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ORIGINAL ARTICLE

Exploring the utilization potential of *Lantana camara*: particleboard and briquette development

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Abstract This study explores the utilization potential of *Lantana camara* (LC), a woody shurb eradicated from the forest and non-forest areas, for developing particleboards and briquettes. Research was conducted in four stages, the initial stage examined the anatomical characteristics of LC wood to assess its industrial suitability. The second stage focused on investigating the physical and mechanical properties of LC wood. In the third stage, 19 mm thick particleboards were manufactured using urea–formaldehyde as a binder, with a comprehensive evaluation of their physical and mechanical characteristics. The final stage investigated the development of briquettes and conducted a thorough analysis of their fuel properties. LC exhibits a composition of 25% lignin and 65% cellulose. Additionally, the cellular characteristics of LC, including the number of cells per ray and the cell frequency, were observed to be 12.5 and 4.6/mm. Moreover, particleboards from both LC (woody shrub) and *Melia dubia* (hardwood) demonstrated comparable basic densities, approximately 410–550 kg/m^3 for LC and 481–501 kg/m^3 for *Melia dubia*. Further, LC briquettes exhibited an enhanced energy density of 23 GJ/m^3 compared to other commercially produced biomass. Hence, the study highlights the promising potential of LC as an alternative/substitute raw material to conventional wood for manufacturing value-added products.

Keywords *Lantana camara* · Invasive weed · Particleboard · Briquette · Calorific value

Introduction

The escalating demand for wood and timber products stands out as a significant catalyst for the alarming rate of deforestation, significantly impacting ecosystems and exacerbating climate change and biodiversity issues (Risse et al. 2019). The unrestrained production of panel products has fueled uncontrolled deforestation and the over-

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exploitation of plantations and natural forests. Consequently, there is a burgeoning interest in investigating alternative wood and wood-based bioresources sources. Unfortunately, a persistent imbalance exists between the demand for timber and timber-derived goods and the current timber resources, leading to continuous deforestation without sufficient replanting efforts. The rising demand for wood-based panel products challenges the future obtainability and base materials supply in the panel industry. Yet, the imperative to decrease dependence on wood, timber, and foresty asserts has prompted a renewed emphasis on exploring alternative materials to substitute wood in producing panel products. In instances of a disparity between the availability and demand for raw materials, the utilization of secondary raw materials, including agricultural residues, bamboo processing wastes, and other nonwood bio-resources, becomes a viable consideration. Using alternative wood resources for panel products will contribute to the circular economy, enhance waste management and utilization, support environmental cleanliness, preserve biodiversity, and reduce production costs for companies searching for raw materials.

A diverse array of value-added products has been reported and produced utilizing alternative bio-resources, encompassing materials such as wood chips (Liu et al. 2022), wood bark (Kairytė et al. 2020), sawmill shavings (Seraj et al. 2023), bamboo (Ranjan et al. 2024; Sewar et al. 2024) and bamboo waste (Kelkar et al. 2023), and other lignocellulosic materials (Wang and Dai 2005; Bredihhin et al. 2013; Mundike et al. 2017; Jiang et al. 2018; Gillela et al. 2022; Avudaiappan et al. 2023; Birniwa et al. 2023; Sheeba et al. 2023; Sewar et al. 2024). These materials are combined with a suitable binder and subjected to heat and pressure, creating products that extend beyond traditional offerings. The substitution of raw materials aims to alleviate the strain and reduce excessive reliance on wood/timber bioresources. India’s particleboard (PB) industry has achieved successful commercialization, which can be attributed to favourable conditions for raw material supply and anticipated future market demands. Timber residues, small-diameter timber trunks, and various types of agricultural waste can be effectively utilized through the PB manufacturing process. Particleboards find numerous non-structural architectural applications, including producing furniture, kitchen worktops, sliding doors, tabletops and speakers, cabinets (Sandberg 2016).

Lantana camara (LC) is among the most lethal invasive plants worldwide (Sandham et al. 2010; Priyanka and Joshi 2013; Ray and Ray 2014; Negi et al. 2019). This shrub, reaching heights between half a meter and two meters, is endemic to the tropics and subtropics of the Americas. Based on research and estimations, LC has proliferated to encompass 50 countries, with the number of species varying from 50 to 270 distinct organisms. A more precise assessment suggests approximately 150 species (Munir 1996; Negi et al. 2019). The introduction of Lantana in India occurred in the early nineteenth century. Since its introduction, it has spread extensively throughout the country, colonizing roadsides, railway tracks, crop field edges, non-forested areas, and forested regions, eventually becoming fully naturalized (Bhagwat et al. 2012).

Various research projects and investigations are ongoing across different regions of India, utilizing adaptation pathways for control and management. Assessing the practical application potential of Lantana, sourced from both forest and non-forest areas, is crucial to assigning economic value to this untapped bio-resource on a large-scale industrial level (Kumar et al. 2009; Sahoo et al. 2009, 2021; Deo 2010b; Deo and Acharya 2010; Kumar and Chandrashekar 2013; Ray and Ray 2014; Mundike et al. 2017; Shaik et al. 2022; Gillela et al. 2022; Ramkumar et al. 2023). Lantana stalks, owing to their slender nature, high durability, and abundant lignocellulosic material, present a viable alternative supply of raw material for industrial-level panel goods. Advancements in machinery and technology in India now enable the straightforward processing of Lantana stalks into particles, chips, or fibres. These processed materials can be utilized on an industrial scale, either partially or entirely, as a source of wood and lignocellulosic raw materials for an eco-friendly approach to manufacturing panel products. Given these significant challenges, there are synergistic benefits to utilizing Lantana stalks in particleboard production. Firstly, it is an alternative or complete substitute for wood in particleboard production sourced from forests and other agroforestry products. Secondly, areas surrounding hotspot locations may experience increased employment opportunities, providing rural residents with a new source of income through the production of particleboard from Lantana. Addressing the interconnected challenges of Lantana woody weed management (as a bio-resource) and the demand–supply imbalance in wood and wood-based industries, this research extensively explores the potential of Lantana as a renewable supply for particleboard and briquette manufacture. Papadopoulos 2006, explored the internal adhesive strength of conventional particleboard by varying the quantities of Urea Formaldehyde (UF) resin. Furthermore, it examined the influence of mat moisture content (MC), wax content, and platen temperature on the efficacy of the bonding process. The study revealed that boards bonded with UF were significantly more adversely impacted by the inclusion of wax. The escalation of wax content from 0 to 1% resulted in a notable 30% reduction in internal bond strength (IB). The addition of wax interferes with the hydrogen bonding forming while using UF resin (Papadopoulos 2006).

The study encompassed four stages. Firstly, an investigation was conducted to understand the anatomical characteristics of Lantana wood. Secondly, the physical and mechanical properties of lantana wood were examined, with subsequent comparison to selected rattan and bamboo species. In the third stage, single and three-layer particleboards (PB) with a thickness of 19 mm were produced from Lantana particles, utilizing urea–formaldehyde as a binder. Finally, the study examined the development of briquettes from the LC. This exploration may pave the way for new opportunities in utilizing Lantana as an alternative raw material to substitute conventional wood/timber in producing particles for value-added products such as particleboards and briquettes.

Materials and methods

Biomass from LC was sourced from the village of Gottipura in Hosakote, Bangalore. The geographical distribution of Lantana in a forested region and the collection process are depicted in Fig. 1. The Lantana wood and twigs underwent a process of chipping and hammer milling, resulting in the conversion of the material into particles. The Lantana wood were carefully cut into lengths ranging from 2 to 4 feet and then immersed in water to eliminate mud and other undesired extraneous materials. Knots and other irregularities, such as crooked wood, were separated and transformed into 2-foot wood stalks and subjecting the Lantana wood to sun-drying. The dried wood were then shaped into irregular patterns, each approximately 2 feet long, using a cross-cutting saw. The optimal moisture content for processing Lantana wood with a chipper is 30–40%. Nevertheless, it is noteworthy that moisture content up to 50% in Lantana may still be deemed acceptable for chipper processing. The Lantana wood is introduced into the chipper, where they undergoes chipping through a combination of shearing action and the impact of the knife. Subsequently, the resulting chips are fed into the hammer mill to process further and generate particles of varying sizes. The sized particles undergo drying until their moisture content reaches approximately 3–5%. Following the drying process, the particles are subjected to sieving, and based on their size, they are classified into face particles and core particles. Efforts were made to produce high-quality particleboards with enhanced strength, a smooth surface, and improved swelling properties. This was achieved by ensuring a homogeneous mix of particles with a high degree of slenderness (long, thin particles) while avoiding oversized particles, splinters, and dust. ASTM E11 Sieve No. 4 & 10 segregates face particles within the 0.5–2.00 mm range, while Sieve No. 10 & 40 was used for coarse particles ranging from 2.01 to 4.75 mm.

Anatonamical study

Three sample blocks measuring 2.0 × 2.0 × 2.5 cm were extracted from the tree and immersed in boiling water until the blocks reached a softening state. Subsequently, a microtome was employed to cut sections from the softened block's cross, tangential, and radial surfaces, facilitating detailed analysis and examination. Microscopic examination was conducted to qualitatively and quantitatively observe each section of the slide under the microscope. Wood chips from the radial region underwent scratching and maceration to quantify fibre and vessel content using a mixture of 30% nitric acid (HNO_3) and a small amount of potassium chlorate ($KClO_3$). The heating process continued until the wood pieces achieved a colorless state. Subsequently, the specimens underwent a water-washing step to eliminate any residual acid. Thirty intact fibers were then selected for the measurement of lengths and diameters. The double-wall thickness was determined by subtracting the fibre's diameter from the lumen's diameter. Additionally, vessel length measurements were taken from the macerated material. The measurements were conducted using a Leica microscope, specifically the Laborlux-S POL model, along with dedicated image analysis software (Sharma et al. 2015).

Preparation of binder

LC particleboards were prepared using conventional UF resin. Urea–formaldehyde-based thermosetting compositions are widely used in the panel industry for they are inexpensive, highly reactive, compatible with wood, have a lower curing temperature and shorter pressing time compared to most resins (Ansell 2015; Dunky 2017; Ramkumar et al. 2023; Němec et al. 2024). The resin was formulated with a molar ratio of urea to formaldehyde of 1:1.72 or a weight ratio of urea to formalin of 1:2.3. Furthermore, in the preparation of the binder, a 10% melamine incorporation was implemented based on the weight of the total urea, contributing to the formulation of the adhesive. The reaction process allows the reactants to react at pH 8.0 for 90 min at a temperature of 90 °C ± 2 °C under reflux conditions. This procedural step is essential for the comprehensive formation of methylol urea. The ensuing reaction is finalized by introducing minimal amounts of dilute glacial acetic acid, with the pH carefully maintained within the range of 4.5–5.0. This addition facilitates the formation of UF polymer. After achieving the desired viscosity, indicated by a flow time in a B-4 flow cup of 16–17 s under hot conditions, the pH of the resin is adjusted to a range of 7.5–8.0. Following this, the resin undergoes a cooling process. Once the temperature reaches 60 °C, a second urea addition, constituting 10% based on the weight of the

Fig. 1 Collection and sampling of *Lantana camara*

initially taken total urea, is introduced. This sequential step plays a pivotal role in the resin formulation, contributing to the overall composition and properties of the final product. This addition serves to mitigate formaldehyde emission levels in the final product. Incorporating a second urea serves a crucial purpose, namely, maintaining a sufficient free urea within the resin system. This free urea acts as a scavenger, effectively capturing any residual free formaldehyde present after the preparation process and absorbing free formaldehyde generated during the hot pressing of the particleboard. The current study used melamine as a scavenger to absorb free formaldehyde from the UF resin. This strategic use of melamine aims to enhance the efficiency of formaldehyde removal from the resin system, aligning with efforts to minimize formaldehyde emissions in the final particleboard product. Tables 1 and 2 provide the resin properties and formulations.

