

## Article

# The Feasibility of Producing Particleboards with Waste Wood from Civil Construction and Epoxidized Waste Cooking Oils

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**Abstract:** The feasibility of using epoxidized waste cooking oils as a partial replacement for synthetic resins in the manufacture of lignocellulosic composites where the reinforcement is comprised of mechanically ground wood from civil construction waste wood (CCWW) was investigated. For this study, the wood-epoxy composite was prepared using the thermo-curing technique, and wood particle contents of 20 and 30% (*m/m*) were studied with a matrix comprised of 50% epoxidized vegetable oil and 50% petroleum-based epoxy resin. The specific mass of the composites was in the range of 1130 to 1380 kg/m<sup>3</sup>, with the lowest value for the highest content of wood particles. Fourier transform infrared spectroscopy was successfully used to monitor the epoxidation of the vegetable oils and the subsequent curing of the epoxy resins and particleboards. Thermal stability of the composite was dictated by its lignocellulosic content, and significant mass losses occurred at temperatures higher than 300 °C, regardless of the wood particles content. The introduction of CCWW particles into the polymeric matrices did not promote the desired effect of improving the mechanical properties in regard to those of the cured blend of epoxy resins. However, the produced particleboards still met the standards of the American National Standards for general purpose boards in regard to their physical and mechanical properties (e.g., density, tensile strength). Hence, the use of wood waste and waste cooking oil to produce particleboards was deemed justified within the framework of a cascading lifecycle-extended service for both wastes.

**Keywords:** epoxy resin; epoxidized oil; wood-epoxy composite; civil construction waste wood



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## 1. Introduction

The recycling, repurposing, and upcycling of waste construction materials, such as wood, are currently being considered as a way to drastically reduce the volume of waste and the demand for virgin raw materials, thus fitting into the concept of circular economy [1]. Furthermore, because wood is a biodegradable material from renewable sources and presents exceptional mechanical and thermal characteristics, the repurposing of waste wood in a cascading service lifecycle allows for the efficient use of resources, extending total biomass availability within a bio-economy system [2]. Globally, it has been consistently reported that most of the wood waste generated in the construction and demolition sectors are destined to landfills or to energy recovery by incineration as refuse-derived fuel [3]. However, disposal in landfills is not an environmentally friendly alternative since eventually the waste wood will be anaerobically decomposed leading to the generation and emission of methane [3], an aggressive greenhouse gas with global warming potential 25 times that of CO<sub>2</sub> [4]. Energy recovery by incineration should be considered an end-of-life stage in the carbon lifecycle of wood products, as a form of delaying CO<sub>2</sub> emissions [2] and of avoiding emissions of carcinogenic compounds generated by incomplete

combustion of treated wood products [5]. Therefore, alternative uses for wood wastes from construction and demolition sectors currently are being extensively researched, with production of particleboards and of wood–cement composites comprising most of the studied applications [6].

Particleboards are relevant value-added products in the wood-based industry with a wide spectrum of applications, encompassing flooring coverage and underlayment, partitioning or wall paneling, false ceiling, furniture, core material for doors, speaker boxes, and other products. Particleboards can be manufactured from ground lignocellulosic particles of waste wood, with the resultant product being considered suitable for furniture and interior applications [7]. A plethora of studies has demonstrated the feasibility of using waste wood to produce particleboards based on the properties of the products, which are compatible with those of the products manufactured with virgin wood materials, thus complying with commercial standards for particleboards [1,7–17]. In most of these studies, the waste wood particles were bonded by urea–formaldehyde or phenol–formaldehyde resins to form the composite material.

The type of polymer used to aggregate wood particles in the particleboard production is a rather relevant parameter for it significantly influences curing time and the mechanical performance of the composite [1]. Another relevant aspect that should be observed is the sustainability of the polymer used, since renewability is a major factor and most of the currently used polymers are derived from petroleum, a nonrenewable source. Epoxidized vegetable oils have been considered a suitable candidate for complete or partial replacement of synthetic petroleum-derived polymers in the production of wood-based composites [18] and lignocellulosic waste-based composites [19]. Vegetable oils present the advantage of presenting double bonds in their fatty acid chains that can be readily functionalized into epoxides by means of nontoxic oxidizing agents, avoiding the use of the hazardous compounds, such as epichlorohydrin, which is used in the synthesis of the epoxy resin diglycidyl ether of bisphenol A (DGEBA), a commonly used polymer in the production of composite materials [20]. Although the use of virgin vegetable oils presents a sustainable alternative to produce epoxy resins, it is the use of waste cooking oil that not only is renewable and less costly but also fit into the cascading lifecycle of vegetable oils in a circular economy.

Waste cooking oils, when improperly discarded, are a major burden to the sewage treatment facilities, incurring costs and energy expenditure of 0.45 Euro/kg oil and of 3 kWh/kg oil, respectively [21]. The global production of waste cooking oil is currently estimated to be in the range of 41 to 67 Mt/year, representing about 20 to 32% of the total vegetable oil consumption [22]. Therefore, using waste cooking oils as precursor material to epoxidized vegetable oils not only alleviates the burden of treatment in sewage treatment plants but also increases the service lifetime of the oil into a cascading lifecycle. Waste cooking oils have been thoroughly researched recently as a low-cost precursor material for a variety of oleochemical products [22,23], including plasticizers and epoxy resin matrices for use in composite materials [24–27]. To the best of the authors' knowledge, no work has been published in the literature researching the concomitant use of waste wood and epoxidized waste cooking oil to produce particleboards. However, the thermoset polymers originated from epoxidized vegetable oils usually present inferior mechanical performances than petrochemical-derived epoxy resins, such as diglycidyl ether of bisphenol A (DGEBA) and other petrochemical-derived epoxy resins. Epoxidized oils toughen composite matrices but promote over plasticization and lowered crosslink densities when compared to petroleum-based resins [27]. To overcome these hurdles, blends of epoxidized vegetable oils and petroleum-derived epoxy resins have been studied as matrices of composite materials to achieve enhanced mechanical properties in a partially renewable bio-based composite [28].

In view of the aforementioned, it was the aim of the present work to investigate the feasibility of using waste wood from construction and demolitions sectors as reinforcement in the production of particleboards in which epoxidized waste cooking oil is used as a matrix, either as full or as partial replacement of a petroleum-derived epoxy resin.

## 2. Material and Methods

### 2.1. Material

Waste cooking soybean oil was collected from the local cafeteria at the School of Engineering of Universidade Federal de Minas Gerais, Brazil. The civil construction waste wood (CCWW) was acquired from a construction site of a local contractor in the municipality of Belo Horizonte, MG, Brazil. The CCWW was collected, segregated, and further identified as parts of plywood, joists, boards, slats, doors, and pieces of skirting boards. Glacial acetic acid (99.7%), iodine-monochloride Wijs solution, potassium iodate, potassium iodide, hydrochloric acid, sodium thiosulfate, soluble starch, chloroform, hydrobromic acid 48%, diethyl ether (99%), and gentian violet were purchased from Synth (São Paulo, SP, Brazil), and Amberlite IR-120 (hydrogen form) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Araldite GY 260 (Bisfenol A epoxy resin), Aradur 956 (tetrahydromethylphthalic anhydride), and Accelerator DY062 (Benzyl dimethylamine) (Huntsman catalogue) were acquired from local markets.

