Potential biomass pre-treatments for the identified/quantified feedstocks

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Waste biorefinery technologies for accelerating sustainable energy processes (WIRE)

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List of acronyms

MDF	Medium-density fiberboard
HDF	High-density fiberboard
S_{BET}	BET surface area
OSB	Oriented strand board

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Executive summary

This report compiles key data on the production of biological waste, particularly citrus and wood residues, which have significant valorization potential. It also provides an overview of the main pretreatment technologies used to improve the properties of these residues and optimize their subsequent valorization. By highlighting the benefits of converting these waste streams into valuable products, this report aims to promote sustainable practices in the agricultural and forestry sectors.

1. Introduction:

Waste management is one of the most pressing environmental challenges faced globally today. Waste generation is increasing at an unprecedented rate due to rapid industrialization, urbanization, and rising consumerism, endangering ecosystems, public health, and the economy. Waste disposal methods, such as landfilling and incineration, contribute to greenhouse gas emissions, soil and water contamination, and loss of biodiversity. In response to these challenges, there is a growing focus on sustainable waste management practices, particularly through the concept of a circular economy. This approach emphasizes waste reduction, recycling, and the valorization of waste materials, turning them into valuable resources instead of environmental burdens. A large portion of such waste is directly burned and evaluated. The ashes formed by burning are thrown into nature, and as a result of mixing with drinking water through rain and snow, they endanger human health. They also reduce the fertility of the soil and cause environmental pollution (Sümer et al., 2016).

On the other hand, some of the waste citrus peels are used as animal feed, some are dried and evaluated, and the rest are taken to urban solid waste storage facilities. This situation creates a significant problem, especially for municipalities in settlements where citrus production is carried out (Yaman, 2012). These wastes require innovative solutions for waste reduction and management. These wastes can be transformed into valuable products through processes.

The valorization of biological waste involves converting waste materials into valuable products, thereby reducing environmental impact and creating economic value. This shift from waste disposal to waste utilization is a critical component of sustainable development and is gaining traction in industries worldwide. Two prominent examples of biological waste that hold significant potential for valorization are citrus waste and wood waste, both of which are produced in large quantities and pose substantial environmental challenges if not properly managed. Tables 1, 2, 3, and 4 show the production quantity of citrus spices (FAO provides these data) in some European countries (FAO, 2024).

Table 1. Production quantity of lemons and limes (ton)

	2019	2020	2021	2022
France	10 040	9 980	22 810	21 690
Greece	82 260	87 190	86 700	89 850
Italy	445 950	473 280	466 990	476 310
Portugal	23 190	25 200	27 190	30 620
Spain	884 890	1 100 470	1 017 360	863 240
Türkiye	950 000	1 188 517	1 550 000	1 323 000

Table 2. Production quantity of oranges (ton)

	2019	2020	2021	2022
France	8 890	8 160	10 630	9 760
Greece	849 080	886 640	818 310	873 670
Italy	1 650 210	1 772 770	1 770 910	1 783 110
Portugal	346 510	355 280	363 920	378 450
Spain	3 226 870	3 343 960	3 604 800	2 817 400
Türkiye	1 700 000	1 333 975	1 742 000	1 322 000

Table 3. Production quantity of pomelos and grapefruits (ton)

	2019	2020	2021	2022
France	8 500	8 420	9 400	9 370
Greece	3 100	3 160	2 890	2 640
Italy	5 210	5 460	5 460	5 460
Portugal	220	220	220	220
Spain	70 470	79 790	79 970	76 660
Türkiye	249 185	238 012	249 000	198 000

Table 4. Production quantity of tangerines, mandarins, clementines (ton)

	2019	2020	2021	2022
France	34 360	46 570	45 350	50 750
Greece	150 640	171 870	180 950	201 490
Italy	763 610	660 280	826 470	801 240
Portugal	42 140	42 240	43 420	42 890
Spain	1 826 330	2 172 180	2 009 520	1 800 490
Türkiye	1 400 000	1 585 629	1 819 000	1 865 000

Citrus fruits, which include oranges, lemons, mandarins, limes, and grapefruits, are widely consumed worldwide, generating significant amounts of waste in the form of peels, seeds, and pulp. Citrus waste constitutes nearly 50% of the wet fruit mass after juice extraction (Sharma et al., 2017). This means that approximately 7.5 million tons of citrus waste were generated in these countries during 2022. Traditionally, these residues have been considered a disposal problem. However, with proper mechanical pre-treatment, citrus waste can be repurposed for various food applications, taking advantage of its nutritional and aromatic qualities.

