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ORIGINAL ARTICLE

Use of secondary fibres from recycling processes of fibreboard manufacturing and post-consumer waste in medium density fibreboard

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Abstract

Recycling medium-density fibreboard (MDF) enhances material efficiency and contributes to waste management. This study investigates the impact of secondary fibres, generated from recycling of both processing and post-consumer waste, on the properties of new MDF panels. The fibres were recycled using a modified thermo-mechanical pulping (mTMP) and steam treatment (ST) processes. Virgin pine and secondary fibres were studied for their size distributions and morphological features. MDF panels were fabricated by substituting virgin fibres with secondary fibres at 15% and 25% rates, with additional 100% recycled MDF produced using ST-obtained fibres. Secondary fibres from both waste sources were shorter and had more fines than virgin fibres. For recycled MDF incorporating ST fibres, a notable drop in internal bond strength was observed when using fibres from post-consumer fibreboard waste, while modulus of rupture, modulus of elasticity, thickness swelling, and water absorption remained consistent. Increasing substitution rates from 15 to 25% resulted in an insignificant change in the aforementioned physical and mechanical properties. However, MDF produced with 100% recycled fibres exhibited a dramatic decrease in physical and mechanical properties, despite a reduction in formaldehyde content. Compared to MDF with virgin fibres, the internal bond strength of recycled MDF statistically decreased at all substitution ratios. In contrast, other properties were comparable at 15% or 25% rates for fibres produced using the mTMP process. Finally, MDF containing mTMP fibres showed similar density profile values, slightly higher than MDF with ST fibres.

1 Introduction

Medium density fibreboard (MDF) is a composite material made by combining refiner-produced wood fibres with an adhesive, forming the mixture into a mat that is then hot-pressed to create rigid boards. MDF has been commercialized in the United States since 1965 (Suchsland 1987). Softwood fibres are mainly used for MDF like Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.), while hardwoods like beech (*Fagus sylvatica* L.) and oak (*Quercus sp.*) are limitedly used (Benthien et al. 2017; Roffael et al. 2016). MDF panels are widely used in furniture applications, and their annual worldwide production has significantly increased over the past 40 years to over 100 million m^3 (FAO 2025). The estimated yearly global market size is expected to grow from 117 million m^3 in 2024 to 142 million m^3 in 2028 (Anonymous 2024). However, substantial MDF production has also led to a steadily increasing volume of waste MDF, in the form of post-consumer fibreboard and fibreboard processing waste (MDF lifespan 10.7–12.1 years) (Irle et al. 2019, 2023). The increasing volumes of waste MDF and growing environmental regulations are creating the need to develop economically viable recycling strategies. Currently, there is no commercially viable method for MDF recycling, and waste MDF is landfilled or incinerated for energy (Zimmer and Bachmann 2023). These disposal methods do not align with the cascading use of wood composite boards and reduce material efficiency (Kim and Song 2014; Lubke et al. 2020).

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In addition, incomplete combustion or landfilling of MDF waste can pollute the environment by introducing undesired organic compounds, such as pyrroles, amines, and other nitrogen-containing compounds, and by releasing formaldehyde (Lee et al. 2014; Tatàno et al. 2009). Cascading and circular use of wood products reduce the demand for virgin wood, increase carbon sequestration, and reduce greenhouse gas emissions. An example from United Kingdom demonstrates that the recycling of MDF could provide 75% more cumulative climate-change mitigation by 2050 than business-as-usual (Forster et al. 2023). Post-consumer wood waste is a valuable feedstock for the wood panel industry, such as for making particleboard or partially utilized for fibreboard (Iždinský et al. 2020; Nguyen et al. 2023).

Fibreboard processing waste can be recovered through various processes, such as mechanically shred into chips for particleboard, further down to fibres for new fibreboard using thermo-mechanical or hydrothermal treatment, and conversion into platform chemicals via a biorefinery approach (Moezzipour et al. 2017; Roffael et al. 2016; Thakare et al. 2024). Fibres recycled from MDF processing waste using steam explosion treatment showed a 30% reduction in size (Wan et al. 2014). By increasing the steam pressure and duration, steam explosion can achieve up to 80% urea-formaldehyde (UF) resin removal from newly made MDF (Troilo et al. 2023). Similar to steam explosion, steam refining and steam treatment (i.e., without decompressive explosion) can also hydrolyse up to 80% of UF resin present in MDF processing waste under intense recycling conditions (Hagel and Saake 2020; Roffael and Hüster 2012; Schütt et al. 2012). Recycling MDF fibres through mild hydrothermal treatments has also been explored (Lubis et al. 2018a; Moezzipour et al. 2017; Savov et al. 2023a). For instance, Zeng et al. reported that recycled fibres from MDF processing waste were 12% shorter than virgin fibres when treated under gentle cooking conditions (100 °C, 1.01 bar) (Zeng et al. 2018). Recycled MDF fibres, generated through thermo-mechanical pulping (TMP), have been partially substituted virgin TMP fibres to avoid significantly weakening the mechanical performance of MDF containing recycled fibres (Roffael et al. 2010, 2016). MDF is primarily made with the well-developed TMP fibres due to their high yield, cost-effectiveness (Krug et al. 2023; Mertens et al. 2017). Increasing pulping temperatures resulted in increased fines content and decreased fibre length and diameter (Roffael et al. 2009). Recycled TMP fibres often show physical damage and shortening (Nakos et al. 2005). To address these limitations, a modified TMP (mTMP) process could be developed to reduce damage by increasing chip moisture (softening lignin) during defibration. Co-refining virgin wood chips and chips from MDF processing waste using TMP was investigated. A 25% virgin wood substitution resulted in a remarkable drop in internal bond strength, from 1.02 MPa to 0.6 MPa (Mantanis et al. 2004).

Fibre quality like fibre length distribution, acidity, and morphology significantly affects the MDF performance (Cao and Wu 2007; Park et al. 2001). Despite considerable research aiming to retain the original fibre geometry (i.e. length) and morphology during MDF recycling, the resulting fibres are often shorter with more fibre dust and contain contaminants like wax and UF resin residuals (Savov et al. 2023b; Zeng et al. 2018). The mechanical performance of MDF is significantly reduced when substituting 100% virgin fibres with recycled fibres from fibreboard waste (Bütün et al. 2019; Savov et al. 2023a). For example, recycled fibres produced by TMP or hydrothermal methods exhibited shorter lengths and inferior adhesion capacity compared to virgin fibres. Consequently, the panels' mechanical performance, including modulus of rupture and internal bond strength, was significantly decreased (Moezzipour et al. 2017; Roffael et al. 2016; Savov et al. 2023a). However, MDF containing recycled fibres showed reduced formaldehyde content and emission. This reduction has been attributed to the significant amount of ammonia introduced during hydrolytic recycling, which reacts with formaldehyde, resulting in lower formaldehyde levels than in MDF made with virgin fibres (Roffael et al. 2016). With the addition of extra additives (e.g., crosslinkers) to enhance gluing efficiency, MDF containing 25% recycled TMP fibres can achieve thickness swelling and static bending properties comparable to virgin-fibre MDF (Mantanis et al. 2004). Replacing 33% virgin fibres with recycled fibres from MDF processing residues significantly reduced the physical and mechanical properties of MDF when a hybrid resin technology (e.g., adding polymeric diphenylmethane diisocyanate to UF) was not used (Roffael et al. 2016). MDF incorporating 10% recycled fibres obtained via refining or hammer milling of MDF showed increased internal bond strength and reduced values of both thickness swelling and water absorption. This improvement was observed for recycled wood from two pine species (e.g., red or radiata), compared to MDF with virgin fibres (Lubis et al. 2018b). The recycling processes used, along with the waste composition, determine the characteristics of recycled fibres, which in turn affect how much of recycled fibres can be incorporated into MDF without significantly compromising its quality (Benthien et al. 2017; Hong et al. 2020; Lubis et al. 2018b).

