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Interaction between particle size and mixing ratio on porosity and properties of tea oil camellia (*Camellia oleifera* Abel.) shells-based particleboard

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Abstract

This study investigated the interaction between particle size and mixing ratio on the porosity of particleboard and in consequence its effect on the physical and mechanical properties of panels. Tea Oil Camellia Shell (TOCS), which could provide 1.8 million tons of lignocellulose raw material annually, can be a useful resource for particleboard production. In that regard, particleboards with different particle sizes (coarse and fine) and mixing ratios (wood and TOCS) bonded with Polymethylene polyphenyl polyisocyanate (pMDI) were investigated. The results showed that particleboard made with TOCS particles had higher densities than those of commercial wood particles. Furthermore, particleboards made with fine particles had lower porosity. The average values for physical and mechanical properties have shown that except for thickness swelling (TS), most properties were better with coarse particles. In terms of all properties, results showed that adding 50% of commercial wood in conjunction with TOCS particles regardless of particle size can offer acceptable results, which qualified all requirements of EN 312:2010 standard for P2-type particleboard (boards for interior fitments (including furniture) for use in dry conditions). In addition, due to the porous structure of the shells, TOCS-based particleboards have better thermal conductivity compared to wood-based particleboards.

Keywords: Tea oil camellia, Thermal conductivity, Porosity, Agroforestry waste, Particleboard

Introduction

Over one century ago, particleboard panels in the United States and Germany began to be made with the initial purpose of utilizing wood residues and by-products [1]. Furthermore, the advantages of particleboard, such as its biodegradability and mechanical properties, low cost, and flexibility in dimensions, led to the development of particleboard [2]. In today's market, particleboard is an important composite material used in furniture and non-structure building materials [3]. The Food and Agriculture Organization of United Nations (FAO) reported that 45% of the particleboard manufactured worldwide comes from Asia, 27% from Europe, and 26% from the Americas. Furthermore, China is the largest producer of particleboard with an estimated 30 million/m^3 per year [4]. As population growth and technological advancements have increased over the last several decades, the demand for wood resources mainly from the *Eucalyptus* and *Pinus* genera for particleboard manufacturing has also increased [5], In many countries, however, the lack of local resources of wood to supply the particleboard industry pushed up the prices of wood species. This reason, in addition to the flexibility in using different types of raw materials by the particleboard industry, has encouraged the utilization of lignocellulosic materials and crops [6–8].

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One of the raw materials that have shown potential for use in the particleboard industry is Tea Oil Camellia (*Camellia oleifera* Abel.) shells (TOCS), which are considered an agricultural waste of Tea Oil Camellia, one of the major oil crops belonging to the Theaceae family. The majority of the by-product from each ton of fruits is the shell after the oil is extracted. In addition, TOCS with a supply volume of approximately 3.75 million tons annually can provide a vast amount of raw material for the particleboard industry in the southern part of China which is advantageous as part of a circular economy, as well as a way of reducing the environmental risks of burning or discharging these wastes [9–12].

Several factors are taken into consideration when determining the potential of an agricultural waste to be utilized in the particleboard industry, such as its physical and chemical properties, accessibility, supply quantity, and storage capacity [13]. Among the physical properties (micro and macro-structures) porosity is particularly noteworthy; porosity is simply explained by the ratio of the volume of pores to the volume of the whole, and the particleboard's porosity may influence its physical, mechanical, and thermal properties [14].

The porosity can be measured using a variety of methods. These methods are based on gas adsorption, N_2 or He, water vapor, electron microscopy, and mercury intrusion porosimeter. The Mercury method can measure the total intrusion volume and total pore surface area, the pore size and size distribution, and the bulk, apparent, and specific density of particleboards [15]. The International Union of Pure and Applied Chemistry (IUPAC) classified pores into three groups: through pores, blind pores, and closed pores [16]. Particleboard contains voids between the particles and on the particles themselves. It is theorized that in mat-forming under heat and pressure, smaller particles would fill voids between larger ones to contribute to better bonding. For all the mentioned properties, particleboards with the same density but lower porosity offer better values [17].

The particle size and shape of the produced particleboard significantly affect its properties. Particles with a high aspect ratio (Length/Thickness) provide a larger surface area for adhesive contact, and besides, particles with a low aspect ratio and small size serve as fillers to fill the void between larger particles [18]. The effect of particle size on particleboard has been extensively studied; recently Karlinasari et al. and Bazzetto et al. reported coarse particles could have better physical and mechanical properties compared to fine particles in the production of single-layer particleboard with bamboo, however, analysis of IB has shown fine particles are better at bonding due to their vast surface area [19, 20]. Based on the results of Hegazy and Ahmed, fine particles provide better bending strength (BS) and IB properties when producing particleboard with Date Palm, however, thickness swelling is not significantly affected by fine particles [21]. In addition, Nguyen et al. reported small particles (8 mm opening mesh size) of whole Cotton (*Gossypium hirsutum* L.) Stalk provided better mechanical properties than large particles [22].

According to the literature, particle size plays a major role in particleboard manufacturing. Different particle sizes could provide different properties based on the type of raw material, meaning that particle size and geometry optimization are required for any new lignocellulosic materials that may be a competitive alternative to wood species in particleboard manufacturing. Although porosity of particleboard influences its properties, especially those related to physical, thermal, and acoustic properties, only a few investigations have been conducted on this topic, hence this study was conducted with purpose of investigation the effect of particle size (coarse and fine) and mixing ratio (TOCS to commercial wood particles) on porosity of particleboard, and consequently its effect on the physical and mechanical properties.