Wood waste, a byproduct of forestry and wood-processing industries, is another valuable resource that can be repurposed through mechanical pre-treatment. By breaking down wood waste into smaller particles or fibers, it can be used to manufacture engineered wood products like particleboard, oriented strand board (OSB), and medium-density fiberboard (MDF). These products are essential in the construction and furniture industries and are commonly made from wood residues. Table 5 shows the quantity of wood waste (FAO provides this data) in some European Countries (FAO, 2024).

Table 5. Quantity of wood residues (m^3)

	2019	2020	2021	2022
Czechia	665 002	665 002	697 000	690 000
Finland	4 951 657	4 504 000	5 475 422	5 073 112
France	7 166 000	7 652 060	9 424 926	9 424 926
Germany	3 917 715	4 407 594	4 898 058	4 976 648
Greece	4 500	4 500	4 500	4 500
Italy	-	-	-	-
Norway	841 725	764 101	949 812	950 251
Poland	6 700 000	6 900 000	7 200 000	7 250 000
Portugal	872 000	825 000	885 000	874 000
Spain	1 720 338	1 396 787	2 007 464	2 007 464
Sweden	9 407 000	9 600 000	5 757 939	5 706 798
Türkiye	850 000	830 000	500 000	550 000

2. Mechanical Pre-treatments of Citrus and Wood Waste

The mechanical pre-treatment of citrus waste typically involves size reduction methods such as grinding and milling, which break down the fibrous structure of the peel and pulp. This increases the surface area, enhancing the release of valuable bioactive compounds such as flavonoids, pectin, and essential oils (Maqbool et al., 2023). By making these compounds more accessible, pre-treatment not only facilitates their extraction for use as food additives or supplements but also enables the incorporation of whole citrus waste into food products. One notable application of mechanically pre-treated citrus waste is in the production of citrus-based teas. Citrus peels can be used as a flavorful and aromatic ingredient in herbal teas after grinding and drying. Their high content of essential oils, particularly limonene, lends a refreshing citrus aroma and taste to the tea (Xu et al., 2021).

Additionally, the bioactive compounds present in citrus waste, such as vitamin C, flavonoids, and fiber, provide potential health benefits, making citrus waste an attractive ingredient for functional foods (Russo, et al., 2021). Another area where citrus waste can be utilized is in baking. Citrus peel powder, obtained by milling dried citrus peels, can be added to dough for baked goods such as cakes, muffins, and bread. It not only enhances the flavor profile of the final product with its zesty aroma but also improves its nutritional value by adding fiber and antioxidants. Furthermore, citrus peel powder can act as a natural preservative due to its antimicrobial properties, which help extend the shelf life of the food products (Pieracci et al., 2022). The benefits of mechanically pre-treating citrus waste for food applications are multifaceted. Not only does it reduce food waste and divert citrus residues from landfills, but it also adds value to the food industry by providing a cost-effective source of natural ingredients. Moreover, the incorporation of citrus waste into food products aligns with the growing consumer demand for clean-label, natural, and sustainable food choices.

In the production of particleboard, wood waste is ground into fine particles and mixed with resin before being compressed into a mat. The size reduction achieved during mechanical pre-treatment is crucial, as the smaller particles result in a smoother, more uniform surface, which improves the quality of the final product. Particleboard made from mechanically pre-treated wood waste is widely used in cabinetry and furniture, offering an economical and environmentally friendly alternative to solid wood (Lukash et al., 2023). The quantity of particleboard production (FAO provides the data) is given in Table 6 (FAO, 2024).

Table 6. Quantity of particleboard production (m^3)

	2019	2020	2021	2022
Czechia	380 112	387 000	965 000	962 000
Finland	88 000	88 000	54 194	53 594
France	2 796 000	2 221 000	3 281 000	3 177 342
Germany	5 714 719	5 556 360	6 036 276	5 526 329
Greece	323 263	265 076	265 076	265 076
Italy	3 070 000	2 670 000	2 670 000	2 670 000
Norway	277 000	291 000	317 947	284 753
Poland	5 649 945	5 738 550	6 332 992	4 990 000
Portugal	716 000	708 000	743 000	766 000
Spain	1 898 712	1 783 054	2 797 567	2 797 567
Sweden	578 000	561 400	636 000	636 000
Türkiye	4 355 000	4 075 000	5 675 000	5 625 000

In Europe, about 46% of wood waste is recycled, and in Italy, up to 95% of wood waste is utilized in the production of chipboard and particleboard (Pazzaglia & Castellani, 2023). Studies have shown that waste wood, including sawdust and shavings, can be effectively used in particleboard manufacturing, meeting various performance standards (Felix et al., 2015).