While recycling MDF manufacturing (processing) waste is well-studied, reports on recycling post-consumer MDF are rare, largely due to its high contaminant load and complex recycling processes (Altgen et al. 2025; Zimmer and Bachmann 2023). This work aims to study recycled (hereafter referred as secondary) fibres produced from post-consumer MDF and MDF processing waste using an mTMP

process and steam treatment (ST). To address the typically low moisture content (MC) (~10%), a main disadvantage of waste wood, the mTMP process utilizes a patented, optimized digester configuration to enhance steam penetration into the chips (Mäbert 2024). A further objective is to investigate the influence of replacing virgin TMP fibres with secondary fibres from the two recycling processes, mTMP and ST, on the physico-mechanical properties and formaldehyde release of MDF bonded with UF resins. The characteristics of the recycled fibres and the physical and mechanical properties of the laboratory-produced MDF panels were measured and compared against virgin fibres and standard MDF with virgin fibres.

2 Materials and methods

2.1 Materials

TMP virgin fibres from Scots pine (*Pinus sylvestris* L.) and mTMP fibres were obtained from IHD (Institut fuer Holztechnologie Dresden gGmbH, Germany), ST fibres were received from Dieffenbacher Gmbh Maschinen- und Anlagenbau (Eppingen, Germany). Sonae Arauco S.A. (Lugar do Espido, Portugal) provided the UF resin, emulsion wax, and the catalyst (NH_3NO_3). The UF resin had a 63% solids content, a formaldehyde/urea molar ratio of 0.97, a pH value of 8.5, a viscosity of 1,225 ± 75 mPa·s, and a reactivity of 80 ± 20 s. The emulsion wax and catalyst contained 50% and 18% solids content, respectively.

Table 1 Overview of prepared fibres for manufacturing of laboratory MDF (FW denotes fibreboard processing waste, PW denotes post-consumer MDF waste, "1" indicates ST produced secondary fibres)

Abbreviations	Fibre source and secondary fibre rate (based on mass)
Virgin (V)	TMP fibre, 100% virgin pine
V+15%FW	mTMP fibre, 15% derived from MDF processing waste
V+25%FW	mTMP fibre, 25% derived from MDF processing waste
V+15%FW1	ST fibre, 15% derived from MDF processing waste
V+25%FW1	ST fibre, 25% derived from MDF processing waste
100%FW1	ST fibre, 100% MDF processing waste
V+15%PW1	ST fibre, 15% derived from post-consumer fibreboard
V+25%PW1	ST fibre, 25% derived from post-consumer fibreboard
100%PW1	ST fibre, 100% post-consumer fibreboard

2.2 Preparation of secondary fibres

Veolia S.A. (Paris, France) collected and crushed the post-consumer wood waste, which is screened and cleaned by Dieffenbacher to remove foils, light materials, and impurities (e.g., stones, metals, hard plastics). Then fibreboard fractions were sorted out by TOMRA GAINnext optical sorters with AI. MDF processing waste (non-sanded, 3.3 mm thick, 850 kg/m^3) was sourced from Homanit GmbH (Losheim, Germany) and consists of approximately 80% Scots pine (*Pinus sylvestris* L.) and 20% Norway spruce (*Picea abies* L.).

IHD mechanically shredded the virgin wood from debarked round wood and MDF processing waste, using a drum chipper. The resulting chips were then sieved to achieve chip sizes between 3 × 3 mm² and 25 × 25 mm². The TMP virgin fibres were obtained through defibration at a steam pressure of 10.4 bar, a chip pre-heating time of 3–4 min in the digester, and a grinding gap of 40 µm. To obtain the mTMP fibres, the waste MDF chips were blended with virgin wood chips based on dry mass at ratios of 15:85 and 25:75, respectively. After, the mixed chips were defibrated at the same setting as for virgin fibres. Following defibration, the fibres were dried in a flash tube dryer to a moisture content (MC) of approximately 6%.

After sorting the post-consumer fibreboard fraction, Dieffenbacher sieved the material to a chip size ranging from approximately 5 × 5 mm^2 to 60 × 60 mm^2, similar to the MDF processing waste chips provided by Homanit. For the ST process, these chips were fed directly into a pressure vessel without any pre-treatment with water or steam. Steam was then introduced into the vessel, gradually increasing the pressure to between 3 and 20 bar over a defined period, while continuous agitation ensured uniform steam exposure. The chips were subsequently defibrated into individual fibres during controlled pressure release (note: this was not a steam explosion process). Once the pressure returned to ambient (0 bar overpressure), the bottom valve was opened, and the 100% ST fibres were discharged with the help of the agitator. The resulting fibres were then dried in a pipe dryer to a MC of approximately 6% and subsequently mixed with TMP virgin fibres at substitution rates of 15%, 25%, and 100% based on dry fibre mass at the facilities of the Swedish University of Agricultural Sciences (Uppsala, Sweden). The fibres are listed and shown in Table 1; Fig. 1.

2.3 Fibre size characterization

Fibre length distribution was measured by dynamic image analysis (QICPIC, Sympatec GmbH, Clausthal-Zellerfeld, Germany), and a laboratory ultrasonic sifter (VU200, Imal S.r.l., Italy) was used to determine the fibre size frequency

