Potential Use of Residual sawdust—A Versatile, Inexpensive and Readily Available Bio-waste

Mohd Hazim Mohamad Amini

Abstract Biomass commonly comes from plants or lignocellulosic materials. The main chemical components in plant biomass include cellulose, hemicellulose, lignin and extractives. According to their size and geometry, small-sized woody biomass is called different names. Each form has its suitable application. Larger particles are ideal for standard wood composites such as the oriented strand board and particleboard. Medium-sized particles are ideal for energy pellet, pulp and papermaking applications. Meanwhile, smaller particles are suitable for applications involving chemical reactions such as nanocellulose extraction, liquefaction and bioethanol production. Wood plastic composites usually utilise medium to small-sized particles. This chapter will introduce the sources and various applications of these small woody biomass materials.

1 Sources of Material

1.1 Industrial Wood Cutting Waste

There are many sources of biomass particles and sawdust here that could be obtained. It may come from wood processing facilities to make solid wood planks and poles after the cutting process. It was estimated that for every 1000 board feet of lumber produced, 1 tonne of by-products would be created. Woody biomass in the form of sawdust, shavings, slabs and edgings is gathered in sawmills comprising 75% wood and 25% bark portion [1]. Some names are wood fibre, wood flakes, wood chips, wood powder and wood swiths, as shown in Fig. 1.

M. H. Mohamad Amini (✉)
Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, Jeli Campus, 17600 Jeli, Kelantan, Malaysia
e-mail: hazim.ma@umk.edu.my

S. N. Sarmin et al. (eds.), *Wood Waste Management and Products*, Sustainable Materials and Technology, https://doi.org/10.1007/978-981-99-1905-5_11

Fig. 1 Different forms of woody biomass [1]

1.2 *Manufactured Particles*

Biomass sawdust can be classified into wood and non-wood biomass material. Biomass particles may be obtained by intentionally reducing the biomass size for specific usage. Wood and non-wood biomass from the plant parts, including logs, branches, tree stumps or stems, were purposely chipped or ground into a smaller size. Certain types of trees such as the Kenaf, Jute, Flax and Hemp are planted for their fibres, called fibre crops. These plants are considered non-woody biomass materials.

Size reduction of biomass could be made by chopping, chipping, grinding, and milling to perform solid disintegration. After chipping, the grinding process will break the wood into smaller particles through mechanical stress: impact, compression, shear and attrition. Intercellular and intracellular failure will loosen the fibre bonding, making smaller wood particles. Different grinding mills can be utilised, including; impact mills, roller mills, ball media mills, air jets mills and shearing attrition mills [2].

2 Energy Production

The most basic usage of sawdust is for energy production. Using wood-based materials for energy production has a tremendous environmental advantage. Energy generation using woody materials promotes the carbon cycle. When woody material is burned, it releases energy and carbon dioxide. The carbon dioxide from the environment is deposited back into plants during photosynthesis. The tree will be cut down and again generates carbon dioxide before being absorbed by other trees. As new trees grow, the cycle repeats over and over; that is the carbon cycle [3]. It differs from petroleum fuel burning, where carbon release happens one way without recapturing. Energy generation from wood sawdust can be done through 3 main categories, which are:

i. *Direct burning*
   Energy generation by directly burning forest biomass is a part of the global carbon cycle. It is considered carbon neutral because the same amount of CO_2 is released and captured in tree burning and growth [4]. Sawdust may be burned in its original powder form or compressed into pellets and briquettes for easy transportation and handling [5].
ii. *Heat treatment*
   Heat treatment was done to wood sawdust to turn it into charcoal and activated carbon. Pyrolysis involves the thermal degradation of biomass by heat in the absence or limitation of oxygen. Charcoal (solid), bio-oil (liquid) and fuel (gas) products are the output of this process [6]. The solid product, char or charcoal, is commonly compacted into pellets and briquettes for energy storage. Pyrolysis was usually done by heating the sawdust between 300 and 700 °C [7]. Heat treatment at a temperature above 700 °C is called the activation process, producing activated carbon. Considering the high cost of making activated carbon, pyrolysis temperature is enough for energy storage char production.
iii. *Bioethanol production*
   For bioethanol production, three significant steps should be conducted to the sawdust:

   a. Raw material pre-treatment
   b. Hydrolysis of pre-treated raw material
   c. Fermentation of hydrolysed material [8].

