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Optimizing paper sludge content and particle size to enhance particleboard properties

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The pulp and paper industry generates vast quantities of paper sludge, posing significant environmental challenges due to its disposal in landfills or incineration. This study explores the potential of valorizing paper sludge by incorporating it into particleboard production. It aims to optimize sludge content and particle size to enhance board properties—a novel approach to waste management in the wood composites industry. Through systematic variation of sludge content (0–25%) and particle size (< 0.5 to > 2 mm), we assessed the mechanical and physical properties such as internal bond strength (IB), modulus of rupture (MOR), modulus of elasticity (MOE), water absorption (WA), and thickness swelling (TS). The findings indicate that incorporating paper sludge at moderate levels (5–15%) with optimized particle sizes (< 1 mm) significantly improves the mechanical properties of the particleboard, including increased IB, MOR, and MOE while reducing WA and TS. Principal Component Analysis (PCA) further supported these results, revealing that higher-density boards with enhanced mechanical properties absorb less water, highlighting the interrelationship between structural integrity and moisture resistance. The PCA also identified thickness swelling as an independent factor, suggesting that while mechanical properties can be optimized, additional strategies are needed to control swelling. In conclusion, this study demonstrates that up to 15% paper sludge can be effectively used in particleboard production without compromising quality, provided particle size is carefully controlled. This approach not only offers a sustainable solution for managing paper sludge but also contributes to the development of eco-friendly composite materials, aligning with circular economy principles.

Keywords Paper sludge valorization, Particleboard manufacturing, Waste management, Mechanical properties, Dimensional stability

The pulp and paper industry, a pivotal sector in global manufacturing, faces a significant environmental challenge due to the generation of paper sludge. This byproduct, which results from papermaking and recycling processes, has grown exponentially, with global production exceeding 400 million tons of wet paper sludge annually[1]. Conventional disposal methods, including landfilling and incineration, are becoming progressively unsustainable due to increasingly stringent environmental regulations, escalating costs, and heightened awareness of their ecological impact. This predicament necessitates the development and implementation of innovative strategies for the sustainable management and utilization of paper sludge[2,3]. The magnitude of paper sludge production and the environmental concerns associated with traditional disposal methods underscore the urgency of finding alternative solutions. The paper industry's significant role in the global economy, coupled with growing environmental consciousness, has led to increased scrutiny of its waste management practices. As sustainable waste management becomes increasingly important, the potential to incorporate paper sludge into composite materials is gaining attention[2–4]. The effectiveness of this approach depends not only on the amount of sludge used but also on the size and shape of the particles involved.

Paper sludge is a complex, heterogeneous mixture of cellulose fibers, minerals, and organic compounds[4]. Its composition exhibits significant variability contingent upon several factors, including the nature of waste fibers utilized as input material, specific processing methodologies employed in paper recycling and deinking operations, and diverse chemical additives used in papermaking[5]. For example, sludge derived from recycled office paper may possess a distinct fiber and mineral content profile compared to that originating from newsprint

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or packaging materials. The mineral content typically encompasses substances such as calcium carbonate, kaolin, and titanium dioxide, which are commonly employed as fillers or coatings in paper production. This compositional variability presents both challenges and opportunities for the utilization of paper sludge in secondary applications[5,6].

Recent research has elucidated substantial potential for the reuse and recycling of paper sludge in diverse fields[3,4,7]. Studies have demonstrated that cellulose fibers extracted from paper mill sludge can effectively enhance paper coatings, improving properties such as porosity, permeability, gloss, and brightness[8]. Furthermore, investigations into the enrichment of cellulose content in paper sludge utilizing protic ionic liquids and deep eutectic solvents have underscored its potential as a cellulose-rich feedstock for biorefinery applications[9]. The construction and building materials sector has emerged as a promising avenue for paper sludge utilization. Chimphango et al.[10] successfully employed paper sludge as a filler in cement boards, achieving strength comparable to conventional boards. Ashori et al.[4] demonstrated that paper sludge could replace up to 10% of wood fibers in medium-density fiberboard without compromising strength properties. Govindan and Kumarasamy[11] incorporated paper sludge into brick production, potentially offering a sustainable alternative to traditional brick manufacturing processes. In fiber-cement composites, Yadollahi et al.[12] conducted a comprehensive study on cement composites reinforced with 10–50% paper sludge, providing extensive data on density, strength, and water resistance properties. However, the integration of paper sludge into wood-based materials, particularly particleboard, presents significant challenges in terms of material compatibility and performance. Kwon et al.[13] investigated particleboard fabrication using paper sludge in proportions ranging from 10 to 50%. Their findings revealed a correlation between increased sludge content and decreased density and flexural strength, which they attributed to poor compatibility between the sludge and wood particles. Corroborating these results, Özdemir et al.[14] reported a decline in mechanical properties in particleboards containing more than 10% paper sludge, citing weak fiber-matrix interactions as the primary cause. Ntougias et al.[15] substantiated these findings, attributing the decreased flexural strength in sludge-containing particleboard to poor surface adhesion between the sludge and wood particles. Despite these challenges, the potential benefits of incorporating paper sludge into wood-based composites warrant further investigation. Xing et al.[16] discovered that including secondary paper mill sludge as a binder in wood-cement particleboard composites reduced formaldehyde emissions by up to 50%, highlighting an additional environmental benefit beyond waste utilization. This finding underscores the multifaceted potential of paper sludge in addressing both waste management and product performance concerns.

Particle size and shape critically influence the mechanical properties of particleboards, significantly affecting performance through several mechanisms:

1. Surface area-to-volume ratio: Smaller particles have a higher surface area-to-volume ratio, which can lead to improved resin coverage and bonding. Gozdecki et al.[17] demonstrated that decreasing particle size from 1.0 mm to 0.5 mm in wood-polymer composites resulted in a 15% increase in tensile strength due to enhanced interfacial adhesion.
2. Particle packing efficiency: Particle size distribution affects the packing density of the board. Nemli et al.[18] found that using a mixture of fine (0.25–0.5 mm) and coarse (1.0–2.0 mm) particles in a 30:70 ratio improved modulus of rupture (MOR) by 18% compared to boards made with only coarse particles.
3. Stress distribution: Particle shape influences stress transfer within the board. Juliana et al.[19] observed that flake-like particles with aspect ratios > 3:1 resulted in 25% higher modulus of elasticity (MOE) compared to more equidimensional particles, due to improved stress distribution along the fiber direction.
4. Vertical density profile: Particle size affects the formation of the vertical density profile during hot pressing. Cai et al.[20] reported that smaller particles (< 0.5 mm) led to steeper density gradients, resulting in 10–15% higher surface MOR but 5–8% lower internal bond strength compared to boards with larger particles (1.0–2.0 mm).
5. Resin consumption: Particle size impacts resin consumption and distribution. Dziurka and Mirski[21] found that reducing particle size from 1.2 mm to 0.5 mm increased resin consumption by 20% but resulted in a 30% improvement in internal bond strength due to more uniform resin distribution.
6. Hygroscopic behavior: Particle geometry affects the board's response to moisture. Ashori and Nourbakhsh[22] demonstrated that particleboards made with smaller particles (< 0.5 mm) exhibited 12% lower thickness swelling after 24-hour water immersion compared to boards with larger particles (1.0–2.0 mm) due to improved particle encapsulation by the resin.

Understanding these complex relationships between particle characteristics and board properties is crucial for optimizing particleboard performance, especially when incorporating alternative materials like paper sludge. This study aims to elucidate these relationships in the context of paper sludge valorization, contributing to the development of more sustainable and high-performance particleboard products.

The present investigation seeks to bridge the gap between the established potential of paper sludge in various applications and its specific utilization in particleboard production. Based on prior studies, we hypothesize that the incorporation of paper sludge, particularly in optimized content and particle sizes, can enhance board properties such as mechanical strength and dimensional stability. This hypothesis is supported by earlier research that shows smaller particle sizes in composite materials lead to better interfacial bonding and higher mechanical strength[17,18]. Moreover, studies like Taramian et al.[23] indicate that while increased cellulose content (such as from paper sludge) can raise water absorption, this effect may be mitigated by particle size optimization. By focusing on these critical parameters—sludge content and particle size—this study aims to test these hypotheses, providing a comprehensive understanding of their effects on board properties and exploring optimization strategies for achieving desirable board characteristics.

Materials and methods

Materials

The primary lignocellulosic component utilized in this study was derived from a blend of hardwoods. The raw material underwent a series of processing steps to achieve the desired particle characteristics for particleboard production. Initially, the logs were reduced to chips using a laboratory-scale drum chipper. Subsequently, these chips were further processed into smaller particles using a laboratory-scale ring flaker. To ensure optimal moisture content for board manufacture, the resulting particles were subjected to a drying process until they reached a moisture content of 7%. A screening procedure was then implemented to remove oversized particles, ensuring a more uniform particle size distribution. The final wood particles exhibited the following physical characteristics: thickness of 0.07 mm, width of 8.3 mm, length of 15.8 mm, and density of 0.59 g/cm^3.

Paper sludge was sourced from Latif Paper Products Co. (Iran). Table 1 provides information on the chemical and morphological properties of the paper sludge used in this study, as determined by the Tappi test method. The paper sludge underwent a two-stage drying process to mitigate mold and fungal growth risks. Initially air-dried to 20% moisture content, it was oven-dried at 100 °C for 24 h, reaching 6–7% humidity. The dried sludge was ground using a Pallman mill and classified into four size fractions using ASTM E11 standard sieves: >2 mm, 1–2 mm, 0.5–1 mm, and < 0.5 mm. This approach enables a systematic investigation of sludge particle size effects on particleboard properties, potentially optimizing paper sludge utilization in sustainable wood composite manufacturing.