Materials and methods

Materials

A Camellia oil factory provided TOCS and commercial wood particles whose majority was gum (*Eucalyptus grandis* × *urophylla*) with an approximate age of 5 years were supplied by a particleboard factory in Guangdong province, China. In Table 1, the chemical composition of TOCS and wood particles is shown. In the study, Polymethylene polyphenyl polyisocyanate (pMDI) was used as the binder, which was obtained from Wanhua Chemical Group in Yantai, China, with a solid content of 99.2%, a viscosity of 150 to 250 mPa•s, and a density of 1.22 to 1.25 g/cm^3 at 25 °C.

Table 1 Chemical composition of TOCS and wood

Composition	Cellulose	Lignin	Hemicellulose	Extractive	Ash	Reference
TOCS	12.02 (0.23)	32.30 (1.21)	32.78 (0.34)	16.48 (0.28)	3.30 (0.06)	[23]
Wood (gum)	58	22	14	4	0.2	[24]

Content (% dry weight particle)

Particles preparation

TOCS were cleaned and chipped with a knife ring flaker (Grinder CM200, Beijing Grinder Instrument Co., Ltd, China). After that, the TOCS and wood particles were classified using ASTM standard sieves. Particles passed through mesh sizes 6, 14, and 20 in sequence; those that passed through mesh 6 but remained in mesh 14 were known as coarse particles, and those that passed through mesh 14 but remained in mesh 20 were known as fine particles, Fig. 1. The average aspect ratio of each particle size was determined by digitizing 500 randomly selected particles (for each mesh size) and using ImageJ software to measure their average lengths and widths. In addition, the bulk density of particles was measured in a beaker glass of 2000 cm^3 by forming particles.

Table 2 Particle ratio of single layer TOCS particleboard

Group	Board type	Coarse TOCS (%)	Fine TOCS (%)	Coarse wood (%)	Fine wood (%)
A	A1	100	–	–	–
	A2	50	50	–	–
	A3	–	100	–	–
B	B1	–	–	100	–
	B2	–	–	50	50
	B3	–	–	–	100
C	C1	50	–	50	–
	C2	50	–	–	50
	C3	–	50	50	–
	C4	–	50	–	50
	C5	25	25	25	25

Manufacturing of particleboards

On a computer-controlled laboratory hot press machine (XINXIELI Enterprise Development Co., Ltd, Suzhou, China), 3 groups of homologous single-layer particleboards with 10 mm thickness were produced to study the effect of particle size and mixing ratio. Table 2 lists the different groups and treatments in this study. During the first stage, 10% of pMDI adhesive is sprayed on the particles in a lab blender according to the dry weight of the particles. Later, the resinated particles were manually distributed in a forming box of 350 × 350 mm^2 with a target density of 720 kg/m^3, and the moisture of the mat before hot-pressing was adjusted to be 8%. The press variables were adjusted in 5 min pressing at 180 °C and 3.5 MPa considered for pick pressure.

For each treatment, three panels were manufactured. After hot pressing, panels were stored at room temperature for a while and then cut into specimens (250 mm × 50 mm × 10 mm for BS tests and 50 mm × 50 mm × 10 mm for other tests). Afterward, the samples were conditioned in a climatic chamber for 2 weeks at 20 °C and 65% relative humidity to prepare for physical and mechanical testing. In Fig. 2, surfaces of manufactured particleboards are shown on the laboratory scale.

Characterization of particleboards

In this study, 9 samples were considered for each test. The mechanical tests were carried out on a universal testing machine (CMT5504, Shenzhen Rethink Cooperation, China) by implementing the EN standards, as follows; EN 310:1993 for the modulus of rupture (MOR) and modulus of elasticity (MOE), EN 319:1993 for the internal bonding (IB), and EN 13,446:2002 for the face and edge screw withdrawal resistance (FSW/ESW) [25–27]. In terms of physical tests, water absorption (WA) and thickness swelling (TS) were determined

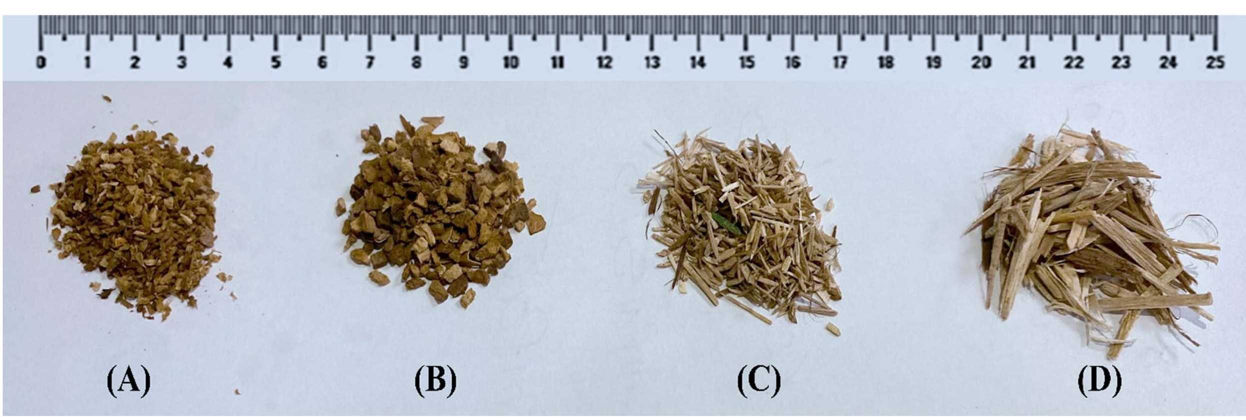

Fig. 1 Digital image of TOCS and wood particles sieved with different ASTM mesh size, (**A**): TOCS + 14–20, (**B**): TOCS + 6–14, (**C**): Wood + 14–20, (**D**): Wood + 6–14