Sawdust is a lignocellulosic material which contains lignin, cellulose and hemicellulose. Pre-treatment of sawdust is needed to delignify the material. Delignification is essential to weaken the bond between cellulose and hemicellulose. It is a crucial step to ensure the success of the hydrolysis process. Pre-treatment techniques can be grouped into four categories, including acid pre-treatment (dilute acid, steam explosion, organosolv), neutral pre-treatment (liquid hot water), alkaline pre-treatment (sodium hydroxide, ammonia fibre expansion, soaking in aqueous ammonia) and ozonolysis [9]. Hydrolysis of cellulose and hemicellulose will produce fermentable sugars, including glucose, xylose, arabinose, galactose and mannose. Lastly, fermentation of reducing sugars will produce bioethanol [10].

3 Composite

Sawdust is a very suitable material for composite. Because of its tiny particle size, it can be mixed uniformly with polymer and adhesives. Different kinds of wood composite, such as particleboard, fibreboard and wood plastic composite, can be produced using sawdust as the main component.

Particleboard and fibreboard are made from mixtures of wood particles and fibres with adhesive or binder, respectively. Particleboard and fibreboard save a lot of wood waste, turning them into valuable, solid wood alternatives. Particleboard is prepared by mixing sawdust with 6–12% loading of thermosetting adhesives such as urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenolic resins (PF and TF), and isocyanates (pMDI). Larger particles are commonly placed at the core, while smaller particles are placed at the surface. Mixed resin-sawdust are flat-pressed at a high temperature between 100 and 180 °C for the resin to cure, forming a flat panel. The density of commercial particleboard is commonly set at 650–700 kg/m^3.

Fibreboard utilises wood fibre which is produced with the pulping process. Thermochemical pulping is usually employed to separate wood particles into individual fibres. Separated fibres were mixed with 2–3% of thermosetting binders and flat-pressed at a high temperature to cure. Fibreboards are categorised according to their density which is Medium Density Fibreboard, MDF (750–800 kg/m^3) and Hardboard (900–1100 kg/m^3) [11].

Wood plastic composite is the combination of wood and plastic or polymer. The thermosetting or thermoplastic polymer can be used as the matrix, the material that encapsulates the wood particles and holds them together. Thermosetting polymers are commonly available in liquid form. A polymer such as epoxy, unsaturated polyester and polyurethane can be directly mixed with sawdust using a simple mixer. Mixtures were laid into the mould, degassed using a vacuum bag and left to harden. An example of thermosetting wood plastic composite is the sisal fibre, and wood flour composites were made using unsaturated polyester thermosets by Marcovich et al. [12].

To produce wood plastic composite using thermoplastic as the matrix, the processes that might be involved include extrusion, injection moulding, and compression moulding or thermoforming (pressing) [13]. The plastic and wood were heated and blended when the thermoplastic melted. The sawdust-melted polymer mixture is then shaped before cooled down to harden. Wood plastic composite has many advantages, especially in automotive industries. The presence of sawdust in plastic composite increases the mechanical strength and reduces the material weight of automotive parts. Therefore it causes a reduction in vehicle fuel consumption, lowers production cost, increases passenger safety and improves the vehicle's interior parts' biodegradability [14]. Some wood composites made using sawdust are tabulated in Table 1.

4 Animal Feed

Sawdust is originally a non-edible substance for animals. Sawdust for animal feed is possible with pre-treatments required to make the produced animal feed pellet digestible. An example of research on sawdust as fish feed has been done by Sharma et al. [25]. A blend of protein-rich yeast *Candida utilis*, enzymatically hydrolysed

Table 1 Wood composite based on sawdust

No	Material	Bending strength	Tensile strength	References
1.	Corncob and sawdust particle board using urea-formaldehyde as binder	82.555 N/mm^2	NA	Akinyemi et al. [15]
2.	Wood sawdust-based particle board using ionic liquid-facilitated fusion process	NA	10.4 N/mm^2	Orelma Tanaka [16]
3.	Hybrid particleboards using coconut fibre and sawdust	17.8 N/mm^2	NA	Tawasil et al. [17]
4.	Sugarcane bagasse particleboard	11.44 N/mm^2	NA	Yano et al. [18]
5.	Particleboard from mixed-wood sawdust and *Cocos nucifera* (Coconut) husks (bonded with UF)	1.44 N/mm^2	218.03 N/mm^2	Dadzie et al. [19]
6.	Particleboards produced from wood chip wastes and modified cassava starch	35.7 N/mm^2	NA	Akinyemi et al. [20]
7.	particle boards from polystyrene-wood wastes	4.3 N/mm^2	NA	Akinyemi et al. [21]
8.	Wood Plastic Composites From Sawdust And Recycled Polyethylene Terephthalate (PET)	27.08 N/mm^2	NA	Rahman et al. [22]
9.	Poly(vinyl chloride)/wood sawdust composites	~39.00 N/mm^2	NA	Sombatsompop and Chaochanchaikul [23]
10.	*Albizia richardiana* King & Prain wood particles and recycled polyethylene terephthalate (PET) wood plastic composite	~32.00 N/mm^2	NA	Siddikur Rahman et al. [24]