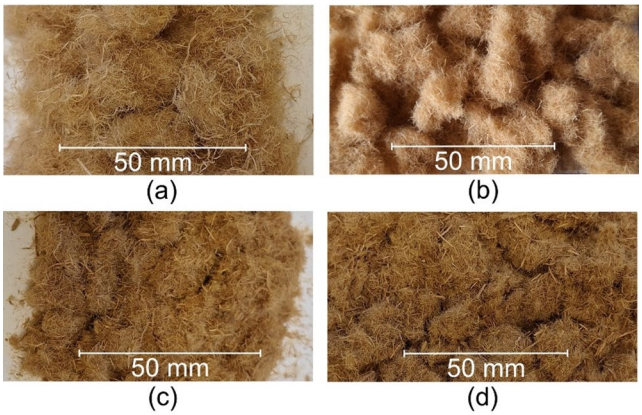

Fig. 1 Virgin and secondary fibres: (a) virgin (V), (b) v + 25%FW, (c) 100%FW1, (d) 100%PW1

based on mass ratio. For fibre characterization, fibres were automatically introduced using the QICPIC analyser's FIBROS fibre feeder (designed for fibre separation), which was equipped with a 2 mm sieve. A high-speed camera then measured the sieved fibres (measuring range M9: 17 µm – 33,792 µm; 75 frames/second). The WINDOX software (Sympatec, GmbH, Clausthal-Zellerfeld, Germany) was used to determine **fibre** length (Feret max) and diameter (DIFI) from projected 2D contour images and to calculate size distributions (Teuber et al. 2016; Witt et al. 2007). The fibre size was characterized concerning the median (X_{50}) and mean based on the volume model (Q_3). Five replicates of 1 g fibres were measured for the prepared fibres (Table 1). As a complementary measurement to the optical method, the fibres' geometric parameters were also characterized by sieving based on mass per fraction. Fibres underwent a stack of sieves comprised of sieve sizes 0.098 mm, 0.131 mm, 0.217 mm, 0.514 mm, 1.24 mm, and 1.98 mm. The sieving time was 3 min per batch.

2.4 MDF fabrication

The gluing recipe comprises approximately 10% UF resin and 1% emulsion wax (both based on the dry mass of the fibres), along with 1% catalyst (NH_3NO_3), based on dry mass of UF resin. The fibres were first loosened using an air extraction unit (ASA 1051, Holzkraft, Hallstadt, Germany) to reduce compaction, and then oven-dried to a MC of approximately 2–3%. Fibres were first sprayed with wax, then with the UF resin and catalyst gluing mix, using a laboratory drum-type horizontal mixer (FM 130 D, Gebrüder Lödige Maschinenbau GmbH, Paderborn, Germany) equipped with a 1 mm nozzle. The spraying process utilized an air pressure of 0.05 bar and a total blending time of 5 min. The MC of resinated fibres was about 10%. The blend was manually placed into a wooden mould (450 × 450 × 300 mm³) for pre-pressing, forming an MDF mat approximately 70 mm thick. This mat was then hot-pressed with a pressing machine (LAP 200, Gottfried Joos Maschinenfabrik GmbH & Co. KG, Pfalzgrafenweiler, Germany) at 200 °C for 10 s/mm using displacement control to 10 mm thickness. The target density for the MDF panels was 700 kg/m³. The produced MDF measured 465 × 465 × 10 mm³, with two panels per sample. After cooling and resin post-curing for 2–3 days, the MDF panels were sanded to a final thickness of 8 mm by removing approximately 1 mm from both surfaces. Subsequently, the panels were cut and conditioned in a climate chamber at 20 °C and 65% relative humidity.

Table 2 Specification of physical and mechanical testing, standards and number of specimens (No.) tested per MDF

Abbreviations	MDF property	No	Standards	Equipment/ Method	Dimension (mm × mm × mm)
DP	Density Profile	8		DAX 6000	50 × 50 × 8
Density	Density (kg/m³)	16	(CEN 323 1993)	Scale (0.01 g)	50 × 50 × 8
TS	Thickness swelling ()	8	(CEN 317 1993)	Imal UV 200	50 × 50 × 8
WA	Water absorption ()	8	(CEN 317 1993)	Imal UV 200	50 × 50 × 8
IB	Internal bond strength (MPa)	8	(CEN 319 1993)	MTS Criterion	50 × 50 × 8
MOR	Modulus of rupture (MPa)	3	(CEN 310 1993)	MTS Criterion	50 × 220 × 8
MOE	Modulus of elasticity (MPa)	3	(CEN 310 1993)	MTS Criterion	50 × 220 × 8
FC	Formaldehyde content (mg/100 g)	1	(ISO 12460-5, 2015)	Perforator method	2.5 × 2.5 × 8

2.5 Evaluation of MDF properties

The physical and mechanical characteristics of MDF and the formaldehyde content were assessed following the standards listed in Table 2. The 3-point static bending and internal bond (IB) strength were determined by an MTS Criterion universal test machine (Criterion series, MTS Systems Corporation, Minnesota, USA). A Density Profiler (DAX 6000, Fagus-GreCon Greten GmbH & Co. KG, Alfeld, Germany) at a measurement speed of 0.1 mm/s was used to measure the vertical density profile of the panels. Variations in the morphology and the MDF surfaces and areas of fractures following 3-point bending tests were observed using stereomicroscopy (Zeiss Discovery V12, Carl Zeiss Microscopy

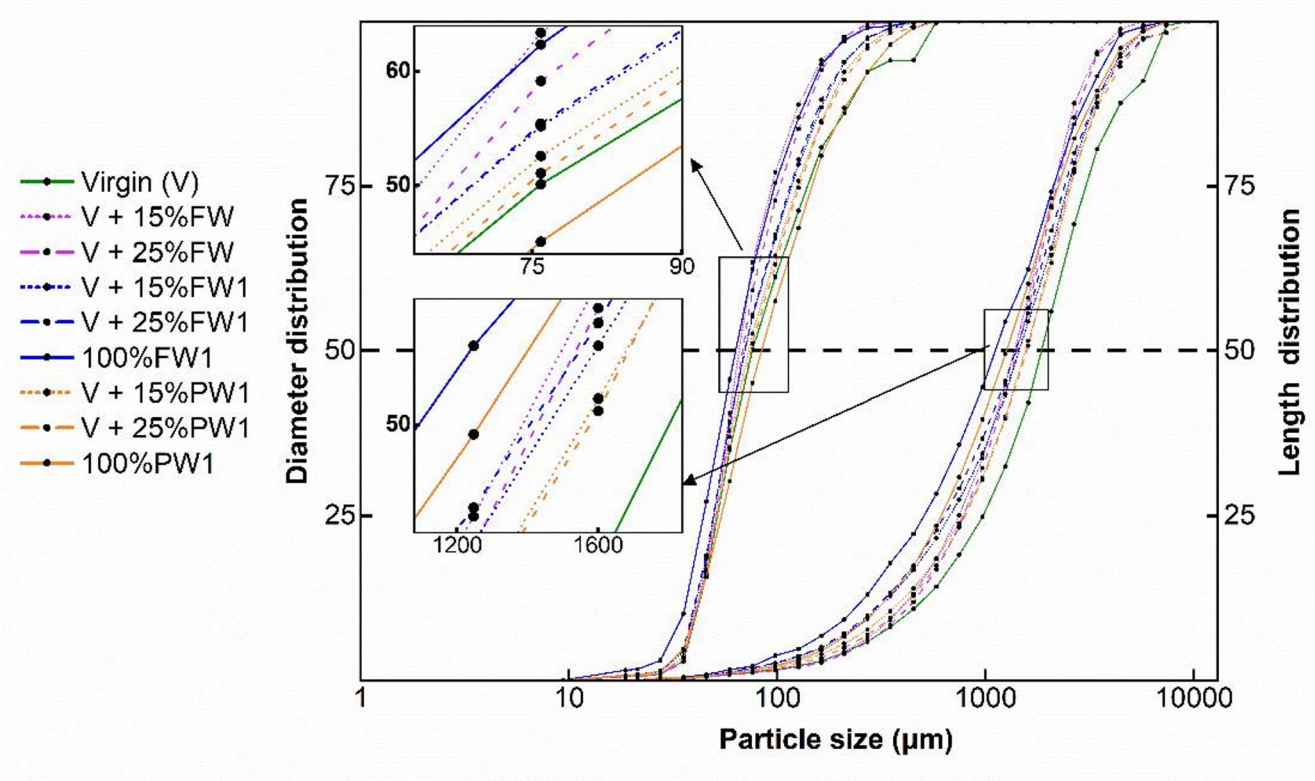

Fig. 2 Fibre diameter (left) and length (right) cumulative size distribution of fibres