The adhesive component utilized in this study was a commercial-grade urea-formaldehyde (UF) resin. This UF resin exhibited specific physical properties, namely a density of 1.24 g/cm^3 and a solid content of 60%. The formaldehyde to urea mole ratio (F/U) of the resin was 1.6, which provides insight into the stoichiometric relationship between formaldehyde and urea in the resin's molecular structure.

Lab production of boards

The experimental design for single-layer particleboard preparation is delineated in Table 2, which presents the formulations and corresponding abbreviations employed. The study focused on two primary variables: paper sludge content and particle size. Other manufacturing parameters were maintained constant across all treatments, including resin content (12%), hardener content (2%), press closing rate (10 mm/s), press pressure (30 kg/cm^2), press temperature (180 °C), board thickness (16 mm), and target density (0.75 g/cm^3). For each formulation, three replicate boards were fabricated to ensure statistical reliability. The manufacturing process involved blending dried woody particles with UF adhesive and sludge particles in proportions specified in Table 2, using a rotating drum-type mixer. The homogenized mixture was then evenly distributed in a molding frame to ensure uniform density. Particleboard formation was achieved using a laboratory-scale hydraulic hot press. The nominal dimensions of the pressed panels were 400 × 400 mm^2. To maintain consistent thickness across all experimental runs, stop bars were employed during the pressing process. Following fabrication, the particleboards underwent a cold pressing procedure for 4 h. This extended cold pressing phase facilitated gradual cooling of the boards and mitigated potential thickness swelling, thereby preventing dimensional instability and associated defects. It is noteworthy that no additional hydrophobic substances or wax were incorporated into the board composition. Post-pressing, the boards were trimmed to final dimensions of 380 × 380 mm^2. Subsequently, all board samples underwent a standardized conditioning process for two weeks in a controlled environment of 65% relative humidity and 25 °C temperature. This conditioning step ensures equilibration of moisture content and stabilization of board properties before further testing and analysis.

Testing methods

A comprehensive suite of standardized tests was conducted to evaluate the mechanical and physical properties of the specimens. A static bending test (EN 310) was employed to determine the modulus of rupture (MOR) and Modulus of Elasticity (MOE)[30]. Internal bond strength (IB) was assessed according to EN 319[31], and screw withdrawal according to EN 320[32]. Water absorption (WA) and density tests were carried out following EN 317[33] and EN 323[34], respectively. For these tests, specimens were fully submerged in distilled water at 25 °C for durations of 2 h and 24 h. All tests were done with 6 replicates.

Properties	Value	Tappi test method
Acid-insoluble lignin*	16.6	T 222 om-22[24]
Acid-soluble lignin	0.39	UM 250[25]
Total inorganic, %	47.4	T 211 om-22[26]
Total organic, %	53.6	T 211 om-22[26]
Dry matter, %	56.4	T 550 om-22[27]
pH	7.1	T 252 om-22[28]
Fiber length, mm	0.79	T 271 om-22[29]
Fiber width, µm	22.7	T 271 om-22[29]
Aspect ratio	59.8	Calculated from T 271 om-22[29]

Table 1. Chemical and morphological properties of paper sludge. *Klason lignin.

Treatment code	Paper sludge (wt%)	Particle size (mm)	Wood particle (wt%)	UF (wt%)
Control	0	0	88	12
5-1	5	> 2	83	12
5-2	5	1–2	83	12
5-3	5	0.5–1	83	12
5-4	5	< 0.5	83	12
10-1	10	> 2	78	12
10-2	10	1–2	78	12
10-3	10	0.5–1	78	12
10-4	10	< 0.5	78	12
15-1	15	> 2	73	12
15-2	15	1–2	73	12
15-3	15	0.5–1	73	12
15-4	15	< 0.5	73	12
20-1	20	> 2	68	12
20-2	20	1–2	68	12
20-3	20	0.5–1	68	12
20-4	20	< 0.5	68	12
25-1	25	> 2	63	12
25-2	25	1–2	63	12
25-3	25	0.5–1	63	12
25-4	25	< 0.5	63	12

Table 2. Experimental design for particleboard production with varying paper sludge content and particle size.

Field emission scanning electron microscopy (FE-SEM)

FE-SEM was employed to analyze the distribution of sludge particles within the particleboard layer. A Hitachi S-4160 (Japan) instrument operating at 15 kV accelerated voltage. This setting optimized visualization of the composite's microstructure and sludge particle distribution.

Statistical analysis

The experimental data were subjected to statistical analysis using a one-way analysis of variance (ANOVA) for a completely randomized design. The experimental framework incorporated two treatments and their interactions. To discern significant differences among means, Duncan's Multiple Range Test (DMRT) was employed as a post-hoc analysis. Statistical significance was established at both 95% ($p \leq 0.05$) and 99% ($p \leq 0.01$) confidence levels.

Principal component analysis (PCA)

To further explore the relationships between the physical and mechanical properties of the particleboards, a PCA was performed. PCA is a statistical technique used to reduce the dimensionality of a dataset while retaining most of the variance. It identifies the principal components that explain the maximum variance within the data, allowing for the investigation of underlying patterns and correlations among variables. The PCA was conducted on a set of critical variables, including density (kg/m^3), MOR (MPa), MOE (MPa), IB (MPa), WA 2-h (%), WA 24-h (%), TS 2-h (%), TS 24-h (%), and SWR (face and edge, N/mm). Before conducting PCA, the suitability of the data was tested using the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's Test of Sphericity to ensure that the dataset was appropriate for factor analysis. The KMO value was 0.735, and Bartlett's test yielded a significance level 0.000, indicating that the dataset was suitable for PCA. The PCA was carried out using Varimax rotation with Kaiser normalization to improve the interpretability of the results. Components with eigenvalues greater than 1 were retained, and the resulting factor loadings were analyzed to identify the key components that explained the most variance in the dataset.

Results and discussion

Statistical analysis

Tables 3 and 4 present comprehensive data on the mechanical and physical properties of particleboards incorporating varying amounts of paper sludge with different particle sizes, along with the statistical analysis of these effects. These tables provide crucial insights into the complex relationships between sludge incorporation parameters and board characteristics.

MOR and MOE exhibited statistically significant responses to sludge content and particle size ($p < 0.01$, Table 4). The relationship between these mechanical properties and the experimental factors was non-linear. At 5% sludge content, MOR and MOE increased for most particle sizes, suggesting potential for property enhancement at low sludge incorporation levels. The improvement in MOR and MOE at 5% sludge content, particularly with smaller particle sizes (0.5–1 mm), confirms our hypothesis that optimized sludge content and

Treatment	Mechanical properties					Physical properties				
	MOR (MPa)	MOE (MPa)	IB (MPa)	SWR-edge (N/mm)	SWR-face (N/mm)	WA 2-h (%)	WA 24-h (%)	TS 2-h (%)	TS 24-h (%)	Density (kg/m^3)
Control	21.2 (4.21)*	1309.60 (73.37)	1.00 (0.25)	52.00 (17.90)	86.00 (12.12)	80.76 (13.99)	95.85 (13.24)	22.75 (3.25)	26.86 (3.68)	730 (1.008)
5 – 1	22.75 (2.73)	1929.30 (425.50)	0.80 (0.10)	52.50 (22.71)	49.48 (4.44)	81.91 (4.05)	100.60 (4.44)	28.88 (3.22)	28.33 (2.58)	713 (0.809)
5 – 2	18.37 (1.31)	1547.21 (265.54)	0.84 (0.11)	37.67 (20.03)	56.12 (8.50)	86.71 (7.30)	110.11 (12.72)	26.01 (1.80)	28.14 (3.03)	700 (0.84)
5 – 3	34.12 (5.72)	2690.49 (497.63)	0.95 (0.23)	59.83 (23.30)	61.52 (10.72)	91.13 (9.03)	104.84 (13.30)	25.23 (3.66)	30.05 (3.39)	725 (0.958)
5 – 4	29.09 (8.30)	2290.42 (743.48)	0.84 (0.27)	70.50 (18.62)	57.72 (1.5)	78.26 (6.84)	92.78 (14.56)	27.27 (2.53)	33.07 (3.45)	773 (0.848)
10 – 1	21 (3.93)	1855.43 (347.20)	0.44 (0.10)	31.75 (2.25)	52.39 (17.29)	116.03 (15.42)	136.82 (28.82)	29.10 (2.83)	34.87 (4.24)	650 (0.449)
10 – 2	24.5 (5.46)	2158.06 (482.02)	0.74 (0.11)	53.00 (8.54)	61.11 (26.24)	91.09 (8.24)	96.73 (8.31)	29.46 (2.95)	21.75 (0.80)	723 (0.746)
10 – 3	34.12 (1.31)	2995.98 (111.40)	0.68 (0.37)	50.00 (12.12)	67.31 (29.38)	87.53 (6.90)	99.87 (7.88)	21.83 (2.15)	27.01 (5.25)	733 (0.687)
10 – 4	28 (2)	2446.17 (171.81)	0.94 (0.07)	50.50 (11.30)	65.78 (22.52)	105.93 (14.14)	127.95 (15.62)	24.07 (3.17)	32.27 (2.52)	675 (0.940)
15 – 1	20.56 (2.73)	1786.48 (240.55)	0.57 (0.08)	23.33 (4.04)	45.55 (16.69)	121.34 (7.50)	125.52 (10.52)	32.62 (1.95)	28.96 (1.94)	670 (0.572)
15 – 2	26.68 (1.51)	2305.82 (135.33)	0.74 (0.10)	39.83 (8.31)	52.71 (19.40)	106.49 (8.98)	103.38 (14.57)	25.03 (1.70)	18.99 (1.58)	682 (0.745)
15 – 3	29.75 (8.93)	2557.48 (769.80)	1.09 (0.06)	56.17 (7.68)	68.69 (28.38)	86.34 (12.78)	99.70 (5.38)	19.98 (1.61)	22.25 (2.14)	723 (1.094)
15 – 4	32.81 (3.47)	2816.62 (297.60)	1.12 (0.41)	92.33 (8.08)	89.26 (35.68)	77.77 (5.53)	98.39 (4.50)	19.05 (1.67)	29.88 (2.32)	748 (1.12)
20 – 1	22.09 (0.37)	1894.01 (33.94)	0.72 (0.03)	40.67 (7.63)	57.91 (18.02)	97.92 (3.71)	100.89 (13.93)	24.61 (1.65)	19.74 (1.09)	696 (0.721)
20 – 2	28.87 (1.31)	2474.43 (113.17)	0.52 (0.10)	35.67 (0.57)	52.32 (17.97)	104.13 (11.04)	107.90 (13.93)	20.10 (1.87)	20.37 (2.65)	676 (0.524)
20 – 3	24.93 (2.27)	2131.25 (192.59)	0.93 (0.23)	63.55 (3.46)	42.47 (15.09)	101.02 (10.21)	108.28 (14.83)	17.45 (1.71)	19.69 (3.14)	663 (0.931)
20 – 4	18.37 (4.73)	1565.59 (403.75)	0.90 (0.12)	50.17 (8.98)	53.43 (21.26)	101.54 (9.29)	121.82 (14.96)	18.34 (1.87)	32.07 (1.18)	659 (0.904)
25 – 1	7.43 (1.51)	631.84 (129.35)	0.18 (0.03)	56.40 (6.40)	27.45 (13.79)	158.83 (6.92)	165.48 (11.43)	29.83 (2.08)	25.89 (1.14)	549 (0.185)
25 – 2	14.87 (2)	1259.95 (171.23)	0.26 (0.06)	19.50 (6.5)	24.46 (5.58)	123.44 (7.42)	150.22 (13.68)	22.71 (1.45)	30.15 (4)	622 (0.265)
25 – 3	20.78 (3.95)	1753.87 (336)	0.80 (0.09)	46.33 (7.02)	58.34 (34.40)	89.93 (8.31)	89.00 (13.94)	26.54 (1.01)	26.17 (4.00)	719 (0.809)
25 – 4	21 (5.72)	1766.43 (482.45)	0.51 (0.19)	21.00 (7.21)	53.54 (10.92)	99.17 (12.31)	116.56 (14.37)	23.55 (2.04)	38.39 (2.82)	704 (0.515)