sulphite-pulped spruce wood, and enzymatically hydrolysed brown seaweed was prepared. The results of the salmon feeding trial showed that the wood could replace parts of a conventional fishmeal diet without harmful effects.

The effect of wood kraft pulp feed on cow's digestibility, ruminal characteristics, and milk production performance has been done by Nishimura et al. [26]. The use of kraft wood pulp feed for lactating dairy cows made the same rumen fermentation characteristics as those in cows given a large amount of roughage. The milk productivity was also unchanged when using the new feed type.

Rabbit feed using sodium hydroxide-treated sawdust has been done by Omole and Onwudike [27]. Food consumption of food containing sawdust treated with 6%

solutions of sodium hydroxide is higher than consumption of sawdust treated with 0–3% sodium hydroxide. Rabbits given sawdust treated with 4 or 5% sodium hydroxide showed the best weight gain and efficiency of feed utilisation than that given sawdust treated with 0 or 1% sodium hydroxide solutions.

A minimal number of research has been done on using sawdust as animal feed. Digestibility of the sawdust becomes the main issue, while pre-treatment of the sawdust makes the process uneconomical and costly to be done commercially.

5 Adsorbent

Sawdust can be used as an adsorbent to remove contamination from water. The unmodified wood sawdust is the lowest cost material used to clean up dyes, oils, toxic salts, pharmaceutical substances and many more from the environment. The mechanism of contaminant adsorption onto the sawdust surface involves ion exchange and hydrogen bonding. The cell walls of sawdust mainly consist of cellulose and lignin, where there are abundant hydroxyl groups which can contribute to a high number of binding sites.

There are many factors affecting the adsorption process of contaminants by wood sawdust. Solution temperature, contact time, initial concentration of pollutant, adsorbent dosage and solution pH are among the determinant of adsorption effectiveness. Commonly, too high in temperature will decrease adsorption. A longer contact time allows the contaminant to be adsorbed onto the adsorbent surface. Higher adsorbent dosage made the water cleaning process faster, but for economic reasons, optimum dosage should be investigated to prevent wastage. The pHzpc, or the point where the adsorbent is in neutral charge. The surface charge of the adsorbent is positive when the solution pH is below the pHzpc value, while it is negative at a pH over the pHzpc. The adsorption depends on the charge of the adsorbate. For example, a positively charged metal ion will be more attracted to the adsorbent when the pH of the solution is above pHzpc, due to the negative charge of the adsorbent [28].

Suitable treatments can improve the adsorption performance of wood sawdust. Modification can be done to increase the number of pores or increase chemical binding sites on the surface of the adsorbent. For example, modification using alkaline solution on the sawdust of deciduous softwood–poplar and coniferous softwood-fir were found to result in adsorption increment of 5 times for copper ions and 15 times for zinc ions [29]. In another research on potassium hydroxide, KOH-modified poplar sawdust also showed an increment in metal ion adsorption, up to 94.3% for copper ion and 98.2% for zinc ion, compared to unmodified poplar [30]. A list of sawdust used for the adsorption of contaminants is tabulated in Table 2.