GmbH, Jena, Germany) and scanning electron microscopy (SEM). The fractured samples were observed directly using the stereomicroscope. For SEM, 1×1 cm^2-sized samples were cut out from the tension side of the fractured samples using a small hacksaw. The fibres and fractured ends were mounted on stubs using carbon tabs and coated with gold using an Emitech K550X sputter coater (K550X, Emitech Ltd., Kent, UK). Observations were made using a Philips SEM (XL 30, Philips, Eindhoven, Netherlands) operated at 10 kV accelerating voltage with images recorded digitally.

2.6 Statistical analysis

Physical and mechanical results were analyzed using the Kruskal–Wallis test, followed by Dunn's Post-hoc test, with RStudio 2024.04.2 (Posit Software, Boston, United States) at a significance level (α) of 0.05. To assess the effects of waste source (FW, PW), dataset 1 (MDF with ST fibres, excluding the 100% ratio) was used. For the effects of process (mTMP, ST), dataset 2 (MDF with FW fibres, only the 15% and 25% substitution ratios were included) was used. The effects of the secondary fibre ratio (15% and 25%) were determined using data from these two selected datasets.

Table 3 Length (Feret max) and diameter (DIFI) of fibres

Fibre samples	Median length (µm)	Median diameter (µm)	Mean length (µm)	Mean diameter (µm)
Virgin (V)	1877±268	78±18	2261±510	114±42
V+15%FW	1380±95	64±2	1518±79	79±4
V+25%FW	1423±98	67±2	1587±97	83±6
V+15%FW1	1474±70	69±3	1742±94	94±11
V+25%FW1	1428±52	69±1	1762±132	94±7
100%FW1	1124±151	64±6	1587±137	80±4
V+15%PW1	1566±80	73±3	1833±95	100±2
V+25%PW1	1581±25	75±1	1912±133	103±10
100%PW1	1289±163	86±9	1637±141	119±13

3 Results and discussion

3.1 Fibre geometry and morphology

3.1.1 Fibre geometry

Figure 2 displays the cumulative distributions of fibre diameter and length. Table 3 provides the average values and standard deviations of fibres measured from five replicates. The reference virgin fibres had a median diameter of approximately 0.8 mm and a median length of 1.9 mm. Their corresponding mean values were about 20% and 46% larger, respectively. This difference between the mean and median

indicates that the fibre distributions were right-skewed, as larger values in the right "tail" disproportionately increase the mean. Substituting virgin fibres with secondary fibres generally reduced fibre length while keeping the diameter at a similar level. Samples with 25% secondary fibres showed comparable median and mean fibre length and diameter to those with 15% secondary fibres. However, 100% secondary fibre samples (100%PW1 and 100%FW1) exhibited a 31% and 40% reduction in fibre length, respectively, compared to virgin fibres. Simultaneously, their fibre diameter either increased by 10% (100%PW1) or decreased by 19% (100%FW1). Previous studies reported that secondary fibres from MDF processing waste, treated with steam explosion or hydrothermal processes, were approximately 30% shorter than virgin MDF fibres (Lubis et al. 2021; Wan et al. 2014). Another study by Zeng et al. noted a 12% reduction in mean length when comparing recycled fibres from MDF off-cuts to virgin MDF fibres (Zeng et al. 2018). The differences observed in fibre length reduction across these studies and the present research are likely due to variations in fibre materials and the specific recycling techniques used.

The fibre geometry by mass ratio from ultrasonic sieving is shown in Fig. 3. The fibres were categorized into six categories ranging from 0 to 1.98 mm (Fig. 3, legend). TMP virgin fibres contained 5% fines (particles passing through a 0.089 mm sieve) and 35% coarse fibres (≥1.24 mm). The secondary fibre sample (100%FW1) contained 120% more fines and 54% fewer coarse fibres compared to the reference fibre sample; a trend also observed in sample 100%PW1. Incorporating secondary fibres into the mixture increased the fine fibre content, while the proportion of coarse fibres decreased relatively to the reference fibre category, and this was consistent to previous studies (Savov et al. 2023b; Zeng et al. 2018). The significant increase in the fines content of secondary fibres may be attributed to the presence of unhydrolyzed resin in fibres and hemicellulose degradation. Degradation of hemicelluloses can occur either during the recycling process or during hot-pressing at temperatures above 150 °C in MDF manufacturing (Kwon JinHeon and Ayrılmıs 2016; Moezzipour et al. 2017). Such degradation reduced the fibres' flexibility and therefore mechanical fibre strength (Pere et al. 2019; Wang et al. 2019). Subsequently, the fibres tend to become more rigid and fragile, making them prone to break during recycling. Moreover, secondary fibres were found to contain cured resin both on the surface and within the fibres, which may further increase fibre rigidity (Troilo et al. 2023; Zeng et al. 2018).

3.1.2 Fibre surface structure and fracture morphology

Stereomicroscopic images of the fractured surfaces are shown in Fig. 4. SEM images of the fibres and the fractured

