

Mechanical characterization of mixed particleboard panels made of recycled wood and Arundo donax

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ARTICLE INFO

Keywords:

Giant reed
Wood based panel
Granular material
Mechanical properties

ABSTRACT

The giant reed, *Arundo donax* (*A. donax*) is a fast and naturally growing species in the Mediterranean Area indicated as one of the 15 invasive species with greatest impact by the European Commission within the Ecosystem Vulnerability Key Action. It is a greatly available but non-fully exploited material regarded as a problem both in agriculture and in watercourse management. This study explores the potential use of *A. donax* as an alternative material in the production of particleboard panels. The research, conducted in collaboration with the industrial sector, evaluates the mechanical and physical properties of sandwich particleboards in which part of the recycled wood chips are replaced with varying percentages of *A. donax* chips only in the core of the board. The work demonstrates the feasibility of such a board using industrial procedures and the capability of *A. donax* to improve the physical and mechanical performance of the recycled wood particleboard without altering the production process or adding resin. The particleboards were manufactured in three densities (550, 680 and 750 kg/m³) and tested for thickness swelling, surface soundness, internal bond and bending strength. The results reveal that particleboards containing 20–35 % of *A. donax* by mass, particularly for high densities, improved mechanical properties and reduced the thickness swelling, meeting the requirements for class P4 particleboards resulting in an upgrade of the wood recycled panel's classification. This investigation highlights the viability of integrating *A. donax* into particleboard production, potentially reducing reliance on imported wood, improving the mechanical properties of recycled wood particleboards and promoting sustainable and locally sourced materials.

Symbols

ρ	Density [kg/m ³]
σ_c	Compression stress [MPa]
E_c	Compression Young modulus [GPa]
$\sigma_{t,0}$	Tensile stress, parallel to the fiber [MPa]
$E_{t,0}$	Tensile Young modulus parallel to the fiber [GPa]
$\sigma_{t,90}$	Tensile stress, perpendicular to the fiber [MPa]
$E_{t,90}$	Tensile Young modulus perpendicular to the fiber [GPa]
τ	Shear stress [MPa]
G	Shear elastic modulus [GPa]
G_t	Swelling in thickness [%]
t_1	Initial thickness [mm]
t_2	thickness of the test piece after immersion [mm]

$f_{t\perp}$	Perpendicular tensile strength [MPa]
F_{max}	Breaking Load [N]
a	Length of the test piece [mm]
b	Width of the test piece [mm]
E_m	Bending modulus of elasticity [GPa]
l_1	Distance between the supports [mm]
F_1	Loads at 10 % of the maximum load [N]
F_2	Loads at 40 % of the maximum load [N]
t	Thickness of the test specimen [mm]
a_1	a_1 is the deflection at the mid-length corresponding to F_1 [mm]
a_2	a_2 is the deflection at the mid-length corresponding to F_2 [mm]
σ_m	Bending strength [MPa]

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1. Introduction

Particleboards made of wood are extensively utilized in mass furniture production and construction sectors. Despite wood being considered a renewable resource, the growth rate of trees varies depending on the species ranging from 30 cm to 1 m per year, taking 3–40 years to grow before they can be cut and used for engineering purposes. The extensive and widespread use of this resource combined with the long regrowth time is causing deforestation in vast areas of the planet. During the last two decades global forest extent decreased by 1 million km² (2.4 % of the forest area since 2000) (Potapov et al., 2022; Hansen et al., 2013; Keenan et al., 2015). Deforestation of forests is an important global issue because these forests harbor a high percentage of land biodiversity and play a critical role in the global carbon and water cycles (Zeppetello et al., 2020; Xu et al., 2022). Moreover, the conversion of forests into other land uses contributes approximately 20 % of the world's greenhouse gas emissions (GHG) accelerating deforestation rates have dramatic impacts on global climate change (Zeppetello et al., 2020).

There are countries, such as Italy, which are major importers of wood, Italian annual imports (excluding furniture) are valued at approximately 3–4 billion euros, while its exports are estimated at around 1.5–2 billion euros each year according to the Economic Observatory of the Italian Ministry of Foreign Affairs (Ministero degli Affari Esteri e della Cooperazione, 2023). From an economic perspective importing a significant amount of wood creates challenges in the trade balance, while from an environmental standpoint wood imports lead to an increase in CO₂ emissions due to the logistics required for transportation which could be reduced by using autochthonous materials.

There are lignocellulosic resources of waste origin with great industrial potential that are available but under-used and can contribute to reducing the uncontrolled logging of forests (Jimenes and Sanchez, 1989; Jimenez et al., 1990). They may be classified as industrial waste (primarily derivatives from pulp, paper and wood processing), forestry waste (residues from forestry and cleaning), agricultural waste (crop residues, nuts, grains and surplus crops) and urban waste (recycled wood, wastepaper and cardboard among others).

The volume of post-consumer waste wood is increasing alongside rapid urbanization and industrialization, according to Eurostat data from 2014 Europe generates every year around 60 million tons of wood waste collected from various sectors. Germany is the leader in the collection of wood waste in Europe with around 6.6 million tons in 2016 while Italy, the United Kingdom and France produce around 4 million tonnes per year (Nguyen et al., 2023). Despite differences in wood waste management recycling rates vary from country to country with high percentages ranging from 85 % to 95 % in countries such as Sweden, Switzerland, Norway, the Netherlands and Finland. A great part of this recycled material is then used in particleboard production, Italy leads among European countries with 42 % followed by Austria with 33 % (Nguyen et al., 2023).

Wood waste comes from various resources which makes it a non-homogeneous material due to the multiplicity of wood types, applications and sources (Bergeron, 2014). Various physical and chemical contaminants are present in waste wood which pose challenges to recycling processes and influence the properties of recycled products. Nowadays, several mechanical processes can separate physical contaminants in wood waste such as plastic, metal or fabrics. However, chemical contaminants resulting from wood preservatives, paints, glues, etc. are more difficult to eliminate resulting in the mechanical properties of particleboards being inferior to those made with virgin wood.

In the production of particleboard panels, the potential use of non-wood plants as a substitute for wood or part of it has been studied for several decades to confer innovative properties on traditional products. These non-wood materials are hazelnut shells (Cintura et al., 2024a;

Cintura et al., 2024b), coffee parchment (Scatolino et al., 2017), tobacco stalk (Jimenez et al., 2020), peanut hull (Guler et al., 2008), sycamore leaves (Pirayesh et al., 2015), rice straw (Yang et al., 2003), recycled wood (Stanková and Pipíška, 2017; Iždinský et al., 2020; Lima et al., 2020) and in particular *A. donax* that has demonstrated good potential (Flores-Yepes et al., 2011; García-Ortuño et al., 2011; Ferrández-García et al., 2012; Nazerian and Moazami, 2015).

In this paper, the idea is to implement recycled wood particleboard produced by a certified supply chain and enhance its properties by adding *A. donax* particles. It has been widely demonstrated in the literature that the use of *A. donax* as a substitute for wood provides sufficient mechanical properties to a particleboard to ensure its commercialization. Studies have also been conducted on panels where wood particles were partially replaced with *A. donax* particles in the case of single-layer panels (Ferrandez-Villena et al., 2020a, 2020b). Other studies have shown that the use of this material improves the water resistance of particleboard compared to its wood-based counterpart (Flores-Yepes et al., 2012).

Arundo donax is a perennial herbaceous plant that belongs to the group of giant reeds. Its stem called culm, can reach a height of 6–8 m, it is hollow with diameters ranging from 20 to 30 mm while the thickness of the walls varies between 1 and 4.5 mm. It is native to central Asia and has gradually spread and established itself in all countries bordering the Mediterranean Sea due to its high tolerance to different climates and soil conditions (Polunin and Huxley, 1965). Recently it has been indicated as one of the 15 invasive species that have had the greatest impact in the Mediterranean area by the European Commission within the Ecosystem Vulnerability Key Action (Balaguer, 2004).