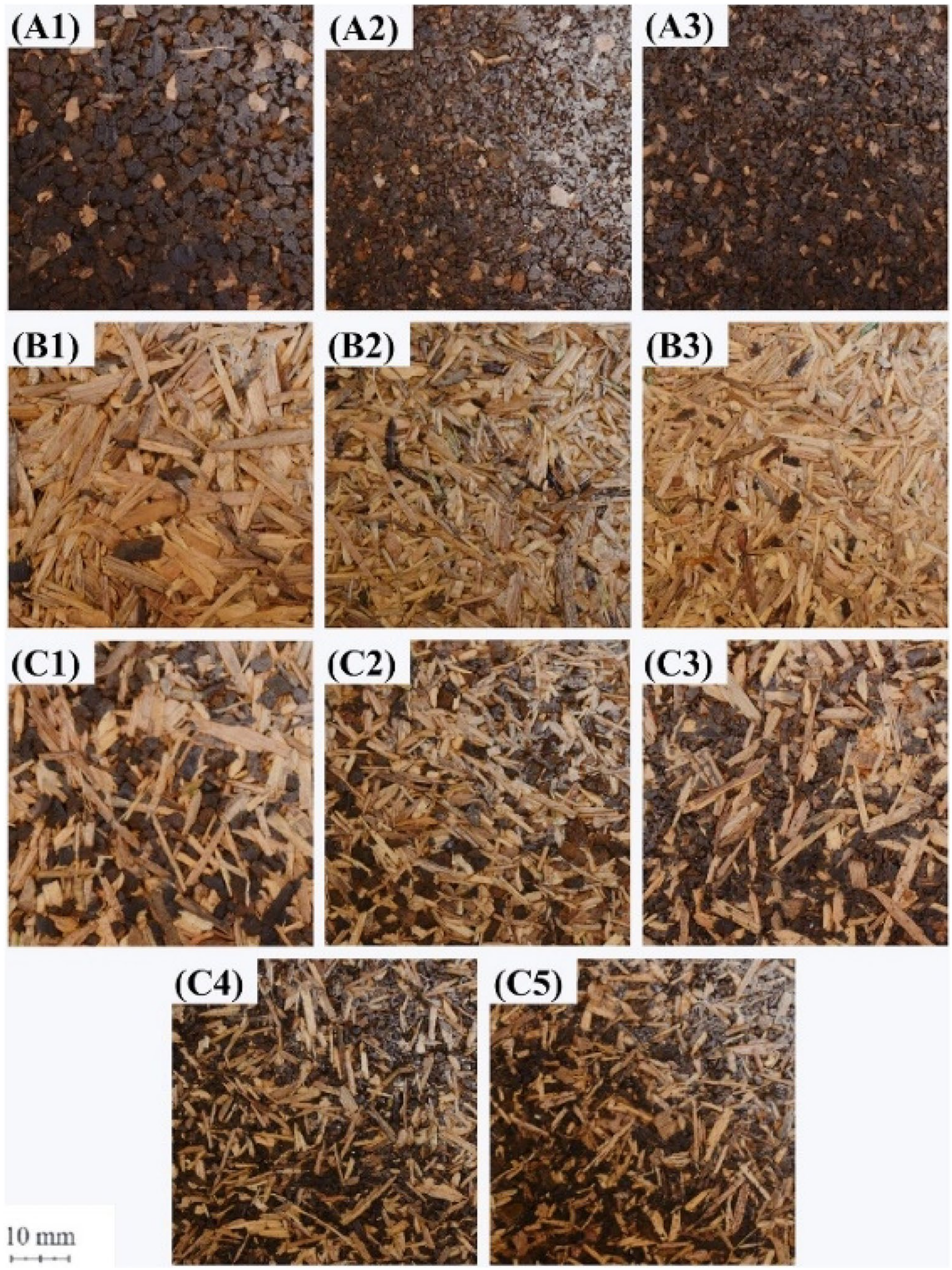

Fig. 2 Digital image of different particleboards surfaces in this study

using EN 317:1993 [28]. The vertical density profiles were determined using an X-ray densitometry system, DPX300-LTE IMAL-PAL Group, Russia. A Mercury intrusion porosimeter, AutoPore IV 9500, USA. was used to measure the particleboard porosity. Thermal conductivity was observed with XIATECH TC3000E-Xiatech Electronics Co., Ltd. China.

Statistical analysis

One-way analysis of variance (ANOVA) was performed with a completely randomized design using SPSS (Statistical Package for Social Sciences) software to analyze significant differences between factors; the *p* value level for statistical significance was ($P<0.05$). Duncan's test was used to compare means.

Results and discussion

Interaction between particle size and mixing ratio on porosity

The results of the Mercury intrusion porosimeter can be found in Table 3. It was observed that particle size and mixing ratio is influenced on porosity of particleboards. While panels with coarse particles (46.2% for TOCS and 48.2% for wood) had higher porosity than particleboards with fine particles (43.5% for TOCS and 47.1% for wood), which may be explained by the fact that larger particles leave more space between particles that caused higher porosity. The smaller particles can fill voids between the larger particles and enhance the adhesion of panels, as described above. Hence, the porosity of A2 and B2 panels, which were a combination of coarse and fine particles, was a bit lower than rest [15].