Table 3. Physical and mechanical properties of particleboards with varying paper sludge content and particle size. * The standard deviation is written in parentheses.

particle size can enhance mechanical properties. This enhancement is likely due to the higher surface area-to-volume ratio of smaller particles, which improves resin bonding and stress distribution within the board, as supported by previous studies[35]. The non-linear relationship observed, where mechanical properties peak at moderate sludge contents and decline at higher levels, suggests a critical threshold beyond which the wood fiber network is disrupted, leading to diminished mechanical performance. These findings align with Kwon et al.[13] and Özdemir et al.[14], who also reported that excessive sludge content can negatively impact board strength due to poor interfacial adhesion between sludge and wood particles. However, higher sludge contents (> 20%) generally decreased MOR and MOE values. Particle sizes in the range of 0.5–1 mm often yielded the best MOR and MOE values, indicating an optimal particle size for mechanical property enhancement. These findings partially corroborate work by Xing et al.[16], who reported potential for mechanical property improvement in particleboards with optimized sludge incorporation. The interaction between sludge content and particle size was significant for both MOR and MOE, with the optimal sludge content for these properties varying with particle size.

Statistical analysis revealed significant effects of sludge content and particle size on both face and edge screw withdrawal resistance ($p < 0.01$, Table 4). SWR exhibited complex behavior in response to the experimental factors. Face SWR generally decreased with increasing sludge content, while edge SWR showed greater variability. Interestingly, the highest SWR values were often observed at 15% sludge content with smaller particle sizes, suggesting the potential for optimizing fastener-holding capacity through controlled sludge incorporation. This non-linear relationship between SWR and sludge parameters aligns with findings by Ayrilmis et al.[36], who reported the complex effects of filler incorporation on the fastener-holding properties of composite panels. A significant interaction was observed between sludge content and particle size, with 15% sludge content and smaller particle sizes often yielding the best SWR values.

Internal bond strength demonstrated a complex relationship with sludge content and particle size, as evidenced by the statistically significant effects ($p < 0.01$, Table 4). IB values fluctuated non-linearly with changes in sludge content and particle size. The highest IB (1.12 MPa) was achieved with 15% sludge content and < 0.5 mm particles, surpassing the control board's IB of 1.00 MPa. This finding suggests potential for IB enhancement through optimized sludge incorporation. However, a sharp decline in IB was observed at 25% sludge content for all particle sizes, indicating a threshold beyond which sludge incorporation negatively impacts internal bonding. These results align with observations by Migneault et al.[37], who noted the importance of optimizing filler content and particle size in composite materials for maintaining internal bond strength. The interaction between sludge content and particle size was significant, with the optimal sludge content for IB varying across different particle sizes.

Both 2-h and 24-h water absorption demonstrated statistically significant responses to sludge content and particle size ($p < 0.01$, Table 4). A general trend of increasing WA with higher sludge content was observed, particularly for larger particle sizes. The highest WA values (158.83% for 2-h, 165.48% for 24-h) were recorded

Properties		Corrected model	Intercept	A	B	A × B	Error	Total
MOE	df	20	1	0	15	0	63	84
	M S	1,315,418.686	315,028,905	–	881,803	–	89,375.77	
	F	14.718	3524.769	–	9.866	–		
	Sig.	–	–	< 0.000**	< 0.001**	< 0.000**		
MOR	df	20	1	0	15	0	63	84
	M S	172.712	45,510.839	–	133.847	–	11.606	
	F	14.881	3921.277	–	11.532	–		
	Sig.	–	–	< 0.000**	< 0.001**	< 0.000**		
IB	df	23	1	2	16	0	70	94
	M S	0.21	26.834	0.028	0.169	–	0.055	
	F	3.838	489.996	0.509	3.084	–		
	Sig.	0	0	0.604^{NS}	0.001**	–		
SWR edge	df	20	1	0	15	0	63	84
	M S	1172.306	185398.682	–	1317.393	–	39.825	
	F	29.436	4655.285	–	33.079	–		
	Sig.	0	0	< 0.000**	< 0.001**	< 0.000**		
SWR face	df	20	1	0	15	0	63	84
	M S	1596.087	340697.51	–	1394.081	–	139.361	
	F	11.453	2444.71	–	10.003	–		
	Sig.	0	0	< 0.000**	< 0.001**	< 0.000**		
Density	df	20	1	15	0	0	105	126
	M S	14,099.629	49,971,193.39	15010.4	–	–	1750.928	
	F	8.053	28,539.835	8.573	–	–		
	Sig.	0	0	< 0.000**	0	0		
WA 2–h	df	20	1	0	15	0	105	126
	M S	2178.304	1,175,093.904	–	1856.94	–	91.813	
	F	23.725	12,798.712	–	20.225	–		
	Sig.	0	0	–	< 0.001**	–		
WA 24-h	df	20	1	0	15	0	105	126
	M S	2334.15	1,498,847.588	–	2243.528	–	185.316	
	F	12.596	8088.066	–	12.107	–		
	Sig.	0	0	< 0.000**	< 0.001**	< 0.000**		
TS 2-h	df	20	1	0	15	0	105	126
	M S	103.755	72,134.093	–	91.212	3222	5.316	
	F	19.518	13,569.378	–	17.158	12.43		
	Sig.	0	0	–	< 0.001**	< 0.000**		
TS 24-h	df	20	1	0	15	0	105	126
	M S	174.011	90,531.194	–	165.308	–	8.526	
	F	20.41	10,618.305	–	19.389	–		
	Sig.	0	0	–	< 0.000**	–		

Table 4. ANOVA for the effects of paper sludge content and particle size on particleboard properties. *A* sludge content, *B* sludge particle size, *df* degree of freedom, *MS* mean of squares, *SS* sum of squares, *F* F value, *ns* not significant. *Significant difference at the 5% level. **Significant difference at the 1% level.

at 25% sludge content with > 2 mm particles. This increase in water absorption with sludge incorporation corroborates findings by Taramian et al.[23], who attributed this phenomenon to the hydrophilic nature of cellulose fibers in paper sludge. The observed particle size effect, where larger particles led to higher WA, suggests that particle size optimization could be an essential strategy for mitigating the negative impacts of sludge incorporation on water resistance. The interaction between sludge content and particle size was significant, with the effect of sludge content on WA being more pronounced for larger particle sizes.

Analysis of variance revealed that both sludge content and particle size significantly influenced thickness swelling ($p < 0.01$, Table 4). The relationship between TS, sludge content, and particle size was complex and non-linear. While a general trend of increasing TS with sludge content was observed, this was inconsistent across all particle sizes. The highest 24-h TS (38.39%) was recorded at 25% sludge content with < 0.5 mm particles, contrary to the trend observed in water absorption. This divergence suggests that different mechanisms may govern water absorption and thickness swelling behaviors in sludge-incorporated particleboards. The complex TS behavior aligns with observations by Ashori and Nourbakhsh[22], who noted that optimizing particle size could improve dimensional stability in composite boards. A significant interaction was observed between sludge content and particle size, with different particle sizes showing optimal TS at different sludge contents.

The incorporation of paper sludge into particleboard production significantly influenced board density, as evidenced by the statistical analysis ($p < 0.01$, Table 4). A general trend of decreasing density with increasing sludge content was observed, particularly pronounced for larger sludge particle sizes (> 2 mm). The control board exhibited a density of 730 kg/m^3, while the lowest density (549 kg/m^3) was recorded at 25% sludge content with > 2 mm particles. This reduction in density aligns with findings by Geng et al.[38], who reported similar trends in medium-density fiberboard incorporating paper mill sludge. Interestingly, smaller particle sizes (< 0.5 mm) tended to maintain higher densities across various sludge contents, suggesting that particle size is crucial in determining the final board density. This phenomenon may be attributed to the improved packing efficiency of smaller particles, resulting in a more compact board structure. The interaction between sludge content and particle size was significant, with larger particles showing a more pronounced density decrease at higher sludge contents.