Particleboard manufacturing

Manufacturing particleboard employing a dry process is one of the earliest wood-based techniques. It rose to prominence during the early twentieth century and was designed to efficiently utilize inferior timber and wood waste during the limited availability of high-quality wood. Furthermore, this particleboard manufacturing technology is designed to be applicable for utilizing sawdust, mill residues, waste wood, and other non-wood lignocellulose materials. Reducing wood or timber into particles, typically less than 2 mm in any dimension, and subsequently forming them into panels through compression enables the production of lightweight particleboard with outstanding strength, dimensional stability, and surface properties. This can be achieved cheaply, with the particles bound together using adhesive resin, traditionally UF. Two distinct production methods were employed: flat hot pressing and extrusion. The choice between these methods for product development was based on the specific application of the final product. This study employed the first method, wherein the particles were oriented parallel to the panel surface. Three-layered and single-layered particleboards were produced, utilizing 8% urea formaldehyde resin based on the weight of oven-dry core particles and fine particles, with 12% solid resin based on the weight of the particles. The size of face particles ranged from 0.50 to 2.00 mm, while coarse particles varied from 2.01 to 4.75 mm, influencing the particle's surface area (Youngquist 1999; Pan et al. 2007). As a result, finer particles require a higher resin consumption than core particles; therefore, the resin flow rate for face particles is maintained at a higher level. The mat was formed by arranging lantana face particles and coarse particles in the desired configuration to achieve a density within the target range of 700–800 kg/cm^2. Mat formation was conducted using a lab-scale wooden mould measuring 66 cm × 66 cm × 19 mm, with a manual assembly of face-core-face particle pattern. Additionally,

Table 1 Properties of resin

S. no	Particulars	Findings
1	Flow time of resin using B4 flow cup at 27 ± 2 °C	20–22 s
2	Water tolerance	1:2–1:3
3	Solid content	50%
4	Gelation time	62 s
5	Shelf life	One and a half months

Table 2 Mix proportion for adhesive formation

S. no	Particulars	Face particles (40%)	Core particles (60%)
1	Liquid UF resin	48 gms (12%)	48 gms (8%)
2	Wax emulsion—0.5%	0.48 gms	0.48gms
3	Scavenger—2.5%	2.4 gms	2.4 gms
4	Liquor Ammonia	0.4 ml	0.3 ml
5	Hardener	0.38 gms (0.4)	0.67 gms (0.7)
	Water	2.79 gms (1:8)	0.95 gms (1:4)
6	Particle flow rate	1.5 kgs/10 s	2.5 kgs/10 s
7	Glue flow rate	400 gms/10 s	470 gms/10 s

the shape and size pattern of the chipped particles are depicted in Fig. 2. The face: core particle ratio was taken as 40:60 (Fine: Core), with the target density ranging from 700 to 800 kg/m^3. Based optimization done by our previous research works the ratio was fixed, the ratio of fine and core particles was established to ensure an effective finish for the particleboard. This ratio will balance the mixing of core and fine particles, resulting in a more refined and consistent finish (Prakash et al. 2017; Ramkumar et al. 2023). The specific pressure applied for the material in the compression and curing cycle was 25 and 12 kg/cm^2, respectively. Indeed, comparative studies involving particleboards from *Melia dubia* were also conducted.

Briquetting Manufacturing

Briquetting involved utilizing particles ranging in size from 5 to 7 mm, and the moisture content of Lantana particles was carefully maintained within the range of 15–20%. LC biomass, in its natural state, poses challenges as an energy feedstock due to factors such as elevated moisture content, uneven shapes and sizes, and comparatively low bulk density. Figure 3 displays the outcomes obtained using an industrial briquetting device with a 90 mm diameter and a production capacity ranging from 1.5 to 2.0 tons per hour to create biomass briquettes. This device employs ram and piston technology to propel biomass material into a tapering die through the reciprocating motion of the ram. The reciprocating motion of the two load wheels (flywheels) propels the piston into the die, facilitating the briquetting process. The process induces substantial heat within the die, causing the lignin to soften. As the softened lignin subsequently cools down, it facilitates the binding of fibers, as observed in work (Grover and Mishra 1996). The MC in the feedstock is a crucial factor influencing the quality of briquettes. Therefore, meticulous attention was given to controlling the MC during the briquetting process, as highlighted in the study by Mani et al. (2006).

Testing

Lantana wood, organized by diameter, were chopped and dried until reaching a moisture content of 12%. The density of Lantana wood was assessed in accordance with IS 1708:1986 (Part 2), deriving the mean value from five specimens. The mechanical properties of Lantana wood, including MoR, MoE, compressive strength, and tensile strength, were determined in conformity with IS 1708:1986 (Part 5), IS 1708:1986 (Part 8), and IS 1708:1986 (Part 12), respectively (IS 1708 1986). These evaluations were conducted using five specimens in the universal testing machine (INSTRON Model). The characteristics of Lantana particleboards were assessed through a series of tests encompassing both physical and mechanical aspects. Physical tests were conducted, adhering to the specifications outlined in the Indian Standard IS 2380:1977 (Methods of testing wood particleboards from ligno-cellulosic materials) (IS 2380 1977). For mechanical evaluations, tests such as static bending, MoR, MoE, screw withdrawal and internal bond strength were carried out using the same standard. The test specimens underwent conditioning in a controlled environment with a relative humidity of 65 ± 5% and a temperature of 27 ± 2 °C until their masses reached a stable state.

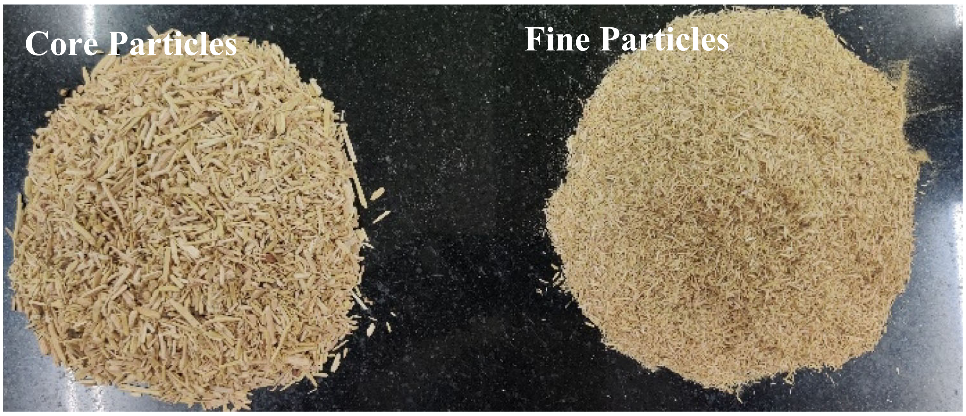

Fig. 2 Segregated core and fine particles based on the size of the particle

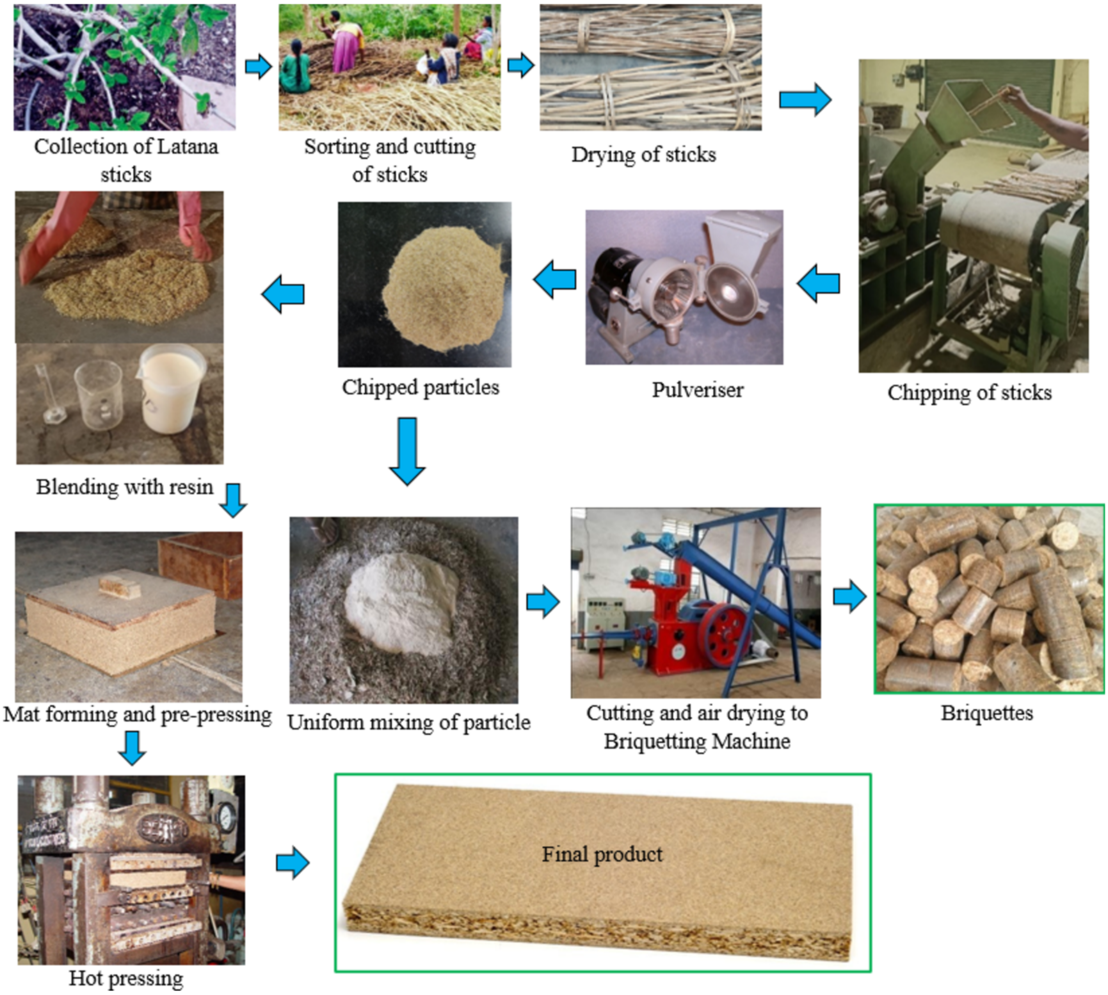

Fig. 3 Manufacturing process of PB and briquette

The particleboard's density was determined per (IS 2380 1977). The average values of five samples, each with dimensions of 150 mm × 75 mm, were calculated. Samples of size 150 mm × 75 mm were used to determine the MC. The sample was initially weighed (M_1), dried in a hot-air oven at 110 °C, and re-weighed (M_2) until a constant weight was achieved. The weight reduction, expressed as a percentage of the specimen's weight when thoroughly dried in an oven, indicates the specimen's moisture content and is determined through calculation. To assess water absorption (WA) and swelling due to general absorption, samples of two sizes were utilized: 300 mm × 300 mm for water absorption and 200 mm × 100 mm for swelling. The test specimens were submerged in water, with the water level reaching 30 mm above the specimen surface, and were allowed to soak for 2 h. The specimens were removed, and any surplus water was eliminated using a dry cloth. Subsequently, mass, length, width, and thickness measurements were promptly recorded. The specimens were then submerged in water for 24 h, and the identical procedure was replicated. The percentage of water absorption, swelling in thickness, length, and width were determined utilizing Eqs. 1–4.