Table 2 List of sawdust used for adsorption of contaminants

No	Adsorbent	Adsorbate	Maximum adsorption capacity	References
1.	Pinewood sawdust modified with maleic acid	Cadmium (II) ions	180.4 mg g^{-1}	Hashem et al. [31]
2.	Ayous (*Triplochiton scleroxylon*) wood sawdust	Paraquat	41.66 μmol/g	Togue Kamga [32]
3.	Sawdust modified with sulphuric acid and formaldehyde	Chromium (VI) ions	8.84 mg/g	Chakraborty et al. [33]
4.	Hexadecylpyridinium bromide-treated sawdust	Allura red AC (dye)	151.88 μmol/g	Saha et al. [34]
5.	*Pinus halepensis* sawdust	Plumbum	8.64 mg/g	Semerjian [35]
6.	*Eucalyptusglobulus Labill* sawdust	Pb (II)	4.80 mg/g	Tejada-Tovar et al. [36]
7.	Magnetised *Tectona grandis* sawdust	Methylene blue	172.41 mg/g	Mashkoor and Nasar [37]
8.	*Picea smithiana* sawdust	Lead (Pb)	6.35 mg/g	Mahmood-ul-Hassan et al. [38]
9.	*Picea smithiana* sawdust	Chromium (Cr)	3.37 mg/g	Mahmood-ul-Hassan et al. [38]
10.	*Picea smithiana* sawdust	Cadmium (Cd)	2.87 mg/g	Mahmood-ul-Hassan et al. [38]
11.	Pine Sawdust	Cadmium Ions	3.47 mg/g	Liu et al. [39]
12.	Sawdust	Eriochrome Black T (EBT)	40.96 mg/g	Akhouairi et al. [40]

6 Nanocellulose

Nanocellulose is a material extracted from the plant cell wall. It is cellulose in nanometer size, high strength, excellent stiffness and large surface area [41]. Nanocellulose can be categorised into three main types; nanocrystalline cellulose, nanofibrillated cellulose, and bacterial nanocellulose [42].

i. Nanocrystalline cellulose
   Nanocrystalline cellulose consists of highly crystalline particles. The extraction was commonly done using acid hydrolysis/heat-controlled techniques. The crystals from cellulose fibres were extracted by hydrolysis of amorphous cellulose regions using sulphuric acid, resulting in highly crystalline particles with dimensions depending on the source of raw material. Sulphuric acid hydrolysis gives a negative charge of sulphate half-ester groups onto the surface of the particles, creating electrostatic repulsion between particles that prevents agglomeration [43].

ii. Nanofibrillated cellulose
Nanofibrillated cellulose is bundles of cellulose chain molecules stretched with a long and flexible cellulose nanofibre network. It has a size of 1–100 nm, with alternating crystalline and amorphous domains along the structure. It is produced by delamination of wood pulp through mechanical force after chemical and enzyme treatment. Nanofibrillar cellulose, cellulose nanofibre and cellulose nanofibril are used for microfibrillated cellulose and are commercially available [44]. The surface of nanofibrillated cellulose can be modified through polymer grafting, adding coupling agents and many more.
iii. Bacterial nanocellulose
Bacterial nanocellulose is generated by the bacteria such as *Gluconacetobacter, Sarcina, Aerobacter, Agrobacterium, Alcaligenes, Acanthamoeba, Achromobacter, Azotobacter, Rhizobium, Escherichia, Pseudomonas, Salmonella* and *Zooglea* [45]. It has various biomedical applications due to its biocompatibility and non-toxic properties [46]. Because bacterial nanocellulose is not extracted from wood materials, it will not cover extensively in this chapter.

Nanocellulose has various applications, from the engineering and electronic sector to biomedical purposes. Nanofibrillated cellulose has the potential to be utilised in nanocomposite making. Nanofibrillated cellulose can be solution cast, in situ polymerisation or through melt mixing for blending with thermoplastics. In biomedical applications, nanofibrillated cellulose is used in medicine for drug delivery in human blood. Cellulosic nanofibres were also used as a material for the development of nanocomposite scaffolds which match the strength of the original ligaments or tendons. Due to its large surface area, cellulose nanofibril also has the potential to be used as an adsorbent for contaminations from water. In the papermaking industry, the strong affinity of cellulose nanofibre with cellulosic pulp and their ability to form a 3D network made them an excellent additive to increase paper strength [47].

7 Agricultural Cultivation Media

In the agricultural sector, sawdust is commonly used as mushroom cultivation media. Mushrooms can be grown on any sawdust as the media. However, different compositions of sawdust type will affect the mushroom's growth rate and number of fruiting bodies. In South East Asia, rubberwood sawdust is commonly used as it can be found abundantly in rubber plantation agricultural activity [48].

The growth performance of *Pleurotus ostreatus* from various agricultural wastes mixed with rubber tree sawdust in Malaysia has been done by Ahmad Zakil et al. [49]. Different agricultural wastes were mixed with rubberwood sawdust, including the oil palm empty fruit bunch, oil palm press fibre sugarcane bagasse and corn cob. Results showed the highest total average yield of *P. ostreatus* was 207.96 g/bag on when using the combination of sugarcane bagasse and rubberwood sawdust at a ratio of 1:1.