A. donax could be an alternative material to wood for different reasons: exhibits a high growth rate typically reaching maximum height within 4–6 months from germination, grows autonomously without pesticides and irrigation, has good mechanical properties as shown in recent research (Molari et al., 2021), has phytoremediation capability, meaning it can phytoextract heavy metals and/or induce the degradation of organic compounds in contaminated soils (Kausar, et al., 2012; Barbosa, et al., 2015; Fiorentino, et al., 2017) and can also be used as a biofilter for the treatment of contaminated water or wastewater (Mavrogianopoulos et al., 2002). Cultivations of *A. donax* have the advantage of not requiring artificial irrigation, except in the initial phase and do not need pesticides allowing cultivation in areas unsuitable for other species resulting in significant economic savings (Efthymia et al., 2015; Pilu et al., 2013). The annual crop yield depends on several factors such as the soil, climate, use of fertilization and irrigation. Various studies in the literature have led to different results ranging from 51.4 Mg DM ha⁻¹ to 20 Mg DM ha⁻¹ (Ceotto et al., 2021; Alexopoulou et al., 2015; Danelli et al., 2021).

The starting point of the project was the Gruppo Saviola company's particleboard for indoor use made with recycled wood chips and urea-formaldehyde resin, a resin commonly used in this sector because it is the most economical and provides good mechanical performance and durability to particleboard. Over the years more eco-friendly alternatives have also been studied regarding the resin such as the use of non-modified starches (Ferrández-García et al., 2012) and the study of panels without the use of resin (Ferrandez-Villena et al., 2020a, 2020b). However, for this project it was decided to keep the same resin for industrial reasons. The recycled wood chips were partially substituted with *A. donax* chips using different percentages of substitution to study the variations in the physical and mechanical characteristics of the particleboards with the variation of *A. donax*. The objectives included determining the optimal percentage of *A. donax* that corresponds to the best mechanical performance and ensuring an enhancement of the mechanical properties of the particleboard while maintaining the same density and adhesive used.

2. Materials and methods

2.1. Materials

In the particleboard panels two different particle size distributions of recycled wood are used: one composed of finer particles in the range $0.1 \text{ mm} < d < 2 \text{ mm}$ and one composed of coarser particles in the range $0.5 \text{ mm} < d < 4 \text{ mm}$ where d is the particle size. The first particle size distribution is used to manufacture the outer layers of the particleboard, while the second one is used for the core layer. The company's proprietary granulometric distributions were used which are not reported here for confidentiality reasons. The recycled wood particles were provided by Saviola Group. Giant reed was collected from cultivation at the

Table 1

Average and standard deviation of the density and mechanical properties of Arundo donax.

Parameters	Value
Density ρ [kg/m^3]	647.7 (± 0.04)
Compression stress σ_c [MPa]	57.04 (± 0.05)
Compression Young modulus E_c [GPa]	13.40 (± 0.33)
Tensile stress, parallel to the fiber $\sigma_{t,0}$ [MPa]	111.70 (± 0.12)
Tensile Young modulus parallel to the fiber $E_{t,0}$ [GPa]	15.29 (± 0.07)
Tensile stress, perpendicular to the fiber $\sigma_{t,90}$ [MPa]	11.22 (± 0.14)
Tensile Young modulus perpendicular to the fiber $E_{t,90}$ [GPa]	1.05 (± 0.16)
Shear stress τ [MPa]	18.40 (± 0.12)
Shear elastic modulus G [GPa]	2.96 (± 0.23)

Table 2

Nomenclature of the particleboards manufactured.

Type of Board	Quantity of A. donax particles in the core [%]	Quantity of recycled wood particles in the core [%]	Density [kg/m^3]
A550	0	100	550
A680	0	100	680
A750	0	100	750
B550	10	90	550
B680	10	90	680
B750	10	90	750
C550	20	80	550
C680	20	80	680
C750	20	80	750
D550	35	65	550
D680	35	65	680
D750	35	65	750
E550	50	50	550
E680	50	50	680
E750	50	50	750

Department of Agricultural and Food Sciences of the University of Bologna, in Cadriano, Italy. Before processing the apical and basal parts of the culms as well as the leaves were removed.

The density and mechanical properties of A. donax are reported in Table 1 (Molari et al., 2021).

A. donax was dried using an oven at a temperature of $T = 85^\circ\text{C}$ until reaching a mass variation of less than 0.1 % after 24 h in the oven (Cintura et al., 2022). The weight loss of the dry material ranged from 28 % to 43 %.

To understand the effect of the particle size and geometry on the physical-mechanical properties of particleboard the slenderness (length/thickness) and aspect ratio (length/width) of the chips are measured. Optimal values for the slenderness ratio according to the literature (Flores-Yepes et al., 2011; Sackey and Smith, 2009; Arabi et al., 2023) range between 90 and 12. The dimensions of the particles were measured using an optical microscope Olympus SZX10 followed by analysis of the images using AutoCAD 2023 software.

Urea formaldehyde resin (Sadecol L) in a liquid form was used for particleboard manufacture together with the hardener CTZ (Amm. Solfato). The resin and the hardener were supplied by the SADEPAN Company.

2.2. Manufacturing procedure

The manufacturing process aims to follow and replicate the company's production process, but it is based also on literature evidence regarding particleboards similar to the one produced here (Nunes et al., 2021; Sackey et al., 2008). The particleboard panels produced a sandwich panel consisting of three layers: two thin outer layers and a thick inner layer, the core of the particleboard. The outer layers are made of recycled wood chips with a finer particle size distribution to ensure a uniform and completely planar surface for the nobilization of the particleboard. The composition of these outer layers is the same as that used by the Saviola Company with no modifications made during this experimental campaign. The core was modified by substituting part of the recycled wood chips with chips of A. donax.

Different particleboards were manufactured by varying the density and the percentage of A. donax in the core layer, Table 2 includes the 15 types of specimens that were manufactured and the related notation.

The manufacturing of the particleboard followed three phases. The first phase (Fig. 1(a)) consisted of mixing the components. The outer layers were made of recycled wood chips, resin and water were mixed in the same percentages for all densities and not reported here for confidentiality reasons. For the core A. donax and recycled wood chips were mixed varying their percentages as reported in Table 2, the percentage

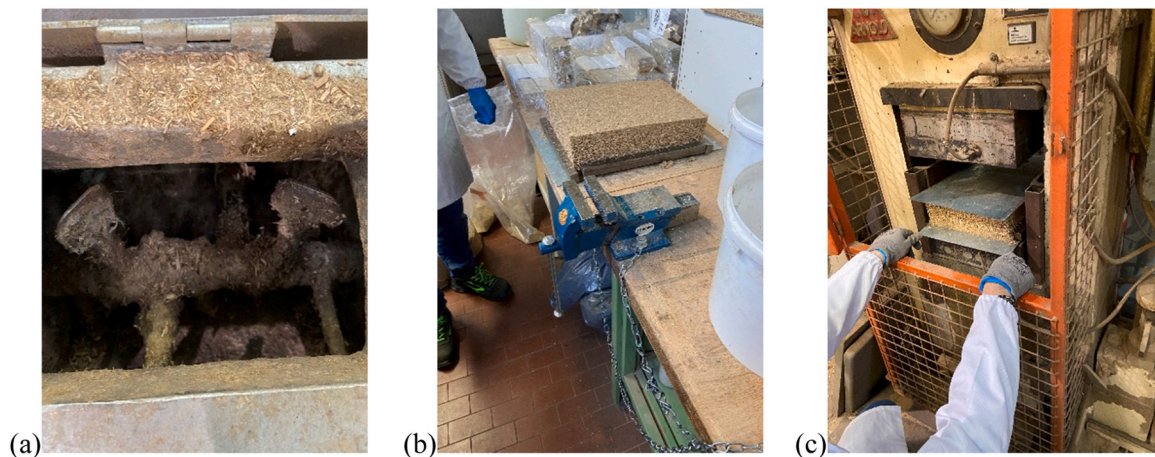


Fig. 1. Steps followed for the particleboard production process: (a) mechanical mixing of the materials, (b) preforming the particleboard by applying manual pressure, (c) hot molding of the particleboard.