### 2.2. Methods

#### 2.2.1. Epoxidation of Waste Cooking Oil and Characterization of the Epoxidized Oil

The adopted procedure for epoxidation of the waste cooking oil was proposed for heterogeneously catalyzed reaction by Lage et al. [29]. Epoxidation of the waste cooking oil was performed in a mechanically stirred jacketed reactor with a reflux condenser, with the jacket coupled to a thermostatic bath (Lucadema, SP, Brazil). Fifty grams of the waste oil were added to the reactor together with 22.1 g of Amberlite IR-120 as a heterogeneous catalyst, while the reactor was being heated. Upon reaching the desired temperature of 70 °C, a solution comprised of 16 mL of hydrogen peroxide 50% (*m/m*) and 4.5 mL of anhydrous acetic acid was dropwise-added to the reactor in a 5-h period with constant stirring at 500 rpm. Upon reaching 5 h, distilled water at room temperature was added to the reactor to stop the ongoing reactions. The resultant product, the epoxidized waste oil (EWO), was extracted with lukewarm distilled water to remove residual polar compounds. Subsequently, diethyl ether was used to remove traces of water, and the solvent was removed from the epoxidized oil in a rotary evaporator. The EWO was placed in an incubator at 50 °C for 12 h to remove the residual solvent. The iodine values (IV) of the waste cooking oil and of the epoxidized waste oil were determined in accordance with ASTM D5554-95 standard [30], and the waste oil double bond conversion (DBC) to oxirane rings (i.e., epoxy groups) was determined by

$$DBC(\%) = 100 \left( \frac{IV_{WCO} - IV_{EWO}}{IV_{WCO}} \right) \quad (1)$$

where  $IV_{WCO}$  is the iodine value of the waste cooking oil, and  $IV_{EWO}$  is the iodine value of the epoxidized waste cooking oil. The epoxidized waste oil was also analyzed by Fourier transform infrared spectroscopy (FTIR) using a Shimadzu IRAffinity-1 spectrophotometer, with a DLATGS detector. Spectra were obtained within the wavenumber region of 700 to 4000  $\text{cm}^{-1}$  with a resolution of 4  $\text{cm}^{-1}$ . An attenuated total reflectance accessory with a ZnSe Crystal was employed for the spectra acquisitions of the samples.

#### 2.2.2. Preparation and Characterization of Waste Wood Particles

Waste wood went through a manual sorting process to remove metal, plastic, paper, and other impurities. The separated CCWW was comminuted in a Rototec disk mill with a 1 CV motor and a 220 RN disk. The obtained CCWW particles were then classified in a sieve assembly shaker, and the fractions of particles with sizes larger than 1 mm (16 # Tyler) and within a size range of 0.5 mm (32 # Tyler) to 1 mm (16 # Tyler) were separated for use as reinforcement in the production of the particleboards. With the conditions employed in the comminution of the wood, the fraction passing through the 32 # sieve was insignificant (~3%). Working with particle sizes smaller than 0.5 mm was not justifiable due

to the higher energy input needed to comminute the wood into finer particles. The initial moisture content of the separated particles was determined to be 15% and the particles were subsequently dried to moisture contents of 6 to 8% in a convective oven at 150 °C for 24 h. The average apparent density of the CCWW particles was determined using a pycnometer.

### 2.2.3. Preparation and Characterization of Particleboards

The epoxidized waste oil and the wastewood particles were used in the preparation of the particleboards using two distinct epoxy matrices: pure EWO and a blend of EWO and commercial diglycidyl ether of bisphenol A (DGEBA) in equal mass proportions (1:1 m:m). Initially to the epoxy resins (EWO or EWO-DGEBA), hardener and accelerator were mixed in a mechanically stirred vessel at 500 rpm for 20 min to ensure a homogeneous mixture. Upon completion of the mixing, CCWW particles were mixed with the epoxy mixture in amounts of 20 and 30% (*m/m*). The minimum content of waste wood particles to be used in the preparation of the particleboards was determined by preliminary tests to be 20% (*m/m*). Particle amounts below the determined minimum resulted in inhomogeneous mixtures of waste wood particles and epoxy resins. Particle contents higher than 30% did not allow for effective crosslinking and interactions of the polymeric matrices and particles. The epoxy resin–waste wood particles mixture was poured into acetic silicon molds, which in turn were put in a muffle oven to promote the cure of the resins and form the composite materials. The curing program was conducted in two steps: an initial step in which the mixture was subjected to a temperature of 100 °C for 2 h; and, without removing the mold from the oven, a subsequent step, in which the mixture was subjected to a temperature of 150 °C for 7 h. After 48 h of cooling, the finished composites were removed from the mold and left to rest at room temperature for a seven-day post-curing period. Three replicates of each sample were prepared for further analysis and mechanical tests. The experimental conditions applied to the production of particleboards are presented in Table 1.

**Table 1.** Planning and experimental conditions for the preparation of specimens.

Specimen	Composition	Content of Epoxidized Oil (%)—DGEBA (%)	Content of CCWW (%)	Particle Diameter $\phi$ (mm)
CP1	Epoxidized oil	100–0	0	-
CP2	Epoxy resin and epoxidized oil	50–50	0	-
CP3	Epoxy resin and epoxidized oil	50–50	20	>1.0
CP4	Epoxy resin and epoxidized oil	50–50	30	>1.0
CP5	Epoxy resin and epoxidized oil	50–50	20	1.0 > $\phi$ > 0.5
CP6	Epoxy resin and epoxidized oil	50–50	30	1.0 > $\phi$ > 0.5

The prepared particleboards were analyzed by FTIR with the same equipment and at the same conditions employed for the analysis of the epoxidized waste oil (Section 2.2.1), following the recommended standard practices in ASTM E1252–98 [31]. Thermogravimetric analysis of the prepared particleboards was performed to verify their thermal stability. A Shimadzu DTG-60 (Shimadzu, Japan) was used for the analysis, within the temperature range of 25 to 600 °C, with a heating rate of 10 °C min<sup>-1</sup>, under a nitrogen atmosphere with a flow rate of 50 mL min<sup>-1</sup>, alumina crucible and sample mass of approximately 10 mg. Scanning electron microscopy was used to study the morphology of the prepared particleboards. Images were obtained with a FEI Quanta 200 FEG Scanning Electron Microscope with Nanofabrication System (Bruker-AXS Microanalysis GmbH, Berlin, Germany). The composite samples were fixed to the support (stub) with the aid of self-adhesive double-sided carbon tape, prepared with a carbon film to ensure nongranulation of the conductive layer, and subsequently analyzed at an acceleration voltage of 20 kV. The density of the particleboards was determined with a hydrometer as described in ASTM D792-8 [32]. The moisture contents of the produced particleboards were determined by an oven drying method. A forced-convection oven at 105 ± 0.5 °C was used to dry 10-g particleboard