Research has also been done on the cultivation of oyster mushrooms (*Pleurotus ostreatus*) using Moso bamboo sawdust showed a faster growth rate of 3–7 days than conventional cultivation media. When mixed with rice bran, it gives an even better yield of 97.9 ± 3.9 g/bottle and fruiting bodies at 33.6 ± 4.2 no/bottle [50].

8 Clay, Cement, Concrete and Building Materials

Sawdust is commonly added to building materials to reduce its original weight. Low thermal conductivity, high sound absorption and good sound insulation are among the wood characteristics favourable for building material [51]. An attempt to produce lightweight concrete using a mixture of sawdust and cement has successfully created a block of concrete that can withstand more than 2.8 N/mm^2, despite the increment in water absorption due to the presence of the sawdust [52]. The incorporation of sawdust into unfired clay blocks showed that up to 2.5% of sawdust could be added to make a good block with particle sizes ranging between 600 and 425 μm [53].

Sawdust has been tested for sand replacement in cement blocks for up to 15% content. Volumetric shrinkage and concrete density decrement were observed, with an increment of water absorption when the sawdust percentage was increased. Testing on two types of concrete prepared, the natural weight concrete, NWC and lightweight concrete recorded 34 MPa and 21 MPa compressive strength, respectively. Therefore, these concretes can be used for structural applications. Up to 21.42% reduction in the heating, ventilation and air-conditioning (HVAC) energy was also recorded in sawdust added concretes [54]. High thermal insulation is favourable in tropical countries as it minimises heat transfer from the outer side of the building into the occupied space.

9 Liquefaction

Biomass liquefaction is a technique of dissolving woody materials into liquid form for obtaining biofuels, bio-based materials and chemicals. Various wood liquefaction techniques include hydrothermal liquefaction, organic solvent liquefaction, co-solvent liquefaction, microwave-assisted liquefaction and plasma electrolytic liquefaction [55].

9.1 Hydrothermal Liquefaction

Hydrothermal liquefaction of sawdust is conducted near (subcritical) or above (supercritical) the critical point of water, which is 374 °C, under 22.1 MPa pressure. Before liquefaction, pre-treatment is necessary to facilitate access to the internal structure of wood for fractionation. Physical action (pulverisation and irradiation), chemical treatment (alkali, acid, organosolv and ammonia explosion), or combination of them as physicochemical (steam explosion, carbon dioxide explosion and wet oxidation) and biological pre-treatment (enzymolysis). General parameters of hydrothermal liquefaction are conducted at a low-temperature range between 200 and 400 °C and high pressure between 5 and 25 MPa. Sawdust will be converted into a bio-oil fraction, a gas fraction and a solid residue after the liquefaction process [56].

9.2 Co-solvent Liquefaction

Hydrothermal liquefaction can be done with co-solvent to assist the liquefaction process. The hydrothermal liquefaction of rice straw with methanol co-solvent has been done by Yerrayya et al. [57]. The presence of methanol as a co-solvent to water at 50:50 has improved the yield of bio-crude production up to 36.8 wt.%. Another hydrothermal liquefaction of rice straw with glycerol as co-solvent. Using 5 wt% of Na_2CO_3 as catalyst and 260 °C heating temperature for 1 h, the process yielded 50.31 wt% of bio-oil and 26.65 wt% of solid residue [58]. Meanwhile, hydrothermal sugarcane bagasse at 320 °C reaction temperature, 15 min reaction time and 10 wt% potassium hydroxide, KOH as catalyst produce the highest amount of bio-crude of 36.3 wt% [59].

9.3 Organic Solvent Liquefaction

Organic solvent liquefaction can be done at temperatures 240–270 °C without catalysts. The temperature could be lowered to around 80–150 °C with acidic catalysts. Organic solvent liquefaction produces very high yields of solvent solubles of about 90–95% based on the lignocellulosic weight. The conventional liquefaction of wood takes several hours of treatments with a higher temperature required at 300–400 °C with or without catalysts. Conventional liquefaction also yields less, around 40–60%, due to the conversion of the woody material into gaseous compounds [60].