$$\text{Water absorption, WA }(\%) = \frac{\mathrm{M_o} - \mathrm{M_1}}{\mathrm{M_1}} \times 100 \tag{1}$$

$$\text{Swelling in Thickness }(\%) = \frac{\mathrm{T_o} - \mathrm{T_1}}{\mathrm{T_1}} \times 100 \tag{2}$$

$$\text{Swelling in Length }(\%) = \frac{\mathrm{L_o} - \mathrm{L_1}}{L_1} \times 100 \tag{3}$$

$$\text{Swelling in Width }(\%) = \frac{W_\mathrm{o} - \mathrm{W_1}}{W_1} \times 100 \tag{4}$$

where $\mathrm{M_o}$: is the initial mass before submersion in water, $\mathrm{M_1}$: is the final mass after submersion in water, $\mathrm{T_o}$: is the average thickness before a test, $\mathrm{T_1}$: is the average thickness after test, $\mathrm{L_o}$: is the average length before the test, $\mathrm{L_1}$: is the average length after test, $\mathrm{W_o}$: average length before test and $\mathrm{W_1}$: average length after test.

A 5-ton INSTRON universal testing machine was employed to determine the MoE and MoR. The test specimen, measuring 600 × 50 × 19 mm, was utilized for the evaluation. In the bending test, the span was set at 24 times the nominal thickness to ensure pure bending during the test. The test specimen was supported at both ends, either by rollers or knives, and the specimens were subjected to a load applied at the centre, with a rate of 1 mm/min (Fig. 4a). The MoE and MoR were calculated from the load–deflection curves using Eqs. 5 and 6, respectively.

$$\mathrm{MoR} = \frac{3P_{max}L}{2bh^2} \times 100 \tag{5}$$

$$\mathrm{MoE} = \frac{P_pL^3}{4\delta bh^3} \times 100 \tag{6}$$

where $\mathrm{P_p}$: relative to the center of the span, δ: the amount of bending deformation (mm), $\mathrm{P_p}$: is the difference between the upper limit load and lower limit load in the proportional limit (N), h: is the thickness of specimen (mm), b: width of the specimen (mm), $\mathrm{P_{max}}$: maximum load (N) and L: span (mm).

The internal bond strength assessment was conducted using a 1-ton INSTRON universal testing machine, employing a continuous crosshead speed of 0.8 mm/min. Here, $\mathrm{F_{max}}$ represents the failure load, and (a × b) denotes the cross-sectional area of the specimen (Fig. 4c). A test specimen measuring 500 mm × 50 mm was utilized. The internal bond strength (f_t) was calculated in accordance with Eq. 7 (IS 2380 1977).

$$\text{Tensile strength perpendicular to the surface (Internal bond strength)} = \frac{F_{max}}{a \times b} \tag{7}$$

A threaded screw of size no. 8, with a length of 50 mm, was vertically drilled into particleboards, both on their edges and faces (Fig. 4b). The specimen's dimensions were 150 × 75 × 19 mm (length × width × thickness). The screw withdrawal resistance was determined by measuring the maximum pull, and the average of five measurements was calculated for accuracy.

The Lantana particles were pulverized for chemical and elemental analysis. The Lantana biomass powder that passed through 40 mesh sieves but was retained on a + 60 mesh sieve was utilized for analysis. The determination of lignin content employed the standard method (TAPPI T222 om-88), whereas the hemicellulose content was determined using a specific method (ASTM D1104-56 1978; TAPPI T 204 om-98 2002). To ascertain the gross calorific value (GCV), a sample of wood powder weighing one gram was transformed into pellets, subjected to oven drying at 80 °C, and combusted within an oxygen bomb calorimeter (LECO AC-350). A proximate analyzer (LECO TGA-701) was utilized to ascertain the ash and volatile matter content (VCC) in accordance with ASTM (ASTM D 5142-02 1994). The following equation was employed to formulate an estimate of the fixed carbon content (FCC):

$$FCC(\%) = 100 - [\text{Volatile content} + \text{Ash content} + \text{Moisture content}] \tag{8}$$

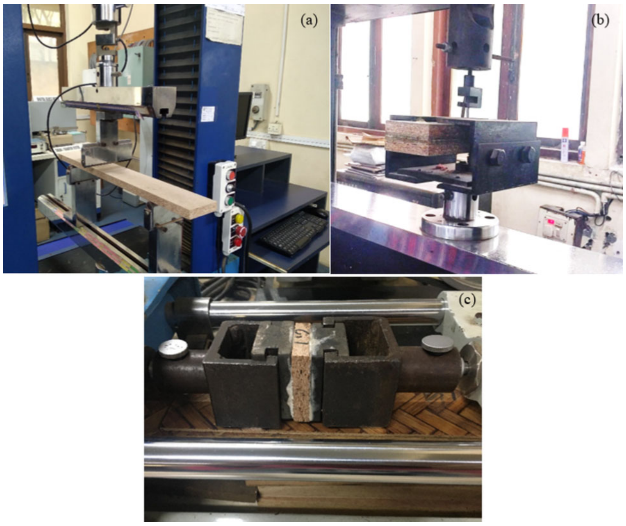

Fig. 4 Testing setup **a** Bending strength, **b** Nail snd screw withdrawal, **c** Internal bond strength

The elemental characteristics, specifically carbon and hydrogen, were assessed by employing a CHN analyzer (LECO- CHN-2000) in accordance with the standard procedure (ASTM D3176-89 2002). To mitigate experimental and instrumental errors, the trials were replicated five times, and the obtained data was utilized to calculate and present average values. The elemental composition of the ash was analyzed using a scanning electron microscope (SEM) coupled with Energy Dispersive X-ray Fluorescence Spectroscopy (EDXRF), specifically the Mini Pal 2 from PANalytical. The ash samples underwent a process of fine grinding, oven drying, and subsequent formation into pellets for analysis. The experimental data is presented as the average values obtained from five distinct locations within the samples, and the results were obtained in the form of elemental oxides (Kumar and Chandrashekar 2014).

The following formula was used to compute the sample's MC.

$$\mathrm{MC} = \frac{\mathrm{W}_1 - \mathrm{W}_2}{\mathrm{W}_2} \times 100 \tag{9}$$

where W_1 = Initial mass, g; W_2 = Oven dry mass of sample, g

Upon ejection, the density of the briquettes was promptly determined. Equation 10 determined the density ($\mathrm{kg/m^3}$) of the samples (D).

$$\text{Density (D)} = \frac{\mathrm{W_b}}{\mathrm{V_b}} \times 100 \tag{10}$$

where $\mathrm{V_b}$ is cylindrical briquette volume and $\mathrm{W_b}$ is the oven-dry mass of briquettes. The density of the briquettes was assessed employing stereometric techniques. A digital weighing balance was utilized to measure the mass of the briquette, while its volume was approximated by determining its radius and height using callipers (Demirbaş and Şahin 1998). The energy density (ED) of briquettes was determined using Eq. 11, as proposed by de Castro e Freitas et al. (2016).

$$\mathrm{ED} = \mathrm{D} \times \mathrm{GCV} \tag{11}$$

where D is the density of briquettes ($\mathrm{kg/m^3}$) and GCV is the briquette's gross calorific value (MJ/kg).

Results and discussion

Anatomical properties of Lantana

The vessels typically exist individually or in 2–3 radial multiples, occasionally containing tyloses. The average vessel length and diameter were measured at 197.3 and 116.4 µm, respectively, with a frequency of $7.8/\mathrm{mm}^2$. Additionally, the fibers exhibited an average length and diameter of 1369.4 and 16.5 µm, respectively, with an average fiber wall thickness of 9.23 µm. The rays were observed to be multiseriate, with a length and diameter averaging 129.6 and 25.1 µm, respectively. Each ray comprises 12.5 cells, and they occur with a frequency of 4.6/mm. The anatomical features of LC are presented and visually represented in Fig. 5. A previous study reported that a positive correlation exists between fiber wall thickness and density, suggesting that an increase in these parameters enhances the mechanical properties of wood (Hamdan et al. 2020). Another report indicated that anatomical properties such as fiber length, fiber wall thickness, and vessel diameter significantly impact the material's density and mechanical properties. The strength of wood is associated with a smaller vessel diameter and thicker fiber wall (Riesco Muñoz and Barrio Anta 2010; Sotannde et al. 2010; Van Duong and Matsumura 2018). The current study aligns with previous findings regarding the relationship between density and mechanical properties in particleboards. The particle and fiber board industries are heavily dependent on using short-rotation timber species, including but not limited to Eucalyptus, Poplar, Rubber wood, *Melia dubia*, and others. In the present study, the anatomical characteristics of LC were compared with those of *Melia dubia*. The results indicate that the observed characteristics fall within similar ranges for both materials, encompassing basic density, chemical composition, fiber wall thickness, fiber length, and vessel diameter. Consequently, the findings suggest that LC, compared favourably in anatomical characteristics with *Melia dubia*, could be an ideal or substitute material for industrial applications, particularly in developing particleboards and fiber boards.