In conclusion, this comprehensive analysis of particleboard properties reveals intricate relationships between paper sludge content, particle size, and board characteristics. The non-linear trends observed across multiple properties underscore the complexity of sludge incorporation in particleboard production and highlight the potential for property optimization through careful control of sludge content and particle size. The study demonstrates that both sludge content and particle size had significant effects on all studied properties, and their interactions were also significant in most cases. The relationships were often non-linear, with optimal values occurring at moderate sludge contents (usually 5–15%) and smaller particle sizes (typically < 1 mm). These findings highlight the complexity of sludge incorporation in particleboard production and underscore the importance of carefully optimizing both parameters to achieve desired board properties. The significant interactions between sludge content and particle size across all properties suggest that these factors cannot be considered in isolation when optimizing particleboard formulations. Instead, a holistic approach considering both parameters simultaneously is necessary to achieve the best balance of physical and mechanical properties in sludge-incorporated particleboards.

PCA and factor analysis

To further explore the relationships between the variables affecting particleboard performance, a Principal Component Analysis (PCA) was conducted. The results, summarized in Table 5, revealed two principal components that together explained 62.04% of the total variance in the dataset. Component 1, accounting for 49.57% of the variance, showed strong positive correlations with density, MOR, MOE, and IB while exhibiting strong negative correlations with WA 2-h and WA 24-h. This suggests that higher-density boards with better mechanical properties tend to absorb less water, enhancing moisture resistance. Component 2, explaining 12.47% of the variance, primarily reflected dimensional stability, with strong correlations to TS 2-h and TS 24-h. This indicates that higher swelling rates reduce board stability in moist conditions. The independent swelling behavior suggests manufacturers should focus on controlling thickness swelling while optimizing other mechanical properties.

Figure 1 presents a visual representation of the PCA results, showing the clustering of variables based on their component loadings. The graph illustrates that density, MOR, MOE, and IB are grouped under Component 1, while thickness swelling variables are more aligned with Component 2. This graphical representation helps visualize the relationships between the board properties, showing the trade-off between mechanical strength and moisture resistance (represented in Component 1) and the independent influence of thickness swelling (Component 2). The correlation matrix and PCA findings show that variables like density, MOR, MOE, and IB are positively correlated, while WA is negatively correlated with these variables. This suggests that denser particleboards with better mechanical properties resist water absorption, enhancing their durability in humid environments. However, thickness swelling is not closely related to the other mechanical properties, as it forms its own independent component (Component 2). This indicates that even though denser boards absorb less water, they can still be prone to swelling, emphasizing the need for separate strategies to minimize swelling in moisture-sensitive applications.

The PCA results reveal the critical trade-offs between structural integrity and dimensional stability. While increasing density and smaller particle sizes (< 1 mm) improves mechanical properties and reduces water absorption, attention must be paid to controlling thickness swelling, particularly in environments with high moisture exposure. By integrating the PCA results from Table 5; Fig. 1, manufacturers can focus on:

- **Optimizing particle size**: Smaller particles improve bonding and minimize void formation, reducing water absorption.
- **Moderating sludge content**: Keeping sludge content between 5 and 15% ensures a balance between mechanical performance and moisture resistance.
- **Controlling thickness swelling**: Separate considerations for reducing swelling, such as additional treatments or resin modifications, must be implemented for moisture-sensitive applications.

Component	Variance explained (%)	Key variables	Correlations
1	49.57	Density, MOR, MOE, IB, water absorption (negative)	Positive correlations with mechanical properties and negative with water absorption
2	12.47	Thickness swelling (TS2, TS24)	Positive correlations with thickness swelling

Table 5. PCA results for particleboard properties.

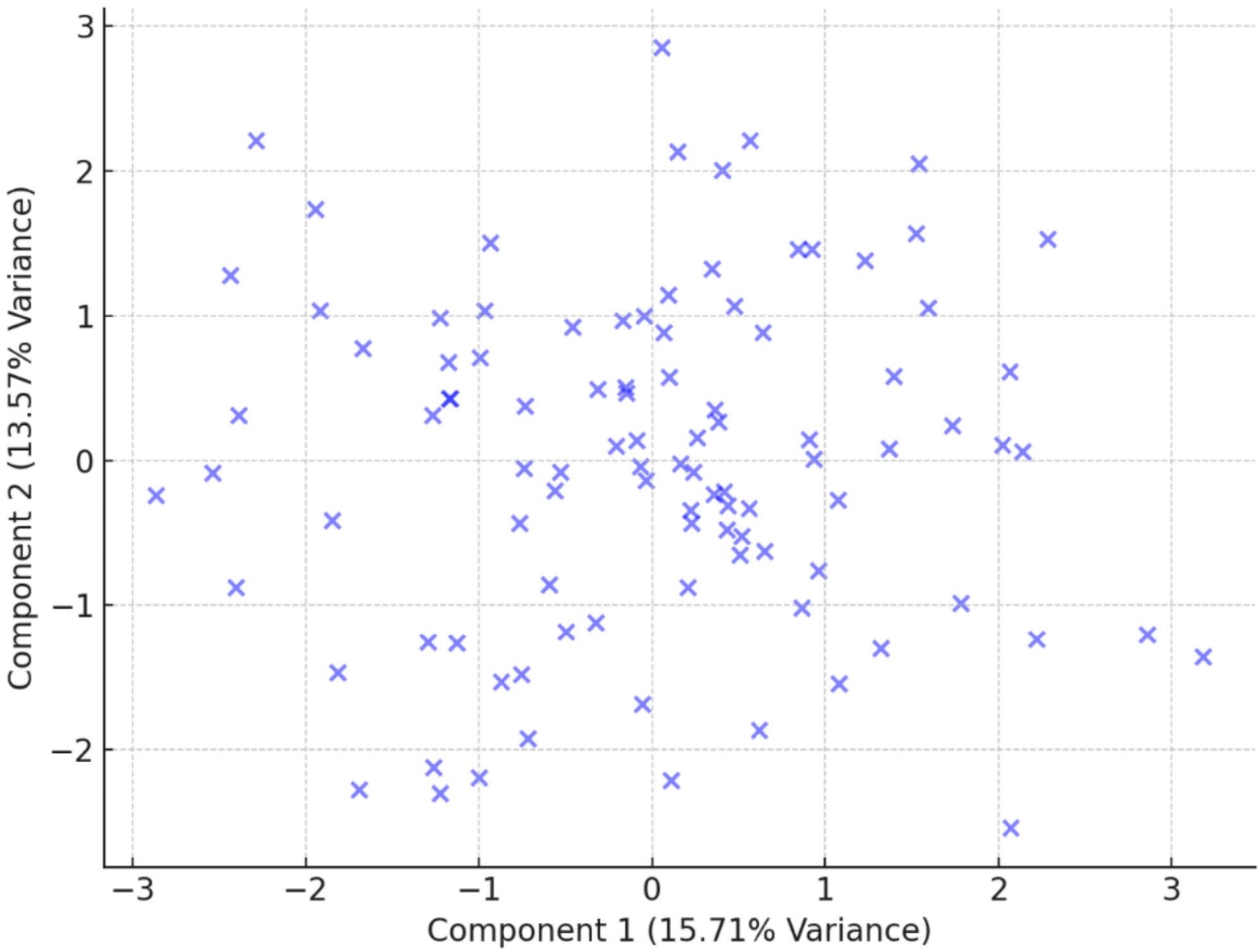

Fig. 1. Correlation of mechanical and physical properties of sludge-enhanced particleboards based on PCA results.

MOR and MOE

The incorporation of paper sludge into particleboard production presents both challenges and opportunities for enhancing mechanical properties. Analysis of Fig. 2 in conjunction with Table 4 reveals nuanced effects of sludge content and particle size on the MOR and MOE of particleboards. The control board, devoid of sludge, exhibited an MOR of 21.2 MPa and an MOE of 1309.60 MPa (Table 4). Upon introducing 5% sludge, MOR increased across all particle size ranges, with the 0.5–1 mm fraction yielding the highest value of 34.12 MPa. The trends in MOR and MOE reflect the complex interactions between particle size and sludge content. Smaller sludge particles (< 0.5 mm) tend to integrate more effectively within the wood fiber network, minimizing disruption to the load-bearing structure. This explains the better performance of boards with smaller particles across different sludge contents. The initial improvement in MOR and MOE at 5% sludge content, particularly for 0.5–1 mm particles, suggests an optimal balance where sludge particles fill voids without significantly compromising the wood fiber continuity. As sludge content increases, larger particles (> 2 mm) create more significant discontinuities in the wood matrix, leading to stress concentration points and reduced overall mechanical performance. The sharp decline in properties at high sludge contents (> 20%) indicates a critical threshold beyond which the wood fiber network is excessively disrupted, regardless of particle size. This microstructural change likely results in a less efficient stress transfer mechanism within the board, explaining the observed reductions in both MOR and MOE.