Table 3

Type of tests carried out, standard associated with each test, number and dimensions of the specimens required for the physical-mechanical tests.

Test	Normative	Number of Specimens	Dimensions of specimen [mm]
Swelling in thickness, 24 h	EN 317 (1993)	8	50 × 50 × 22
Surface soundness	EN 311 (2002)	8	50 × 50 × 22
Internal Bond	EN 319 (1993)	8	50 × 50 × 22
Three-point bending	EN 310 (1993)	6	300 × 50 × 22

of resin used in the core was the same for all densities.

In the second phase (Fig. 1(b)) the three layers constituting the particleboard were manually positioned inside a pre-mold with dimensions of 32 x 25 x 30 cm. A pressure was manually applied to the material to create a pre-forming to partially eliminate the air and replicate the industrial production.

For the third phase (Fig. 1(c)) the pre-formed material was placed inside a hot press for the molding process. The particleboards were produced through a hot-pressing process with a pressure of 300 bar and a temperature of 190 ~ 210 °C to ensure the catalysis of the resin inside the particleboard and the evaporation of the water, the board was

maintained inside the press at a constant temperature for approximately 4 min.

This procedure was carried out for all the different types of particleboards reported in Table 2. The density was adjusted by varying the amount of material used for the particleboard manufacturing while the pressure applied by the machine remained the same.

Before proceeding with the testing phase all the particleboards were squared to remove the edges, resulting in particleboards measuring 300 x 200 × 22 mm and they were cut using a circular saw to obtain the specimens for the different tests.

2.3. Methods

A granulometric study was conducted on the particles of *A. donax* and recycled wood of the sandwich particleboard core. A non-automated process was carried out to obtain a three-dimensional characterization of each particle using two optical microscope images, followed by post-processing with AutoCAD. The first microscope image was used to measure the length and width of each particle while the second microscope image, taken from a side view, allowed the measurement of the particle thickness. This approach enabled a three-dimensional characterization crucial for non-cylindrical particles like those studied, where the width is approximately three times the thickness. In total, 100

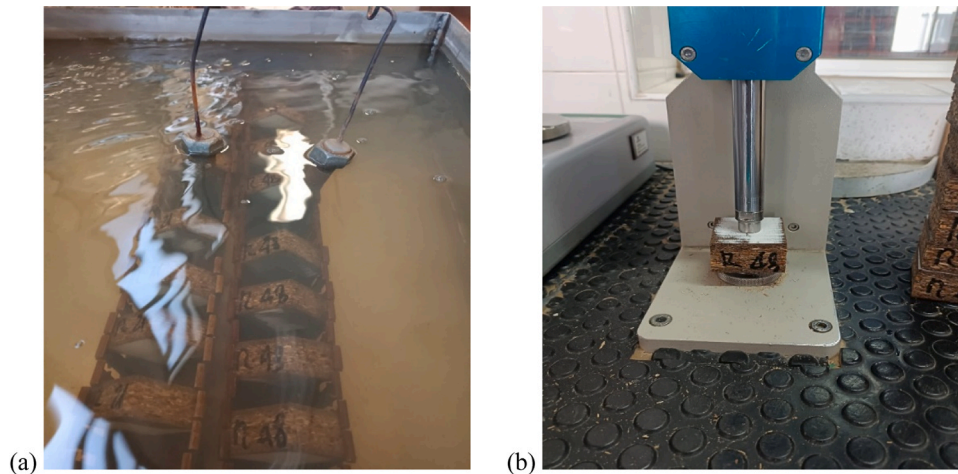


Fig. 2. (a) Immersion of the specimens in the water bath. (b) Thickness swelling test on a sample with a cross-section area of 50 × 50 mm.

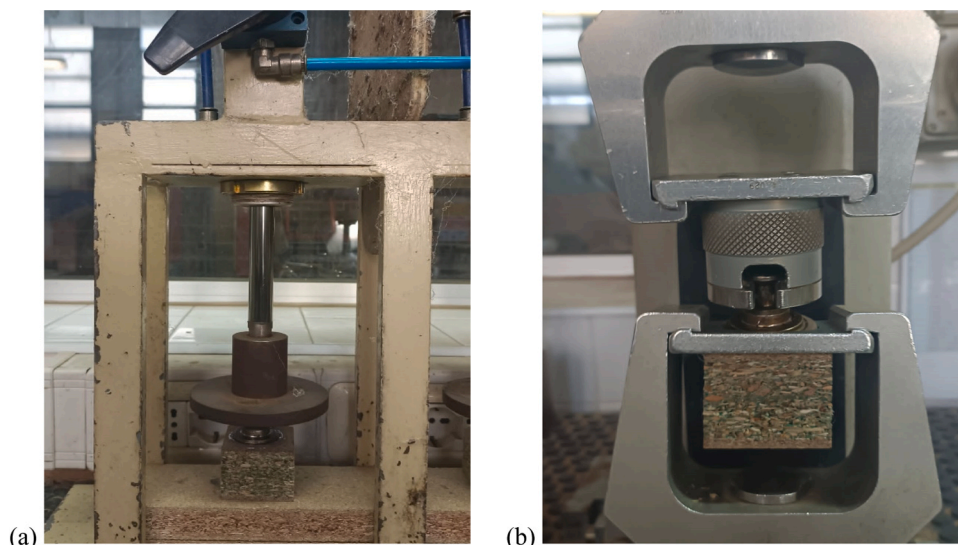


Fig. 3. (a) Test preparation. (b) Surface soundness test on a sample with a cross-section area of 50 × 50 mm.

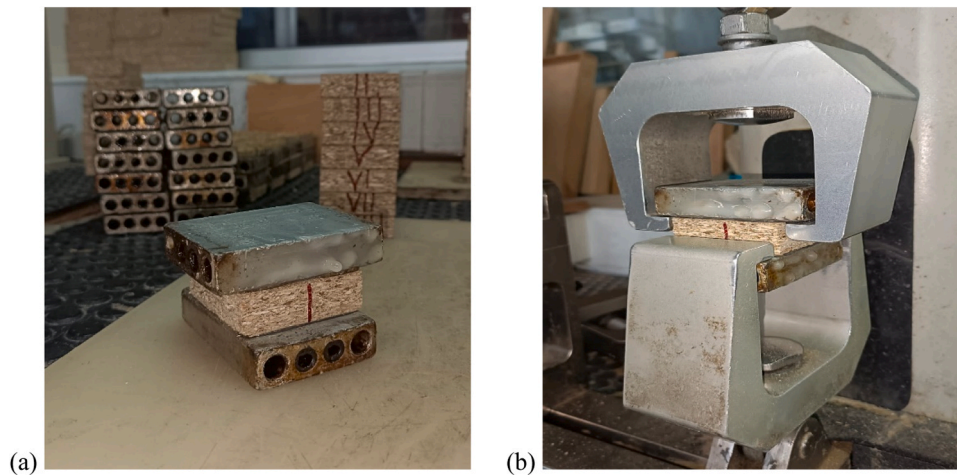


Fig. 4. (a) Adhesion of the specimen to the steel plates. (b) Internal bond test on a sample with a cross-section area of 50 × 50 mm.

randomly selected particles of recycled wood and *A. donax* were analyzed for each sieve fraction.

From these measurements two dimensionless values were obtained: the slenderness ratio (length/thickness ratio) and the aspect ratio (length/width ratio) which, according to various studies, influence the mechanical properties of particleboard (Flores-Yepes et al., 2011; Arabi et al., 2023; Sackey and Smith, 2009).