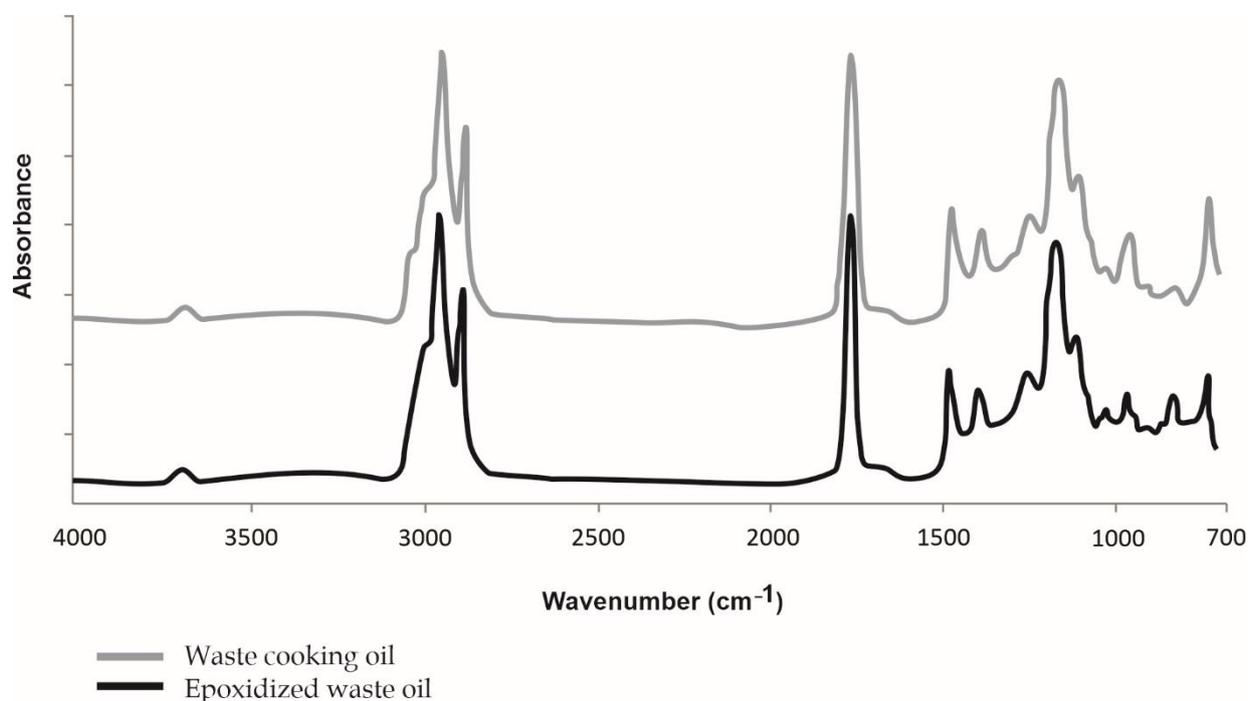
specimens from the initial moisture content down to an endpoint, with weighing of the samples in 3-h intervals. The endpoint was assumed to have been reached when the change in weight was smaller than 2 mg in a three-hour interval. The weighing was performed after the oven-dried samples reached room temperature in a desiccator. The laboratory relative humidity was 60% and the oven cavity relative humidity was 1.4%. The moisture content of the samples was calculated by subtracting the weight of the sample at the endpoint from the initial weight of the sample, with the difference divided by the weight of the sample at the endpoint. The tensile properties of the prepared particleboard specimens were determined using an AUTOGRAPH model AG-IS universal testing machine, with a maximum capacity of 100 kN, operating with a load cell of 2000 kgf and speed of elongation of 5 mm min<sup>-1</sup>. The specimens for determination of the tensile properties were prepared in accordance with ASTM D3039/D3039M-08 [33]. All determinations were performed with five repetitions.

### 3. Results and Discussion

The iodine value of the waste cooking oil was determined as 100 g I<sub>2</sub>/100 g, and the IV of the epoxidized waste oil was determined as 3.5 g I<sub>2</sub>/100 g, corresponding to a conversion of double bonds to epoxy groups of 96.5%, indicating the efficiency of the epoxidation process. FTIR spectra for the waste cooking oil and for the epoxidized waste oil are presented in Figure 1. The FTIR spectrum presented in Figure 1 is an average of the spectra of specimens CP3, CP4, CP5, and CP6. The spectra of specimens CP3, CP4, CP5, and CP6 are qualitatively identical, with small variations in peak intensities only. Thus, an averaged spectrum is qualitatively representative of all the specimens. The second derivative of the spectra was taken (not shown) to obtain a better resolution of the peaks due to significant overlapping of absorption peaks in the regions where the vibrations of aliphatic double bonds are present. The peaks at the range 2980–2850 cm<sup>-1</sup> are assigned to C–H stretching vibration of aliphatic–CH<sub>2</sub> in fatty acids, respectively. The presence of epoxide groups is verified in the spectrum of the epoxidized oil by the absorbance peaks at 916 and 822 cm<sup>-1</sup> assigned to the stretching vibrations of C–O and C–O–C of oxirane rings, respectively. The absence of a band at ~3470 cm<sup>-1</sup> in the spectrum of the epoxidized oil indicates that epoxide rings were not opened by an eventual excess of hydrogen peroxide [34]. A peak corresponding to the stretching vibration of *cis*-olefinic bond HC=CH is identified at 3010 cm<sup>-1</sup>. Other bands associated to the vibrations of aliphatic double bonds in the oil are observed at 721, 806, and 833 cm<sup>-1</sup>, assigned to the combination of out-of-plane deformation and rocking vibration in *cis*-disubstituted olefins C=C; at 902 and 959 cm<sup>-1</sup>, assigned to the out-of-plane deformation of *trans* HC=CH; and a weak band at 1657 cm<sup>-1</sup>, assigned to the stretching of disubstituted *cis*-olefinic C=C. Peaks corresponding to aliphatic double bonds vibrations are scarcely observed in the spectrum for the epoxidized waste oil, demonstrating the effective conversion of double bonds into oxirane rings.

The most common noncellulosic polysaccharides of the cell walls in wood are glucuronoxylan, arabinoglucuronoxylan, galactoglucomannan, glucomannan, xyloglucan, homogalacturonan, rhamnogalacturonan I, rhamnogalacturonan II, arabinogalactans, and arabinogalactans type II [35]. Hence, the characteristic absorbance peaks of these types of polysaccharides should appear in the fingerprint region of the FTIR spectra of the prepared particleboards (Figure 2). The second derivative of the spectra was taken (not shown) to obtain a better resolution of the peaks due to significant overlapping of absorption peaks in the fingerprint region. Pectin is readily identified by the absorbance peaks at 827, 910, 968, 1074, 1097, 1230, and 1417 cm<sup>-1</sup>. The peaks at 827, 910, and 968 cm<sup>-1</sup> are attributed to ring vibrations in pectin; the peaks at 1074 and 1097 cm<sup>-1</sup> are attributed to C–O stretching and to C–C stretching ring of rhamnogalacturonans; and the peaks at 1230 and 1417 cm<sup>-1</sup> are assigned to C–O stretching in pectins and to COO<sup>-</sup> symmetric stretching of free carboxyl groups of rhamnogalacturonan and homogalacturonan, respectively [36]. The presence of mannose-containing hemicellulose is verified by the absorbance peaks at 808 cm<sup>-1</sup> (ring

vibration) and at  $867\text{ cm}^{-1}$  (C1–H bending) [36]. The peaks at 891, 1160–1165, 1176, and  $1471\text{ cm}^{-1}$  are characteristic of xylose-containing hemicellulose [36,37], with the peaks at 891 and at  $1160\text{--}1165\text{ cm}^{-1}$  assigned to C1–H bending and to glycosidic bond vibrations (O–C–O), respectively. The stretching vibrations of the rings in galactans are verified by the presence of absorbance peaks at  $1039$  and  $1074\text{ cm}^{-1}$  [36]. The presence of cellulose is verified by the absorbance peaks at  $1160\text{--}1165$ ,  $1310$ ,  $1361$ , and  $1430\text{ cm}^{-1}$ . The absorbance bands at  $1160\text{--}1165\text{ cm}^{-1}$  are attributed to glycosidic bond vibrations (O–C–O), the bands at  $1310$  and  $1430\text{ cm}^{-1}$  are attributed to  $\text{CH}_2$  symmetric bending or  $\text{CH}_2$  rocking vibration, and the band at  $1361\text{ cm}^{-1}$  is attributed to C–H vibrations and  $\text{CH}_2$  bending in cellulose [36]. The absorbance bands related to the epoxy matrix of the particleboards are at the ranges  $1250\text{--}1126$ ,  $950\text{--}860$ , and  $865\text{--}785\text{ cm}^{-1}$ . The band at  $1250\text{ cm}^{-1}$  corresponds to asymmetric stretching vibration of unreacted epoxy rings and the bands at  $865\text{--}785\text{ cm}^{-1}$  are attributed to symmetric stretching vibration of unreacted epoxy rings. The aliphatic ethers resultant of the curing of the epoxy ring are identified by small peaks at  $1126\text{ cm}^{-1}$  and  $827\text{ cm}^{-1}$  attributed to the asymmetric and symmetric stretching of the –C–O–C– bonds, respectively.