Properties of Lantana wood

Tables 3 and 4 provide an overview of LC particles' physical and chemical composition and the mechanical characteristics of Lantana wood. The properties of Lantana wood exhibit variability based on their thickness. The mechanical properties of Lantana are notably affected by the diameter of the wood. Both essential density and mechanical characteristics demonstrate linear variations as the stem diameter increases from the base to the top. Nevertheless, these properties exhibit similarities with wood/bamboo/ agro-residue bioresources, suggesting promising potential for utilization. The LC weed, particularly, possesses favourable attributes such as noteworthy tensile strength and bending properties. Specifically, the density of Lantana falls within the range of 471–561 $\mathrm{kg/m^3}$. The findings indicate that Lantana woodwith a thickness exceeding 2.1 cm exhibit values comparable to those of Rattan and Cane species. However, when compared to

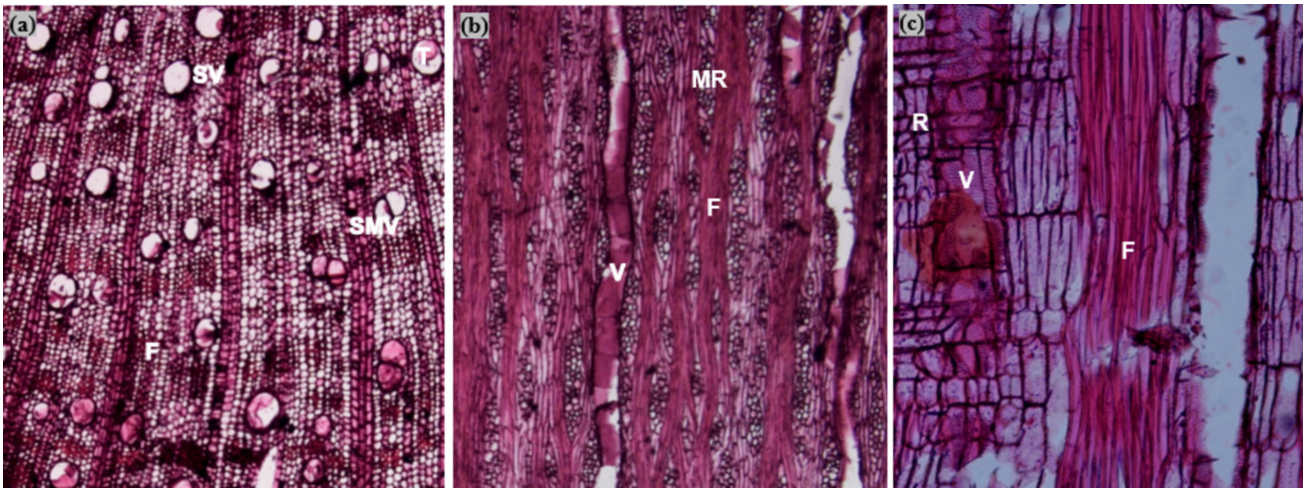

Fig. 5 Wood microscopic structure of *LC* **a** cross-section shows radial multiple vessels (RV) and solitary vessel (SV) **b** tangential sections showing multiseriate ray (MSR) and **c** radial section shows ray vessel pit (RVP)

solid wood, such as *Melia dubia*, the density values of Lantana are similar. The mechanical properties, including compressive and tensile strength, align closely with those of cane and rattan species (Yang et al. 2020). Nevertheless, Lantana exhibits slightly lower values compared to bamboo and solid wood. The Lantana bioresource holds significant potential as an eco-friendly and sustainable material for various livelihood applications, including toys, furniture, and other value-added products. This potential places it in a favourable standing compared to traditional materials like wood, rattan/cane and bamboo (Prakash et al. 2017; Yang et al. 2020; Ranjan et al. 2024). The distinctive attributes of the LC, including its thick and durable particles, ease of workability during milling and chipping, and chemical composition comparable to other ligno-cellulosic materials, position it as a promising option for environmentally conscious and sustainable product development (Deo and Acharya 2010; Bhagwat et al. 2012; Lee et al. 2022; Ramkumar et al. 2023). The properties of particleboards are very much dominated by cellulose, hemicellulose, lignin content, and extractives of wood particles. In this research, it has been noticed that the holocellulose content of *Lantana camara* is within the range of 66.89% that is lower than eucalyptus 72–75%, poplar 78%, or bamboo 70.42%. At the same time, it is more than that of bagasse and rice straw that varies between 58 and 60% (Soni et al. 2006; Baharoglu et al. 2013; Nadir et al. 2016; Mundike et al. 2017; Mesquita et al. 2019; Mahmud and Anannya 2021; Gillela et al. 2022; Hossain et al. 2024). Nevertheless, a thorough research effort, coupled with analytical and chemical studies, is imperative to gain a deeper understanding of the strength properties of Lantana in comparison to other bioresources.

Properties of particleboards

The board's physical and mechanical properties were determined and Figs. 6, 7, 8, 9, 10 present the results of the test samples. Furthermore, a comparative analysis with other lignocellulosic materials, such as *Melia dubia* (wood particles), was undertaken to understand its behaviour in developing particleboards (Saravanan et al. 2013).

Density of PB

Figure 6 illustrates the density values of particleboards crafted from Lantana and *Melia dubia*. Specifically, the density for three-layer particleboards made from Lantana

Table 3 Properties of Lantana wood

Location	Density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of rupture (MPa)	Modulus of elasticity (MPa)
LC (< 2 cm)	471 ± 61	21 ± 4.2	35 ± 4.8	41 ± 5.5	3748 ± 415
LC (2.1 cm – 3.5 cm)	544 ± 74	24 ± 3.1	42 ± 5.6	48 ± 6.8	4137 ± 357
LC (> 3.6 cm)	561 ± 68	26 ± 2.7	44 ± 4.4	49 ± 6.1	4249 ± 466

Table 4 Chemical composition of LC particles

Location	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Pectin (%)	Ash content (%)
LC	43.0 ± 4.1	23.5 ± 3.0	25 ± 3.0	3.0	1.0

measured 889 ± 69 kg/m^3, while the density for single-layer particleboards made from Lantana was 840 ± 94 kg/m^3. Compared with other ligno-cellulosic materials, the board density for *Melia dubia*-based particleboards was 888 kg/m^3. The study reveals that particleboards made from Lantana particles, bonded with the same UF resin adhesive, showed a density comparable to those crafted from *Melia dubia* particles. This similarity in density underscores the importance of lignin and cellulose, the primary components of wood, in imparting strength to the wood structure. In the examined study, LC contained 25% lignin and 65% cellulose, two crucial components with a substantial impact on density and mechanical properties. The number of cells in a ray emerged as a pivotal factor influencing density, and in the case of LC, the number of cells per ray and the frequency of cells were determined to be 12.5 and 4.6/mm, respectively. Interestingly, these values were found to be comparable to those observed in *Melia dubia* (Kumar et al. 2009; Swaminathan et al. 2012; Kumar and Chandrashekar 2013; Dhaka et al. 2020; Hamdan et al. 2020; Sharma et al. 2021; Lakshmanan et al. 2023). The study found that LC shrub stems and *Melia dubia* hardwood had similar basic densities, approximately 500 kg/m^3. LC's density ranged from 410 to 550 kg/m^3, while *Melia dubia* showed a range of 481–501 kg/m^3, emphasizing their proximity in basic density values (Swaminathan et al. 2012; Ramkumar et al. 2023). This similarity in basic density between LC and MD may be attributed to their comparable chemical compositions, particularly in cellulose and hemicellulose components.

In general, various factors such as particle size, slenderness, density, chemical components, compatibility, particle amount, resin content, and other processing parameters play a role in the properties of particleboards (Youngquist 1999; Pan et al. 2007; Baharoglu et al. 2013; Lakshmanan et al. 2023; Dhanakodi et al. 2023; Ramkumar et al. 2023). The overall density of particleboards produced from LC and MD falls within the 840–889 kg/m^3 range. However, as depicted in Fig. 6, no significant difference was observed in the multi-layer particleboards from both materials. This lack of distinction can be attributed to factors such as the number of cells per ray, frequency of cells, basic density, fiber wall thickness, vessel diameter, and other chemical compositions (Copur et al. 2007; Swaminathan et al. 2012; Baharoglu et al. 2013; Kumar and Chandrashekar 2013, 2014; Dhaka et al. 2020; Gursoy and Ayyildiz 2020; Lakshmanan et al. 2023). Regarding the finishing and smoothness of PB, crucial factors include particle size, resin content, and process parameters. These elements play a vital role in influencing the overall quality of the production process. PB crafted from three-layer particles exhibited superior gap-filling ability, fewer voids, and a smoother surface (Ramkumar et al. 2023). In contrast, PB produced from a single-layer structure had a rough surface with limited pits. This study suggests that constructing three-layered particleboards may result in smoother and enhanced properties compared to single-layer PB from Lantana particles. In three-layer particleboards, the placement of fine particles (0.5 mm $< x <$ 2.0 mm) on the surface (both upper and inner) and coarser particles (2 mm $< x <$ 4.75 mm) in the middle contributes to better dimensional stability.

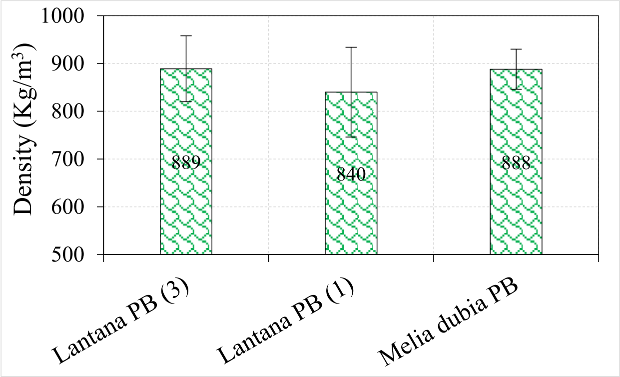

Fig. 6 Density of various PB from different bioresource sources

Also, The particle size selected for the study, based on (Youngquist 1999; Wang and Sun 2002; Pan et al. 2007; Cosereanu et al. 2015; Ranjan et al. 2017; Mundike et al. 2017), ranged from 4 to 40 mesh. This size range resulted in improved values for absorption, swelling, density, modulus of elasticity (MoE), modulus of rupture (MoR), and internal bond strength (IB). These particle sizes provided optimal results due to better resin distribution and bonding. A suggested ratio of fine particles to core particles is 40:60 percent for optimal results (Prakash 2013).

Water absorption and swelling of PB

The dimensional stability of the particleboard was evaluated through surface absorption, swelling, and water absorption tests. The moisture content of the particleboards ranged from 5 to 7%, and the observed variation was found to be impacted by the presence of functional groups in the chemical components, particle porosity, and the density of both Lantana and *Melia dubia* particles. (Baharoglu et al.