Four different tests were carried out to perform a mechanical and physical characterization of the particleboard, these tests were chosen as suggested by EN 312 standard (2010) for the classification and characterization of different categories of particleboards.

Table 3 reports the four tests, the normative associated with the test, the number and the dimensions of the specimens tested for each type of particleboard manufactured according to the standard EN 326-1 (1994).

Before testing the samples were kept for 24 h in a conservation chamber at a temperature of 20 °C and a relative humidity of 65 %.

The Swelling in thickness test as specified in the EN 317 (1993) standard was performed to determine the thickness swelling of a specimen with a cross-section of 50 × 50 mm after complete immersion in controlled water at a constant temperature of 20 °C and a pH of 7 for 24 hours. The specimens were maintained separated from each other and the surfaces of the water bath as reported in Fig. 2(a). For each particleboard type 8 specimens were tested as suggested by EN 326-1 (1994), the tests were performed with the IMAL testing machine (Model IB600, IMAL, S.R.L., Modena Italy) Fig. 2(b).

During the immersion period the specimens were covered with 25 mm of water to ensure proper immersion. For each test the water in the bath was changed following the standard recommendation (EN 317, 1993). The swelling in thickness G_t was calculated according to the Eq. 1:

$$G_t = \frac{t_2 - t_1}{t_1} 100 \quad (1)$$

Where t_1 is the thickness of the test piece before immersion expressed in millimeters and t_2 is the thickness of the test piece after immersion expressed in millimeters.

The Surface soundness test aimed to determine the tensile strength perpendicular to the surface of the particleboard and the adhesion between the outer and the inner layers of the particleboard. Eight square specimens of 50 × 50 × 22 mm were tested as suggested by the standards EN 326-1 (1994). Circular grooves were cut into the surface of the specimens according to the standard EN 311 (2002). On the surface of the specimen a heated steel pad is glued using a hot-melt adhesive with a melting point under 150 °C, Fig. 3(a) shows test preparation: the hot pad is pressed onto the surface of the specimen and held with a light pressure



Fig. 5. Three-point bending test on a sample of 300 × 50 × 22 mm.

of 0.1 N/mm² to 0.2 N/mm² until the adhesive has cooled and hardened. The tests reported in Fig. 3(b) were carried out at a constant speed so the failure occurred in 60–90 s (EN 311, 2002).

Fig. 4(b) shows the Internal bond (IB) test performed to determine the tensile strength perpendicular to the plane of the particleboard. As suggested by the standards EN 326-1 (1994) 8 square specimens of 50 × 50 × 22 mm were tested. The specimens were glued to both the surface and metal test blocks as shown in Fig. 4(a). Excess glue was removed before proceeding with the test. The load was applied at a constant rate of crosshead movement throughout the test and the rate of loading was adjusted so that the maximum load was reached within (60 ± 30) s as reported in the standard EN 319 (1993).

Tensile strength perpendicular to the plane of the particleboard of each test piece is calculated according to Eq. 2:

$$f_{t\perp} = \frac{F_{\max}}{a \cdot b} \quad (2)$$

Where F_{\max} is the breaking load expressed in Newton, a and b are respectively the length and width of the test piece expressed in millimeters.

The Three-point bending tests were carried out on samples of 300 × 50 × 22 mm. Three specimens were cut for each manufactured particleboard and two particleboards were manufactured for each type

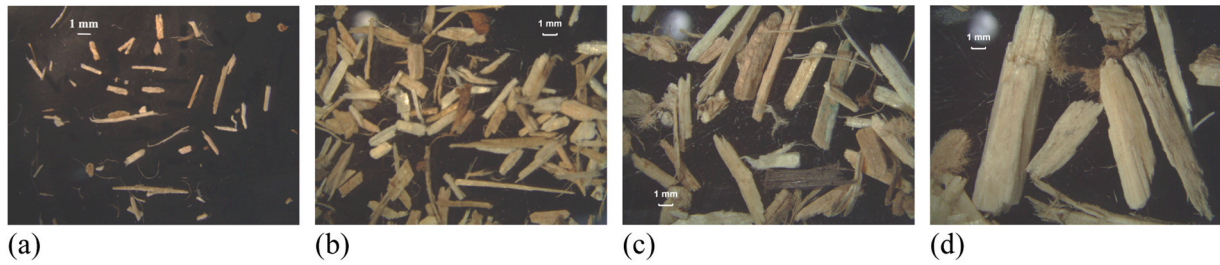


Fig. 6. Size of particles of sieve-fractionated particles of wood recycled chips: (a) between $0.5 < d < 1$ mm; (b) between $0.5 < d < 1$ mm; (c) between $1 < d < 2$ mm; (d) between $2 < d < 4$ mm.

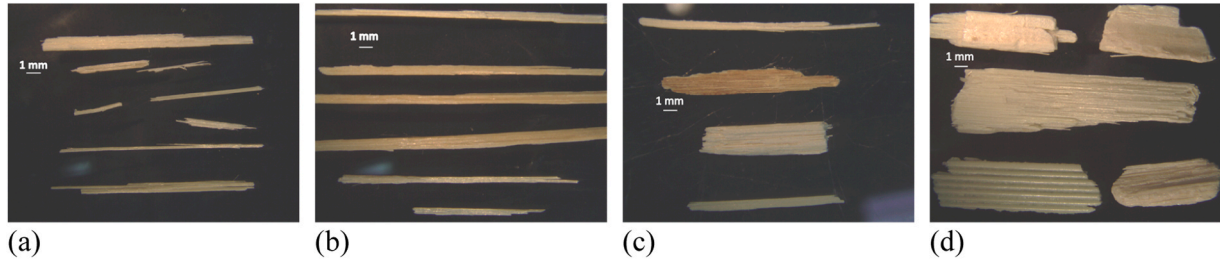


Fig. 7. Size of particles of sieve-fractionated particles of *Arundo donax* chips: (a) between $0.5 < d < 1$ mm; (b) between $0.5 < d < 1$ mm; (c) between $1 < d < 2$ mm; (d) between $2 < d < 4$ mm.

Table 4

Average values and standard deviations for the length of the particles, slenderness ratio (SR) and aspect ratio (AR), for *A. donax* and recycled wood.

Material	Sieve-fractionated Particle [mm]	The average length of the particles [mm]	SR	AR
A. donax	$d < 0.5$	5.54 (± 2.1)	39.84 (± 19.65)	12.85 (± 6.34)
	$0.5 < d < 1$	9.75 (± 4.4)	64.31 (± 38.51)	20.74 (± 12.42)
	$1 < d < 2$	11.55 (± 6.6)	65.04 (± 58.13)	20.98 (± 18.75)
	$2 < d < 4$	24.31 (± 14.9)	41.26 (± 38.11)	13.31 (± 12.29)
Recycled wood	$d < 0.5$	1.98 (± 1.1)	18.97 (± 12.80)	6.12 (± 4.13)
	$0.5 < d < 1$	3.27 (± 1.6)	16.46 (± 11.28)	5.31 (± 3.64)
	$1 < d < 2$	5.05 (± 2.6)	16.31 (± 10.40)	5.26 (± 3.35)
	$2 < d < 4$	12.79 (± 5.8)	14.92 (± 7.53)	4.81 (± 2.43)

of particleboard, a total of six specimens were tested (EN 326-1, 1994). The test procedure follows the standard EN 310 (1993) using a span length of 250 mm.

A strain gauge (KFGS-10-120-C1-11 L1M2R of 10 mm length) was placed on the bottom face of each specimen and was glued with CC-33A adhesive. Fig. 5 reported the bending test conducted under displacement control (displacement rate of 2 mm/min) ensuring that the specimen fracture occurs in approximately 100 s, in compliance with the standard (EN 310, 1993).