This initial enhancement aligns with findings by Xing et al.[16], who reported improved mechanical properties in wood-cement particleboards with low levels of paper sludge incorporation. However, as sludge content increased beyond 5%, a general decline in MOR was observed, particularly for larger particle sizes (> 2 mm). This trend is consistent with observations by Kwon et al.[13], who reported diminishing flexural strength with increased sludge content in the 10–50% range. MOE exhibited similar trends, with initial increases at 5–10% sludge content for most particle sizes, followed by declines at higher sludge levels. The 0.5–1 mm particle size consistently demonstrated superior MOE values across varying sludge contents, with a peak of 2995.98 MPa at 10% sludge content. These findings partially corroborate the work of Özdemir et al.[14], who noted declining mechanical properties in particleboards containing more than 10% paper sludge. However, our results indicate a potential for property enhancement at lower sludge levels (5–15%) when combined with optimized particle

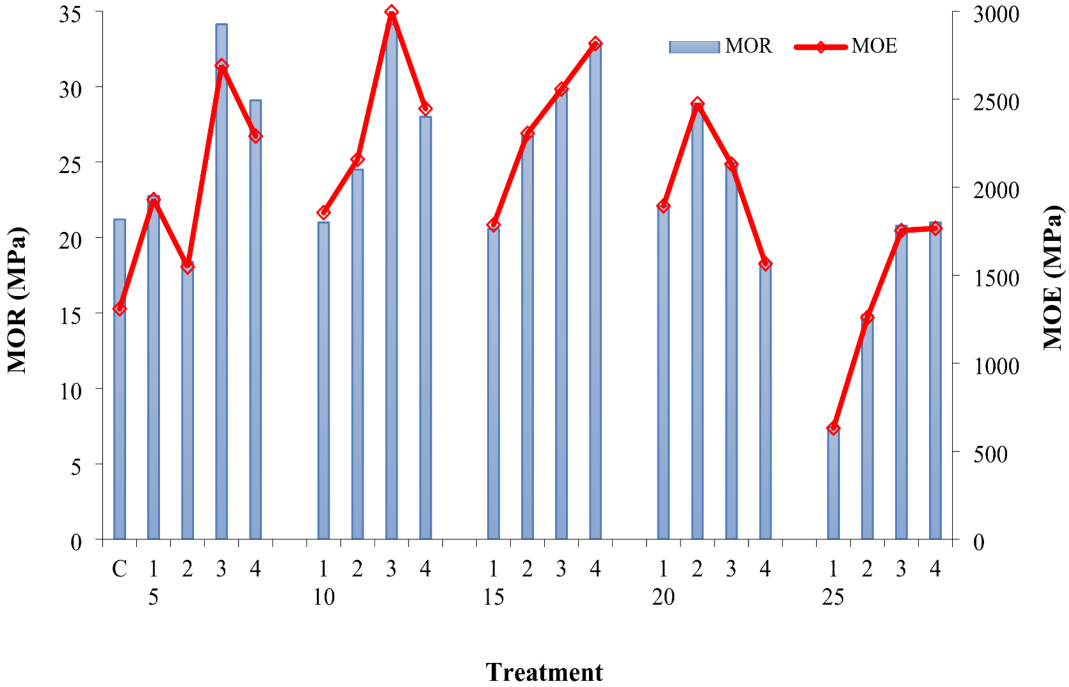

Fig. 2. Effects of paper sludge content and particle size on MOR and MOE of particleboards.

sizes. The observed decline in both MOR and MOE at higher sludge contents (mainly 25%). However, our study extends these insights by demonstrating the potential for property improvement at lower sludge contents and with optimized particle sizes. Optimal mechanical properties were achieved with 5–15% sludge content and particle sizes between 0.5 and 1 mm. These findings suggest that optimizing these parameters can enhance the mechanical properties of particleboards compared to those without sludge, offering a promising avenue for paper sludge valorization in wood composite manufacturing. The reduction in MOR and MOE observed with increasing paper sludge content in particleboards can be attributed to several interconnected factors. A primary concern is the poor interfacial adhesion between sludge particles and the wood matrix. The hydrophilic nature of paper sludge can interfere with bonding between wood particles and urea-formaldehyde resin, creating weak boundary layers at sludge-wood interfaces. These weak points become stress concentration areas, compromising the overall mechanical integrity of the composite. The incorporation of paper sludge also alters the density profile of the particleboard. Adding paper sludge to wood-based panels decreases the vertical density gradient, resulting in lower surface densification. This reduction in surface density is crucial, as it typically leads to reduced bending strength and stiffness, directly impacting MOR and MOE values.

The characteristics of cellulose fibers in paper sludge differ from those in wood. As shown in Table 1 of the study, paper sludge fibers had an average length of 0.79 mm and a width of 22.7 µm. These shorter fibers may not provide the same level of reinforcement as longer wood fibers, potentially leading to reduced load-bearing capacity and elasticity in the composite structure. The high mineral content in paper sludge (47.4% total inorganic content, as per Table 1) also contributes to the reduction in mechanical properties. These inorganic particles, including calcium carbonate and kaolin, do not form strong chemical bonds with wood particles or adhesives. As the proportion of these non-binding components increases with higher sludge content, the overall strength of the particleboard matrix decreases. The addition of paper sludge may also affect urea-formaldehyde resin distribution within the particleboard. The high specific surface area of paper sludge particles can lead to increased resin absorption, potentially resulting in resin-starved areas within the board. This uneven resin distribution can create weak points in the composite structure, reducing mechanical performance. Increasing sludge content likely increases particleboard porosity. The data in Table 4 show a general trend of decreasing density with increasing sludge content, particularly for larger particle sizes. This increased porosity can lead to a reduction in the effective cross-sectional area capable of bearing loads, thus decreasing both MOR and MOE. Lastly, the paper sludge used in this study had a lower lignin content (16.6% acid-insoluble lignin) than typical wood. Lignin plays a crucial role in the natural binding of wood fibers. The reduced lignin content in sludge-wood composites may result in fewer natural fiber-fiber bonds, necessitating greater reliance on the adhesive for structural integrity. These factors collectively contribute to the observed reduction in MOR and MOE as sludge content increases beyond optimal levels. The interplay between these factors is complex and can vary based on the specific characteristics of the sludge, wood particles, and manufacturing parameters. Future research could focus on modifying sludge properties or optimizing processing conditions to mitigate these adverse effects and expand the range of sludge incorporation without compromising mechanical performance.

Density and IB

Figure 3 illustrates the effects of paper sludge content and particle size on the density and internal bond strength (IB) of the fabricated particleboards. Analysis of this figure, alongside data from Table 4, shows several significant trends and relationships. The control board without sludge had a density of 730 kg/m³. Our hypothesis that smaller sludge particles (< 0.5 mm) would result in higher board density is supported by the observed data. Boards incorporating smaller sludge particles maintained higher densities across different sludge contents, with the highest density (773 kg/m³) recorded at 5% sludge content and < 0.5 mm particle size (Fig. 3). This trend can be attributed to the better packing efficiency of smaller particles, which fills interstitial spaces more effectively, leading to a more compact board structure. These findings align with Geng et al.[38], who observed similar density trends in medium-density fiberboard with sludge incorporation. The decrease in density with larger particles and higher sludge contents suggests that larger particles create more voids, reducing the overall board compactness, a conclusion supported by Taramian et al.[23]. The lowest density (549 kg/m³) was observed at 25% sludge content with > 2 mm particles.

The results confirm the hypothesis that smaller sludge particles (< 0.5 mm) enhance internal bond strength (IB). The highest IB value (1.12 MPa) was achieved with 15% sludge content and < 0.5 mm particles, surpassing the control board's IB of 1.00 MPa (Table 4; Fig. 3). This improvement is likely due to the increased surface area provided by smaller particles, which facilitates better resin penetration and bonding. This finding aligns with Huang et al.[39], who observed that optimizing particle size can enhance bonding in wood-based composites. The sharp decline in IB at higher sludge contents (> 20%) indicates a threshold where excessive sludge disrupts the wood fiber network, leading to weaker internal bonds, corroborating observations by Migneault et al.[37]. The highest IB (1.12 MPa) was achieved with 15% sludge content and < 0.5 mm particles. A sharp decline in IB was observed at 25% sludge content for all particle sizes. The complex relationship between density, IB, sludge content, and particle size observed in this study highlights the importance of careful parameter optimization in sludge-incorporated particleboard production. The maintenance of IB values comparable to or higher than the control board at specific sludge contents, particularly with smaller particle sizes, suggests potential for successful sludge valorization without compromising board integrity.

The alterations in density and internal IB observed with varying paper sludge incorporation can be attributed to several technical factors. The general trend of decreasing density with increasing sludge content is primarily due to the lower intrinsic density of paper sludge compared to wood particles. As sludge replaces a portion of the wood material, the board density decreases. This effect is modulated by particle size, with smaller sludge particles (< 0.5 mm) tending to fill interstitial spaces more effectively, leading to higher densities compared to larger particles (> 2 mm). The formation of voids, particularly with larger sludge particles and higher sludge contents, further contributes to density reduction. Moreover, differences in compressibility between paper sludge and wood particles may affect the board's overall compaction during the pressing process, influencing final density. The inverse relationship between density and sludge content, particularly pronounced for larger particle sizes, can be explained by the lower intrinsic density of paper sludge compared to wood fibers and the reduced packing efficiency of larger particles. Smaller sludge particles (< 0.5 mm) mitigate this density reduction by more effectively filling interstitial spaces within the wood fiber network. The non-linear relationship observed in IB with varying sludge content and particle size reflects the competing effects of increased bonding sites and wood network disruption. Smaller particles provide a larger surface area for resin bonding, potentially enhancing IB.