The possible chemical compounds that can be produced from the organic solvent liquefaction are resins such as phenolic resins (novolac and resol type), polyurethanes and epoxy, which are commonly used in wood composite making [61, 62]. An experiment on the effects of phenol, ethylene glycol (EG) and ethylene carbonate (EC) solvents shows phenol as the optimum solvent for bamboo liquefaction with a yield of up to 99%. The liquefaction utilises hydrochloride acid at a temperature of 180 °C in autoclaves for different reaction periods [63].

9.4 Microwave-Assisted Liquefaction

As its name mentioned, microwave-assisted liquefaction is the method to increase liquefaction yield by combining chemical processes and microwave irradiation. Using microwave heating brings the energy directly into the target object due to the applied electromagnetic field. Microwave heating ensures faster heat penetration into the bulk material. Therefore the reaction time can be reduced, which may also reduce the cost of operation [64].

Microwave-assisted liquefaction has been researched by Xue et al. [65] using polyethylene glycol (PEG-400) and glycerol mixture as liquefying solvents together with 97 wt% sulphuric acids as a catalyst at a reaction temperature of 140 °C. A high liquefaction yield (97.47%) was achieved in just 5 min to obtain the polyol. In their research, the polyol produced was made into polyurethane resin.

Another research used pinewood particles as the raw material, with polyethylene glycol and glycerin (70/30 w/w) as the liquefaction reagent. The solvent-to-wood ratio was 7:1, and the liquefaction was done using two types of catalysts, which were 3% of sulphuric acid and phosphoric acid. Liquefaction was done at 150 °C with the help of microwave irradiation. It was found that using microwave heating, the wood meal completely dissolved in just 2 min, compared to 30 min using conventional heating [66].

10 Conclusions

Sawdust has a wide variety of potential uses, from energy generation to chemical extraction. Sawdust cannot be treated as trash but as a new source of income generation for the company. It is also a sustainable way of using wood resources as efficient as possible to guarantee the future of our forests. Hopefully, this book chapter has given some insights into the usefulness of wood sawdust.

References

1. Saal U, Weimar H, Mantau U (2019) Wood Processing Residues. In: Wagemann K, Tippkötter N (eds) Biorefineries. Springer International Publishing, Cham, pp 27–41
2. Arif Hakimi Saadon SZ, Osman NB, Yusup S (2022) Chapter 5—Pretreatment of fiber-based biomass material for lignin extraction. In: Yusup S, Rashidi NA (eds) Value-chain of biofuels. Elsevier, pp 105–135
3. Bergman R et al (2014) The carbon impacts of wood products. For Prod J 64(7–8):220–231
4. Routa J et al (2011) Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. GCB Bioenergy 3(6):483–497
5. Obi OF (2015) Evaluation of the effect of palm oil mill sludge on the properties of sawdust briquette. Renew Sustain Energy Rev 52:1749–1758
6. Demirbas A, Arin G (2002) An overview of biomass pyrolysis. Energy Sour 24(5):471–482