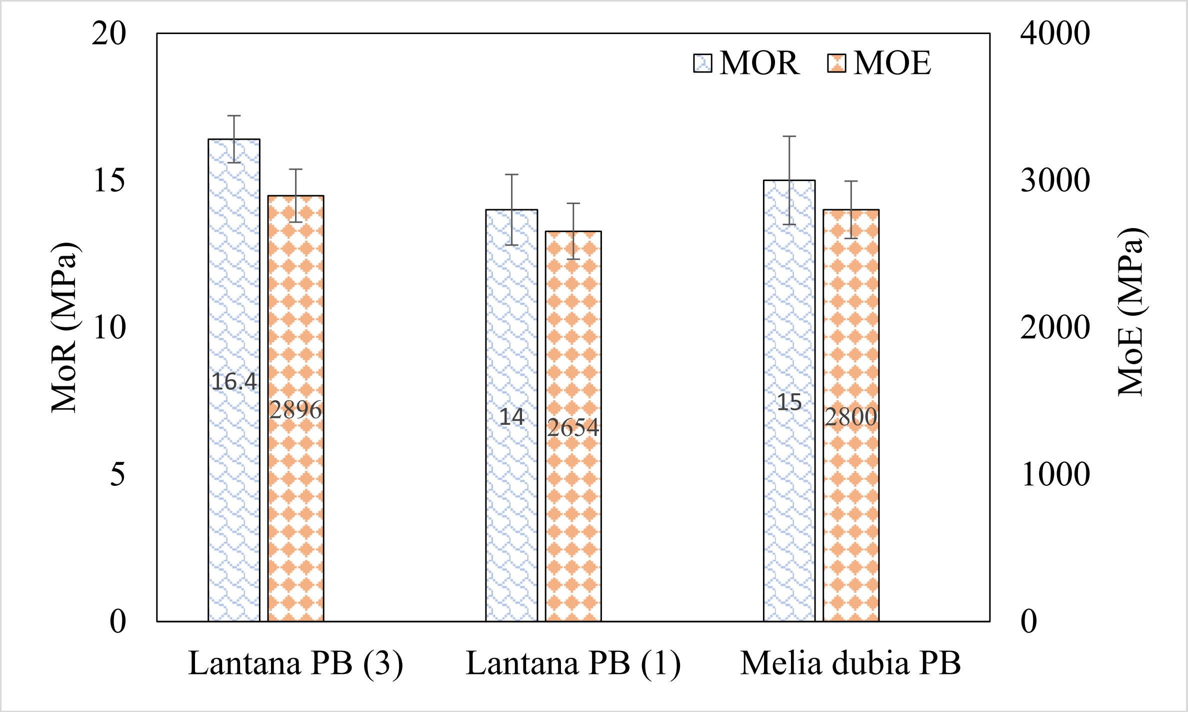

Fig. 7 MoR and MoE of various PB from different bioresource sources

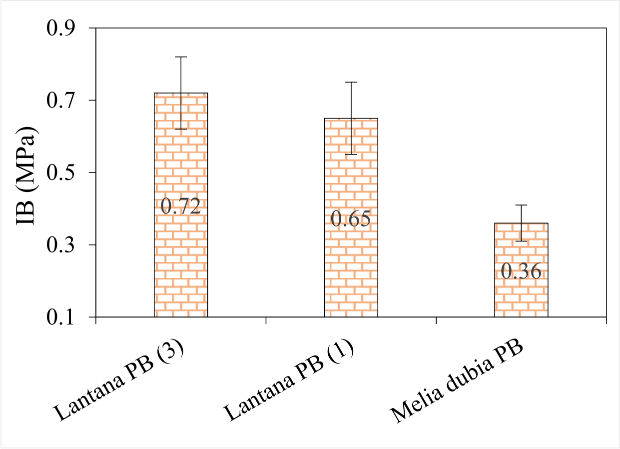

Fig. 8 Internal bond strength of various PB from different bioresource sources

2013). Importantly, all particleboard's moisture content complied with Indian and international standards, falling within the specified range of 5–13% (IS 3087 2005; BS EN 312:2010 2010). Table 5 presents the values of water absorption for both 2 h and 24 h. It was observed that both swelling and water absorption values of particleboards increased with a longer soaking time. Following a 2-h immersion, the absorption values of Lantana particleboards ranged from 29.7 to 21.5%, with corresponding thickness swelling values falling within the range of 11.6–9.4%. After 24 h of immersion, the absorption values for Lantana particleboards extended from 66.8 to 39.6%. Additionally, the surface absorption values for three-layer particleboard and single-layer particleboard from Lantana are 5.0% and 6.3%, respectively. As expected, the three-layer particleboard outperforms the single-layer particleboard made from Lantana. Comparatively, the absorption and swelling values are similar to those of *Melia dubia* particleboard. This indicates that the dimensional stability of particleboards is influenced by several factors, including particle hygroscopicity, density, compaction, resin content, compression cycle during pressing, particle size, shape, and the chemical composition of the particles (Papadopoulos 2006; Cosereanu et al. 2015; Sharma et al. 2021; Martins et al. 2021; Lakshmanan et al. 2023).

In the present study, both Lantana and *Melia dubia* have 25% and 28% lignin contents, respectively, imparting a hydrophilic nature and exhibiting water-repellent effectiveness. In general, voids within PB can facilitate the penetration of water molecules during immersion, increasing the distance between particles and potentially causing internal swelling in the boards (Back 1987; Papadopoulos 2006). This study utilised particle sizes ranging from 2 to 11 mm in both multi-layer and single-layer particleboards. A liquid urea–formaldehyde resin with a 50% solid content was employed, and 0.5% wax emulsion, based on the liquid resin, was added to enhance the hydrophobic properties of the particleboard. The compression cycle applied a total pressure of 25 kg/cm^2,

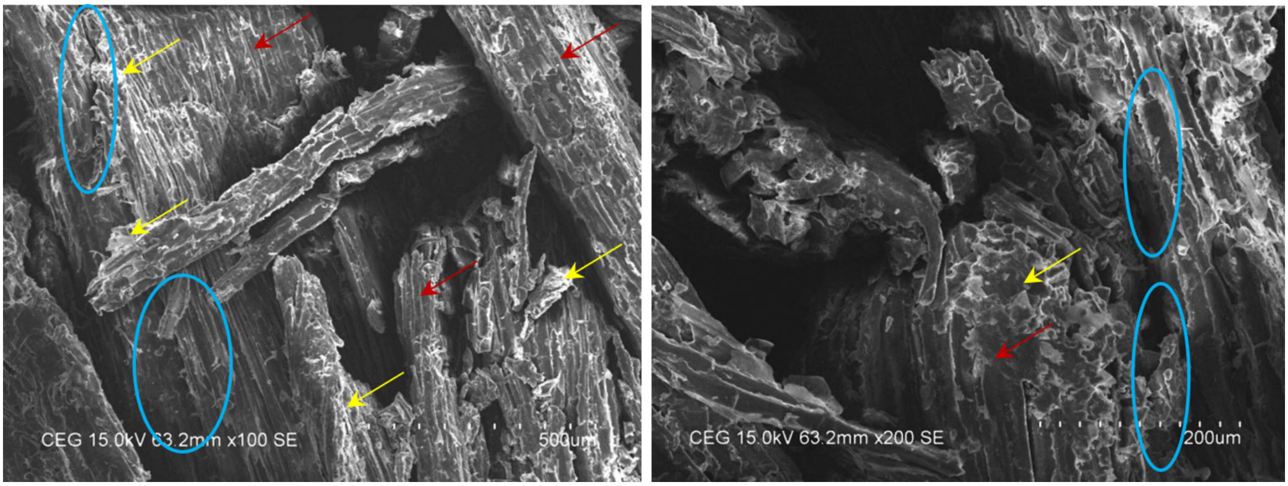

Fig. 9 Spread of adhesive on Lantana particles to provide effective bonding

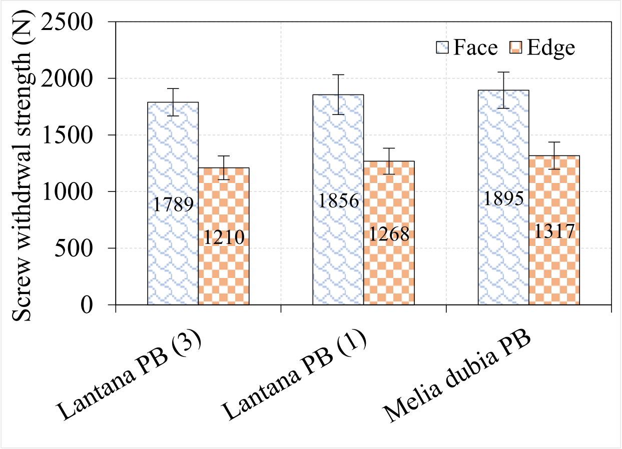

Fig. 10 Screw withdrawal strength of various PB from different bioresource sources

resulting in high compactness on the surface by reducing porosity in the particleboard due to the smaller particle size. Additionally, using wax emulsion in the adhesive system acted as a waterproofing agent, forming an emulsion-based polyvinyl urethane layer on the particleboard surface. The results indicated comparable performance between the three-layer and single-layer particleboards from LC, exhibiting performance similar to that of *Melia dubia* particles. For general-purpose particleboards, the Indian standard specifies a maximum absorption of 40% and 80% for 2 h and 24 h of soaking for three-layer boards. For single-layer boards, the recommended maximum absorption is 25% and 40% for 2 h and 24 h of soaking. A maximum thickness swelling of 12% and 10% is also specified for three-layer and single boards made from lignocellulosic materials. The results obtained in our study indicate that the boards produced meet the requirements outlined by IS 3087:2005 for general-use boards (IS 3087 2005). These findings are comparable to commercial particleboards from wood and other wood particleboards.

Modulus of rupture of PB

Indeed, the MoR is a measure of the bending strength of a test specimen using a three-point bending test. This property characterizes a material's ability to withstand bending forces without breaking. MoR is a crucial parameter, especially when materials are subjected to bending loads, such as in constructing beams or other structural elements. The MoR values for particleboards produced from Lantana, and *Melia dubia* were depicted in Fig. 7. Specifically, the

Table 5 Physical properties of PB

Properties, Unit	LC (3 layer PB)	LC (1 layer PB)	*Melia dubia* (3 Layer PB)	Minimum values for Gr II (multi layer)	Minimum values for (single layer)
Moisture content, %	5.38 (0.2)	6.21 (0.2)	6.79 (0.1)	5–15	5–15
Water absorption (2 h)	29.7	21.25	38.8	40	25
Water absorption (24 h)	66.8	39.58	75.2	80	40
General swelling, % Thickness	11.6	9.44	11.87	12	10
Surface absorption, %	5.05	6.28	7.24	9	9

Table 6 Properties of biomass

Species	Basic density (g/cm^3)	Proximate analysis (wt% dry basis)				Ultimate analysis (wt% dry basis)		Holo-Cellulose (% O.Dry wt)	Lignin (% O. Dry wt)	Calorific value (MJ/kg)
		MC	Ash	VCC	FCC	C	H			
L. camara	0.51	5.5	1.0	76.4	18.6	46.1	6.5	66.5	25.0	18.7

Table 7 Elemental analysis of biomass

Biomass feedstock	CaO	K_2O	SO_3	P_2O_5	SiO_2	MgO	Na_2O	Cl
L. camara	46.83	26.83	2.38	6.20	1.70	10.15	1.50	1.04

Table 8 Properties of LC briquettes

Wood species	Density (kg/m^3)	Calorific value (MJ/kg)	Energy density (GJ/m^3)
L. camara	1250	18.6	23.3

MoR values for particleboards made from Lantana were 16.4 ± 1.7 MPa for the three-layer board and 14 ± 2.1 MPa for the single-layer board. The Fig. 7 illustrates that the MoR of LC particleboards (both 3-layer and single-layer PB) is slightly superior to particleboards made from MD particles. This observation may be attributed to the influence of fiber wall thickness and vessel diameter, which significantly impact material density and mechanical properties. In this study, the mean wall thickness of Lantana was measured at 9.23 µm, with an average vessel diameter around 116.4 µm. In *Melia dubia*, the mean wall thickness ranged from 4.15 to 5.08 µm, and the average vessel diameter was between 193.07 and 202.76 µm. After 20 min of heat pressing at 150 °C, the Lantana particles were softened, allowing the UF resin to establish chemical connections with the particles before cross-linking with their functional groups. In the resistance against deformation under longitudinal (tensile) and compression (flexural) loading, it was concluded that the primary determinant of the mechanical properties of the particleboard is the bonding created between the UF resin and the particles at the interface (Kord et al. 2016; Lakshmanan et al. 2023).