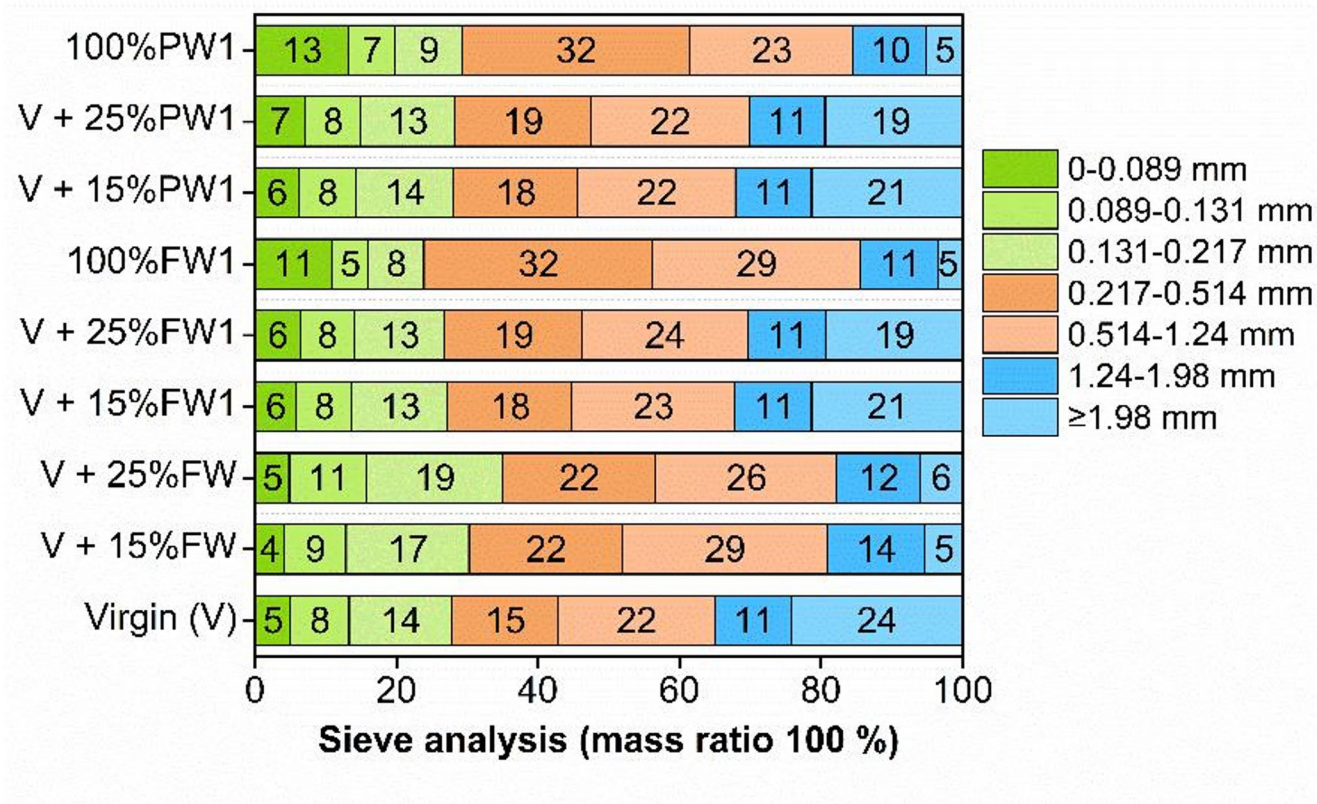

Fig. 3 Fractional distribution of fibres by sieve analysis

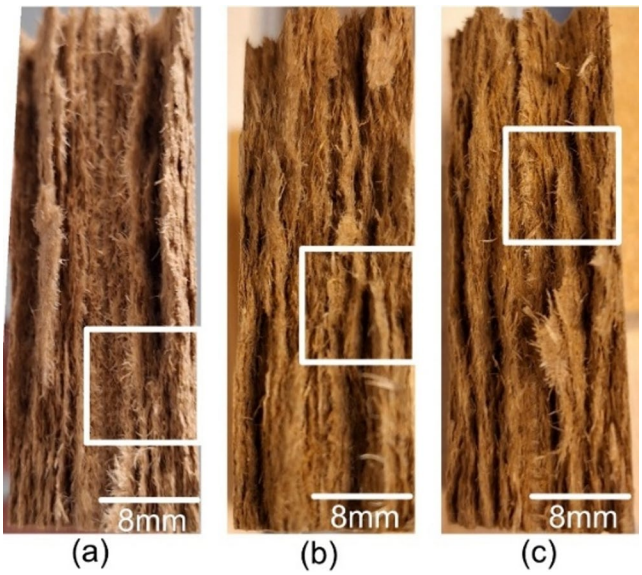

Fig. 4 Stereomicroscopic images of the fractured samples: (a) Virgin, (b) 100%FW1, (c) 100%PW1, white boxes highlight areas of interest. The tension side is on the right for all specimens

surfaces of the MDF samples are presented in Fig. 5. Stereomicroscopy observations showed the characteristic lamellar mat structure that is expected for MDF that fails under bending (Fig. 4a-c). The thickness of the lamellae varied but was of the order of 0.6–2.2 mm along the axis within the panel. Compared to the reference, MDF made with 100% secondary fibres from ST gave a dark yellowish-brown colour ascribed to secondary fibres (Hagel and Saake 2020). Fibre samples retained their rectangular structure, and no fibre fibrillation was observed. The virgin TMP fibres exhibited relatively clean and uncontaminated surfaces (Fig. 5a) compared to the secondary fibres (Fig. 5b-c). Notably, secondary fibres from post-consumer fibreboard waste showed more surface contaminants than fibres from MDF processing waste. Furthermore, the secondary fibres also displayed greater fibre damage, evidenced by small fibre fragmentation and cell wall delamination on their surfaces, which aligns with previous research (Lubis et al. 2018b). Recycled fibres subjected to severe processing conditions exhibited increased fibre fragmentation and a higher content of fines, although more UF resin was effectively removed (Troilo et al. 2023). An uneven fracture surface and fibre pull-outs