A comparison revealed, although particleboards in group A indicated higher volume density than group B; however, the results of porosity indicated nearly the same values, due to the fact that density and porosity are inversely related it has been found that when TOCS particles are used, particleboard has shown a higher porous structure than commercial wood particles. Based on measured values for group C, it was shown that TOCS fine particles could better infiltrate and fill the gaps between wood particles due to their geometry, the panels C3 and C4 containing the same porosity of 43.8% indicating the lower values in group C [29]. Pore diameter results for group A indicated smaller pore diameters than group B. In general, porosity is caused by voids between the particles in the panel and by structural elements in the wood [30]. In TOCS-based particleboards it has been found that created pores by particle overlapping occur with smaller pore diameter due to TOCS particle geometry, or in comparison with common wood, the TOCS structure contains more pores with smaller diameters. However, Ferro et al. found pore diameter varies depending on the raw material type [31].

Analysis of vertical density profile and compaction ratio

The vertical density profile (VDP) can be used to analyze and describe the strength of the wood-based panels across a variety of thicknesses and help to achieve ideal values for different properties [32]. In general, a flat shape indicates the VDP of the homologous single-layer particleboard. As Fig. 3 illustrated, the density values for all panels in the first 1 mm of surfaces are nearly 800 kg/m^3, while the minimum density in the internal region of the panels is about 650 kg/m^3, due to direct contact of the panels with hot pressing plates, resulting in more densification for the surfaces [27]. During the hot-pressing process, particle size and particle combination play an important role in heat transfer from surfaces to the core region of particleboard that affects the VDP [20]; however, the particle size or combination of particles had no significant effect on the VDP. For all treatments, the average density ranged between 687 and 705 kg/m^3. The lower density of particleboard could result in lower physical and mechanical properties due to the higher porosity of the panels [33]. It is also found that particleboards in group A had a higher density at surfaces in comparison to particleboards in group B, it could be due to the lower heat transfer of TOCS particles related to the higher porosity of its structure. Compared to solid material and voids filled with air, the heat transfer of air inside the voids is much lower [25]. The lower heat transfer between the surface and the core zone may cause more densification of surfaces [34].

The compaction ratio of particleboard is calculated by panel density to raw material density. It can show the potential of raw materials for proper pressing and compaction. The lower density of the raw materials can lead

Table 3 Porosity of single layer TOCS particleboard

Group	Board type	Porosity (%)	Volume density (kg/m^3)	Apparent density (kg/m^3)	Total pore volume (ml/g)	Average pore diameter (nm)
A	A1	46.2	748	1390	0.61	12.35
	A2	44.3	758	1411	0.57	11.21
	A3	43.5	778	1379	0.56	10.37
B	B1	48.2	720	1390	0.67	15.20
	B2	47.5	726	1383	0.65	15.97
	B3	47.1	734	1389	0.64	14.93
C	C1	44.5	767	1384	0.58	15.51
	C2	46.4	755	1412	0.61	13.96
	C3	43.8	797	1421	0.55	13.71
	C4	43.8	779	1387	0.56	13.90
	C5	46.3	792	1397	0.54	14.22

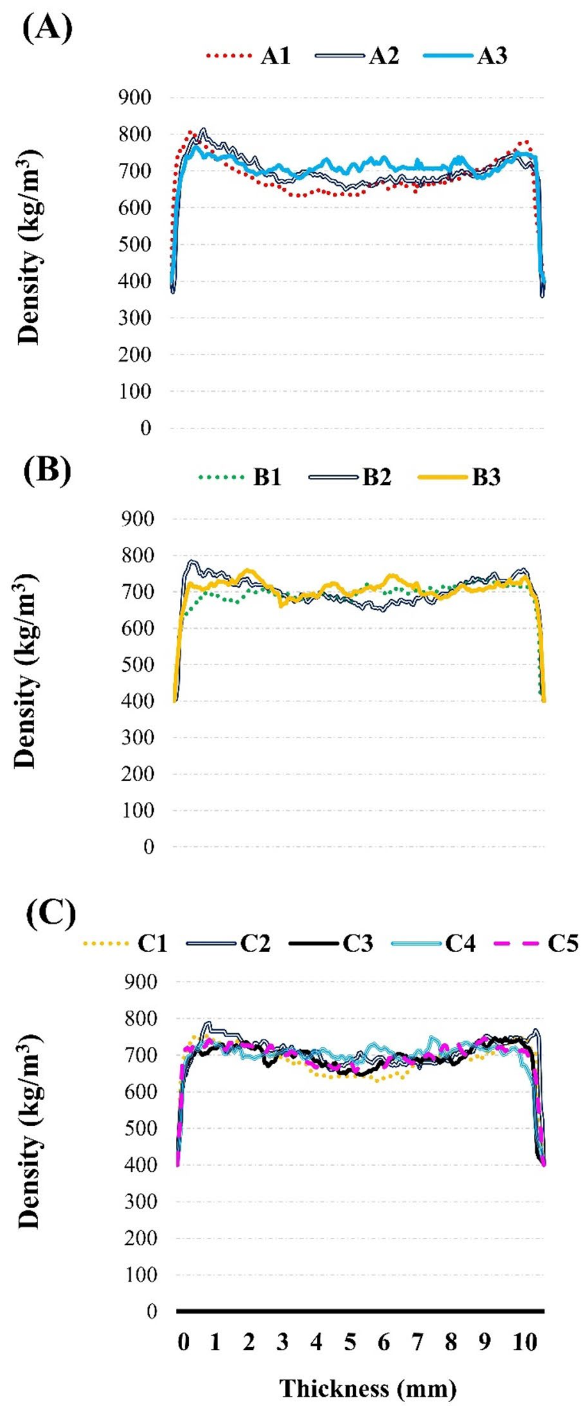

Fig. 3 Vertical density profile of particleboards, (**A**): group A (TOCS-based), (**B**): group B (wood-based), (**C**): group C (mix of TOCS and wood)