Moreover, MoR increases with higher lignin content in LC particles, in proportion to MD particleboards. By serving as a filler and facilitating mechanical interlocking with particles, the rise in lignin concentration has the potential to bring about changes in the mechanical properties of the particleboard, improve compatibility, and reduce porosity, resulting in medium-density particleboards. Additionally, the three-layered particleboard, characterized by fewer voids, can better dissipate tensile and compressive forces during bending loads, leading to an increased MoR (Zvirgzds et al. 2022; Lakshmanan et al. 2023). Hammer-milled particles of Lantana exhibited MoR values comparable to particleboards made from various ligno-cellulosic materials, including wood lops, tops, and resources such as Poplar, Acacia catechu, *Melia dubia*, Pinus, Populus, Fagus, cassava stalks, agro residue, and bamboo (Nath et al. 2011; Prakash 2013; Dhaka et al. 2020; Sharma et al. 2021; Martins et al. 2021; Lee et al. 2022; Zvirgzds et al. 2022). However, when bamboo particles were used, previous studies reported higher MoR values than other ligno-cellulosic materials (for example, MoR—25 N/mm^2 by Nath et al. (2011). This difference could be attributed to factors such as the higher density of bamboo particles, slenderness ratio, utilization portion of bamboo, their long and thin geometry, and the silica content in bamboo particles. A study suggested that the thin and long dimensions of bamboo particles influenced the MoR values (Nath et al. 2011). In contrast, using consistent parameters for particleboards, Lantana particleboards demonstrated MoR values similar to those made from *Melia dubia* particles. Additionally, three-layer particleboards consumed a higher resin content during glueing than single-layer particleboards made from Lantana. This can be attributed to the larger surface area of particles in three-layer boards, leading to increased resin intake per unit area, ultimately enhancing the strength of the boards. Nevertheless, the MoR values of Lantana align with the specified requirements outlined in (IS 3087 2005).

Modulus of elasticity of PB

The Modulus of Elasticity (MoE), a parameter that signifies the stiffness of particleboard, was evaluated through three-point bending strength testing. Figure 7 illustrates MoE values for particleboards crafted from Lantana and *Melia Dubia*. Specifically, MoE values for 3-layered and 1-layered Lantana particleboards were 2896 ± 267 MPa and

2654 ± 243 MPa, respectively. The MoE values for Lantana particleboards were observed to be comparable and slightly higher than those of *Melia dubia*. Specifically, the MoE values for *Melia dubia* particleboards were 3955 ± 450 MPa for 3-layered boards and 2800 ± 310 MPa for 1-layered boards. Particleboards manufactured using LC particles demonstrated slightly superior properties to those crafted using *Melia dubia*. This enhancement in properties could be attributed to increased cell length, higher cell count in a ray, and elevated cellulose and lignin content in LC. The longer fibers of Lantana cellulose (LC), measuring 1369.4 µm, exceeded those of *Melia cubia*, where the mean fiber length ranged from 716 to 1055.5 µm in slow and fast-grown species (Swaminathan et al. 2012).

In addition, one can infer that the microscopic elasticity of particleboard is contingent upon the alignment and interconnection of chemical bonds among functional groups within particles, polymeric resins, and their ability to withstand weight under applied loads (Baharoglu et al. 2013; Lakshmanan et al. 2023). During the initial loading phase, LC and *Melia dubia* particles demonstrated comparable elastic behavior, underscoring the impact of functional groups and physical contact points in the hot pressing process. This procedure can potentially augment densification by fostering substantial chemical bonding, ultimately raising the flexural stress of the particleboard. Moreover, the mechanical properties of particleboards are influenced by myriad factors, including slenderness, bulk density, chemical components, adhesive compatibility, particle amount, resin content, particle alignment, and other processing parameters. The greater bulk, thickness, and hardness of Lantana particles, combined with their elastic attributes, led to lower MoE values compared to *Melia dubia*, which is consistent with findings from previous studies (Deo 2010a; Ramkumar et al. 2023). Overall, the MoE values of Lantana particleboards conform to the standards specified in (IS 3087 2005).

Internal bond strength of PB

The internal bond strength of particleboards indicates their tensile strength perpendicular to the surface, reflecting particle shape and size, resin content, pressure, curing temperature, board thickness, and board density. Figure 8 illustrates the tensile strength of particleboards made from Lantana, and *Melia dubia*. Specifically, the tensile strength values are 0.61 ± 0.1 MPa for single-layer particleboard and 0.75 ± 0.1 MPa for three-layer particleboard from Lantana. Compared to *Melia dubia* and other lignocellulosic materials, single-layer and three-layer particleboards from Lantana exhibited similar results. The three-layer particleboard displayed superior tensile strength compared to the single-layer particleboard, which was attributed to better resin spread and fewer voids in the board's structure. Optimal particle packing was observed in the three-layer particleboard, enhancing internal bond strength. Notably, Lantana particles demonstrated a hard, tough nature and high inhomogeneity compared to wood-based particleboards. Throughout the particle processing, Lantana particles exhibited durability and toughness, distinguishing them from *Melia dubia* particles and other wood-based lignocellulosic materials, as reported by Deo (2010a) and Ramkumar et al. (2023).

In general, formaldehyde resin establishes a mechanical bond with lignocellulosic materials through hydrogen bonds. This bonding phenomenon is likely attributed to the extensive coverage and penetration of UF resin into the pores and crevices of LC particles, ultimately enhancing bonding significantly and resulting in better mechanical interlocking. The enhanced bonding at the interfaces between UF resin and particles led to efficient stress transfer along these interfaces, as observed in the study by Wong et al. (1996) and Nath et al. (2011). The research conducted by Papadopoulos et al. in 2006 emphasized the detrimental impact of wax on the bonding performance of boards with UF resin. An increase in wax content from 0 to 1% resulted in a 30% reduction in IB (Papadopoulos 2006; Martins et al. 2021). Therefore, a balanced bonding performance and absorption were achieved by adopting a 0.5% wax content (Deppe 1977). Notably, the internal bond strength of both single-layer and three-layered particleboards meets the requirements specified for grade-2 particleboards in accordance with the IS 3087:2005 standard for particleboards of wood and other lignocellulosic materials (medium density) intended for general purposes (IS 3087 2005).

A representative section was chosen for SEM analysis to explore the morphological features of Lantana particleboards, as depicted in Fig. 9. Throughout the compression and curing cycle, the application of 25 kg/cm^2 pressure and a temperature of 150 ± 5 °C results in the cross-linking of the 50% solid content of urea–formaldehyde resin with the lignocellulosic components of the cells in Lantana particles. Even though identifying individual particles in the composite was challenging, the SEM and microscopic images enabled the observation of two key features: (i) the Lantana particle structure, comprising parallel fibers (indicated by brown arrows), and (ii) the adhesive distributed in a networked morphology, accumulating in the white areas (highlighted by yellow arrows). The microscopic analysis indicates a relatively homogeneous distribution of the adhesive within the particle matrix. At higher magnification, the presence of sharp breaks (highlighted by the blue circle), potentially resulting from the rigidity of the matrix, is also evident. The SEM and microscopic images reveal that the compressed Lantana particles exhibit the formation of an agglomerated structure. This agglomeration reflects the enhancement in the particleboard's internal bond strength and flexural strength, attributed to the reaction between the ligno-cellulosic components and the UF matrix during the curing process.

Screw withdrawal strength of PB

Screw withdrawal strength serves as a crucial indicator for assessing the joint strength of panel products during application. In Fig. 10, the screw withdrawal strength of Lantana, and *Melia dubia* particleboards is presented, along with their respective minimum required values as per IS 3087:2005. For three-layer particleboards from Lantana, the average face values were 1789 N and 1856 N, while the edge values were 1210 N and 1268 N. Comparable test values have been observed in other lignocellulosic materials. Specifically, withdrawal strength values for bamboo (Bambusa bamboo) and *Melia dubia* were 2990 N and 1895 N for the face and 1550 N and 1317 N for the edge, respectively. Similar results were observed for particleboards from A. Catechu and *Melia dubia*. Using UF resin, particleboards produced from bio-resources such as Lantana, bamboo and *Melia dubia* meet the minimum requirements of the IS 3087:2005 standard for general-purpose applications. It is important to note that all particleboard panels pressed at 160 ± 5 °C with a compression cycle for 8 min at 25 kg/cm^2 and a curing cycle for 7 min at 12 kg/cm^2 can yield superior panel products. The superior bonding performance observed in Lantana particleboards with UF resin may be attributed to the enhanced compatibility of Lantana particles with UF resin. This improved compatibility, coupled with the high coverage and penetration of UF resin into the pores and crevices of LC particles, ultimately resulted in a threefold enhancement in bonding. This phenomenon led to a more effective mechanical interlocking between UF resin and particles. The strengthened bonding at the interfaces facilitated an efficient transfer of stress along the particle interfaces, as discussed in the study by Nath et al. (2011) and Bonilla et al. (2015).

Biomass properties and fuel characteristics of briquettes

The summarized results of the physical, chemical, and elemental properties of LC biomass are presented in Tables 6 and 7. Additionally, Table 8 outlines the properties of LC briquettes. Key indicators of quality raw material for briquette development include ash content and fixed carbon content (FCC). For LC, the ash content, FCC, lignin content, and calorific value were recorded as 1.0%, 18.6%, 25%, and 18.7 MJ kg-1, respectively. The low ash content, around 1%, positions LC as a highly desirable fuel for boilers (McKendry 2002; Kumar et al. 2009). The results also highlight an elemental carbon content of approximately 46% in LC, positively influencing the calorific value (Kumar and Chandrashekar 2013). Elemental analysis revealed the presence of calcium (CaO—47%), potassium (K_2O—27%), and other minor elements in the biomass. The higher calcium content compared to silica (SiO_2—1%) and chloride (Cl—1%) in the ash of LC briquettes is advantageous for fuel utilization. Briquettes with high CaO and low ash content are effective in furnaces for cement clinker production (Ramkumar 2013; Konde et al. 2021). These characteristics of LC briquettes may alleviate boiler issues such as fouling, slagging, sintering, and corrosion when used as fuels (Olofsson et al. 2002; Cristescu et al. 2015). Furthermore, calcium and magnesium increase ash melting point, preventing ash-related problems (Öhman and Nordin 2000; Eufrade Junior et al. 2017).

In 2013, a study demonstrated that the optimum moisture content for briquette production is 10–15% (Kumar and Chandrashekar 2013). Similarly, in our study, we maintained the moisture content of LC briquettes at around 10–15% during the production process. This ensured a trouble-free briquetting process with minimal blockages and cracks. Throughout the process, the machine performed flawlessly with low power consumption, and the densification of the briquettes was effective. The optimal moisture content facilitates bonding through van der Waals forces by increasing the contact area between the Lantana particles (Grover and Mishra 1996). Table 6 presents the density (1250 kg/m^3), calorific value (18.6 MJ/kg), and energy density (23.3 GJ/m^3) of briquettes from LC. Silva et al. 2019 observed similar values from briquettes produced from eucalyptus wood waste (Density—1000 kg/m^3) (Silva et al. 2019). Comparable values have also been reported for the energy density of Eucalyptus clones of 4.5 and 5.6 years (Ramírez-Gómez et al. 2014; Eufrade Junior et al. 2017).

