poboljšan*	decrease *smanjen*

can be beneficial in terms of transverse tensile strength, which has been shown in some studies to be improved up to a certain level of recycled material, which the scientists attribute to an increase in surface area and better adhesion.

However, there is controversy regarding the transverse tensile strength, e.g. Zeng *et al.* (2018) describe that adhering paraffin and glue residues reduce the transverse tensile strength and also the flexural strength, which may explain the problems with internal bonding (IB) above a certain proportion of recycled particles. Hydrothermal degradation of hemicelluloses may also play a role. Hemicelluloses are responsible for forming hydrogen bonds with the resin. The degradation of hemicelluloses means fewer hydroxyl groups, which reduces the potential for bonding between wood and resin (Moezzipour *et al.,* 2018).

The reason for the high thickness swelling of MDF recycled by the hydrothermal method could be the removal of lignin from the fibre surface due to the effect of heat and the increased fibre swelling. In fact, the intense heat of the hydrothermal process leads to an increase in fibre hygroscopicity (Lykidis and Grigoriou 2008; Michanickl and Boehme 2003). Fibre length plays an important role in the dimensional stability of MDF boards. Therefore, a greater reduction in fibre length will result in increased thickness swelling of MDF boards. As mentioned above, fibres from electrical heating are significantly longer than fibres from hydrothermal heating. The reason for the significant reduction in the bending test parameters (MOR and MOE) in the boards produced with fibres from the hydrothermal process can be explained by the influence of hydrothermal heating on the thermal degradation of the wood components, in particular the lignin degradation (Table 4). Lignin plays a very important role in the self-bonding mechanism, and lignin condensation reactions that occur within and between fibres during hot pressing can improve the properties of MDF boards (Okuda *et al.,* 2006). Zhang *et al.* (2013) reported that the reduction in lignin content leads to a reduction in the modulus of elasticity of individual fibres, which may affect the quality of the boards produced. Yilgor *et al.* (2001) found that the decrease in mechanical properties is mainly due to thermal decomposition of the wood during hydrothermal treatment, confirming the work of Franke and Roffael (1998a) and Lykidis and Grigoriou (2008) on thermohydrolysis. It is assumed that the UF resin is hydrolysed again by the residual acid during hot pressing, as described by Lubis *et al.* (2018a).

Indeed, the lower levels of hemicelluloses in the hydrothermally recycled fibres compared to the electrical heating method (Table 4) lead to lower IB values in the boards made from them. Hemicelluloses are responsible for the formation of hydrogen bonds with the resin. The reduction of hemicelluloses means fewer hydroxyl groups, which reduces the potential for the formation of bonds between wood and resin (Popović *et al.,* 2015). The IB strength of MDF can be influenced by natural bonds formed by hydroxyl groups of hemicelluloses.

3.4 Literature-based approaches to increasing the proportion of recycled content in particle and fibreboard production
3.4. Pristupi povećanju udjela recikliranog materijala u proizvodnji ploče iverice i vlaknatice utemeljeni na literaturi

Waste wood is currently mainly used in the production of particleboard. As the proportion of recycled material is usually only between 20 and 30 % due to the process, the problems identified need to be addressed. By evaluating and supplementing the results of the literature studies, the project "ReSpan - Recycling of particleboard materials", on which this article is based, has derived the following approaches to potentially increase the proportion of recycled fibre in the production of wood-based materials:

- Improving sorting technology: The use of advanced sorting technologies can improve the efficiency of waste wood processing and lead to more homogeneous and higher quality recycled material. This step could be further supported by more efficient disposal and collection systems.
- Use of alternative adhesives: The use of alternative, more environmentally friendly adhesives can reduce formaldehyde emissions from recycled wood-based materials. In the future, it would certainly make the most sense to use binders that are easier to degrade or reactivate. This could revolutionise future recycling processes and significantly improve the sustainability of the wood processing industry. In this context, it would also be interesting to know whether the bond strength can be increased by using bioadhesives. The use of pMDI could also be useful for the adhesive problem, as the binder is known to form strong bonds and could compensate for the problem of residual adhesive adhesion.
- Optimisation of process technology: It would also be conceivable to adapt the production processes for recycled fibreboards to include a combination of recycled fibres in the core layer and high-quality materials in the outer layers. One step would be to adapt the process technology to produce particles with a suitable geometry. In addition, the development of alternative processes would be a sensible step. For example, solvolytic processes that keep the used adhesive reactive in a similar way to existing chemical processes would make sense.
- Use of a mixture of recycled OSB, particleboard and plywood for the production of MDF: This could initially expand the range of applications within the waste wood classes. As described in the article, chipboard and MDF particles are well suited for recycling. The materials could be pre-shredded, thermohydrolytically treated and then thermomechanically defibrated, possibly destroying the glue bridges from MUF and PF bonding. The fibres could then be used to make MDF.

4 CONCLUSIONS
4. ZAKLJUČAK

The literature review has provided a comprehensive overview of the state of the art in particleboard and MDF recycling technology, particularly with regard to pulping processes and the resulting physical and mechanical properties. Despite significant progress, no large-scale industrial recycling processes have been fully established, mainly due to challenges such as degradation of physical and mechanical properties and inefficiencies of current recycling methods. Most research and practical applications still focus on the degradation of UF resins, while emerging techniques such as ohmic heating, as investigated by Moezzipour *et al.* (2018), show potential for improving mechanical properties.

Future advances in this area could benefit from the development of adhesive systems designed for easier degradation and reactivation, supporting circular economy goals. In addition, optimising process technology - possibly by combining different recycled wood types such as OSB, particleboard and plywood in MDF production - could create more versatile applications. Improved sorting technologies and a more efficient collection system for waste wood materials could also lead to more homogeneous recycled material quality, overcoming current limitations in physical and mechanical properties.

While the post-millennium literature provides valuable insights and advances, a shift towards industry-ready recycling processes is still needed to effectively meet sustainability and recycling goals. Collaborative efforts between research and industry can help bridge this gap and provide a robust foundation for future large-scale recycling systems that are better aligned with environmental goals and regulatory standards.

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