The modulus of elasticity E_m and the bending strength σ_m was calculated following EN 310 (1993). E_m was calculated according to Eq. 3:

$$E_m = \frac{l_1^3 (F_2 - F_1)}{4bt^3 (a_2 - a_1)} \quad (3)$$

Where l_1 is the distance between the supports, b is the width of the test piece, t is the thickness of the test specimen (all expressed in

millimeters). F_1 and F_2 are the loads at 10 % and 40 % of the maximum load expressed in Newton, a_1 and a_2 are the deflection at the mid-length of the specimen corresponding to F_1 and F_2 .

The bending strength is expressed according to Eq. 4:

$$\sigma_m = \frac{3F_{\max} l_1}{2bt^2} \quad (4)$$

Where F_{\max} is the maximum load expressed in Newton.

3. Results and discussion

3.1. Geometric study of chips

The *A. donax* particles were shredded using a mechanical hammer shredder and sieved adopting the same granulometric distribution as the recycled wood particles for the particleboard's core.

Fig. 6 shows the recycled wood particles present in the core of the board, while Fig. 7 shows the *A. donax* chips for various particle size distributions.

Table 4 reports the mean values with their respective standard

Table 5

Average values and standard deviations for thickness swelling 24 h (TS 24 h), surface soundness and Internal bond (IB) for all specimens.

Specimens	TS 24 h [%]	Surface soundness [MPa]	IB [MPa]
A550	11.78 (± 6.20)	0.72 (± 0.04)	0.31 (± 0.02)
B550	13.95 (± 0.44)	0.70 (± 0.26)	0.37 (± 0.11)
C550	13.41 (± 1.13)	0.71 (± 0.09)	0.36 (± 0.05)
D550	13.12 (± 1.44)	0.78 (± 0.20)	0.31 (± 0.01)
E550	14.16 (± 0.99)	0.54 (± 0.22)	0.33 (± 0.05)
A680	14.66 (± 1.07)	1.55 (± 0.17)	0.56 (± 0.08)
B680	14.20 (± 1.23)	1.71 (± 0.14)	0.38 (± 0.05)
C680	14.06 (± 0.98)	1.67 (± 0.18)	0.48 (± 0.04)
D680	12.24 (± 0.69)	1.81 (± 0.08)	0.34 (± 0.01)
E680	11.75 (± 0.54)	1.59 (± 0.23)	0.44 (± 0.09)
A750	14.27 (± 1.18)	1.24 (± 0.12)	0.38 (± 0.08)
B750	11.86 (± 0.98)	1.20 (± 0.08)	0.48 (± 0.07)
C750	10.73 (± 0.74)	1.13 (± 0.31)	0.57 (± 0.09)
D750	9.99 (± 2.00)	1.02 (± 0.22)	0.44 (± 0.03)
E750	11.31 (± 0.49)	0.86 (± 0.10)	0.32 (± 0.11)

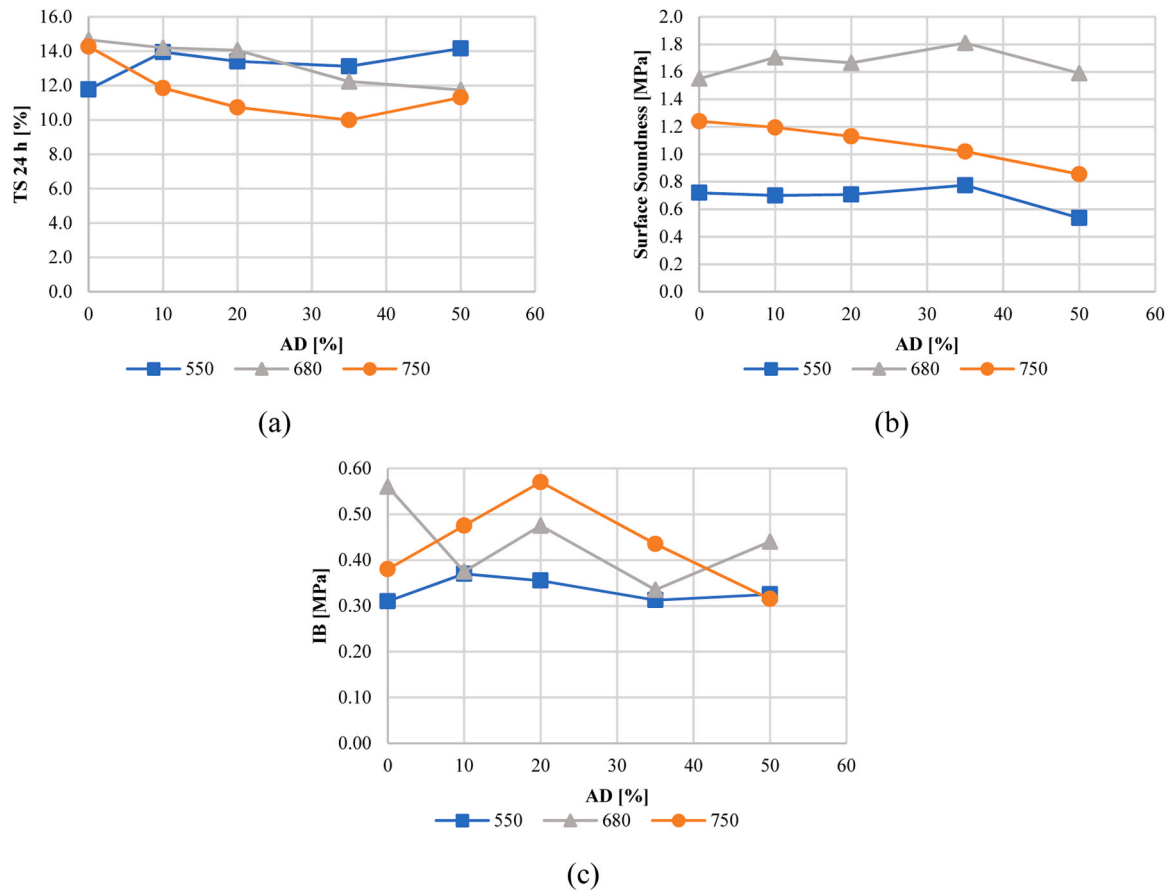


Fig. 8. The trend of (a) Thickness swelling 24 h (TS 24 h), (b) Surface soundness and (c) Internal bond (IB), for the three densities and the variation of the quantity of A. donax in the core of the particleboard.

deviations for the length of the particle's slenderness ratio (length/thickness ratio) and aspect ratio (length/width ratio) for the recycled wood chips and *Arundo donax*.

As can be observed from Table 4 *Arundo donax* particles exhibit a more elongated and slender geometry compared to recycled wood particles. Additionally, they show greater heterogeneity between the different particle sizes in contrast to recycled wood particles. The slenderness ratio (SR) for *A. donax* ranges from 39.84 to 64.31, while for wood it ranges from 14.92 to 18.97. Previous studies (Flores-Yepes et al., 2011; Arabi et al., 2023; Sackey and Smith, 2009) have shown that higher SR values should lead to an increase in the bending strength (σ_m) and Modulus of Elasticity (E_m) of the particleboard. Moreover, the higher AR values of *A. donax* particles should ensure greater screw withdrawal resistance in the particleboard.

For *A. donax* the lowest SR and AR values are observed for particle sizes with $d < 0.5$ mm, while the highest values are observed for the medium particle size range of $0.5 < d < 2$ mm.

3.2. Physical and mechanical properties

Table 5 reports the average and standard deviation of thickness swelling, surface soundness and internal bond for the specimens.

Fig. 8 illustrates the trend of thickness swelling, surface soundness and internal bond concerning the quantity of *A. donax* and the densities of 550, 680 and 750 kg/m³.

For the density 550 kg/m³ the different percentages of *A. donax* in the core do not influence the value of Thickness swelling, surface soundness and Internal bond (Fig. 8(a), (b) and (c)).