Table 4 Density and compaction ratio of different TOCS-based particleboards

Group	Sample	Panel density (kg/m^3)	Raw material density (kg/m^3)	Compaction ratio
A	A1	687 (26)	820	0.83 (0.019)
	A2	698 (22)		0.85 (0.018)
	A3	705 (21)		0.86 (0.018)
B	B1	691 (19)	550	1.25 (0.026)
	B2	695 (16)		1.26 (0.025)
	B3	700 (21)		1.27 (0.030)
C	C1	693 (15)	685	1.01 (0.022)
	C2	696 (16)		1.01 (0.026)
	C3	695 (19)		1.01 (0.019)
	C4	693 (14)		1.01 (0.021)
	C5	701 (21)		1.02 (0.020)

to better compaction and bonding between particles. The compaction ratio should fall between 1.3 and 1.6 for best properties, anything beyond this range may result in higher spring-back and increase internal stresses in particleboard [35]. The density and compaction ratios of the panels are reported in Table 4. The apparent density of raw materials for TOCS and wood particles were 820 and 550 kg/m^3, respectively. Because of the lower particle density in group B, a compact ratio of 1.25–1.27 was observed, whereas for group A this ratio was 0.83–0.86. According to the observed results for both groups, coarse particles showed higher residual compressive stresses due to bigger voids between these particles, which resulted in lesser density and reduced compaction [36]. Furthermore, the bulk density of different particle sizes is also an effective parameter in determining particleboard compaction ratio. Bulk density measured by TOCS was 314 ± 4.15 kg/m^3 for coarse particles and 341 ± 4.01 kg/m^3 for fine particles. In contrast, that for coarse wood particles was 121 ± 2.50 kg/m^3 and for fine particles, it was 135 ± 1.92 kg/m^3. Since smaller particles with a lower aspect ratio can fill spaces left by large particles, their bulk densities are higher and the porosity is decreased as a result [37]. According to aspect ratio calculations, TOCS particles were found to have values of 1.52 ± 0.14 and 1.87 ± 0.21, and commercial wood particles were found to have values of 5.69 ± 2.13 and 5.34 ± 2.33 for coarse and fine particles, respectively. In addition, lower bulk density of the particles can result in a higher compaction ratio, giving more surface area and allowing the adhesive to be better infiltrated, which is likely to affect the properties of the panels [38, 39].

Effects of particle size and combination on mechanical properties

It has been shown that particle size distribution and particle combination play an important role in the production of particleboard with the use of lignocellulosic materials [40]. The mean values and analysis of variance for mechanical tests are presented in Table 5, also Fig. 4 is presented effect of particle size on both TOCS-based and commercial wood-based particleboards which had different mechanical properties after mat-forming consisting of coarse, fine, or mixed particles, regardless of the raw material type [18]. In group A, panels produced with coarse particles have shown the MOR and MOE values of 6.79 and 1123 N/mm^2, while those produced with fine particles had values of 5.43 and 955 N/mm^2. In general, the reason that coarse particles exhibit higher MOR and MOE values is that bigger particles are more capable of bearing bending loads than fine particles, and with decreasing particle size, non-glued particles increase, which reduces the BS, a similar phenomenon has also been reported for particleboard made from rice straw [41] and maize cob [42]. As already shown in Fig. 1, the TOCS particles with granular shapes have a lower aspect ratio than their wood counterpart. Normally, slender particles with a high aspect ratio result in higher BS [43]. The density profiles also revealed that the face layers in A1 are slightly denser, which means more materials were available to absorb tensile and compressive forces caused by

Table 5 Effect of particle size and combination on mechanical properties of single layer TOCS-based particleboard

Group	Board type	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	FSW (N)	ESW (N)
A	A1	6.79 (0.39)^{a}	1123 (46)^{a}	1.46 (0.12)^{cd}	549 (62)^{b}	946 (63)^{a}
	A2	4.97 (0.22)^{b}	943 (52)^{b}	1.21 (0.19)^{bc}	371 (63)^{a}	720 (90)^{a}
	A3	5.43 (0.53)^{b}	955 (97)^{b}	0.75 (0.11)^{a}	450 (51)^{ab}	789 (87)^{a}
B	B1	21.77 (1.02)^{f}	3120 (210)^{c}	1.79 (0.34)^{f}	1051 (209)^{fg}	2589 (222)^{e}
	B2	19.85 (1.53)^{e}	2970 (92)^{c}	1.24 (0.28)^{bc}	1009 (96)^{ef}	2730 (164)^{ef}
	B3	20.23 (1.27)^{e}	2980 (143)^{c}	1.65 (0.25)^{f}	1127 (109)^{g}	2988 (213)^{f}
C	C1	12.49 (0.76)^{c}	2097 (136)^{d}	1.52 (0.12)^{de}	693 (121)^{c}	1665 (210)^{c}
	C2	14.41 (1.14)^{d}	2206 (157)^{d}	1.07 (0.11)^{b}	864 (104)^{de}	2004 (212)^{d}
	C3	14.36 (1.58)^{d}	2125 (254)^{d}	1.71 (0.21)^{ef}	732 (59)^{cd}	1729 (357)^{cd}
	C4	14.47 (0.51)^{d}	2067 (125)^{d}	1.25 (0.24)^{bc}	734 (70)^{cd}	1770 (282)^{cd}
	C5	13.58 (1.10)^{d}	2121 (91)^{d}	1.82 (0.18)^{f}	1079 (110)^{g}	2394 (231)^{b}

^{abcdefg} Values with the same letters are not significantly different by Tukey HSD test ($P < 0.05$)