**Figure 1.** FTIR spectra for waste cooking oil and for epoxidized waste oil.

The average moisture content of all particleboard specimens was  $8.5 \pm 0.7\%$ . The average apparent density of CCWW particles was determined as  $250\text{ kg/m}^3$  ( $0.250\text{ g/cm}^3$ ), and the average density of the particleboards was determined as  $1330\text{ kg/m}^3$  ( $1.33\text{ g/cm}^3$ ), with minimum  $1130\text{ kg/m}^3$  ( $1.13\text{ g/cm}^3$ ) and maximum  $1380\text{ kg/m}^3$  ( $1.38\text{ g/cm}^3$ ). The variation of the density of the produced particleboards as a function of the CCWW particle contents is presented in Figure 3. Notice that for the particleboards with 20% particle contents the CCWW particles contribute to the slight increase in density of the particleboards in regard to the cured blend of epoxy resins, whereas the particleboards with the highest CCWW particles content presented the lowest densities. Hence, it can be inferred herein that the crosslinking densities of the particleboards with 20% CCWW particles are higher than that of the particleboards with 30% contents, demonstrating not only that the crosslinking of the epoxy resins was more effective for the 20% CCWW particles content particleboard but also that interactions between the resins and the particles were more intensive in this case. Thus, it should be expected that the particleboards with 30% CCWW particles would present more void spaces in their structure than those of the particleboards with 20% particle contents. The particle sizes did not affect the densities of the particleboards produced

thereof, i.e., the particleboards with the same contents of particles but with particles of distinct granulometries presented statistically similar densities. The densities of the herein produced particleboards are within the range of densities of other lignocellulosic-based particleboards similarly produced with matrices comprised of blends of epoxidized oils and petroleum-based epoxy resins. These densities are 1.180–1.208 g/cm<sup>3</sup> for composites of corn-based distillers dried grains and blends of epoxidized soybean oil and DGEBA [38] and 1.068–1.096 g/cm<sup>3</sup> for composites of sisal fibers and blends of epoxidized linseed oil and DGEBA [27].

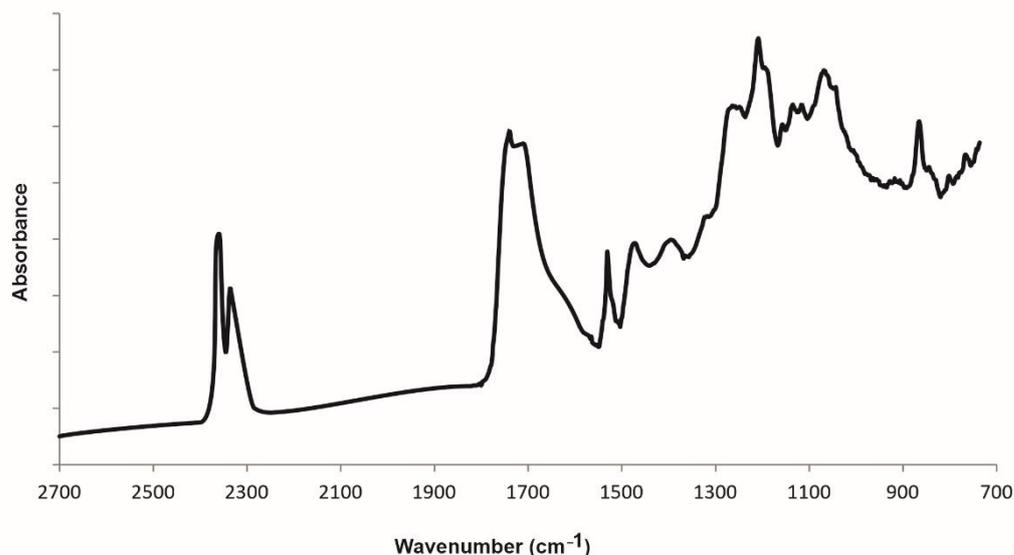


Figure 2. FTIR spectrum for CCWW-EWO-DGEBA particleboard.

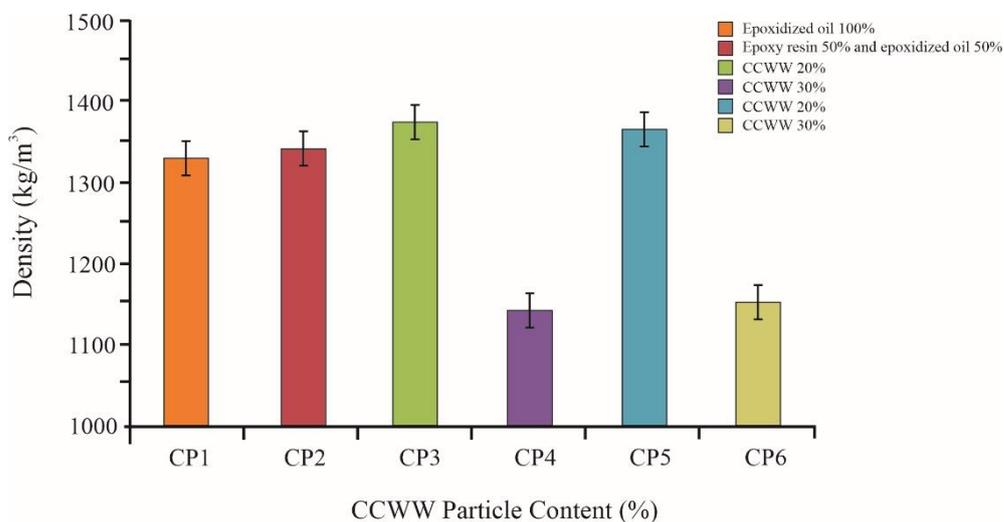
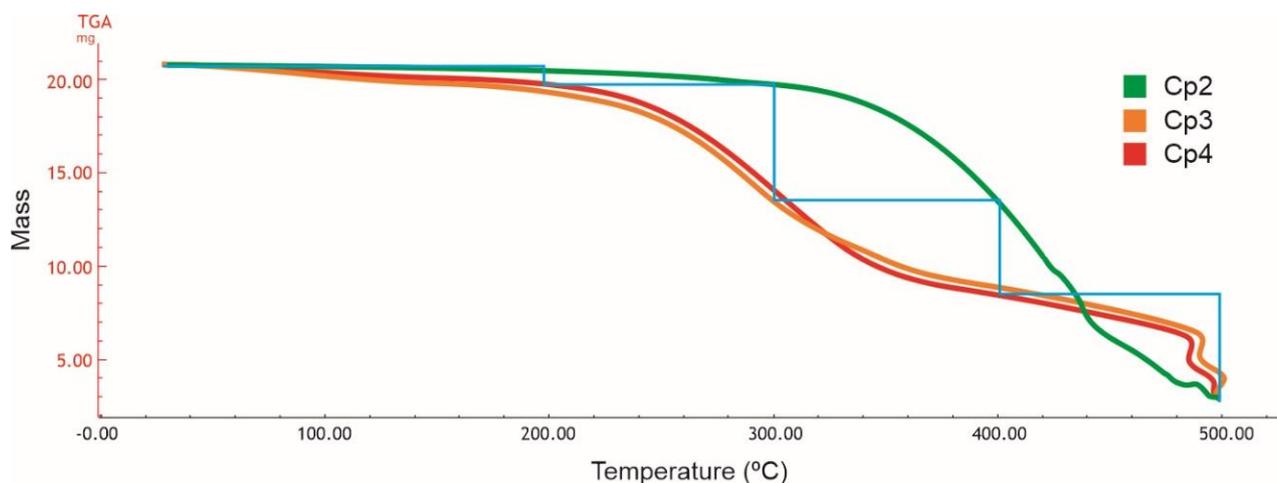