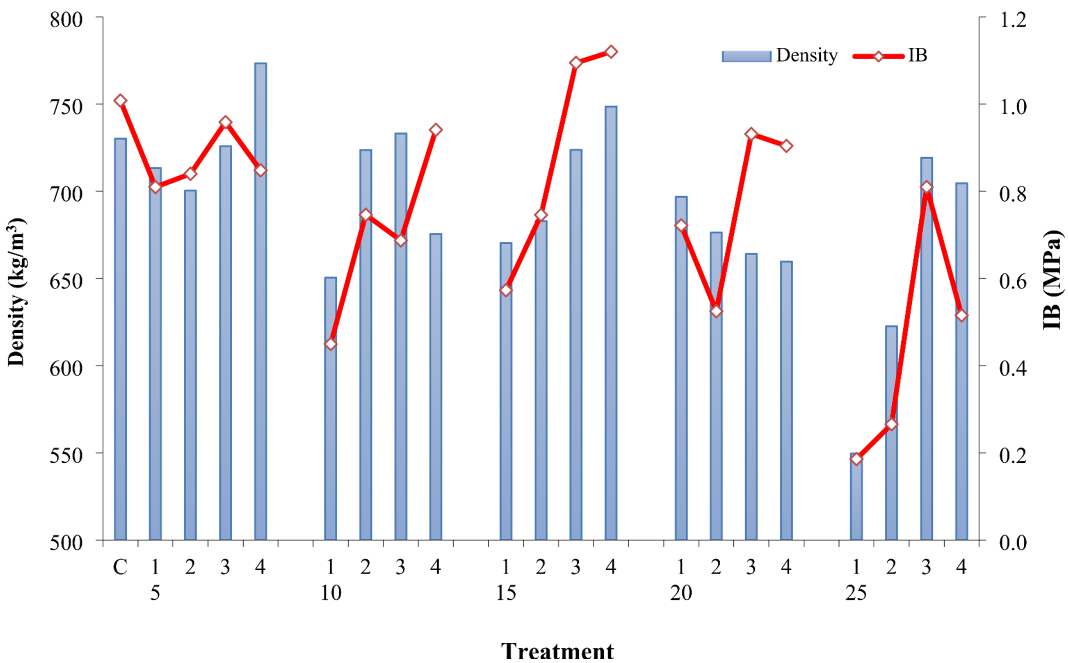

Fig. 3. Effects of paper sludge content and particle size on density and IB of particleboards.

However, as sludge content increases, it begins to disrupt the continuity of the wood fiber network, eventually leading to reduced IB. The optimal performance observed at 15% sludge content with < 0.5 mm particles represents a balance between these opposing factors, where the benefits of increased bonding sites outweigh the negative effects of network disruption.

The relationship between sludge incorporation and IB is more nuanced, exhibiting non-linear trends. At moderate sludge contents (5–15%), particularly with smaller particle sizes, IB values comparable to or exceeding those of the control board were observed. This can be attributed to the increased surface area for adhesive bonding provided by smaller sludge particles, potentially enhancing overall board cohesion. However, at higher sludge contents (> 20%), a sharp decline in IB was evident across all particle sizes. This deterioration may be due to several factors, including the shorter fiber length of paper sludge (average 0.79 mm) providing less reinforcement than wood fibers and the high mineral content (47.4% inorganic) potentially interfering with wood-resin bonding.

The hygroscopic nature of paper sludge likely contributes to both density and IB variations. Localized swelling and stress within the board structure may lead to reduced density and weakened internal bonds. Furthermore, the high specific surface area of sludge particles can affect resin distribution and absorption, potentially resulting in resin-starved areas that impact density and bonding strength. The observed non-linear relationships between sludge content, particle size, and board properties underscore the complexity of sludge incorporation in particleboard production. These findings highlight the importance of carefully optimizing sludge content and particle size to achieve the desired density and internal bond strength characteristics. Future research could focus on elucidating the specific mechanisms underlying these complex interactions, potentially through advanced microscopy and spectroscopic techniques, to further refine the process of sludge incorporation in particleboard manufacturing.

Screw withdrawal resistance

Figure 4 illustrates the effects of paper sludge content and particle size on the screw withdrawal resistance (SWR) of the particleboards, both on the face and edge. Analysis of this figure, in conjunction with data from Table 4, reveals several significant trends and relationships. The control board without sludge had a face SWR of 86.00 N/mm. Generally, face SWR decreased with increasing sludge content, particularly for larger particle sizes (> 2 mm). At 5% sludge content, face SWR ranged from 49.48 N/mm to 61.52 N/mm, lower than the control. Interestingly, the highest face SWR (89.26 N/mm) was observed at 15% sludge content with < 0.5 mm particles. A sharp decline in face SWR was evident at 25% sludge content for all particle sizes. We hypothesized that smaller sludge particles (< 0.5 mm) would improve screw withdrawal resistance (SWR) by enhancing the homogeneity of the board structure. This hypothesis is supported by our results, where the highest face SWR (89.26 N/mm) and edge SWR (92.33 N/mm) were observed at 15% sludge content with < 0.5 mm particles (Fig. 4). The improved SWR at this particle size and sludge content is likely due to better packing density and interfacial bonding, which distributes stress more uniformly during screw insertion and withdrawal. These findings are consistent with the results of Gozdecki et al.[35], who reported that smaller particles improve mechanical properties in wood-polymer composites due to enhanced interfacial adhesion. The decline in SWR at higher sludge contents, particularly with larger particles (> 2 mm), suggests that excessive sludge leads to weaker internal structure, which is in line

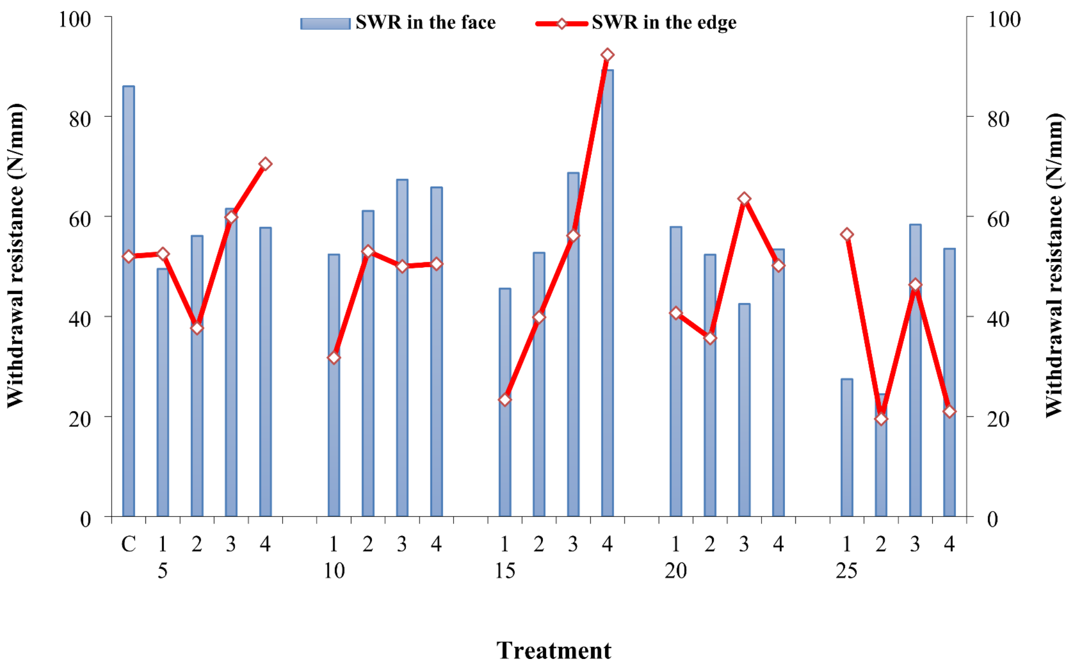

Fig. 4. Effects of paper sludge content and particle size on face and edge screw withdrawal resistance of particleboards.

with observations by Nemli et al.[40]. This explains the better SWR performance of boards with smaller particles across different sludge contents. The improvement in SWR at 15% sludge content, particularly for smaller particle sizes, suggests an optimal microstructure where sludge particles enhance local density and potentially improve interfacial bonding without significantly compromising the integrity of the wood fiber network. The sharp decline in SWR at higher sludge contents (> 20%) across all particle sizes indicates a critical point where excessive sludge incorporation leads to a weakened internal structure, regardless of particle size. This likely results from the formation of sludge-rich regions with poor cohesion to the surrounding wood matrix, compromising the board's ability to resist screw withdrawal forces.

The control board had an edge SWR of 52.00 N/mm. Edge SWR exhibited more variability than face SWR across different sludge contents and particle sizes. The highest edge SWR (92.33 N/mm) was achieved with 15% sludge content and < 0.5 mm particles. Similar to face SWR, a general decline in edge SWR was observed at higher sludge contents, particularly for larger particle sizes. These findings partially align with observations by Ayrilmis et al.[36], who reported a decrease in screw withdrawal resistance with increasing amounts of wood bark in particleboard. They attributed this decline to the lower density and weaker interfacial bonding of bark particles compared to wood particles. Similarly, our results show a general decrease in SWR with increasing sludge content, particularly for larger particle sizes. However, our observation of improved SWR at certain sludge contents (notably 15%) and smaller particle sizes (< 0.5 mm) differs from some previous studies. For instance, Nemli et al.[40] found a consistent decrease in nail withdrawal resistance with increasing content of corn stalk particles in particleboard. Our results suggest that optimizing sludge particle size can potentially mitigate or even reverse this negative trend at certain sludge contents. The improved SWR observed with smaller particle sizes, particularly at moderate sludge contents, aligns with the findings by Cai et al.[41]. They reported that smaller particles generally resulted in better mechanical properties in wood-based composites due to increased surface area for bonding and more uniform stress distribution. The complex relationship between SWR, sludge content, and particle size observed in this study highlights the importance of careful parameter optimization in sludge-incorporated particleboard production. The maintenance or improvement of SWR at specific sludge contents and particle sizes suggests potential for successful sludge valorization without compromising board fastener-holding capacity.