In the case of 680 kg/m³ density it was observed a slightly decreasing trend for the TS and IB (Fig. 8(a) and (c)) with the increment

of the quantity of *A. donax* inside the core of the particleboard. Instead, the surface soundness remains constant, as shown in Fig. 8(b). Finally, the specimens with a density of 750 kg/m³ show a parabolic trend for the TS and the IB (Fig. 8(a) and (c)) with a minimum for the TS at 35 % of *A. donax* content and a maximum for the IB at 20 %. The surface soundness shows a decrease with the increase in the percentage of *A. donax*.

The reason why the 750 kg/m³ density exhibits a countertrend for the IB characteristic compared to the lower densities could be attributed to a better interconnection of the *A. donax* within the particleboard, resulting in improved adhesion to the resin due to increased compaction pressure.

3.3. Three-point bending test

Table 6 presents the mean values and standard deviations of the particleboard panels tested in the three-point bending test. As expected, the performances improve with increasing density.

Fig. 9 shows the trend of σ_m with the percentage of *A. donax* for the three different densities. For densities of 680 kg/m³ and 750 kg/m³ it is evident that there is a parabolic trend in the bending strength (σ_m) with the increasing percentages of *A. donax* in the particleboards. The position of the peak is different for the two densities: for the specimens with a density of 750 kg/m³ the peak is reached for *A. donax* percentages between 10 % and 20 %, while for the specimens with a density of 680 kg/m³ the peak is reached for a percentage of 35 %.

For the density 550 kg/m³ the bending strength σ_m curve exhibits a constant trend, meaning that the addition of *A. donax* does not lead to any variations in bending strength.

For all densities with the addition of 50 % *A. donax* content the

Table 6

Average values and standard deviations in brackets for the maximum load, bending strength σ_m , Modulus of elasticity E_m and the density for the different types of particleboards.

Specimens	Maximum Load [N]	σ_m [MPa]	E_m [MPa]	Density [kg/m ³]
A550	335.19 (± 35.79)	5.43 (± 0.62)	980.27 (± 43.94)	538.1 (± 11.72)
B550	388.83 (± 31.46)	6.29 (± 1.05)	1113.42 (± 144.49)	577.4 (± 16.79)
C550	373.71 (± 62.40)	5.23 (± 1.10)	901.19 (± 70.98)	567.2 (± 20.86)
D550	398.28 (± 105.90)	6.19 (± 1.89)	1077.31 (± 228.68)	560.8 (± 19.81)
E550	335.19 (± 35.79)	5.43 (± 0.62)	980.27 (± 43.94)	555.2 (± 20.40)
A680	896.07 (± 64.44)	10.98 (± 0.60)	1829.95 (± 192.65)	665.8 (± 24.66)
B680	956.58 (± 82.67)	13.02 (± 1.13)	1866.32 (± 121.71)	675.6 (± 19.02)
C680	1070.48 (± 104.66)	14.20 (± 1.36)	1839.96 (± 179.20)	656.6 (± 20.15)
D680	1106.16 (± 67.41)	15.64 (± 0.68)	1937.52 (± 197.23)	701.6 (± 16.58)
E680	724.97 (± 84.01)	9.35 (± 1.02)	1408.89 (± 220.50)	649.9 (± 32.18)
A750	1087.10 (± 164.55)	13.81 (± 2.02)	2131.20 (± 279.97)	720.1 (± 30.91)
B750	1149.01 (± 43.58)	15.77 (± 0.44)	2401.80 (± 140.24)	746.3 (± 12.59)
C750	1158.71 (± 52.30)	15.66 (± 0.73)	2470.79 (± 104.26)	747.9 (± 10.89)
D750	1119.35 (± 91.27)	14.82 (± 1.42)	2282.68 (± 272.53)	730.6 (± 36.05)
E750	954.20 (± 21.57)	12.72 (± 0.30)	2042.62 (± 184.87)	728.8 (± 31.68)

bending strength σ_m exhibited by the particleboards is lower than that at 0 % of A. donax (Fig. 9). This trend can be explained by considering that the A. donax has better mechanical performance concerning recycled wood and the A. donax chips are slenderer than those of recycled wood, which also results in an improvement in the mechanical characteristics of the panels (Flores-Yepes et al., 2011; Arabi et al., 2023). However, the outer surface of A. donax chips is very smooth (Al-Snafi, 2015) compared to the case of recycled wood where the roughness is significantly higher, this could lead to a reduction of the grip between the chips and the adhesive. Initially an improvement in the mechanical properties of the particleboard is observed, particularly in flexural strength due to

the superior mechanical properties of A. donax compared to recycled wood this results in an increase in bending mechanical properties as the σ_m up to a maximum value of A. donax content, beyond this value the positive effects of the better mechanical properties of A. donax compared to recycled wood are outweighed by the negative impact associated with the lower adhesion between the resin and A. donax compared to the adhesion between resin and recycled wood leading to a decline in particleboard performance.

Fig. 10 shows the bending strength σ_m as a function of the density variation for each A. donax percentage. The curves show a linear trend in the case of 0 % A. donax the trend becomes quadratic for 20 % and 30 % and returns linear at 50 % of A. donax crops.

The addition of A. donax chips to the core of the particleboard for percentages ranging from 10 % to 35 % of the total results in an increase in bending mechanical properties for the densities 680 and 750 kg/m³ compared to the case with 0 % A. donax. Conversely, for the case of 50 %, the particleboard characteristics are lower for all densities compared to the 0 % particleboard. Fig. 11 presents a response interpolated surface a 3D curve illustrating how the output data of bending strength σ_m change with two inputs: the density and the A. donax percentage inside the core on the particleboard. It can be observed that there are two peak points of the surface in which the surface is colored in yellow: one corresponds to the density of 750 kg/m³ and with 20 % of A. donax in the core and the second is associated with the density of 680 kg/m³ and with a 35 % of A. donax in the core.

3.4. Discussion

One of the goals of this study was to enhance the mechanical performance of the recycled wood particleboard by keeping the same density and resin while varying the type of material in the inner layer, specifically by substituting recycled wood chips with A. donax chips. This improvement aimed to elevate the particleboard class from P2 to P4 in terms of mechanical properties (EN 312, 2010). Class P4 is associated with load-bearing particleboards suitable for use in dry conditions. The properties considered for the comparison of the two classes of particleboards were: bending strength σ_m , Modulus of elasticity E_m , Internal bond (tensile strength perpendicular to the plane of the particleboard).

The specimens with a density of 680 kg/m³ and the A. donax quantity ranging from 10 % to 35 % exhibited an average bending strength σ_m that exceeds the minimum requirement of 13 MPa associated with the P4 particleboard class as shown in Fig. 12(a), in which the red lines represent the standard limits associated with the P2 and P4 classes of

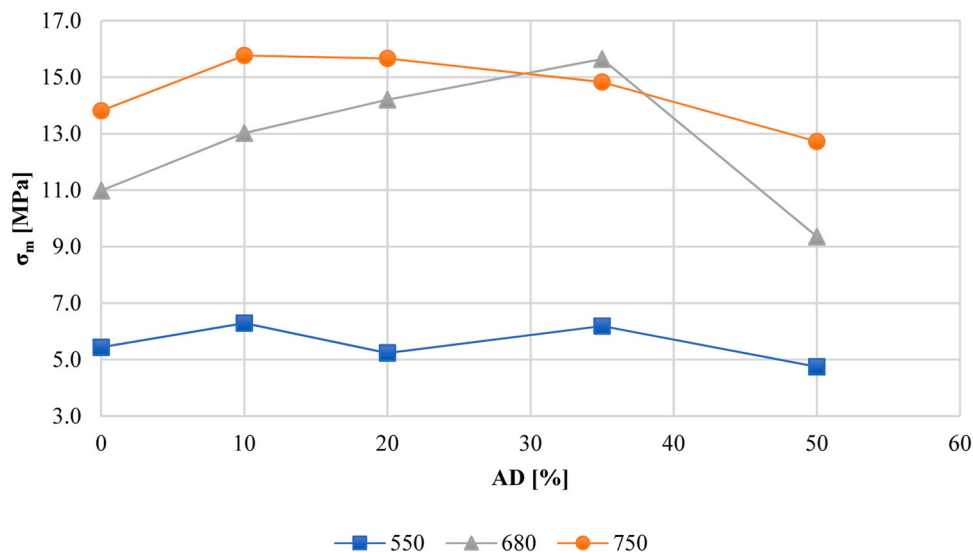


Fig. 9. Bending strength (σ_m) of the particleboard over the quantity of A. donax in the core according to the density of the board.