Figure 3. Density of particleboards as a function of CCWW contents.

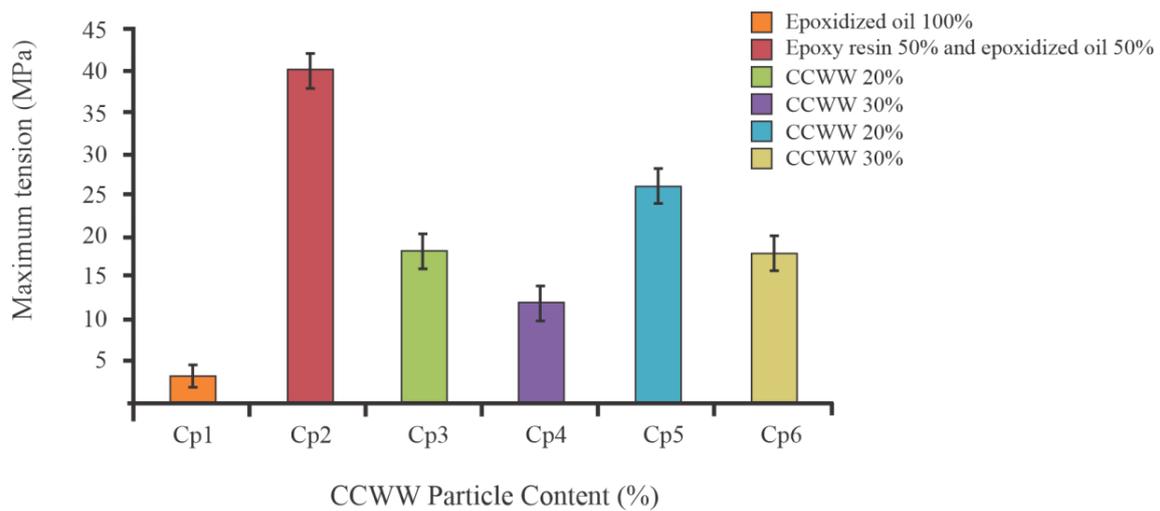
The thermal analysis curves for the studied specimens are presented in Figure 4 CP2. Comprised of neat cured blended resins, the specimens were thermally stable to 298 °C. Although the blending of epoxidized waste oil with DGEBA enhances the thermal stability of the product in regard to the thermal stability of pristine epoxidized waste oil [28], the addition of the reinforcement (CCWW particles) caused the thermal decomposition range of the composite thereof to broaden from about 200 °C to 500 °C. This is because CCWW is comprised of distinct classes of compounds (e.g., pectin, cellulose, hemicellulose, lignin, and other compounds) with distinct thermal stabilities. In general, hemicelluloses are less thermally stable than cellulose and lignin, with thermal degradation occurring in the range

of 200 to 300 °C. The thermal degradation of hemicelluloses is clearly observed in the thermal analysis curves for CP3 and CP4 specimens, corresponding to a mass loss event of about 20.4%. Cellulose thermally degrades in the temperature range of 300 to 400 °C, and its degradation is clearly observed in the thermogravimetric curves for CP3 and CP4 specimens. The thermal degradation of cellulose in the particleboard occurs concomitantly with the thermal degradation of the polymeric matrix, which is comprised of a cured blend of epoxidized waste oil and DGEBA, corresponding to a mass loss event of about 26.9%. Another mass loss event, in the range of 400 to 500 °C, corresponds to the thermal degradation of lignin together with the degradation of the remaining polymeric matrix, with a mass loss event of 26.85%.

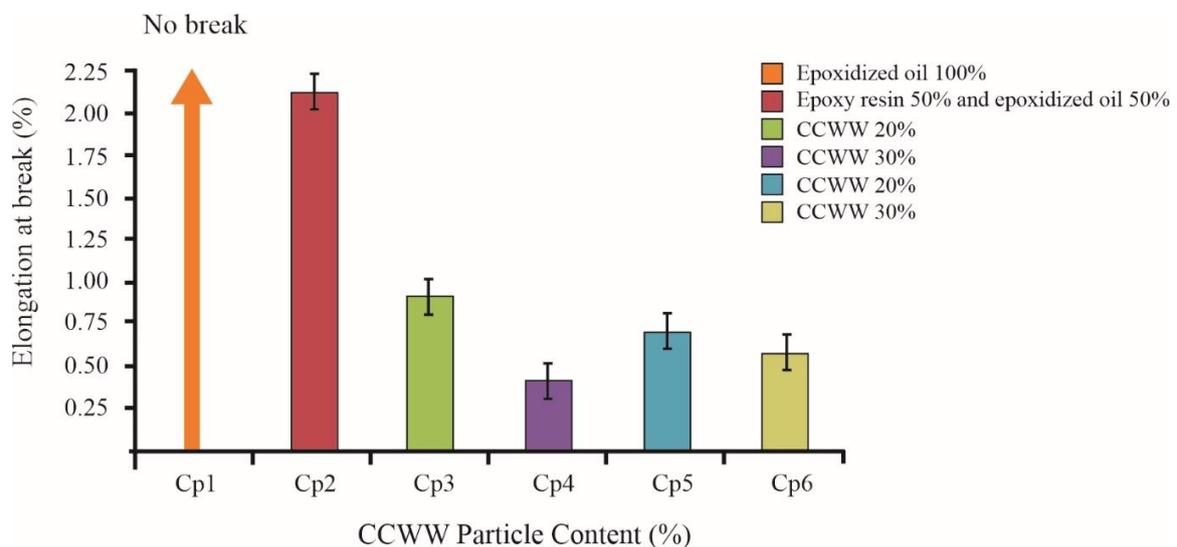


**Figure 4.** Thermal analysis curves for pure cured epoxidized waste oil (CP2) and for particleboard specimens with 20 and 30% CCWW in an epoxidized waste oil–DGEBA matrix (respectively, CP3 and CP4).