The observed trends in SWR for sludge-incorporated particleboards can be attributed to several intricate technical factors. The variation in SWR with different sludge contents and particle sizes is largely influenced by changes in the board's microstructure. Smaller sludge particles (< 0.5 mm) likely fill interstitial spaces between wood particles more effectively, reducing void formation and improving packing density. This could explain the enhanced SWR observed at 15% sludge content with smaller particles. Conversely, larger sludge particles (> 2 mm) may create more voids, leading to stress concentration points and reduced SWR. Interfacial bonding plays a crucial role in determining SWR. Smaller sludge particles provide a larger surface area for adhesive bonding, potentially improving the overall cohesion of the board structure. This aligns with findings by Gozdecki et al.[35], who observed that smaller particles in wood-polymer composites improved mechanical properties due to enhanced interfacial adhesion. The orientation of cellulose fibers in the sludge particles may also influence SWR. Shorter fibers in paper sludge (average length 0.79 mm, as per Table 1) may align differently compared to wood fibers during board formation, affecting load distribution during screw withdrawal tests. This could partially explain the differences observed between face and edge SWR. The hygroscopic nature of paper sludge, which is typically higher than that of wood particles, can lead to localized swelling and stress within the board structure, potentially weakening screw-holding capacity. This effect may be more pronounced with larger sludge particles, explaining the general decline in SWR at higher sludge contents and larger particle sizes. The incorporation of sludge likely alters the vertical density profile of the particleboard. Xing et al.[16] noted that adding paper sludge to wood-based panels flattens the density gradient. This modification in density profile could explain the varied responses in face and edge SWR, as screw withdrawal resistance is closely related to the local density at the point of screw insertion. The high mineral content in paper sludge (47.4% total inorganic content, as per Table 1) may interact differently with screws compared to wood particles. These inorganic particles could create localized areas of higher hardness, potentially improving SWR in some cases but also leading to brittleness and reduced SWR at higher sludge contents. The addition of sludge particles likely affects the distribution and curing of the urea-formaldehyde resin. Smaller sludge particles may allow for more uniform resin distribution, improved bonding, and higher SWR. However, at higher sludge contents, the increased surface area of sludge particles may lead to over-absorption of resin, resulting in resin-starved areas and reduced SWR. Differences in thermal properties between paper sludge and wood particles could affect heat transfer during the hot-pressing process, potentially leading to variations in resin curing across the board thickness. Such variations might explain the differences between face and edge SWR, particularly at higher sludge contents. The inclusion of sludge particles alters the stress distribution within the board during screw insertion and withdrawal. Smaller, well-dispersed sludge particles may help distribute stress more evenly, explaining the improved SWR at moderate sludge contents with smaller particle sizes. Larger particles or higher sludge contents may create stress concentration points, leading to premature failure during screw withdrawal. Lastly, potential chemical interactions between paper sludge components (e.g., residual chemicals from paper processing) and the urea-formaldehyde resin could influence bond strength and, consequently, SWR. These interactions may be more pronounced at higher sludge contents, contributing to the observed decline in SWR. Understanding these technical factors provides deeper insights into the complex relationships between sludge content, particle size, and screw withdrawal resistance in particleboards. Future research could employ advanced microscopy and spectroscopic techniques to elucidate these mechanisms further, potentially leading to optimized formulations for sludge-incorporated particleboards with enhanced fastener-holding properties.

Water absorption

In the investigation of paper sludge incorporation into particleboard production, water absorption (WA) characteristics emerged as a critical parameter for evaluating board performance. Figure 5 illustrates the effects of paper sludge content and particle size on water absorption after 2-h and 24-h immersion periods. Analysis of variance (Table 4) revealed that sludge particle size exerted a highly significant effect ($p < 0.001$) on both 2-h and 24-h water absorption, while sludge content did not demonstrate statistical significance. This finding underscores the paramount importance of particle size in determining the water absorption properties of sludge-incorporated particleboards. The data (Fig. 5) confirm that smaller sludge particles (< 0.5 mm) reduce water absorption (WA), as hypothesized. The control board exhibited 2-h and 24-h WA values of 80.76% and 95.85%, respectively, while boards with smaller sludge particles consistently showed lower water absorption across different sludge contents. This reduction in WA can be attributed to better resin encapsulation of smaller particles, limiting water penetration, as suggested by Migneault et al.[37]. The trend of increased WA with higher sludge content, particularly for larger particles (> 2 mm), aligns with the findings of Taramian et al.[23], who attributed this to the hydrophilic nature of cellulose fibers in paper sludge. Our results highlight the critical role of particle size in managing water absorption in sludge-incorporated particleboards, indicating that optimizing particle size distribution is a viable strategy for mitigating the negative effects of sludge incorporation on water resistance. The maximum 2-h and 24-h WA values (158.83% and 165.48%, respectively) were recorded at 25% sludge content with > 2 mm particles. The influence of particle size on water absorption can be explained by its effect on the board's microstructure. Smaller sludge particles (< 0.5 mm) tend to be more effectively encapsulated by the resin, reducing their exposure to water. Moreover, boards with smaller particles generally have lower void content, limiting water penetration pathways. This explains why boards with smaller particle sizes consistently show lower water absorption across different sludge contents. The general trend of increased water absorption with higher sludge content is due to the hydrophilic nature of cellulose fibers in paper sludge. However, the moderation of this effect by smaller particle sizes suggests that optimizing particle size distribution could be a strategy for managing water absorption in sludge-incorporated particleboards. The non-linear trends observed, particularly for smaller particle sizes, indicate complex interactions between sludge content, particle size, and board microstructure that warrant further investigation.

These findings align with previous research while also offering novel insights. The general trend of increased water absorption with higher sludge content corroborates the work of Taramian et al.[23], who attributed this phenomenon to the hydrophilic nature of cellulose fibers in paper sludge. The observation that smaller sludge particles generally result in lower water absorption is consistent with findings by Migneault et al.[37] in their study of wood-plastic composites. They posited that smaller fiber sizes improved water resistance due to enhanced encapsulation by the hydrophobic matrix. The significant effect of particle size on WA, sometimes overshadowing the influence of sludge content, represents a noteworthy finding. This nuanced relationship is not consistently captured in extant literature, which often prioritizes examining sludge content effects. Furthermore, the non-linear trends observed in WA with respect to sludge content, particularly for smaller particle sizes, suggest the potential for optimizing water resistance through judicious control of both sludge content and particle size. The observed trends in water absorption can be elucidated by several technical factors:

1. Hygroscopic nature of paper sludge: The high proportion of cellulose fibers in paper sludge contributes to increased overall hydrophilicity of the board as sludge content increases.
2. Particle size effect: Smaller particles provide greater surface area for resin coverage, potentially resulting in superior encapsulation of hydrophilic components.

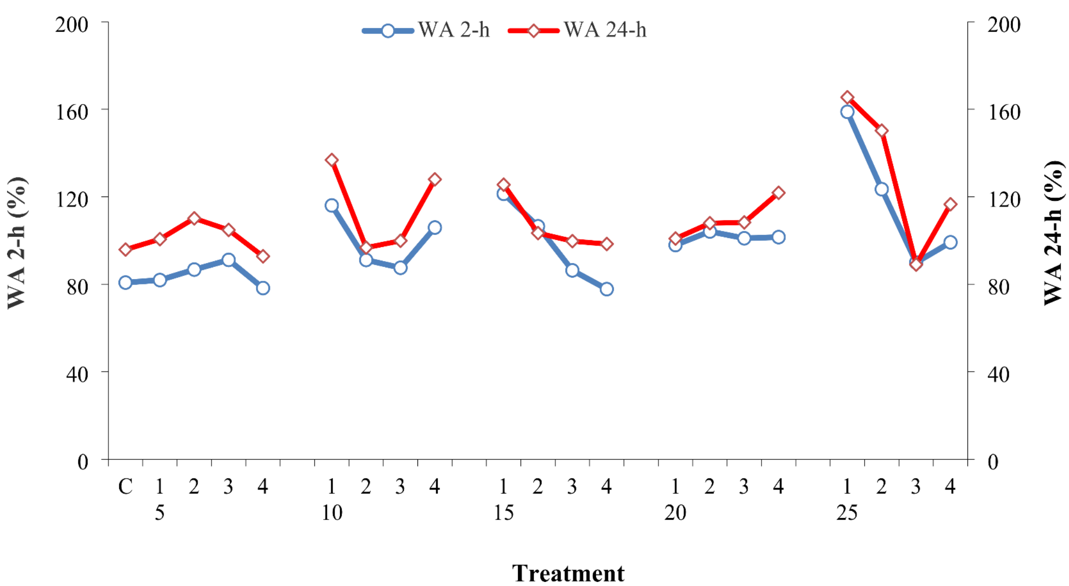

Fig. 5. Effects of paper sludge content and particle size on 2-h and 24-h water absorption of particleboards.

3. Void formation: Larger sludge particles may engender more voids or weak interfacial regions within the board structure, facilitating increased water penetration and absorption.
4. Density variations: As noted in the density analysis, boards with higher sludge content exhibit lower density, generally associated with increased void space and consequent water absorption.

Thickness swelling

Figure 6 illustrates the effects of paper sludge content and particle size on thickness swelling (TS) of particleboards after 2-h and 24-h immersion periods. Analysis of variance (Table 4) revealed that both sludge particle size and content exerted significant effects on TS, with particle size showing high significance ($p < 0.001$) for both immersion periods. The control board, without sludge incorporation, exhibited 2-h and 24-h TS values of 22.75% and 26.86%, respectively (Table 4). At 5% sludge content, 2-h TS ranged from 25.23 to 28.88%, depending on particle size. A general trend of increased thickness swelling was observed with increasing sludge content, particularly pronounced for larger particle sizes (> 2 mm). However, this trend was not strictly linear, with certain combinations of sludge content and particle size demonstrating improved dimensional stability. Our hypothesis that smaller sludge particles (< 1 mm) would reduce thickness swelling is supported by the data (Table 4, Fig. 6). The observed reduction in swelling can be attributed to the better integration of smaller particles within the wood matrix, which enhances resin encapsulation and reduces the exposure of hydrophilic components to moisture. This finding is consistent with the work of Ashori and Nourbakhsh[22], who reported that smaller particle sizes improve dimensional stability due to better compaction and more uniform resin distribution. The non-linear trend observed, where optimal swelling reduction occurs at 5–15% sludge content with smaller particles, further corroborates our hypothesis, emphasizing the critical role of particle size in managing dimensional stability in particleboard production. The increase in thickness swelling with higher sludge contents, particularly for larger particle sizes, can be attributed to the creation of sludge-rich regions within the board. These regions, being more hydrophilic and less densely packed, are prone to greater dimensional changes upon water absorption. The trend divergence between short-term (2-h) and long-term (24-h) swelling behavior suggests distinct mechanisms governing dimensional stability over different time scales. This could be related to the various rates of water penetration and absorption in the heterogeneous microstructure created by sludge incorporation.