Conclusions

This study comprehensively explored the anatomical, physical, chemical, and mechanical properties of LC shrub (a woody weed). The feasibility of producing livelihood products was assessed, including particleboards manufactured from Lantana particles with UF resin as adhesive and briquettes. The findings indicate that creating single-layer and multilayer particleboards and briquettes from Lantana particles is technically feasible. This supports the efficient utilization of renewable biomass through adaptable management. Also, Forest conservation policies are stringent on natural forests and option for industries to get the supply from agroforestry species like Eucalyptus spp, Populus spp, *Hevea brasiliensis* (Rubber wood) and *Melia dubia* of short rotations. In the same aligning of chemical properties and better physical and mechanical properties, this weed LC could be an ideal alternative material for producing particleboard and fibre boards with or without other wood particles). Concluding the obtained results and the comparative study, the following insights were derived:

1. The anatomical properties, such as cell length, thickness, and the number of cells and fibers, along with chemical properties including cellulose, hemicellulose, and lignin content, play a significant role in influencing the density and mechanical properties of particleboards and briquettes made from LC wood.
2. The mechanical properties of LC are significantly influenced by the diameter of the wood, showcasing a linear variation pattern from the base to the top. Despite these variations, the properties exhibit similarities to other ligno-cellulosic materials, such as *Melia dubia* bio-resources, indicating the potential for utilization. LC weed presents favorable properties, including notable tensile strength and bending characteristics.
3. The density of Lantana falls within the range of 471–561 kg/m^3. Notably, Lantana wood with a thickness exceeding 2.1 cm demonstrate values comparable to those of Rattan and Cane species. However, compared to solid wood, such as *Melia dubia*, the density values of Lantana are similar. Furthermore, the mechanical properties of Lantana, including compressive and tensile strength, closely align with those of cane and rattan species.
4. The tensile strength values for Lantana particleboards were determined to be 0.61 ± 0.1 MPa for single-layer particleboards and 0.75 ± 0.1 MPa for three-layer particleboards. Notably, when compared to *Melia dubia* and other lignocellulosic materials, both single-layer and three-layer particleboards from Lantana demonstrated comparable results. Moreover, the three-layer particleboard exhibited superior tensile strength compared to the single-layer counterpart, a difference attributed to improved resin spread and fewer voids in the board's structure.
5. The MoR values for particleboards crafted from Lantana were determined to be 16.4 ± 1.7 MPa for the three-layer board and 14 ± 2.1 MPa for the single-layer board. The MoR of Lantana particleboards, both three-layer and single-layer, was slightly superior to particleboards made from *Melia dubia particles*. This difference in performance is likely influenced by factors such as fiber wall thickness and vessel diameter, which play a significant role in determining the material density and mechanical properties.
6. The MoE values for Lantana and *Melia dubia* particleboards were investigated, revealing distinct results for different layer configurations. In the case of Lantana particleboards, the MoE for 3-layered boards was determined to be 2896 ± 267 MPa, while for 1-layered boards, it was 2654 ± 243 MPa. Interestingly, the MoE values for Lantana particleboards were found to be comparable and slightly higher than those of *Melia dubia*. Specifically, *Melia dubia* particleboards exhibited MoE values of 3955 ± 450 MPa for 3-layered boards and 2800 ± 310 MPa for 1-layered boards. Future works can be explored on variying process parameters like heat, temperature, and lignocellulose materials such as Eucalyptus spp, Populus spp, *Hevea brasiliensis* (Rubber wood) and *Melia dubia* as partial replacements.
7. Briquettes produced from LC exhibited superior performance with characteristics such as lower ash content (1%), higher CaO content in the ash of LC briquettes (47%), elevated calorific value (18.6 MJ/kg), and enhanced energy density in LC briquettes (23 GJ/m^3) compared to other commercially produced biomass. This highlights the promising potential of LC briquettes for industrial production.

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Declarations

Conflict of interest No potential conflict of interest was reported by the author(s).

References

Ansell MP (2015) Wood microstructure-A cellular composite. In: Wood composites

ASTM D 5142-02 (1994) Standard test methods for proximate analysis of the analysis sample of coal and coke by instrumental procedures. ASTM Int

ASTM D1104-56 (1978) A Standards Test Method for Holo-cellulose in Wood. ASTM Int.

ASTM D3176-89 (2002) Standard practice for ultimate analysis of coal and coke. ASTM Int.

Avudaiappan S, Cuello Moreno PI, Montoya RLF et al (2023) Experimental investigation on the physical, microstructural, and mechanical properties of hemp limecrete. Sci Rep 13:22650. https://doi.org/10.1038/s41598-023-48144-y

Back EL (1987) The bonding mechanism in hardboard manufacture review report. Holzforschung. https://doi.org/10.1515/hfsg.1987.41.4.247

Baharoglu M, Nemli G, Sari B et al (2013) Effects of anatomical and chemical properties of wood on the quality of particleboard. Compos Part B Eng. https://doi.org/10.1016/j.compositesb.2013.04.009

Bhagwat SA, Breman E, Thekaekara T et al (2012) A battle lost? Report on two centuries of invasion and management of *Lantana camara* L. in Australia, India and South Africa. PLoS ONE 7:1–10. https://doi.org/10.1371/journal.pone.0032407

Birniwa AH, Abdullahi SS, Ali M et al (2023) Recent trends in treatment and fabrication of plant-based fiber-reinforced epoxy composite: a review. J Compos Sci. https://doi.org/10.3390/jcs7030120

Bonilla S, Marmol G, Fiorelli J, Savastano H Jr (2015) Particleboard with coir fiber and sugar cane bagasse: thermal–physical–mechanical properties. Acad J Civ Eng 33:682–686

Bredihhin A, Mäeorg U, Vares L (2013) Evaluation of carbohydrates and lignocellulosic biomass from different wood species as raw material for the synthesis of 5-bromomethyfurfural. Carbohydr Res 375:63–67. https://doi.org/10.1016/j.carres.2013.04.002

BS EN 312:2010 (2010) Particleboards - Specifications European Committee for Standardization. Eur. Stand. Organ.

Copur Y, Guler C, Akgul M, Tascioglu C (2007) Some chemical properties of hazelnut husk and its suitability for particleboard production. Build Environ. https://doi.org/10.1016/j.buildenv.2006.07.011

Cosereanu C, Brenci LM, Zeleniuc O, Fotin A (2015) Effect of particle size and geometry on the performance of single-layer and three-layer particleboard made from sunflower seed husks. BioResources. https://doi.org/10.15376/biores.10.1.1127-1136

Cristescu C, Sandberg D, Ekevad M, Karlsson O (2015) Influence of pressing parameters on mechanical and physical properties of self-bonded laminated beech boards. Wood Mater Sci Eng 10:205–214. https://doi.org/10.1080/17480272.2014.999703

de Castro e Freitas PC, Silva MF, Silva RT, Coneglian A, Sette CR Jr et al (2016) Evaluation of briquettes from bamboo species produced under different temperatures. Int J Curr Res 8:39260–39265

Demirbaş A, Şahin A (1998) Evaluation of biomass residue 1. Briquetting waste paper and wheat straw mixtures. Fuel Process Technol. https://doi.org/10.1016/S0378-3820(98)00041-1

Deo CR (2010a) Preparation and charactirization of polymer matrix composite using lantana camara.pdf. Ph.D. thesis

Deo CR (2010b) Preparation and characterization of polymer matrix composite using natural fiber *Lantana camara*. J Mech Civ Eng 008:280

Deo C, Acharya SK (2010) Effects of load and sliding velocity on abrasive wear of Lantana camara fibre-reinforced polymer matrix composite. Proc Inst Mech Eng Part J J Eng Tribol 224:491–496. https://doi.org/10.1243/13506501JET699

Deppe HJ (1977) Techinal progress in using Isocynate as an adhesive in particleboard manufacture, Presented at the 11th Particleboard Symposium, Pullman, Washington

Dhaka RK, Gunaga RP, Sinha SK et al (2020) Influence of tree height and diameter on wood basic density, cellulose and fibre characteristics in *Melia dubia* Cav families. J Indian Acad Wood Sci. https://doi.org/10.1007/s13196-020-00265-x

Dhanakodi AKP, Jenifer S, Ramkumar VR et al (2023) Optimization of process parameters during flax and polypropylene composite manufacturing using Box–Behnken design of experiments. Mater Today Proc. https://doi.org/10.1016/j.matpr.2023.11.103

Dunky M (2017) Adhesives in the wood industry. In: Antonio P, Kashmiri LM (eds) Handbook of Adhesive Technology, 3rd Edn. CRC Press, Boca Raton

Eufrade Junior HJ, Nakashima GT, Yamaji FM et al (2017) Eucalyptus short-rotation coppice for solid fuel production. Ind Crops Prod. https://doi.org/10.1016/j.indcrop.2017.07.025

Gillela S, Yadav SM, Sihag K, et al (2022) A review on Lantana camara lignocellulose fiber-reinforced polymer composites. Biomass Convers. Biorefinery

Grover PD, Mishra SK (1996) Biomass Briquetting: Technology and Practices. Regional wood energy development programme in Asia GCP/RAS/154/NET, Field document No. 46. Reg Wood Energy Dev Program Asia

Gursoy I, Ayyildiz H (2020) A design-based research of internet-based marketing plan software development for businesses. Nitel Sos Bilim. https://doi.org/10.47105/nsb.817308

Hamdan H, Nordahlia AS, Anwar UMK et al (2020) Anatomical, physical, and mechanical properties of four pioneer species in Malaysia. J Wood Sci. https://doi.org/10.1186/s10086-020-01905-z

Hossain MJ, Ghosh RK, Das AK et al (2024) Chemical composition and solubility properties of Bambusa bambos at different ages and height positions. Adv Bamboo Sci. https://doi.org/10.1016/j.bamboo.2024.100062

IS 1708 (1986) Methods of testing of small clear specimens of timber, 2nd edn. Bureau of Indian Standards, New Delhi

IS 2380 (1977) Methods of Test for Wood Particle Boards and Boards from Other Lignocellulosic Materials. Bureau of Indian Standards, New Delhi

IS 3087 (2005) Specification for particle boards of wood and other lignocellulosic materials (medium density) for general purposes-specification. Bureau of Indian Standards, New Delhi

Jiang W, Kumar A, Adamopoulos S (2018) Liquefaction of lignocellulosic materials and its applications in wood adhesives—a review. Ind Crops Prod 124:325–342. https://doi.org/10.1016/j.indcrop.2018.07.053

Kairytė A, Kremensas A, Balčiūnas G et al (2020) Evaluation of self-thermally treated wood plastic composites from wood bark and rapeseed oil-based binder. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.118842

Kelkar BU, Shukla SR, Nagraik P, Paul BN (2023) Structural bamboo composites: a review of processing, factors affecting properties and recent advances. Adv Bamboo Sci 3:100026. https://doi.org/10.1016/j.bamboo.2023.100026

Konde KS, Nagarajan S, Kumar V et al (2021) Sugarcane bagasse based biorefineries in India: potential and challenges. Sustain Energy Fuels. https://doi.org/10.1039/d0se01332c

Kord B, Zare H, Hosseinzadeh A (2016) Evaluation of the mechanical and physical properties of particleboard manufactured from canola (*Brassica napus*) straws. Maderas Cienc y Tecnol. https://doi.org/10.4067/S0718-221X2016005000002

Kumar R, Chandrashekar N (2013) Study on chemical, elemental and combustion characteristics of *Lantana camara* wood charcoal. J Indian Acad Wood Sci. https://doi.org/10.1007/s13196-013-0103-x