The ultimate tensile stress and the elongation at break for the cured resins and for produced particleboards are presented in Figures 5 and 6, respectively. As expected, the blending of DGEBA with EWO resulted in a cured matrix with higher ultimate tensile stress than the ultimate tensile stress of the cured neat EWO (Figure 5). This is justified by the presence of aromatic rings in the DGEBA molecule that confers higher mechanical stability to the overall structure of the cured blend of resins than that of the cured neat EWO, which is comprised of long and flexible linear chains of fatty acids esterified to a glycerol molecule. Additionally, the DGEBA molecule presents terminal epoxide groups in the chain, which are more reactive than the internal epoxide groups of EWO, thus allowing for higher crosslinking densities of the cured material, resulting in a more effective transfer of stress throughout the structure of the cured resins. The elongation at break for the cured neat EWO was not determined because there was no rupture of the respective sample (CP1) at the limit of extension of the grips in the testing equipment (Figure 6). The elongation at break of the cured blend of epoxy resins (CP2) could be determined at about 2%, corroborating the fact that the higher crosslinking density of the blend compared to that of the cured neat EWO reduces the ductility of the material. The higher ductility of cured EWO compared to that of DGEBA is attributed to the presence of flexible linear aliphatic chains appended to the epoxy groups of EWO that causes over plasticization of the matrix [27].



**Figure 5.** Ultimate tensile stress for the cured neat resins and for the produced particleboards.



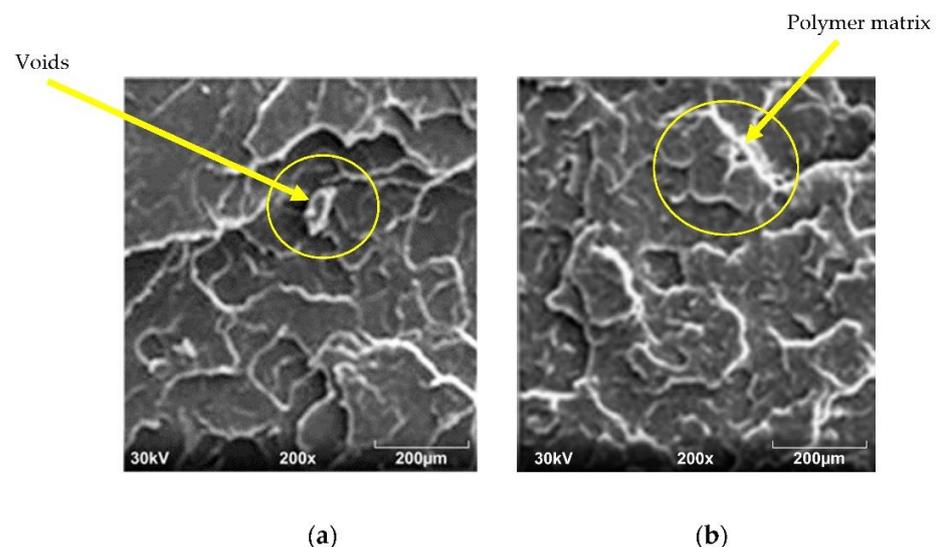
**Figure 6.** Elongation at break for the cured neat resins and for the produced particleboards.

The introduction of CCWW particles as a reinforcement to the blended epoxy resins was expected to increase its stiffness and consequently increase the ultimate tensile stress of the resultant material. However, the opposite was observed, i.e., the ultimate tensile stresses of the produced particleboards were lower than that of the neat, cured blend of resins (Figure 5). This is attributed to a lower crosslinking density in the particleboards than in the cured blended epoxy resins and to poor interactions between the polymeric matrix and the CCWW particles, with consequent weak stress transfer from the matrix to the particles. Although the produced particleboard specimens were visually homogeneous, indicating an adequate dispersion of the particles into the epoxy resins, the wettability of the particles by the blended resins was not quite effective, leading to poor interactions between the phases. Thus, it can be inferred herein that there was low availability of hydroxyl and carboxyl groups from the pectin and holocellulosic fractions of the cell walls in the wood particles to interact with the functional groups of the blended resins and crosslinking agent. The particleboards with 20% CCWW particle contents presented higher tensile strength than those with 30% content, regardless of the particle sizes used (Figure 5), indicating that the lower the particle content the more effective were the interactions between the particles and the resin matrices due to a better dispersal of the particles in the case of 20% content. The particle sizes had a significant effect on the tensile strength of the particleboards, with

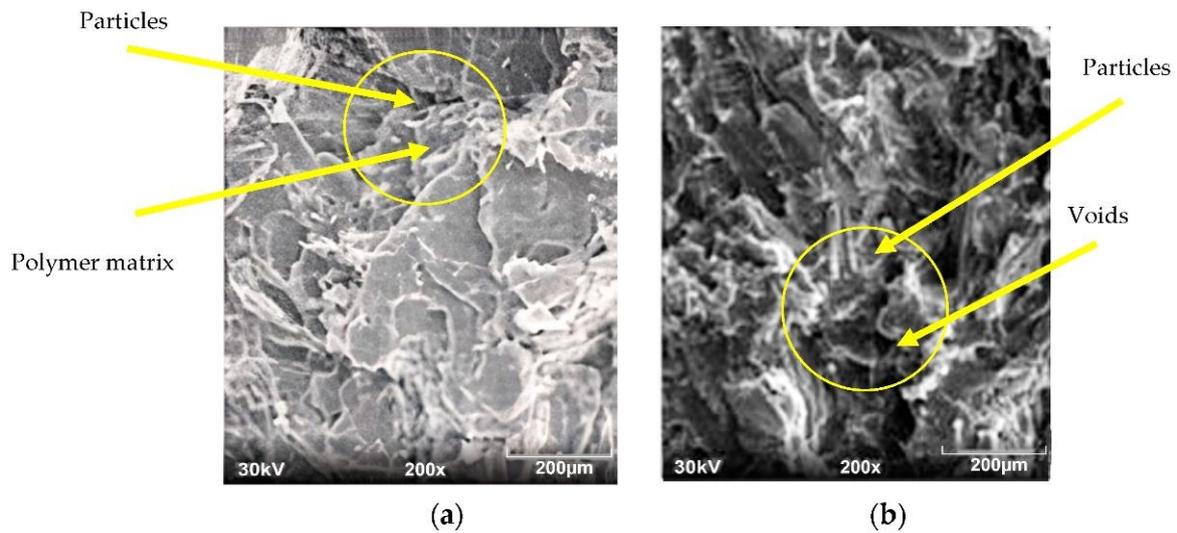
the particleboards comprised of smaller particles (CP5 and CP6) presenting higher ultimate tensile stresses than those comprised of larger particles (CP3 and CP4). Smaller particles present larger surface areas than larger particles, thus presenting higher availability of active sites for interaction with the polymeric matrix, promoting more effective interactions and consequently better stress transfer between the phases.

The elongation at break for the all the specimens follows the same behavior as for the ultimate tensile stress (Figure 6), with particleboards with higher contents of CCWW particles presenting lower elongations at break than those with lower contents of particles, and particleboards with smaller particles presenting lower elongations at break than those with larger particles. The better interaction between the particles and the matrices in the case of smaller particles allowed for higher crosslinking densities in the particleboards and consequently caused the particleboards to be more rigid than those with larger particles, thus reducing their elongation at break.