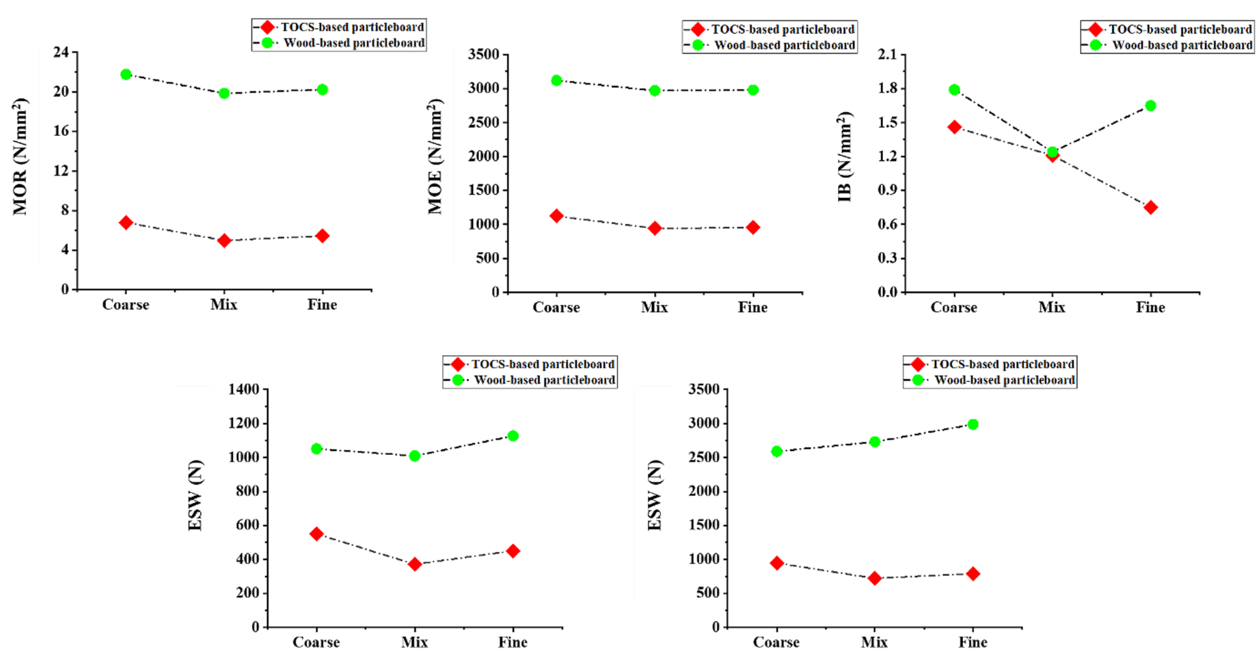

Fig. 4 Effect of particle size on mechanical properties of produced particleboards in this study

bending loads. In general, agricultural wastes due to their properties need to be combined with common wood particles, hence the C group was designed to assess how particle size affects the results in different combinations.

Regardless of the particle size, the panels in group C (mixture of 50% TOCS and 50% commercial wood particles) had a range value of 12.49 to 14.47 N/mm^2 for MOR and 2094 to 2206 N/mm^2 for MOE, which satisfied the EN 312:2010 requirements for particleboard type P2 [44]. Although, mainly studies on the feasibility of lignocellulosic materials have concluded that the amount of these materials cannot exceed 30% [27, 30]. Interestingly, panel C1, which included 50% TOCS coarse and 50% wood coarse, showed a lower MOR than the group average, possibly due to particles overlapping in a mixture of coarse particles. The IB property indicates the quality of interaction between particles and adhesive; recorded values for this property in both groups (A and B) have shown higher values for particleboard produced with coarse particles; however, this difference is more pronounced in group A (A1 was 1.46 N/mm^2 and A3 was 0.75 N/mm^2). In addition, a combination of the coarse and fine particles (A2) resulted in 1.21 N/mm^2, it has shown that IB can be improved by adding a limited percentage of fine particles [15]. Despite this, higher particle densities can contribute to higher IB [45]. However, with the same unit of adhesive, smaller particles cannot create a proper bond between their interparticle due to the oversized surfaces that may cause fragile bonding [46]. It is worth to mentioning, that while TOCS particles had a lower aspect ratio than wood particles, similar results were found in IB. The IB values for group C ranged from 1.071 N/mm^2 to 1.811 N/mm^2, the best combination of particle sizes was 25% of all the sizes (C5), which is similar to the results for wood particles (B1).

In general, screw withdrawal resistance is correlated to the IB strength of particleboard, thus, a high FSW and ESW can indicate good quality of bonding between particles [47]. In group A, particleboard with coarse particles (A1) recorded the highest FSW and ESW, while in group B, the results were contrasted and particleboard with fine particles (B3) showed the highest properties. According to particle geometry, both TOCS fine and wood coarse particles, due to their sizes, offer lower interparticle bonding, although the lowest FSW and ESW in both groups were for panels produced with a mixture of coarse and fine particles, as reported by Cosereanu et al. (2014) [48]. However, Yorur et al. reported that higher density in the core layer may increase ESW, a phenomenon similar to group B [49]. In the case of group A, even though particleboard with fine particles had higher density, the ESW was lower than particleboard with coarse particles. The recorded FSW in group C was 693 to 1079 N and the ESW was 1665 to 2394 N. As a result, it can be concluded that particle size is an important parameter in single layer particleboard to achieve the properties desired for specific applications [19].