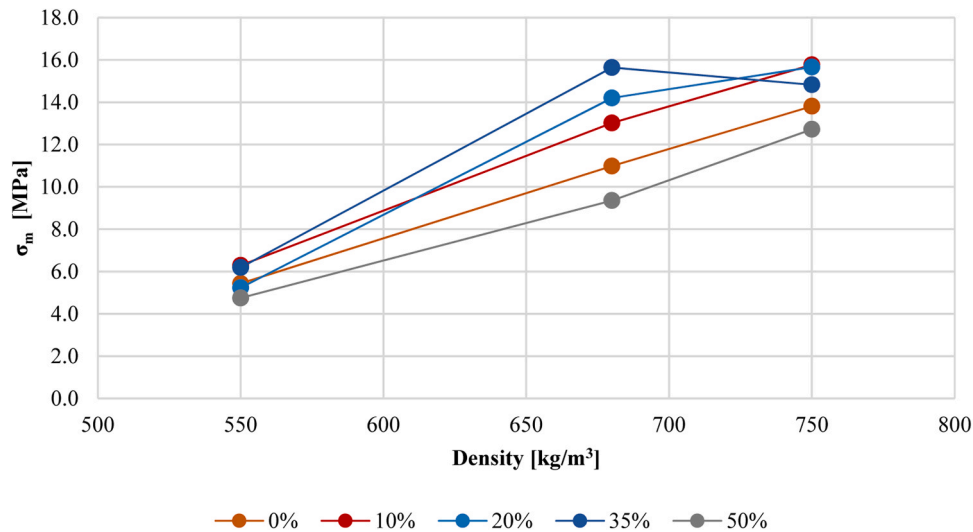


Fig. 10. Bending strength (σ_m) of the particleboard over the Density of the board according to the percentages of A. donax in the core.

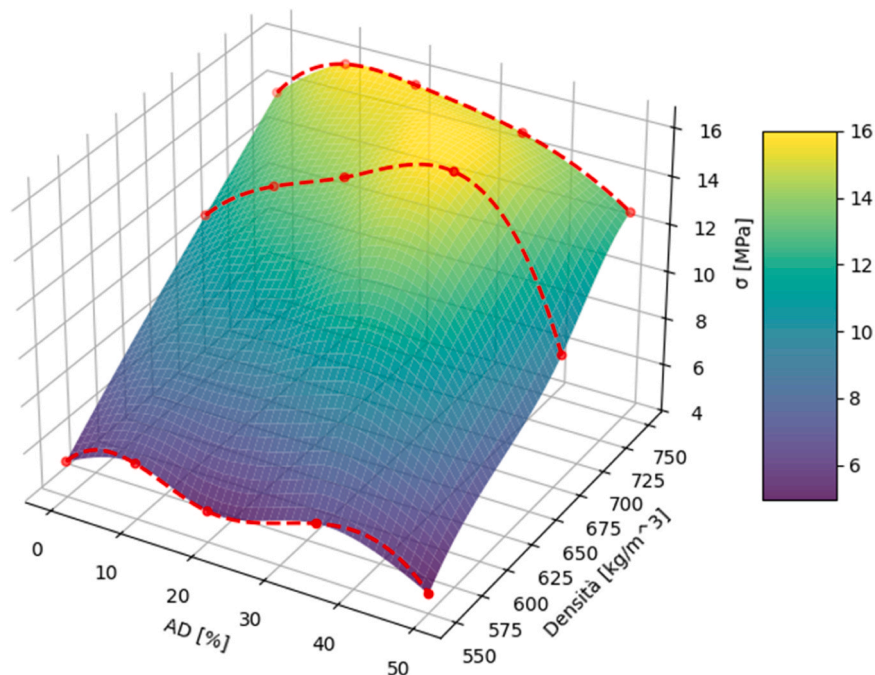


Fig. 11. A response surface with two input variables, the density and the Arundo donax percentage and the output being the bending strength σ_m .

particleboard, however considering the standard deviation the specimen with a 10 % A. donax content does not meet the minimum requirements for P4 classification. The specimens with the 750 kg/m³ density class exhibit average bending strength σ_m values above the standard limit, except for those with an A. donax percentage of 50 %, Fig. 12(a).

Fig. 12(b) reported the average Modulus of elasticity E_m for all the specimens, in which the red lines represent the standard limits associated with the P2 and P4 classes of particleboard. As can be observed only the specimens with a density of 750 kg/m³ exceed the minimum standard requirement except those containing 0 % and 50 % of A. donax.

The threshold value of an internal bond (IB) is set at 0.3 MPa, which is the same for both P2 and P4 class particleboards as shown in Fig. 12 (c), almost all specimens with densities of 680 kg/m³ and 750 kg/m³ exceed this limit.

For the TS, there is no threshold value for the P2 class, while for the P4 class the limit is set at 15 %, this indicates that the particleboard must

have a thickness swelling value below this threshold, as demonstrated in Fig. 12(d) all specimens with added A. donax, having densities of 680 kg/m³ and 750 kg/m³ exhibit thickness swelling values below 15 %, even when taking the standard deviation into account. In contrast specimens without A. donax addition shows thickness swelling values exceeding the standard limit.

Only the specimens with a density of 750 kg/m³ and the quantity of A. donax inside the core of 10 %, 20 % and 35 % are suitable for the P4 class considering also the standard deviation of the data.

In Table 7 the values of bending strength σ_m , Modulus of elasticity E_m , Internal bond (IB) and Thickness swelling obtained in this work were compared with those found in the literature regarding A. donax particleboards. Fernandez-Villena et al. (2020a,b) studied one-layer particleboards manufactured with a mixture of A. donax and wood. The resin that they used was urea formaldehyde, making it a very similar type of board compared to the one manufactured and characterized in

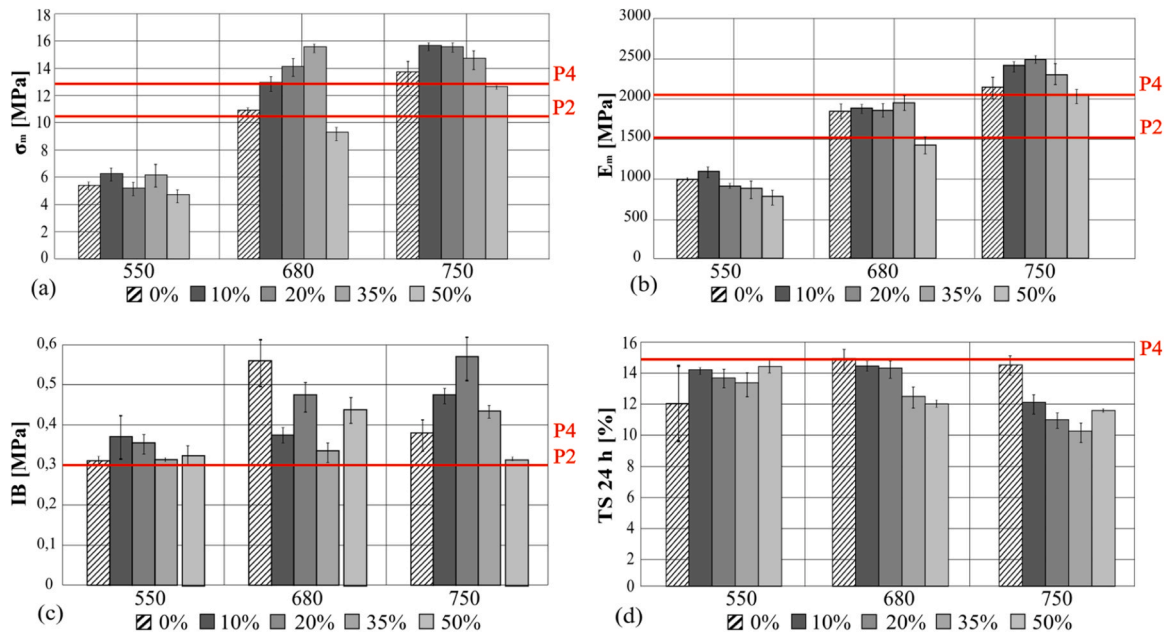


Fig. 12. Comparison with normative limits for different types of particleboard panels for the following characteristics: (a) bending strength σ_m , (b) Modulus of elasticity E_m , (c) Internal bond (IB) and (d) Thickness swelling 24 h.