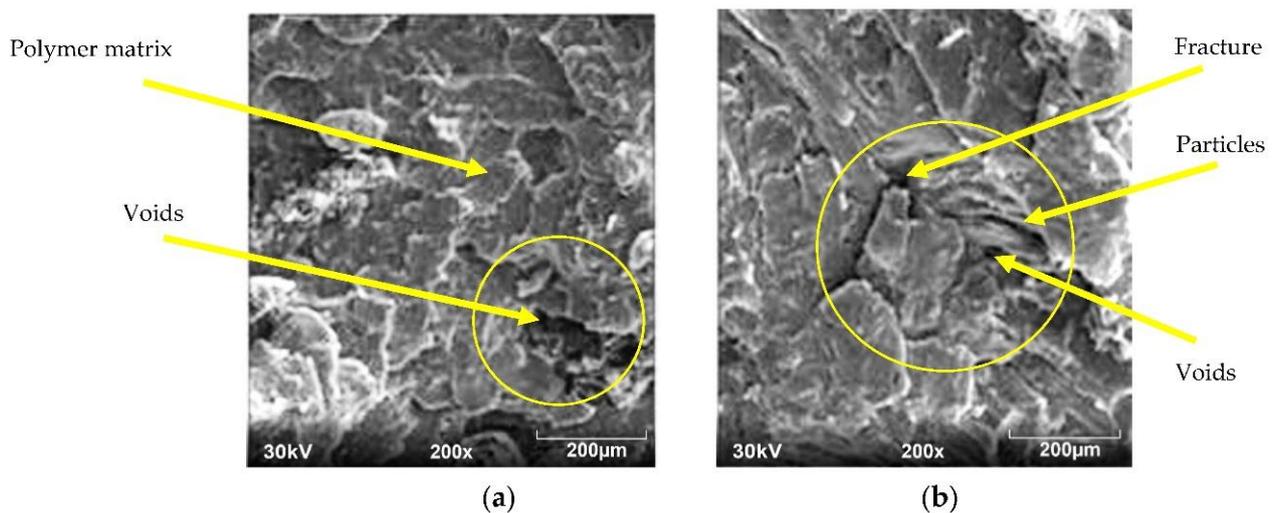
The SEM images of the fracture surface of the blended resin matrices and of the produced particleboards are presented in Figure 7. Figure 7 shows that both CP1 and CP2 specimens comprised of 100% EWO and 1:1 EWO-DGEBA, respectively, present single-phase morphology, demonstrating good miscibility of the resins and of the curing agent. Occasional small gaps are observed in the fractured surface, herein attributed to the portions of the matrix where the crosslinking densities are the lowest due to the presence of long aliphatic chains in the EWO and to eventual unreacted internal epoxide groups in EWO. Furthermore, the fracture of specimens CP1 and CP2 is clearly brittle, typical of epoxy resins, such as DGEBA, which is a rigid, brittle polymer. The SEM images for the fractured surfaces of the particleboard specimens (Figures 8 and 9) clearly depict the presence of gaps larger than those in the neat resin matrices. These gaps are herein attributed to particle debonding from the polymeric matrices, corroborating the previous inferences of poor matrix-particle interactions. These gaps act as stress concentrators and, thus are responsible for the weak stress transfer between the polymeric matrix and the CCWW particles. This corroborates the observed reduction in the tensile strength of the particleboard when compared to that of the neat cured blended resins. Additionally, the dominant type of failure is brittle fracture due to the content of resin in the particleboards being higher than the particle contents. The gaps in the fractured surfaces of the particleboards with smaller particles (CP5 and CP6) are larger than the gaps in the surfaces of particleboards with larger particles (CP3 and CP4), attesting the previous discussion that matrix-particle interactions are more effective in the particleboards with smaller particles than in those with larger particles.



**Figure 7.** SEM images of the tensile fracture surfaces of the epoxy matrix specimens (200×): (a) CP1 and (b) CP2.



**Figure 8.** SEM images of the tensile fracture surfaces of the CCWW particles-epoxy-composites specimens (200×): (a) CP3 and (b) CP4.



**Figure 9.** SEM images of the tensile fracture surfaces of the CCWW particles-epoxy-composites specimens (200×): (a) CP5 and (b) CP6.

#### 4. Conclusions

The feasibility of producing particleboards with blended epoxidized waste cooking oil and petroleum-derived epoxy resin as matrix and civil construction waste wood particles as reinforcement was investigated. Although the introduction of CCWW particles into the polymeric matrices did not promote the desired effect of reinforcement, the particleboards herein produced still met the standards of the American National Standards ANSI A208.1-1999 for general purpose boards in regard to their physical and mechanical properties (e.g., density, tensile strength). Hence, the use of wood waste and waste cooking oil to produce particleboards is justified within the framework of a cascading lifecycle extended service for both wastes. However, further studies should be performed to improve the compatibility between the polymeric matrix and the waste wood particles to improve the mechanical properties of the particleboards. Enhancing the accessibility of oxygenated functional groups of the wood particles (e.g., hydroxyl and carboxyl) would allow for more effective interactions between the polymeric matrix and the particles, and this could be performed by certain pretreatment techniques of the wood fibers, such as vapor explosion, or by increasing the number of carboxylic groups at the wood particle surface by an

intensive oxidative process. The study of more effective alternative crosslinking agents is also recommended.

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## References

- Silva, V.U.; Nascimento, M.F.; Oliveira, P.R.; Panzera, T.H.; Rezende, M.O.; Silva, D.A.L.; Aquino, V.B.M.; Lahr, F.A.R.; Christoforo, A.L. Circular vs. linear economy of building materials: A case study for particleboards made of recycled wood and biopolymer vs. conventional particleboards. *Constr. Build. Mater.* **2021**, *285*, 122906. [\[CrossRef\]](#)
- Besserer, A.; Troilo, S.; Girods, P.; Rogau, Y.; Brosse, N. Cascading Recycling of Wood Waste: A Review. *Polymers* **2021**, *13*, 1752.
- Kern, A.P.; Amor, L.V.; Angulo, S.C.; Montelongo, A. Factors influencing temporary wood waste generation in high-rise building construction. *Waste Manag.* **2018**, *78*, 446–455. [\[CrossRef\]](#)
- IPCC. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S.D., Qin, M., Manning, Z., Chen, M., Marquis, K.B., Averyt, T.M., Miller, H.L., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007; 996p.
- Tsai, W.-T.; Wu, P.-H. Environmental Concerns About Carcinogenic Air Toxics Produced from Waste Woods as Alternative Energy Sources. *Energy Sources Part A Recovery Util. Environ. Eff.* **2013**, *35*, 725–732. [\[CrossRef\]](#)
- Hossain, U.; Poon, C.S. Comparative LCA of wood waste management strategies generated from building construction activities. *J. Clean. Prod.* **2018**, *177*, 387–397. [\[CrossRef\]](#)
- Peđzik, M.; Auriga, R.; Kristak, L.; Antov, P.; Rogozinski, T. Physical and Mechanical Properties of Particleboard Produced with Addition of Walnut (*Juglans regia* L.) Wood Residues. *Materials* **2022**, *15*, 1280. [\[CrossRef\]](#)
- Yang, T.H.; Lin, C.J.; Wang, S.Y.; Tsai, M.J. Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin. *Build. Environ.* **2007**, *42*, 189–195. [\[CrossRef\]](#)
- Felix, A.L.; Narciso, C.R.P.; Lima, F.S.; Mendes, R.F.; Mendes, L.M.; Scolforo, J.R.S. Use of Waste Wood for Particleboard Production. *Key Eng. Mater.* **2015**, *668*, 375–380. [\[CrossRef\]](#)
- Wang, L.; Chen, S.S.; Tsang, D.C.W.; Poon, C.S.; Shih, K. Value-added recycling of construction waste wood into noise and thermal insulating cement-bonded particleboards. *Constr. Build. Mater.* **2016**, *125*, 316–325. [\[CrossRef\]](#)
- Astari, L.; Prasetyo, K.W.; Suryanegara, L. Properties of Particleboard Made from Wood Waste with Various Size. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *166*, 012004. [\[CrossRef\]](#)
- Azambuja, R.R.; Castro, V.G.; Trianoski, R.; Iwakiri, S. Recycling wood waste from construction and demolition to produce particleboards. *Maderas Cienc. Tecnol.* **2018**, *20*, 681–690. [\[CrossRef\]](#)
- Azambuja, R.R.; Castro, V.G.; Trianoski, R.; Iwakiri, S. Utilization of construction and demolition waste for particleboard production. *J. Build. Eng.* **2018**, *20*, 488–492. [\[CrossRef\]](#)
- Laskowska, A.; Mamiński, M. Properties of particleboard produced from post-industrial UF- and PF-bonded plywood. *Eur. J. Wood Prod.* **2018**, *76*, 427–435. [\[CrossRef\]](#)
- Souza, A.M.; Nascimento, M.F.; Almeida, D.H.; Lopes Silva, D.A.L.; Almeida, T.H.; Christoforo, A.L.; Lahr, F.A.R. Wood-based composite made of wood waste and epoxy based ink-waste as adhesive: A cleaner production alternative. *J. Clean. Prod.* **2018**, *193*, 549–562. [\[CrossRef\]](#)
- Iždinský, J.; Vidholdová, Z.; Reinprecht, L. Particleboards from Recycled Wood. *Forests* **2020**, *11*, 1166. [\[CrossRef\]](#)
- Khan, M.U.; Abas, M.; Noor, S.; Salah, B.; Saleem, W.; Khan, R. Experimental and Statistical Analysis of Saw Mill Wood Waste Composite Properties for Practical Applications. *Polymers* **2021**, *13*, 4038. [\[CrossRef\]](#)
- Mandal, M.; Begum, P.; Deka, R.C.; Maji, T.K. Wood flour thermoset composites using chemically modified epoxidized soybean oil. *Eur. J. Wood Prod.* **2019**, *77*, 569–580. [\[CrossRef\]](#)