Effects of particle size and combination on physical properties

A comparison of the mean values and analysis of variance for WA after submersion for 2 and 24 h is presented in Fig. 5. The results showed that the panels in group A were able to absorb a higher percentage of water in 24 h (54.5% to 64.5%) than those in group B (27.7% to 43.7%), similar values to those obtained in other studies of agriculture wastes [50, 51]. A possible explanation could be the chemical composition of lignocellulosic materials, holocellulose containing a high amount of hydroxyl groups and has hydrophilic characteristics, capable of absorbing water, while the amount of cellulose in TOCS is lower than common wood, but its amount of hemicellulose is greater [52]. A second explanation relates to the particle geometry, TOCS particles are granule shape and smaller than wood particles; in general, the vast surface area of smaller particles may have contributed to the uptake of more water [46]. The results of the physical properties analysis have illustrated that in both groups, panels with fine particles captured more water after 24 h of immersion. However, the results of density showed slightly more densification with fine particles, and technically, higher density which reduces porosity (Table 3) resulted in lower WA [33, 53]. In panels A2 and B2, the finding has shown the same results as another study that was devoted to the manufacture of particleboard with maize cob that reported a combination of the coarse and fine particles improved WA [36]. As pore structure affects permeability [54], panels in group A absorbed more overall water in the first 2 h of soaking due to more voids in the structure [55].

The mean values and analysis of variance for TS after submersion for 2 and 24 h are presented in Fig. 6. The most serious impediment to the use of lignocellulosic in composites is its high sensitivity to water, which adversely affects the mechanical properties as well as the long-term durability of the material, especially for outdoor applications. However, the amount of WA has an influence on TS and WA after 24 h for panels in group A was higher than that for group B, but interestingly, swelling in thickness represented a lower percentage, while TS of group A panels was between 9.4 to 10.4%, for group B recorded values were 14.8 to 17.4%.

The chemical composition of the raw material affects the physical properties of particleboard significantly. Therefore, this phenomenon may be connected to the higher content of lignin and extractive materials in