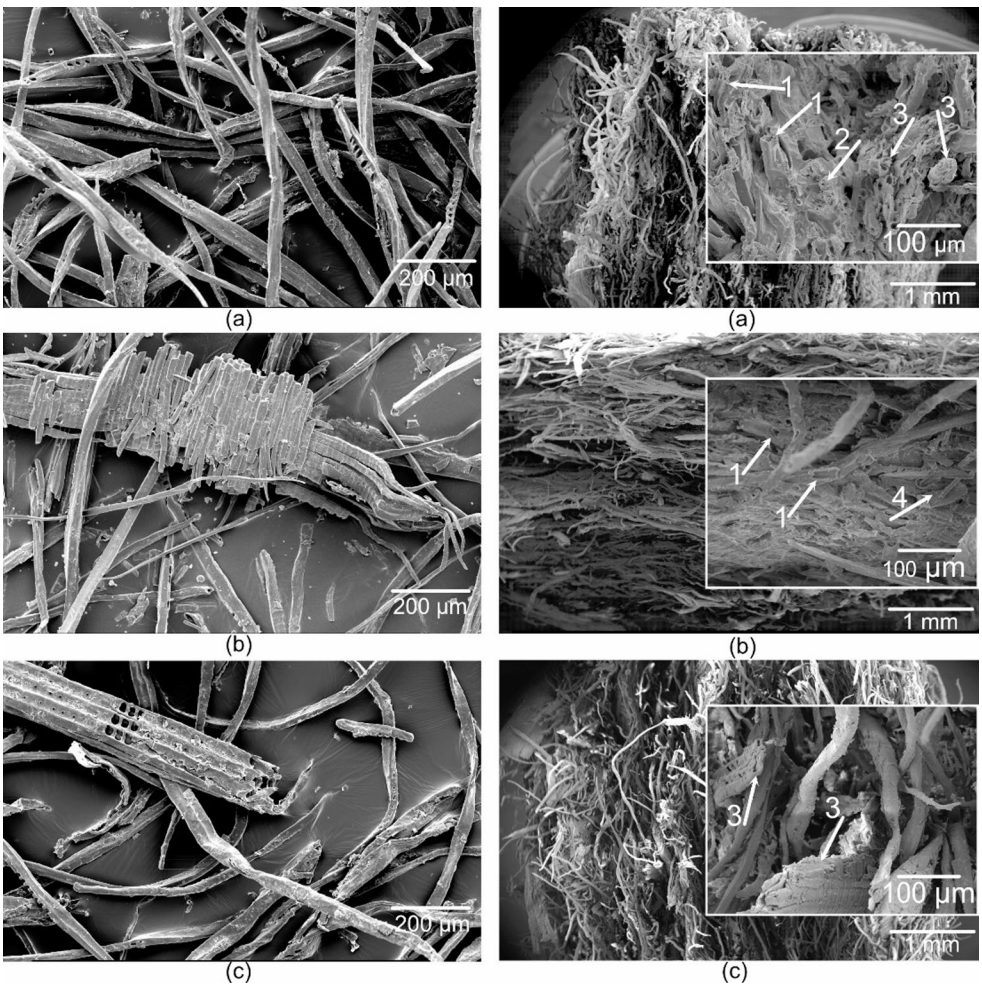

Fig. 5 SEM images of the fibres and fractured samples' areas of interest: (a) Virgin, (b) 100%FW1, (c) 100%PW1. Arrows 1, 2, and 3 indicate fibre breakage of earlywood, latewood, and shives. Arrow 4 is the fibre fragments

were observed for all samples (Fig. 5 mm scale bar). Virgin MDF (Fig. 5a) exhibited a clean and dense panel structure, and fibre breakages of earlywood (arrow 1), latewood (arrow 2) and shives (arrow 3) were noticeable. MDF made with 100% secondary fibres from ST showed a loose and weak MDF structure with small fibre fragments (Fig. 5b, arrow 4) and unclean fibre shives (Fig. 5d, arrow 3). The loose and weak fibre contact observed in secondary fibres may result from their increased fines content and poor compatibility with the resin. Residual resin was found on secondary fibres, which contributed to deteriorated bonding strength (Lubis et al. 2018b; Zhong et al. 2017). SEM examination of fibres and fibre bundles in the reference panel and panels with secondary fibres confirmed the presence of Pinus spp. In the fibre mixture, it was possibly *P. sylvestris* as judged by the characteristic nature of the window pits present.

3.2 MDF properties

3.2.1 Density profiles

The density profile is a key indicator of MDF performance, as it significantly influences both physical and mechanical properties (Wong et al. 2000). Conventional U-shaped density profiles of sanded MDF were expected and observed in Fig. 6. During pressing, heat and pressure densify the mat surfaces first, leading to early resin curing. The cooler, less compressed core results in lower density, forming a typical U-shaped profile with denser faces and a lighter core (Wang et al. 2004). Virgin MDF had the same surface and average density as mTMP MDF (V + 15%FW, V + 25%FW), whereas all ST MDF panels showed lower density, with only 100%FW1 being statistically lower. Recycled MDF panels have been reported to exhibit lower densities compared to MDF with virgin fibres (Lubis et al. 2018b). This reduction is likely due to fibre loss during mat forming, which

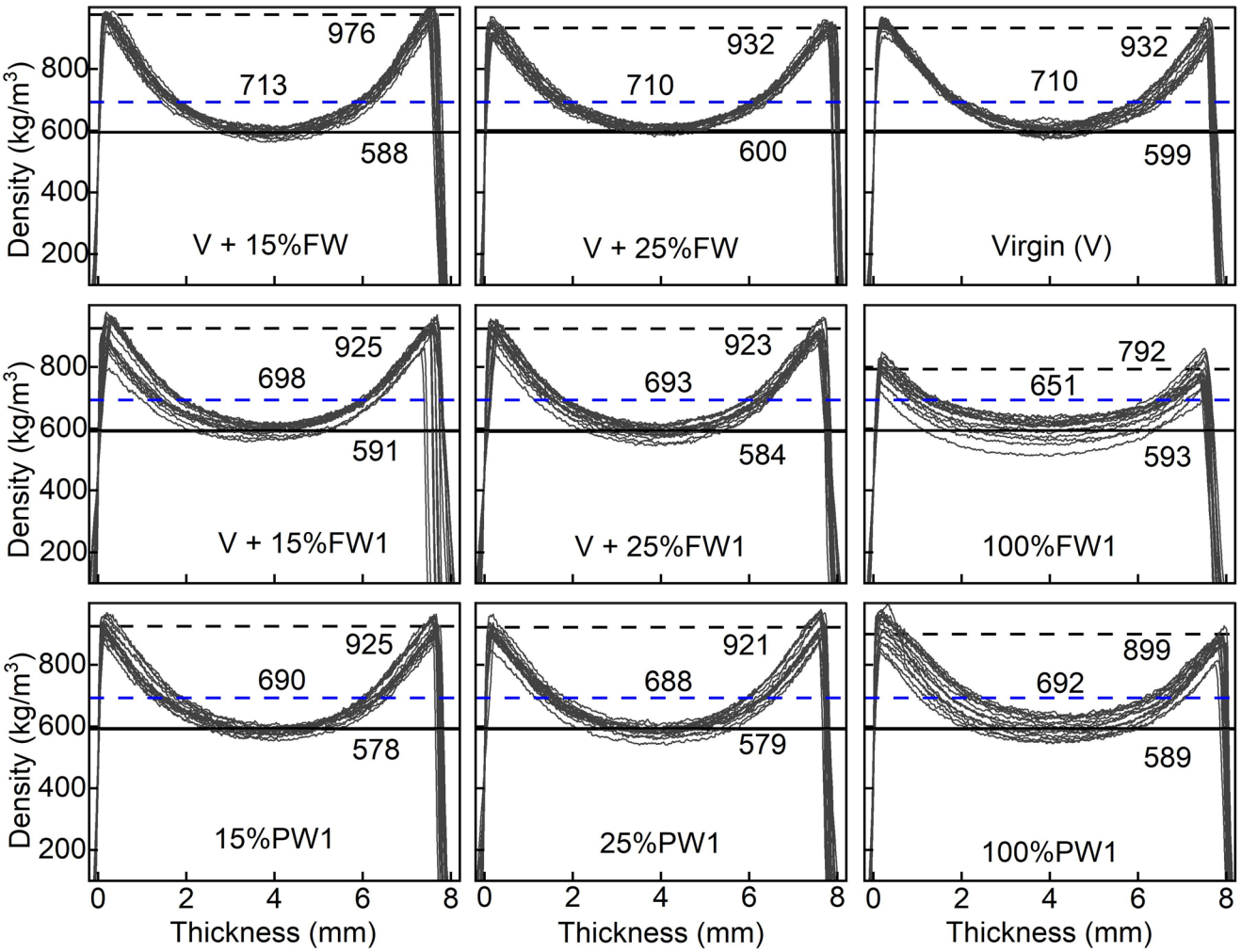

Fig. 6 MDF density profiles. Dashed black lines indicate the sample's surface density, dashed blue lines indicate the sample's average density, and solid black lines show the sample's minimum density

ultimately lowers the average density of the MDF panels. However, the core density of 100%FW1 is comparable to the reference MDF. The ratio between the core and average density values was approximately 85%, which is close to previous studies (Hong et al. 2020; Savov et al. 2023a).