Similarly, oriented strand board (OSB) is produced by cutting wood waste into larger strands, which are then arranged in layers and bonded with resin. Mechanical pre-treatment ensures that these strands are uniform in size and shape, which is important for the strength and durability of OSB panels. OSB is often used in structural applications like flooring and wall sheathing due to its load-bearing capabilities (Fomin et al., 2016). The quantity of OSB production (FAO provides the data) is given in Table 7 (FAO, 2024). Depending on the composition and treatment, up to 100% of the core layer in OSB can be made from wood waste, maintaining the required mechanical properties (Barbirato et al., 2020; Schild et al., 2021).

Table 7. Quantity of OSB production (m^3)

	2019	2020	2021	2022
Czechia	905 491	924 000	745 000	689 000
Finland	0	0	0	0
France	404 000	379 000	402 000	301 927
Germany	1 163 010	1 233 873	1 281 538	1 163 557
Greece	0	0	0	0
Italy	130 000	100 000	100 000	100 000
Norway	0	0	0	0
Poland	938 055	832 614	826 887	810 000
Portugal	0	0	0	0
Spain	1 288	1 946	2 433	2 433
Sweden	0	0	0	0
Türkiye	75 000	75 000	75 000	75 000

Medium-density fiberboard (MDF) is another engineered wood product that benefits from mechanical pre-treatment. In the production of MDF, wood fibers are extracted from waste wood through grinding or refining processes. These fibers are then bonded with resin and compressed into sheets. MDF is prized for its smooth surface and uniform density, making it ideal for detailed work in furniture and cabinetry. The mechanical pre-treatment of wood waste ensures that the fibers are fine and consistent, contributing to the high quality of the MDF/high-density fiberboard (HDF) produced (Song et al., 2018). The quantity of MDF/HDF production (FAO provides the data) is given in Table 8 (FAO., 2024).

Table 8. Quantity of MDF/HDF production (m^3)

	2019	2020	2021	2022
Czechia	42 396	42 800	45 000	41 000
Finland	0	0	0	0
France	898 000	751 000	1 041 873	953 902
Germany	4 505 051	4 599 693	4 692 624	3 791 548
Greece	65 000	75 000	75 000	75 000
Italy	849 689	810 000	810 000	810 000
Norway	0	0	0	0
Poland	3 655 906	3 177 657	3 541 568	3 400 000
Portugal	412 000	423 000	535 000	494 000
Spain	1 540 000	1 448 000	1 448 000	1 448 000
Sweden	0	0	0	0
Türkiye	4 910 000	4 775 000	4 850 000	6 250 000

MDF can incorporate 25% to 75% of wood waste or other fiber sources, depending on the treatment and application (Migneault et al., 2010; Moreno-Anguiano et al., 2022).

By converting wood waste into engineered wood products, the demand for virgin timber is reduced, contributing to forest conservation efforts. Moreover, the repurposing of wood waste in this manner provides a sustainable and cost-effective alternative to solid wood while also reducing waste disposal issues and contributing to a circular economy. Mechanical pre-treatment is thus a critical step in transforming wood waste into high-value products that meet the needs of modern industries.

3. Thermal Pre-treatments of Citrus and Wood Waste

Thermal pre-treatment methods such as torrefaction, pyrolysis, and steam explosion have garnered attention for their ability to enhance the properties of biomass waste, including citrus and wood waste. These processes involve the application of heat under controlled environments to improve the energy content, chemical composition, and reactivity of the waste materials. Such treatments not only improve the handling and storage characteristics of the biomass but also increase its suitability for subsequent conversion into biofuels, chemicals, or value-added products.

3.1. Torrefaction as a Pre-treatment for Biomass Waste

Torrefaction is a mild pyrolysis process that typically occurs at temperatures ranging from 200°C to 300°C in an oxygen-deprived environment. This treatment is widely used to improve the energy density and hydrophobicity of biomass, making it easier to store and transport. For citrus and wood waste, torrefaction has shown promising results in improving their grindability, reducing moisture content, and increasing their energy content.