Kumar R, Chandrashekar N (2014) Fuel properties and combustion characteristics of some promising bamboo species in India. J For Res. https://doi.org/10.1007/s11676-014-0478-6

Kumar R, Chandrashekar N, Pandey KK (2009) Fuel properties and combustion characteristics of *Lantana camara* and Eupatorium spp. Curr Sci 97:930–935

Lakshmanan A, Roy AN, Samanta KK et al (2023) Development of a composite product from fibre yielding crop residues. Ind Crops Prod. https://doi.org/10.1016/j.indcrop.2023.116986

Lee SH, Lum WC, Boon JG et al (2022) Particleboard from agricultural biomass and recycled wood waste: a review. J. Mater. Res. Technol. 20:4630–4658

Liu Z, Han C, Li Q et al (2022) Study on wood chips modification and its application in wood-cement composites. Case Stud Constr Mater. https://doi.org/10.1016/j.cscm.2022.e01350

Mahmud MA, Anannya FR (2021) Sugarcane bagasse—a source of cellulosic fiber for diverse applications. Heliyon 7:e07771

Mani S, Tabil LG, Sokhansanj S (2006) Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenerg. https://doi.org/10.1016/j.biombioe.2005.01.004

Martins RSF, Gonçalves FG, de Alcantara Segundinho PG et al (2021) Investigation of agro-industrial lignocellulosic wastes in fabrication of particleboard for construction use. J Build Eng 43:102903. https://doi.org/10.1016/J.JOBE.2021.102903

McKendry P (2002) Energy production from biomass (part 1): overview of biomass. Bioresour Technol. https://doi.org/10.1016/S0960-8524(01)00118-3

Mesquita RGA, Sanadi AR, Marconcini JM et al (2019) The effect of cellulose nanocrystals in sugarcane bagasse particleboards of pith and fibers. Cerne. https://doi.org/10.1590/01047760201925022621

Mundike J, Collard FX, Görgens JF (2017) Pyrolysis of Lantana camara and *Mimosa pigra*: influences of temperature, other process parameters and incondensable gas evolution on char yield and higher heating value. Bioresour Technol 243:284–293. https://doi.org/10.1016/J.BIORTECH.2017.06.086

Munir AA (1996) A taxonomic review of *Lantana cámara* L. And L. Montevidensis (spreng.) Briq. (verbenaceae) in Australia. J Adelaide Bot Gard 17:1–27

Nadir Y, Nagarajan P, Ameen M, Arif MM (2016) Flexural stiffness and strength enhancement of horizontally glued laminated wood beams with GFRP and CFRP composite sheets. Constr Build Mater 112:547–555. https://doi.org/10.1016/j.conbuildmat.2016.02.133

Nath SK, Mamatha BS, Sujatha D, et al (2011) Development of Bamboo particleboard, IPIRTI Research Report 160, Bangalore

Negi GCS, Sharma S, Vishvakarma SCR et al (2019) Ecology and Use of *Lantana camara* in India. Bot Rev 85:109–130. https://doi.org/10.1007/s12229-019-09209-8

Němec M, Prokůpek L, Obst V et al (2024) Novel kraft-lignin-based adhesives for the production of particleboards. Compos Struct 344:118344. https://doi.org/10.1016/j.compstruct.2024.118344

Öhman M, Nordin A (2000) The role of kaolin in prevention of bed agglomeration during fluidized bed combustion of biomass fuels. Energy Fuels. https://doi.org/10.1021/ef990198c

Olofsson G, Ye Z, Bjerle I, Andersson A (2002) Bed agglomeration problems in fluidized-bed biomass combustion. Ind Eng Chem Res. https://doi.org/10.1021/ie010274a

Pan Z, Zheng Y, Zhang R, Jenkins BM (2007) Physical properties of thin particleboard made from saline eucalyptus. Ind Crops Prod. https://doi.org/10.1016/j.indcrop.2007.03.006

Papadopoulos AN (2006) Property comparisons and bonding efficiency of UF and PMDI bonded particleboards as affected by key process variables. BioRes 1(2):201–208

Prakash V, Uday DN, Sujatha D, Kiran MC (2017) Physical and mechanical properties of particle board from lops and tops of *Melia dubia*. Int J Sci Res 6:1499–1502

Prakash V (2013) Study on suitability of Melia dubia for laminated veneer lumber manufacturing, IPIRTI Research Report No.191/2013, Bangalore

Priyanka N, Joshi PK (2013) A review of *Lantana camara* studies in India. Int J Sci Res Publ 3:1–11

Ramírez-Gómez Á, Gallego E, Fuentes JM et al (2014) Values for particle-scale properties of biomass briquettes made from agroforestry residues. Particuology. https://doi.org/10.1016/j.partic.2013.05.007

Ramkumar VR, Thanigai K, Kiran MC et al (2023) Development of medium density particle board from *Lantana camara*. AIP Conf Proc 2901:050013. https://doi.org/10.1063/5.0179005

Ramkumar VR (2013) Uses of Alternative raw materials in the cement industry as sustainable waste management options, National Seminar on "Quest for Innovations in Civil Engineering—QICE'13" Organized by Vel Tech High Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai

Ranjan MA, Khali DP, Bhatt SH (2017) Effect of cement: wood particle ratio on physical and mechanical properties of cement bonded particle board using Lantana camara. Indian For 143:360–363. https://doi.org/10.36808/if/2017/v143i4/113690

Ranjan M, Kushwaha PK, Nandanwar A, Upadhyay VK (2024) Development of Bamboo reinforced cement bonded particle board. Adv Bamboo Sci. https://doi.org/10.1016/j.bamboo.2024.100095

Ray A, Ray R (2014) Rapid divergence of ecotypes of an invasive plant. AoB Plants. https://doi.org/10.1093/aobpla/plu052

Riesco Muñoz G, Barrio Anta M (2010) Physical properties of thinning wood in maritime pine (*Pinus pinaster* Ait): Case study. Eur J For Res. https://doi.org/10.1007/s10342-010-0388-x

Risse M, Weber-Blaschke G, Richter K (2019) Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products. Sci Total Environ 661:107–119. https://doi.org/10.1016/j.scitotenv.2019.01.117

Sahoo S, Reddy KHK, Dhayal RS et al (2009) Chlorinated hypoelectronic dimetallaborane clusters: synthesis, characterization, and electronic structures of (eta(5)-C5Me5W)(2)B5HnClm (n=7, m=2 and n=8, m=1). Inorg Chem. https://doi.org/10.1021/ic900467d

Sahoo A, Kumar S, Kumar J, Bhaskar T (2021) A detailed assessment of pyrolysis kinetics of invasive lignocellulosic biomasses (*Prosopis juliflora* and *Lantana camara*) by thermogravimetric analysis. Bioresour Technol. https://doi.org/10.1016/j.biortech.2020.124060

Sandberg D (2016) Additives in wood products—today and future development. In: Kutnar A, Muthu S (eds) Environmental footprints and eco-design of products and processes, environment. Springer, Singapore, pp 105–172

Sandham LA, Carroll TH, Retief FP (2010) The contribution of Environmental Impact Assessment (EIA) to decision making for biological pest control in South Africa—the case of *Lantana camara*. Biol Control 55:141–149. https://doi.org/10.1016/j.biocontrol.2009.12.010

Saravanan V, Parthiban KT, Thiruneraiselvan S et al (2013) Comparative study of wood physical and mechanical properties of melia dubia with tectona grandis at different age gradation. Res J Recent Sci 3:256–263

Seraj S, Azargohar R, Dalai AK (2023) Hydrothermal carbonization of sawmill shavings for fuel pellet production: a robust strategy for sustainable energy. J Clean Prod. https://doi.org/10.1016/j.jclepro.2023.138120

Sewar Y, Amran M, Avudaiappan S et al (2024) Bonding strength performance of bamboo-based composite materials: an in-depth insight for sustainable construction applications. Heliyon 10:e32155. https://doi.org/10.1016/j.heliyon.2024.e32155

Shaik RS, Gurusinghe S, Weston LA, Downey PO (2022) A historical perspective on plant invasion in Australia. In: Clements DR, Upadhyaya M K, Joshi S, Shrestha A (eds) Global Plant Invasions. Springer, Cham. https://doi.org/10.1007/978-3-030-89684-3_6

Sharma SK, Shukla SR, Shashikala S, Poornima VS (2015) Axial variations in anatomical properties and basic density of Eucalypt urograndis hybrid (*Eucalyptus grandis* × *E. urophylla*) clones. J For Res. https://doi.org/10.1007/s11676-015-0080-6

Sharma S, Negi A, Behera J, Naryal R (2021) Suitability of medium density particleboard from acacia catechu and melia dubia. J Trop For Sci. https://doi.org/10.26525/JTFS2021.33.3.247

Sheeba KRJ, Priya RK, Arunachalam KP et al (2023) Enhancing structural, thermal, and mechanical properties of *Acacia pennata* natural fibers through benzoyl chloride treatment for construction applications. Case Stud Constr Mater 19:e02443. https://doi.org/10.1016/J.CSCM.2023.E02443

Silva RT, Sette Junior CR, Ferreira A et al (2019) Wood and briquette density under the effect of fertilizers and water regimes. Floresta e Ambient. https://doi.org/10.1590/2179-8087.047116

Soni PL, Naithani S, Gupta PK et al (2006) Utilization of economic potential of *Lantana camara*. Indian For 132:1625

Sotannde OA, Oluyege AO, Adeogun PF, Maina SB (2010) Variation in wood density, grain orientation and anisotropic shrinkage of plantation grown *Azadirachta indica*. J Appl Sci Res 6:1855–1861

Swaminathan C, Vijendra Rao R, Shashikala S (2012) Preliminary evaluation of variations in anatomical properties of *Melia dubia* Cav. Wood Int Res J Biol Sci 1:1–6

TAPPI T 204 om-98 (2002) Solvent Extractives of Wood and Pulp, Test Method T 204 cm-17. Atlanta, Georg. TAPPI Press

Van Duong D, Matsumura J (2018) Transverse shrinkage variations within tree stems of Melia azedarach planted in northern Vietnam. J Wood Sci 64:720–729. https://doi.org/10.1007/s10086-018-1756-2

Wang BJ, Dai C (2005) Hot-pressing stress graded aspen veneer for laminated veneer lumber (LVL). Holzforschung 59:10–17. https://doi.org/10.1515/HF.2005.002

Wang D, Sun XS (2002) Low density particleboard from wheat straw and corn pith. Ind Crops Prod. https://doi.org/10.1016/S0926-6690(01)00094-2

Wong D, Razali K, Shuichi K (1996) Properties of rubberwood LVL reinforced with acacia veneers. Wood Res 8:8–16

Yang S, Xiang E, Shang L et al (2020) Comparison of physical and mechanical properties of four rattan species grown in China. J Wood Sci. https://doi.org/10.1186/s10086-020-1850-0

Youngquist JA (1999) Wood-based composites and panel products. In: Wood handbook: wood as an engineering material

Zvirgzds K, Kirilovs E, Kukle S, Gross U (2022) Production of particleboard using various particle size hemp shives as filler. Materials (Basel). https://doi.org/10.3390/ma15030886