7. Shaaban A et al (2014) Influence of heating temperature and holding time on biochars derived from rubber wood sawdust via slow pyrolysis. J Anal Appl Pyrol 107:31–39
8. Balat M, Balat H, Öz C (2008) Progress in bioethanol processing. Prog Energy Combust Sci 34(5):551–573
9. Xu Z, Huang F (2014) Pretreatment methods for bioethanol production. Appl Biochem Biotechnol 174(1):43–62
10. Sarkar N et al (2012) Bioethanol production from agricultural wastes: an overview. Renewable Energy 37(1):19–27
11. Pizzi A, Papadopoulos AN, Policardi F (2020) Wood composites and their polymer binders. Polymers 12(5):1115
12. Marcovich NE et al (2009) Resin-sisal and wood flour composites made from unsaturated polyester thermosets. Compos Interfaces 16(7–9):639–657
13. Gardner DJ, Han Y, Wang L (2015) Wood-plastic composite technology. Curr For Rep 1(3):139–150
14. Ashori A (2008) Wood–plastic composites as promising green-composites for automotive industries! Biores Technol 99(11):4661–4667
15. Akinyemi AB, Afolayan JO, Oluwatobi EO (2016) Some properties of composite corn cob and sawdust particle boards. Constr Build Mater 127:436–441
16. Orelma H et al (2021) Manufacture of all-wood sawdust-based particle board using ionic liquid-facilitated fusion process. Wood Sci Technol 55(2):331–349
17. Tawasil DN et al (2021) Coconut fibre and sawdust as green building materials: a laboratory assessment on physical and mechanical properties of particleboards. Buildings 11. https://doi.org/10.3390/buildings11060256
18. Yano BB et al (2020) Use of sugarcane bagasse and industrial timber residue in particleboard production. BioResources 15(3):4753–4762
19. Dadzie PK, Awotwe-Mensah M, Amoah M (2021) Materials mix ratio and binder type effects on physical and mechanical properties of particleboard from mixed-wood sawdust and Cocos nucifera (Coconut) husks. J Indian Acad Wood Sci 18(2):128–140
20. Akinyemi BA, Olamide O, Oluwasogo D (2019) Formaldehyde free particleboards from wood chip wastes using glutaraldehyde modified cassava starch as binder. Case Stud Constr Mater 11:e00236
21. Akinyemi BA et al (2019) Durability and strength properties of particle boards from polystyrene–wood wastes. J Mater Cycles Waste Manag 21(6):1541–1549
22. Rahman KS et al (2013) Flat-pressed wood plastic composites from sawdust and recycled polyethylene terephthalate (PET): physical and mechanical properties. Springerplus 2(1):629
23. Sombatsompop N, Chaochanchaikul K (2004) Effect of moisture content on mechanical properties, thermal and structural stability and extrudate texture of poly(vinyl chloride)/wood sawdust composites. Polym Int 53(9):1210–1218
24. Siddikur Rahman K et al (2018) Properties of flat-pressed wood plastic composites as a function of particle size and mixing ratio. J Wood Sci 64(3):279–286
25. Sharma S et al (2018) Microbial protein produced from brown seaweed and spruce wood as a feed ingredient. J Agric Food Chem 66(31):8328–8335
26. Nishimura K et al (2019) Effect of wood kraft pulp feed on digestibility, ruminal characteristics, and milk production performance in lactating dairy cows. Anim Sci J 90(2):189–195
27. Omole TA, Onwudike OC (1981) Investigations of the treatment of sawdust for rabbit feeding. 1. Effect of sodium hydroxide treatment. Animal Feed Sci Technol 6(1):43–50
28. Shukla A et al (2002) The role of sawdust in the removal of unwanted materials from water. J Hazard Mater 95(1):137–152
29. Šćiban M, Klašnja M, Škrbić B (2006) Modified softwood sawdust as adsorbent of heavy metal ions from water. J Hazard Mater 136(2):266–271
30. Kovacova Z et al (2020) Influence of wooden sawdust treatments on Cu(II) and Zn(II) removal from water. Materials 13. https://doi.org/10.3390/ma13163575
31. Hashem A et al (2020) Non-linear adsorption characteristics of modified pine wood sawdust optimised for adsorption of Cd(II) from aqueous systems. J Environ Chem Eng 8(4):103966