The maximum 2-h TS (32.62%) was recorded at 15% sludge content with > 2 mm particles, while the highest 24-h TS (38.39%) was observed at 25% sludge content with < 0.5 mm particles. This trend divergence between short-term and long-term swelling behavior is noteworthy, suggesting distinct mechanisms governing dimensional stability over different time scales. These findings both corroborate and extend previous research in the field. The general trend of increased TS with higher sludge content aligns with work by Geng et al.[38], who attributed this phenomenon to the higher water absorption and subsequent swelling of cellulose fibers in paper sludge. The observation that smaller sludge particles generally result in lower thickness swelling at moderate sludge contents is consistent with findings by Ashori and Nourbakhsh[22], who posited that smaller particle sizes led to improved dimensional stability due to enhanced compaction and resin distribution. The non-linear relationship between TS, sludge content, and particle size represents a significant finding. This complex interplay suggests the potential for optimizing dimensional stability through judicious control of both sludge content and particle size, a nuance not consistently captured in extant literature.

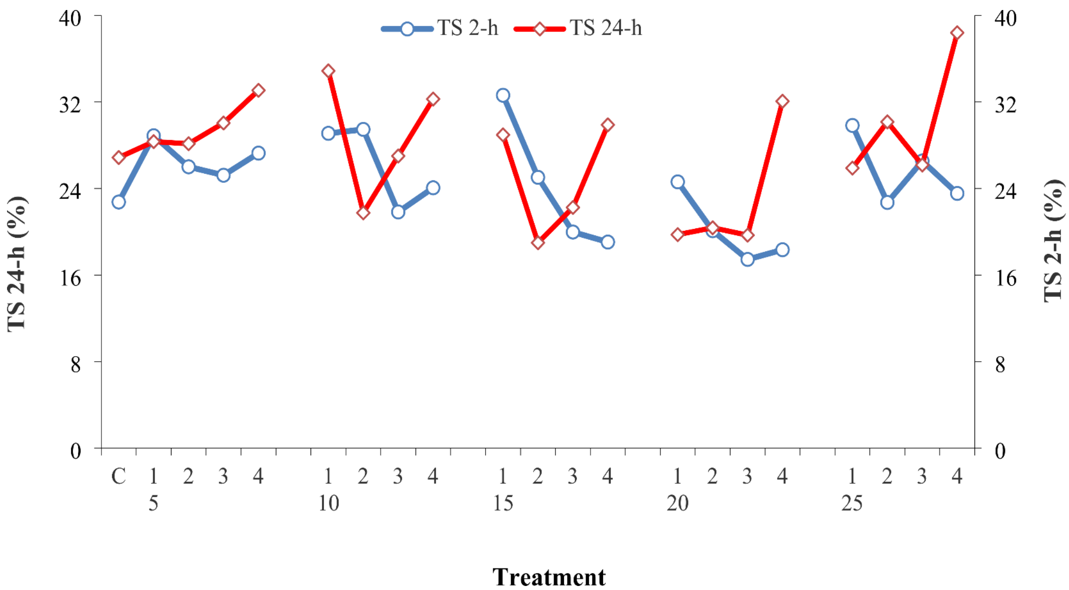

Fig. 6. Effects of paper sludge content and particle size on 2-h and 24-h thickness swelling of particleboards.

Morphological characterization

FE-SEM was employed to elucidate the microstructural characteristics of particleboards incorporating varying amounts of paper sludge. Figure 7 presents micrographs of two representative samples: 15-4 (15% sludge, < 0.5 mm particle size) and 20-4 (20% sludge, < 0.5 mm particle size). Sample 15-4 (Fig. 7a) exhibits a relatively homogeneous distribution of small sludge particles throughout the wood matrix. The interfacial regions between sludge particles and wood fibers demonstrate good adhesion, as evidenced by the absence of significant gaps or voids. The sludge particles, while irregular in morphology, appear well-integrated into the composite structure. The wood matrix maintains continuity with minimal disruption from the incorporated sludge. Notably, the micrograph reveals low porosity, suggesting adequate compaction and densification during board formation. In contrast, sample 20-4 (Fig. 7b) displays a higher concentration of sludge particles, consistent with its increased sludge content. While some areas exhibit good interfacial adhesion, there are also visible regions of detachment and gap formation between sludge particles and the wood matrix. This observation suggests a potential weakening of interfacial bonding at higher sludge concentrations. The sludge particles in 20-4 tend towards agglomeration, forming larger clusters than 15-4. The wood fiber network in 20-4 exhibits more frequent interruptions by sludge particles, leading to reduced matrix continuity. Furthermore, 20-4 demonstrates increased porosity, with more visible voids and pores compared to 15-4, indicating less efficient compaction at higher sludge contents.

The microstructural differences observed between samples 15-4 and 20-4 provide crucial insights into the effects of sludge content and particle size on board structure. The homogeneous distribution and good interfacial adhesion in sample 15-4 (15% sludge, < 0.5 mm) explain its superior performance across multiple parameters. The smaller particle size allows for better integration within the wood matrix, minimizing disruption to the overall board structure. In contrast, the increased porosity, particle agglomeration, and interfacial detachment observed in sample 20-4 (20% sludge, < 0.5 mm) elucidate the mechanisms behind the decline in mechanical properties at higher sludge contents. The tendency for sludge particles to form larger clusters at higher concentrations creates weak points in the board structure, leading to reduced mechanical performance and increased water sensitivity.

In conclusion, the microstructural analysis derived from FE-SEM micrographs provides a physical basis for understanding the mechanical properties reported in Table 3. The superior performance of 15-4 across multiple parameters can be attributed to its better interfacial bonding, reduced void content, and more homogeneous particle distribution. Conversely, the decline in mechanical properties observed in 20-4 correlates with increased porosity, matrix disruption, and particle agglomeration at higher sludge content. This integrated analysis underscores the critical role of microstructure in determining the macroscopic properties of sludge-incorporated particleboards. It highlights the importance of optimizing sludge content and particle size to achieve desired performance characteristics.

Conclusions

This study focused on the innovative utilization of paper sludge in particleboard production, aiming to optimize both sludge content and particle size to enhance board properties. Our findings demonstrate that the mechanical and physical properties of particleboard can be significantly improved by incorporating paper sludge at moderate levels (5–15%) and optimizing particle size to less than 1 mm. Specifically, boards produced under these conditions exhibited enhanced internal bond strength, modulus of rupture, and modulus of elasticity while maintaining better dimensional stability and lower water absorption. The PCA supported these findings by showing strong positive correlations between density, MOR, MOE, and IB, as well as negative correlations with water absorption. This indicates that optimizing particle size and sludge content improves not only mechanical performance but also moisture resistance. The PCA also revealed that thickness swelling is a separate factor, implying that while mechanical and water absorption properties can be optimized, additional interventions are necessary to control dimensional stability, particularly in moisture-sensitive applications.

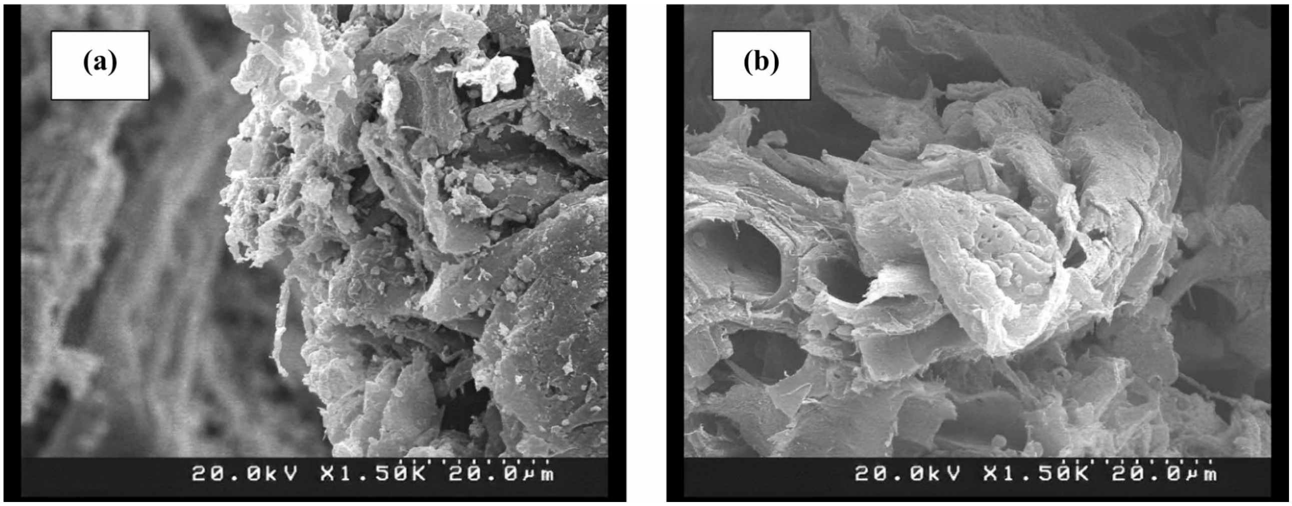

Fig. 7. FE-SEM micrographs of samples (**a**) 15-4 and (**b**) 20-4.

The significance of these results lies in the potential for paper sludge to be effectively integrated into particleboard manufacturing without compromising product quality. This not only provides a sustainable solution for waste management in the paper industry but also offers a pathway for developing eco-friendly composite materials in the wood-based panel industry. Future research should explore further optimization of processing conditions and assess the long-term durability of these sludge-incorporated particleboards under various environmental conditions.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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