3.2.2 Water absorption and thickness swelling

Figure 7a and b display the thickness swelling (TS) and water absorption (WA) of the produced MDF after 2 h and 24 h, respectively. After 2 h of water immersion, TS values generally ranged from 7 to 9%, while WA values were typically between 9% and 11%, except for samples 100%FW1 and 100%PW1. Total TS in MDF is primarily attributed to the release of pressing-induced stress, wood swelling, and the deterioration of inter-fibre bonding (Roffael et al. 2016; Wong et al. 2000). Following 24 h of water absorption, TS values for all samples ranged from 17 to 22%, while WA values varied more broadly, from 31 to 62%. For MDF using fibres from MDF processing waste, increasing secondary fibre content from 15 to 25% slightly reduced TS and WA ($P<0.02$). At a low substitution ratio, the presence of cured resin and wax on secondary fibres may decrease WA, owing to their low affinity for water (Lubis et al. 2018b; Roffael et al. 2016). Conversely, beyond this low threshold, increasing the proportion of secondary fibres to 100% significantly increases both WA and TS, aligning with previous findings (Savov et al. 2023a). This might be attributed to the overall detrimental effects of secondary fibres, including shorter fibre length, higher fines content, and reduced compatibility with the new resin, which collectively lead to reduced density uniformity and potentially increased porosity in the MDF. The detrimental effects of fibre size and bonding capacity were explained in the fibre geometry and morphology section. In MDF made with ST fibres, neither fibre ratio (15% vs. 25%) nor source (FW vs. PW) had a statistically significant effect ($P>0.15$).

3.2.3 Moduli of rupture and elasticity

The MOR and MOE values of the MDF samples are shown in Fig. 8. The reference MDF exhibited a MOR of 36 MPa and an MOE of 3273 MPa. All boards met the EN 622-5 standard for general-purpose MDF used in dry conditions (23 MPa for MOR and 2700 MPa for MOE), except for the samples with 100% substitution rates (ST-100%PW1 and 100%FW1). The static bending properties of MDF are primarily influenced by density profiles and fibre bonding strength (Wong et al. 2000; Zeng et al. 2018). Fibre bonding strength depends on the type and area of fibre bonds, fibre orientation, and fibre strength (Back 1987). MDF made with mTMP fibres showed comparable values to the reference MDF. In contrast, MDF incorporating ST fibres exhibited statistically lower MOR and MOE. The reduction can be attributed to the lower surface and average density (Fig. 6). Notably, 100%PW1 exhibited a 93% lower MOR than V+25%PW1, despite having similar density, likely due to the deteriorated fibre geometry and morphology as discussed above. A high proportion of fine fibres introduces more weak contact points that reduce the load transfer under loading. This is because smaller fibres create a larger total surface area, requiring additional resin for effective bonding (Fernando 2007; Hubbe et al. 2007). The loose fracture of MDF (Fig. 5b-c) made with 100% secondary fibres was also consistent with the detrimental effects of recycled fibres. For ST MDF, replacing secondary fibres from processing waste with those from post-consumer fibreboard waste resulted in no statistically significant change (P-value>0.24). Increasing the secondary fibre content from 15 to 25% did not result in a noticeable change in MOR and MOE (P-value>0.2).

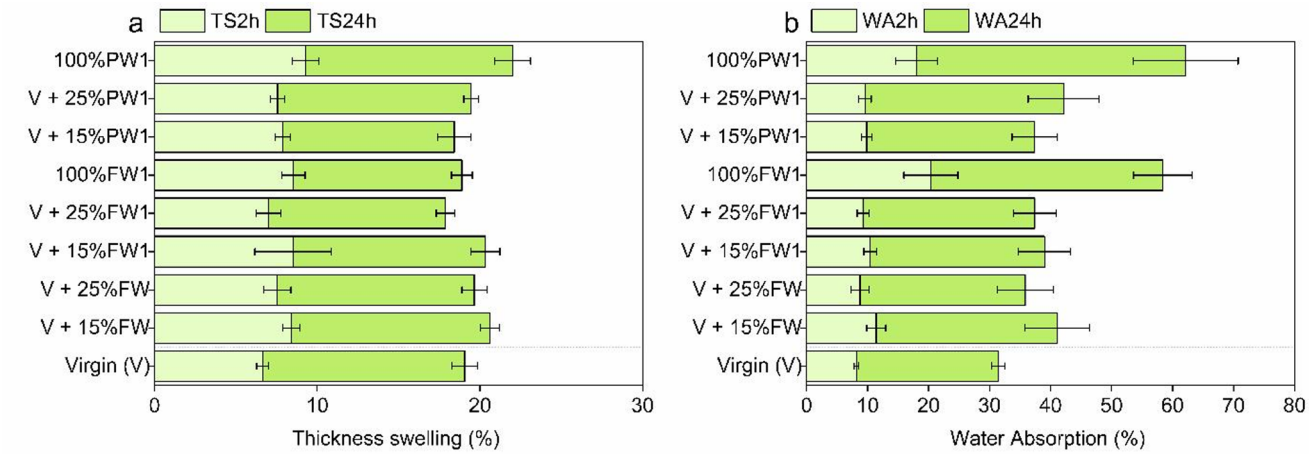

Fig. 7 TS (a) and WA (b) values of MDF using fibres from different recycling processes, secondary fibre ratio, and fibre source

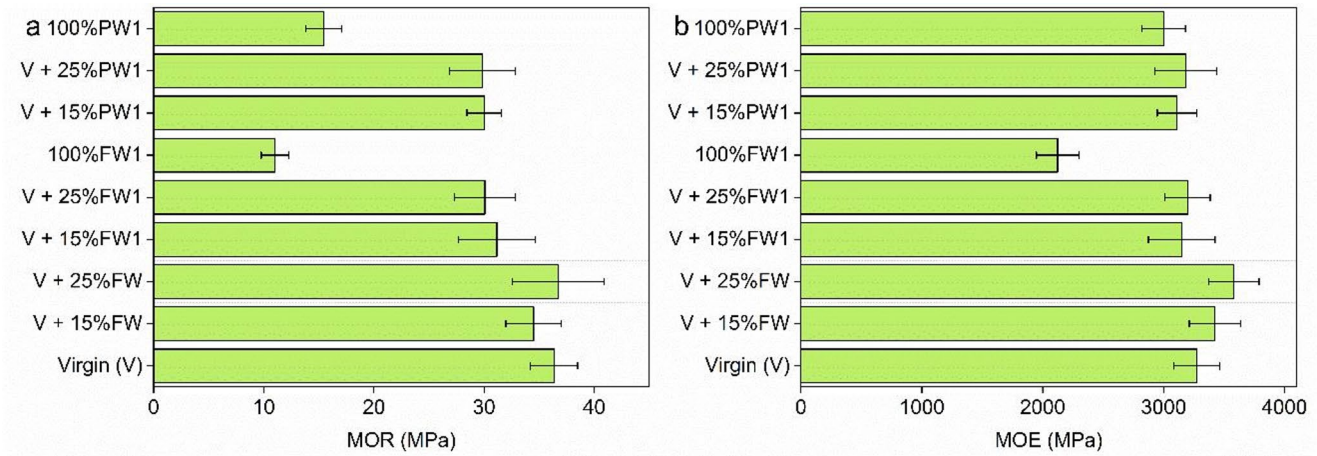

Fig. 8 MOR (a) and MOE (b) values of MDF using fibres from different recycling processes, secondary fibre ratio, and fibre source