Table 7

Comparison of values of Modulus of rupture (MOR), Modulus of elasticity (MOE), Internal bond (IB) and Thickness swelling 24 h (TS 24 h) of particleboard manufactured with Arundo donax or a mixture of Arundo donax and wood, found in literature and results obtained in this work.

Reference	Biomaterial	Binder	Density [kg/m ³]	MOR [MPa]	MOE [MPa]	IB [MPa]	TS 24 h [%]
(García-Ortuño et al., 2011)	A. donax	Urea Formaldehyde	628–758	9.9–17.7	1468–3026	0.26–1.31	15–36
(Flores-Yepes et al., 2011)	A. donax	Urea Formaldehyde	463–612	3.7–10.3	976–1362	\	\
(Flores-Yepes et al., 2012)	A. donax	Phenol-Formaldehyde	\	\	1250–3500	\	7–24
(Ferrández-Villena et al., 2020a)	A. donax	Binderless	735–913	10.5–14.2	1378–2052	0.58–1.12	43–73
(Ferrández-García et al., 2012)	A. donax	Non-modified starches	812–932	3.2–16.7	569–2521	0.04–0.40	18–80
(Ferrández-Villena et al., 2020a, 2020b)	A. donax and Wood	Urea Formaldehyde	631–850	8–19	900–2100	0.45–1.50	18–35
(Ferrández-García et al., 2020)	A. donax	Urea Formaldehyde	719.6–817.8	10.5–17.2	1190–2200	1.00–1.30	19–21
Present work	A. donax and recycled	Urea Formaldehyde	538–748	5.2–15.8	901–2471	0.31–0.57	14.7–10

the present study. Using in their research 50 % A. donax and 50 % virgin wood they obtained physical and mechanical values very similar to those obtained in the present study, as reported in Table 7.

Table 7 shows that the results obtained in this study are consistent with those from similar research both in mechanical and physical terms, which validates the work carried out here.

4. Conclusions

This study analyzed the physical and mechanical properties of a sandwich particleboard consisting of three layers where the outer layers are made of recycled wood and urea formaldehyde, while the inner layer is made of a mix of recycled wood and A. donax in varying quantities along with urea formaldehyde. The particleboards were tested for thickness swelling, internal bond, surface soundness and three-point bending to determine if they meet the minimum regulatory requirements for production and market commercialization.

Most studies in the literature focus on single-layer particleboards, this study, however, focuses the attention and analyses on a particleboard composed of three layers which represents the industrial standard for this type of panel. The two outer layers consist of finer particles with a higher percentage of resin and water, while the thicker inner layer is made of coarser particles. This results in a sandwich panel made with two different materials with distinct mechanical and physical properties.

Many of the choices made in this paper, starting with the material selection, were aimed at addressing issues, gaps, and requests from the

industrial sector including economic considerations, factors often overlooked in other research. For instance, the choice of A. donax was made to improve the mechanical properties of the board without increasing costs or modifying the industrial production process. An important parameter considered in the production process is the pressing time, which is very limited: the particleboard cannot remain under pressure for more than 4 minutes due to economic constraints, as exceeding this time limit would render the panel economically unviable.

A comparison with the literature was conducted to better understand, discuss and validate the results. The conclusions achieved are reported below:

1. The study identified a linear relationship between increased density and the bending properties of the particleboards. Higher densities improve the interconnection between chips and increase the adhesion between the resin and A. donax chips. As A. donax has a smoother outer surface (Al-Snafi, 2015) compared to wood the resin adhesion is more challenging and less stable at lower densities. However, increasing the compaction pressure improves this connection.
2. It was observed that at low densities (550 kg/m³) there are no significant changes in mechanical properties with changing the amount of A. donax inside the core of the particleboard, this is due to a combination of two factors.
3. The optimal quantity of A. donax chips to be included in the core of the particleboard, which yields the best mechanical performance

varies somewhat with the particleboard density. Specifically, as density increases, the optimal quantity of *A. donax* decreases from 20–35 % of the total chips in the inner layer. For all densities examined there was a significant drop in mechanical properties once the *A. donax* quantity reached 50 %, indicating that beyond a certain threshold further additions of *A. donax* lead to a decrease in mechanical properties, as noted in point 1.

- Thickness swelling (TS) tests have shown that the addition of *A. donax* except at a density of 550 kg/m³ reduces particleboard TS and shows a positive effect of the material on the particleboard's water resistance. Since TS is primarily due to fine particle size found in the outer layers of the particleboard where no material changes were made (no *A. donax* chips added) the increase in water resistance that *A. donax* could provide would likely be greater if the material were also used in the outer layers.
- The goal of transitioning from a non-structural P2 class particleboard to a structural P4 class was achieved without increasing the density or the amount of resin and thus the costs of the particleboard. This was made possible by substituting a portion of the recycled wood with *A. donax* only in the inner layer of the board, specifically for the density of 750 kg/m³ particleboards with *A. donax* substitution ranging from 10 % to 35 % meet all the requirements for classification as P4 particleboards. For the density of 680 kg/m³ specimens with 35 % of *A. donax* fulfill three out of the four necessary parameters for P4 classification, the only parameter that did not meet the minimum requirements was the Modulus of elasticity E_m .

The results presented in this study demonstrate the feasibility of producing composite particleboards with the addition of *A. donax* a species that could be cultivated across wide areas of the Italian peninsula including lands unsuitable for food crops.

CRedit authorship contribution statement

G. Donini: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **L. Crociati:** Formal analysis, Data curation. **L. Molari:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **M. Ferrante:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **G. Conidi:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **P. Zambelli:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Funding

Letizia Crociati received funding from the European Union - Next-GenerationEU with funds made available by the Italian Ministry of University and Research under National Recovery and Resilience Plan (NRRP) Mission 4, Component 2, Investment 3.3 (M.D. 117/2023) and by Sadepan Chimica Srl.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve the language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Mattia Ferrante reports equipment, drugs, or supplies and statistical analysis were provided by Gruppo Saviola S.r.l. Giulia Conidi reports

equipment, drugs, or supplies and statistical analysis were provided by Gruppo Saviola S.r.l. Pierluigi Zambelli reports administrative support was provided by Gruppo Saviola S.r.l. Giulia Conidi reports a relationship with Gruppo Saviola S.r.l. that includes: employment. Mattia Ferrante reports a relationship with Gruppo Saviola S.r.l. that includes: employment. Pierluigi Zambelli reports a relationship with Gruppo Saviola S.r.l. that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors wish to acknowledge Mario Marcolongo and Roberto Bianchi of the LISG Lab at the University of Bologna for their help in performing the tests and Prof. Stefania Manzi for her help in the analysis of the microscope.

Data availability

Data will be made available on request.

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