32. Togue Kamga F (2018) Modeling adsorption mechanism of paraquat onto Ayous (Triplochiton scleroxylon) wood sawdust. Appl Water Sci 9(1):1
33. Chakraborty R et al (2021) Adsorption of hazardous chromium (VI) ions from aqueous solutions using modified sawdust: kinetics, isotherm and thermodynamic modelling. Int J Environ Anal Chem 101(7):911–928
34. Saha TK et al (2020) Adsorption characteristics of Allura red AC onto sawdust and hexadecylpyridinium bromide-treated sawdust in aqueous solution. ACS Omega 5(22):13358–13374
35. Semerjian L (2018) Removal of heavy metals (Cu, Pb) from aqueous solutions using pine (Pinus halepensis) sawdust: equilibrium, kinetic, and thermodynamic studies. Environ Technol Innov 12:91–103
36. Tejada-Tovar C et al (2021) Potential use of residual sawdust of eucalyptus globulus Labill in Pb (II) adsorption: modelling of the kinetics and equilibrium. Appl Sci 11. https://doi.org/10.3390/app11073125
37. Mashkoor F, Nasar A (2020) Magnetized Tectona grandis sawdust as a novel adsorbent: preparation, characterization, and utilization for the removal of methylene blue from aqueous solution. Cellulose 27(5):2613–2635
38. Mahmood-ul-Hassan M et al (2018) Kinetics, isotherms, and thermodynamic studies of lead, chromium, and cadmium bio-adsorption from aqueous solution onto Picea smithiana sawdust. Environ Sci Pollut Res 25(13):12570–12578
39. Liu X et al (2019) Adsorption characteristics of cadmium ions from aqueous solution onto pine sawdust biomass and biochar. BioResour 14(2):4270–4283
40. Akhouairi S et al (2019) Natural sawdust as adsorbent for the eriochrome black T dye removal from aqueous solution. Water Air Soil Pollut 230(8):181
41. Phanthong P et al (2018) Nanocellulose: extraction and application. Carbon Resour Conv 1(1):32–43
42. Lavoine N et al (2012) Microfibrillated cellulose—Its barrier properties and applications in cellulosic materials: a review. Carbohyd Polym 90(2):735–764
43. Abitbol T et al (2016) Nanocellulose, a tiny fiber with huge applications. Curr Opin Biotechnol 39:76–88
44. Abdul Khalil HPS et al (2014) Production and modification of nanofibrillated cellulose using various mechanical processes: a review. Carbohydr Polym 99:649–665
45. Skočaj M (2019) Bacterial nanocellulose in papermaking. Cellulose 26(11):6477–6488
46. Sharma C, Bhardwaj NK (2019) Bacterial nanocellulose: present status, biomedical applications and future perspectives. Mater Sci Eng, C 104:109963
47. Kalia S et al (2014) Nanofibrillated cellulose: surface modification and potential applications. Colloid Polym Sci 292(1):5–31
48. Tan YH, Krishnen G (2008) Comparative growth and fructification of the shiitake mushroom, Lentinula edodes, on rubberwood sawdust, palm fibres and grasses
49. Ahmad Zakil F et al (2022) Growth performance and mineral analysis of Pleurotus ostreatus from various agricultural wastes mixed with rubber tree sawdust in Malaysia. Bioresour Technol Rep 17:100873
50. Yamauchi M et al (2019) Cultivation of oyster mushroom (Pleurotus ostreatus) on fermented moso bamboo sawdust. J King Saud Univ Sci 31(4):490–494
51. Mwango A, Kambole C (2019) Engineering characteristics and potential increased utilisation of sawdust composites in construction—A review. J Build Constr Plan Res 7(3):59–88
52. Omar MF et al (2020) Partially replacement of cement by sawdust and fly ash in lightweight foam concrete. IOP Conf Ser: Mater Sci Eng 743(1):012035
53. Jannat N et al (2021) Influence of sawdust particle sizes on the physico-mechanical properties of unfired clay blocks. Designs 5. https://doi.org/10.3390/designs5030057
54. Ahmed W et al (2018) Effective use of sawdust for the production of eco-friendly and thermal-energy efficient normal weight and lightweight concretes with tailored fracture properties. J Clean Prod 184:1016–1027
55. Kim J-Y et al (2019) Overview of the recent advances in lignocellulose liquefaction for producing biofuels, bio-based materials and chemicals. Biores Technol 279:373–384

56. Jindal MK, Jha MK (2016) Hydrothermal liquefaction of wood: a critical review. Rev Chem Eng 32(4):459–488
57. Yerrayya A et al (2020) Hydrothermal liquefaction of rice straw using methanol as co-solvent. Energies 13. https://doi.org/10.3390/en13102618
58. Cao L et al (2016) Effect of glycerol as co-solvent on yields of bio-oil from rice straw through hydrothermal liquefaction. Biores Technol 220:471–478
59. Yerrayya A et al (2022) Optimization of bio-crude yield and its calorific value from hydrothermal liquefaction of bagasse using methanol as co-solvent. Energy 244:123192
60. Shiraishi N (1992) Liquefaction of lignocellulosics in organic solvents and its application. Emerging technologies for materials and chemicals from biomass. American Chemical Society, pp 136–143
61. Pan H (2011) Synthesis of polymers from organic solvent liquefied biomass: a review. Renew Sustain Energy Rev 15(7):3454–3463
62. 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
63. Yip J et al (2009) Comparative study of liquefaction process and liquefied products from bamboo using different organic solvents. Biores Technol 100(24):6674–6678
64. de la Hoz A, Díaz-Ortiz Á, Moreno A (2005) Microwaves in organic synthesis. Thermal and non-thermal microwave effects. Chem Soc Rev 34(2):164–178
65. Xue B-L, Wen J-L, Sun R-C (2015) Producing lignin-based polyols through microwave-assisted liquefaction for rigid polyurethane foam production. Materials 8:586–599. https://doi.org/10.3390/ma8020586
66. Pan H, Zheng Z, Hse CY (2012) Microwave-assisted liquefaction of wood with polyhydric alcohols and its application in preparation of polyurethane (PU) foams. Eur J Wood Wood Prod 70(4):461–470