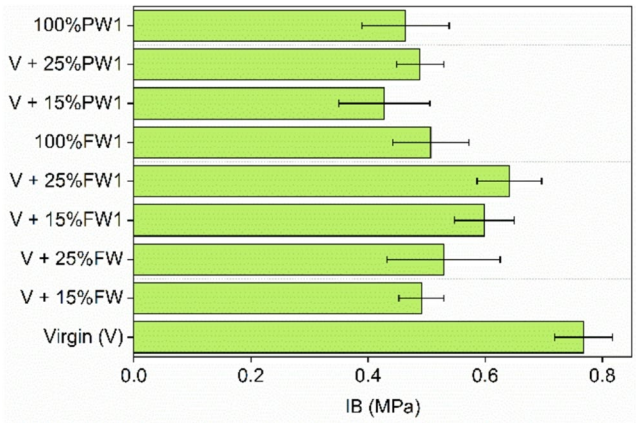

Fig. 9 IB values of MDF using fibres from different recycling processes, secondary fibre ratio, and fibre source

3.2.4 Internal bond strength

Figure 9 presents the internal bond (IB) strength of the MDF samples. The reference MDF exhibited a mean IB value of 0.77 MPa, while the incorporation of secondary fibres reduced IB strength regardless of fibre source, ratio, or recycling process. When the secondary fibre content increased from 15 to 25%, the IB strength did not show a statistically significant change (P-value = 0.1). For ST fibres at both 15% and 25% substitution rates, MDF produced with fibres from post-consumer fibreboard exhibited approximately 26% smaller IB values than those made with fibres from MDF processing waste (P-value < 0.0001). This drop might be attributed to the decrease of core density of 9 kg/m^3(P-value = 0.0054), as core density is a critical factor influencing IB strength in MDF (Wong et al. 2000). A higher density leads to closer fibre contact, promoting inter-fibre bonding. Moreover, fibres from post-consumer fibreboard waste are assumed to contain more contaminants, which would reduce their bonding with the resin. However, with comparable core density, MDF with secondary fibres exhibited a substantial decrease in IB strength compared to the reference MDF. This reduction may be attributed to a smaller effective bonding area due to the shorter fibre length. Furthermore, previous research found that the accumulation of residual resin and wax on recycled fibres could inhibit inter-fibre bond formation (Back 1987; Lubis et al. 2018b; Zeng et al. 2018). Instead of focusing solely on removing the residual resin from secondary fibres, optimizing the process to straighten and flatten fibres could enhance adhesion by increasing the bonding surface (Li et al. 2009). When evaluating IB strength, multiple factors -including density profile, fibre length, and fibre characteristics such as nitrogen content and pH - can influence adhesion (Lubis et al. 2018b).

3.2.5 Formaldehyde content

Figure 10 presents the formaldehyde content (FC) of MDF, which ranged from 1.3 to 6.4 mg/100 g of dry fibre. Compared to MDF made with virgin fibres, MDF containing 100% secondary fibres from ST exhibited significantly lower FC by 74.5% for 100%FW1 and 65.5% for 100%PW1. The reduction in FC observed in samples containing secondary ST fibres could be attributed to the formation of urea, ammonia, and oligomeric decay products, which act as formaldehyde scavengers during the thermo-hydrolysis process (Moezzipour et al. 2018; Roffael et al. 2016; Savov et al. 2023b). For ST MDF from MDF processing waste, increasing secondary fibre content from 15 to 100% lowers the FC. In contrast, samples with mTMP fibres showed a slight increase in FC at a 25% substitution rate. The increase could be linked to a higher retention of non-hydrolyzed UF-binder, likely due to milder recycling conditions, such as lower temperatures and shorter processing durations (Bütün Buschalsky and Mai 2021; Lubis et al. 2018b). However, MDF with PW1 fibres showed unexplained FC content,

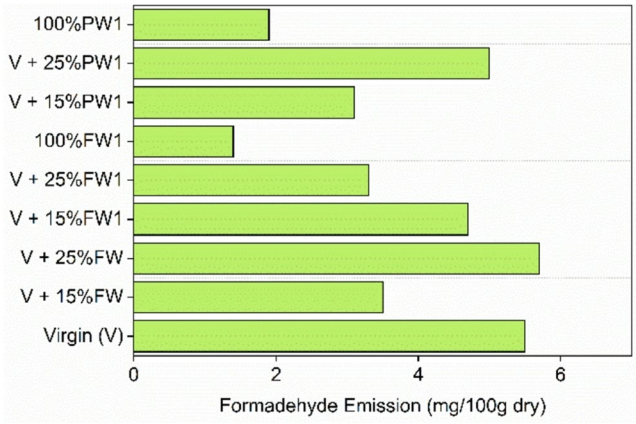

Fig. 10 FC values of MDF using fibres from different recycling processes, secondary fibre ratio, and fibre source

which needs further investigation with replicates. Since FC and formaldehyde release are critical parameters for MDF intended for furniture and indoor applications, monitoring these factors is essential when incorporating secondary fibres.

4 Conclusion

TMP virgin and secondary fibres from both MDF processing waste and post-consumer fibreboard waste displayed distinct size distributions and surface properties. Secondary fibres from both sources were notably shorter and contained more fines compared to the obtained virgin fibre. Furthermore, these secondary fibres exhibited deteriorated surfaces with increased damage and contaminants. For MDF made with ST fibres at 15% and 25% substitution rates, density, TS, WA, MOR, MOE, and IB remained consistent. However, IB strength saw a notable drop when the waste fibre source shifted from processing waste to post-consumer waste. MDF incorporating mTMP fibres showed a slight decrease in both TS and WA as the secondary fibre ratio increased from 15 to 25%. Among MDF containing FW fibres, the ST process yielded a higher IB compared to the mTMP process, though with slightly lower static bending properties (MOR, MOE). Compared to reference MDF, MDF made with 100% secondary fibres showed significantly reduced physical and mechanical properties, although their FC decreased. Interestingly, incorporating secondary fibres at 15% and 25% substitution rates yielded comparable TS, MOR, MOE, and FC to reference MDF. However, properties of IB and WA were reduced regardless of the recycling process or the waste source of the secondary fibres. This study specifically found that post-consumer fibreboard waste fibres had a more detrimental impact on IB strength than MDF processing waste fibres. Future research should also collectively evaluate the physical, chemical, mechanical, and morphological properties of secondary fibres to better understand their differences from virgin fibres.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare to have no conflicts of interest.

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