19. Uppal, N.; Pappu, A.; Gowri, V.K.S.; Thakur, V.K. Cellulosic fibres-based epoxy composites: From bioresources to a circular economy. *Ind. Crops Prod.* **2022**, *182*, 114895. [[CrossRef](#)]
20. Di Mauro, C.; Malburet, S.; Genua, A.; Graillot, A.; Mija, A. Sustainable Series of New Epoxidized Vegetable Oil-Based Thermosets with Chemical Recycling Properties. *Biomacromolecules* **2020**, *21*, 3923–3935. [[CrossRef](#)]
21. Landi, F.F.A.; Fabiani, C.; Castellani, B.; Cotana, F.; Pisello, A.L. Environmental assessment of four waste cooking oil valorization pathways. *Waste Manag.* **2022**, *138*, 219–233. [[CrossRef](#)]
22. Orjuela, A.; Clark, J. Green chemicals from used cooking oils: Trends, challenges, and opportunities. *Curr. Opin. Green Sustain. Chem.* **2020**, *26*, 100369. [[CrossRef](#)] [[PubMed](#)]
23. Foo, W.H.; Koay, S.S.N.; Chia, S.R.; Chia, W.Y.; Tang, D.Y.Y.; Nomanbhay, S.; Chew, K.W. Recent advances in the conversion of waste cooking oil into value-added products: A review. *Fuel* **2022**, *324*, 124539. [[CrossRef](#)]
24. Silviana, S.; Anggoro, D.D. Use of Epoxidized Waste Cooking Oil as Bioplasticizer of Sago Starch-Based Biocomposite Reinforced Microfibrillated Cellulose of Bamboo. *Adv. Sci. Lett.* **2017**, *23*, 2591–2594. [[CrossRef](#)]
25. Tarazona, E.R.T.; Oliveira, L.S.; Rubio, J.C.; Franca, A.S. Preparation, preliminary characterization and mechanical properties of epoxy composites reinforced with spent coffee grounds. In Proceedings of the 8th International Conference on Mechanical and Aerospace Engineering (ICMAE), Prague, Czech Republic, 22–25 July 2017.
26. Suzuki, A.H.; Botelho, B.G.; Oliveira, L.S.; Franca, A.S. Sustainable synthesis of epoxidized waste cooking oil and its application as a plasticizer for polyvinyl chloride films. *Eur. Polym. J.* **2018**, *99*, 142–149. [[CrossRef](#)]
27. Sahoo, S.K.; Khandelwal, V.; Manik, G. Influence of epoxidized linseed oil and sisal fibers on structure–property relationship of epoxy biocomposite. *Polym. Compos.* **2018**, *39*, E2595–E2605. [[CrossRef](#)]
28. Fernandes, F.C.; Kirwan, K.; Lehane, D.; Coles, S.R. Epoxy resin blends and composites from waste vegetable oil. *Eur. Polym. J.* **2017**, *89*, 449–460. [[CrossRef](#)]
29. Lage, F.C.; Suzuki, A.H.; Oliveira, L.S. Comparative evaluation of conventional and microwave assisted epoxidation of soybean oil with citric acid, acetic acid using homogeneous and heterogeneous catalysis. *Braz. J. Chem. Eng.* **2021**, *38*, 327–340. [[CrossRef](#)]
30. ASTM. *D5554-95 Standard Test for Determination of Iodine Value of Fats and Oils*; ASTM International: West Conshohocken, PA, USA, 2011.
31. ASTM. *E1252-98 Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis*; ASTM International: West Conshohocken, PA, USA, 2021.
32. ASTM. *D 792-8 Standard Test Method for Density and Specific Gravity (Relative Density) of Plastics by Displacement*; ASTM International: West Conshohocken, PA, USA, 2008.
33. ASTM. *D3039/D3039M-08 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*; ASTM International: West Conshohocken, PA, USA, 2014.
34. Dominguez-Candela, I.; Lerma-Canto, A.; Cardona, S.C.; Lora, J.; Fombuena, V. Physicochemical Characterization of Novel Epoxidized Vegetable Oil from Chia Seed Oil. *Materials* **2022**, *15*, 3250. [[CrossRef](#)]
35. Donev, E.; Gandla, M.L.; Jönsson, L.J.; Mellerowicz, E.J. Engineering Non-cellulosic Polysaccharides of Wood for the Biorefinery. *Front. Plant Sci.* **2018**, *9*, 1537. [[CrossRef](#)]
36. Liu, X.; Renard, C.M.G.C.; Bureau, S.; Le Bourvellec, C. Revisiting the contribution of ATR-FTIR spectroscopy to characterize plant cell wall polysaccharides. *Carbohydr. Polym.* **2021**, *262*, 117935. [[CrossRef](#)]
37. Coimbra, M.A.; Barros, A.; Rutledge, D.N.; Delgadillo, I. FTIR spectroscopy as a tool for the analysis of olive pulp cell-wall polysaccharide extracts. *Carbohydr. Res.* **1999**, *317*, 145–154. [[CrossRef](#)]
38. Deka, H.; Wang, T.; Mohanty, A.K.; Misra, M. Novel Biocomposites from Biobased Epoxy and Corn-Based Distillers Dried Grains (DDG). *J. Polym. Environ.* **2015**, *23*, 425–436. [[CrossRef](#)]