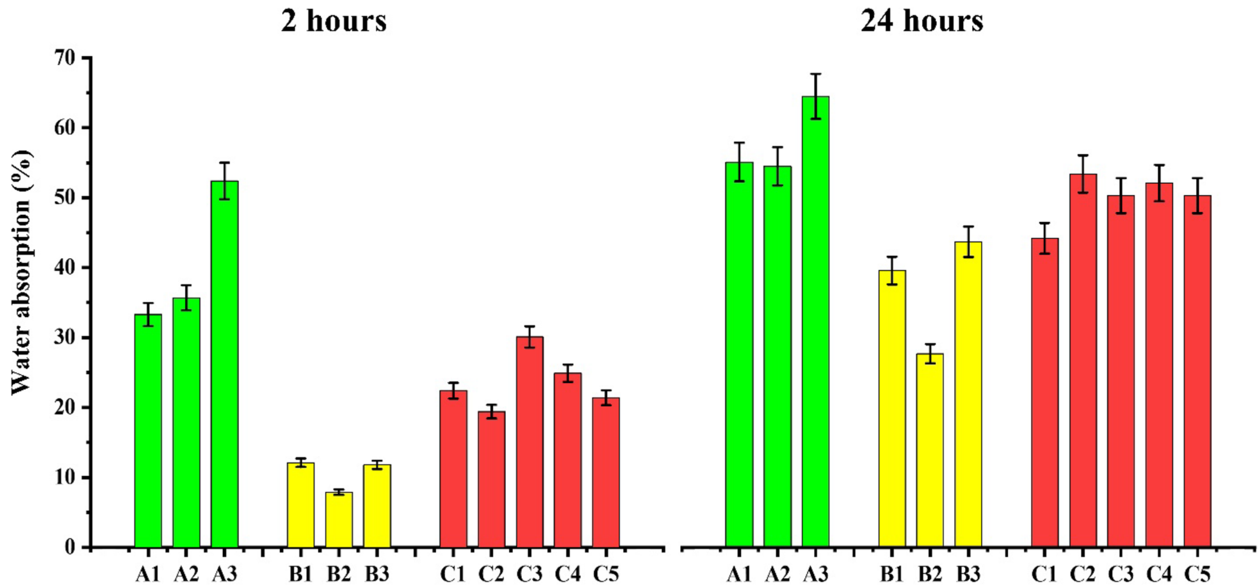

Fig. 5 Water absorption of different particleboards in this study

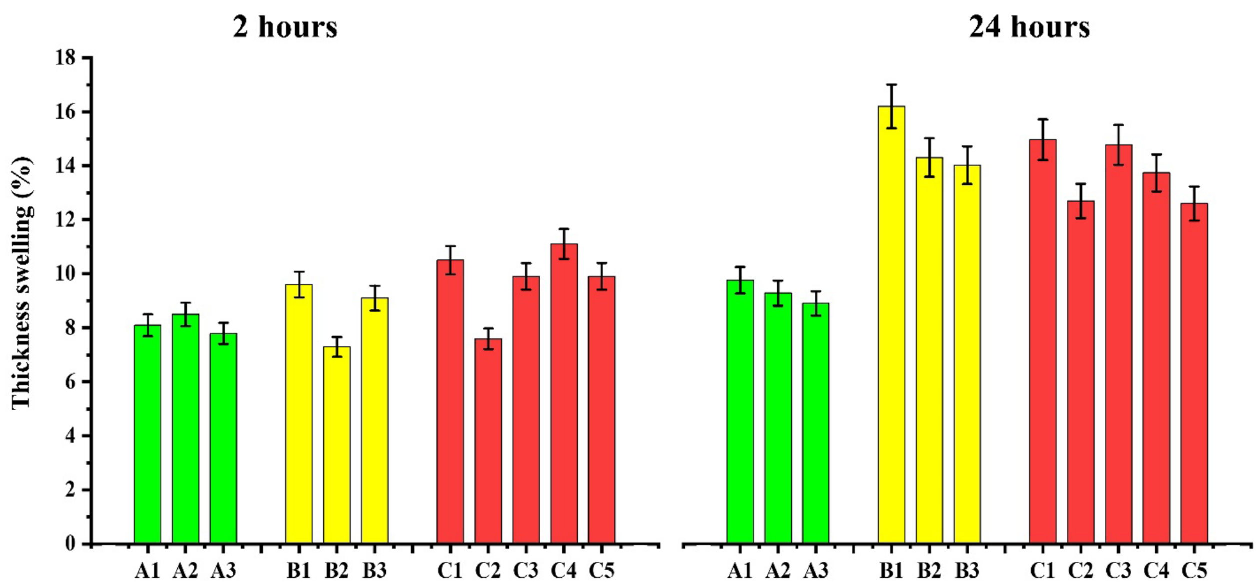

Fig. 6 Thickness swelling of different particleboards in this study

TOCS. In addition, TOCS particles have a lower compaction ratio, which means they have lower internal stresses [56]. Based on the obtained TS value for different particle sizes, coarse particles exhibited a slightly higher swelling, in line with the results of particleboard with rice straw [35]. The physical properties of panels in group C ranged from 44.2 to 53.4% of WA after 24 h and 13.3 to 15.8% of TS. A notable finding is that all panels in this study had TS swelling in thickness of less than 17% after 24 h, which corresponds to the EN 312:2010 specification for non-load-bearing boards in humid conditions. This study evaluated all panels without adding any water repellent materials or any surface treatment-like sanding. The density of particleboards is also one of the factors related to TS, as Zvirgzds et al. (2022) reported that higher density in particleboards regardless of material indicated a lower change in thickness [57]. High density reduces the porosity, resulting in better structure harmony in particleboard.

Effects of particle size and combination on thermal conductivity

Recently, energy consumption has been a hot topic in construction and building materials. Since lignocellulosic resources have a natural porous structure, particleboard produced from them has attracted much attention for insulation materials production [58]. Particleboard thermal conductivity is directly influenced by the density (higher density leads to higher thermal conductivity), which is related to the porosity of panels, hot-pressing variables, and raw material properties [59]. The results of this property have presented in Table 6. It is recommended that building materials have thermal conductivities between 0.035 and 1.60 W/mK [48].

According to a recent study, particle sizes play an important role in thermal conductivity, since they create different pore structures [60]. In this study, no significant differences were found in thermal conductivity between particle sizes, matching the results of particleboard produced with palm tree prunings [61]. However, the particleboard produced from coarse particles had a higher value in group B. In Group A, which was based on TOCS particles, the thermal insulating properties were better than those of commercial wood particles (0.153 W/mK). This can be explained by the structure of TOCS particles. TOCS particles have granules and a lower aspect ratio than wood, and their pore structure (high porosity) is advantageous for the particleboard made with these shells to operate effectively as thermal insulation.

Table 6 Thermal conductivity of single layer TOCS-based particleboard

Group	Board type	Thermal conductivity (W/mK)
A	A1	0.139 (0.009)[a]
	A2	0.139 (0.003)[a]
	A3	0.138 (0.011)[a]
B	B1	0.152 (0.008)[cd]
	B2	0.143 (0.006)[a]
	B3	0.145 (0.005)[abc]
C	C1	0.155 (0.005)[d]
	C2	0.141 (0.006)[a]
	C3	0.156 (0.011)[d]
	C4	0.149 (0.014)[bcd]
	C5	0.142 (0.011)[ab]

[abcd] Values with the same letters are not significantly different by Tukey HSD test (*P* < *0.05*)

Conclusions

The interaction between particle size and the mixing ratio was studied on a single-layer Tea Oil Camellia shells-based particleboard with 10 mm thickness and 720 kg/m^3 density. Due to less interparticle space, particleboard made from fine particles had a higher density and, therefore, lower porosity. The study also found that TOCS particles are more porous than commercial wood particles. Indeed, particleboard's porosity could affect all of its properties, especially its physical properties. Results of WA indicated TOCS particles absorbed almost 60% of water by infiltrating water into the pores within 2 h; however, it was found fine particles due to their large surface absorbed more water than coarse particles, though the difference did not show up in TS. According to our findings, particleboard with TOCS absorbed water more but showed a lower TS after 24 h. Although the particle size did not have a significant effect on the thermal conductivity of panels, the higher porosity TOCS particles provided lower heat transfer, resulting in slightly denser sections close to surfaces. Results of mechanical tests have shown that coarse particles offer better properties than fine particles, especially in terms of load-bearing. In addition, the high surface area of fine particles increased the non-resinated particles, thereby decreasing mechanical properties, particularly in IB and screw resistance. The results of group C have demonstrated a mixing of 50% TOCS particles with 50% of commercial wood (regardless of particle size) could achieve acceptable properties and satisfy all requirements of the EN 312:2010 standard for P2-type particleboard which could be use in the furniture industry, although high WA of TOCS-based particleboard should be solved in future studies.

Abbreviations

TOCS: Tea oil camellia shell; pMDI: Polymethylene polyphenyl polyisocyanate; TS: Thickness welling; FAO: Food and Agriculture Organization of United Nations; IUPAC: International union of pure and applied chemistry; BS: Bending strength; MOR: Modulus of rupture; MOE: Modulus of elasticity; IB: Internal bonding; FSW/ESW: Face and edge screw withdrawal resistance; WA: Water absorption; VDP: Vertical density profile.

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Author contributions

KCC design and carried out the experiment, writing the original draft. XI writing—review & editing, funding acquisition. LG conceived the study on the composition analysis, funding acquisition. CH supervision, conceptualization, funding acquisition. All authors read and approved the final manuscript.

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Availability of data and materials
The data sets used and materials during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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