Research on the torrefaction of woody biomass such as eucalyptus shows that the process enhances the carbon content while reducing the oxygen and hydrogen content, thereby increasing the calorific value of the material. For instance, torrefied eucalyptus exhibited improved fuel properties, with a mass loss of up to 35%, and a significant increase in energy content by 27% (Almeida et al., 2010). This makes torrefaction a viable pre-treatment for producing high-quality fuels from wood waste.

Similarly, torrefaction of citrus waste, such as orange and lemon peels, can enhance their utility as biofuels. Studies have demonstrated that slow pyrolysis of citrus residues results in biochar with higher energy density and greater stability, with citrus char exhibiting energy values comparable to traditional fuels like coal (Volpe et al., 2015). Thus, torrefaction is an essential step in optimizing both wood and citrus waste for energy applications.

3.2. Steam Explosion: Improving Biomass Reactivity and Enzyme Accessibility

Steam explosion is a pre-treatment process that involves exposing biomass to high-pressure steam followed by a rapid pressure drop. This sudden change in pressure disrupts the cell structure of the biomass, making it more accessible for subsequent treatments such as enzymatic hydrolysis or fermentation. Steam explosion is particularly effective in breaking down the lignocellulosic structure of woody biomass and has been widely studied as a method to enhance the digestibility of biomass for biofuel production.

In the context of wood waste, steam explosion has been shown to alter the chemical composition of the biomass significantly. Studies demonstrate that this process reduces the hemicellulose content while increasing the accessibility of cellulose for enzymatic hydrolysis, thus improving the overall efficiency of biofuel production (Sebestyén et al., 2013). Steam explosion also helps to lower the alkali metal content, which can interfere with downstream processes such as gasification or combustion.

For citrus waste, steam explosion can enhance the release of valuable compounds such as pectin and flavonoids, which are widely used in the food and pharmaceutical industries. The pre-treatment improves the extraction efficiency of these compounds by breaking down the tough cell walls of the citrus peels, making the process more efficient and cost-effective (Maqbool et al., 2023).

3.3. Pyrolysis: Maximizing Biofuel Yields from Biomass

Pyrolysis is a more intense thermal treatment than torrefaction, typically conducted at temperatures between 400°C and 800°C. It breaks down the biomass into activated carbon, bio-oil, and syngas, with the proportions of each product depending on the operating conditions. For citrus and wood waste, pyrolysis is particularly valuable for converting these materials into biofuels and chemicals.

In the pyrolysis of wood waste, the yield of activated carbon is influenced by the torrefaction temperature, with studies showing that higher pyrolysis temperatures lead to increased char yields. For instance, radiata pine subjected to pyrolysis after torrefaction produced higher-quality activated carbon with greater carbon content and reduced volatiles (Safaai & Pang, 2021). For citrus waste, pyrolysis offers the potential to create valuable bio-oils and activated carbon. Pyrolysis of orange waste, for example, has been shown to produce bio-oil with a rich mix of carboxylic acids, aldehydes, and phenolic compounds, which can be used in the chemical industry López-Velázquez et al., 2013).

The pyrolysis is a versatile pre-treatment that can maximize the value of citrus and wood waste. The uses and surface areas of activated carbons with varying properties produced through the pyrolysis of wood and citrus waste are presented in Table 9.

Table 9. Previous wood and citrus waste-based activated carbon studies

Raw material	Activation Agent	S_{BET} (m^2/g)	Production Propose	References
Orange Peel	Phosphoric acid	2209	Supercapacitor	Wei et al., 2019
Orange Peel	Potassium hydroxide	638	Battery	Xiang et al., 2017
Lemon Peel	Potassium hydroxide	1113	Adsorption	Weldekidan et al., 2024
Pomelo peels	Zinc chloride	1352	Adsorption	Zhu et al., 2023
Mandarin peels	Phosphoric acid	1021	Adsorption	Koyuncu et al., 2018
Grapefruit Peel	Pyrophosphoric acid	1066	Adsorption	Liu et al., 2018
Scot Pine waste	Zinc chloride	1102	Formaldehyde reducer in particleboard	Ergun et al., 2024
Pistachio wood waste	Ammonium nitrate	1448	Adsorption	Sajjadi et al., 2018
Vatica rassak wood waste	Phosphoric acid	1196	Adsorption	Teong et al., 2021
Willow Wood waste	Potassium hydroxide	2800	Supercapacitor	Phiri et al., 2019
Ash wood waste	Phosphoric acid	623	Filler in foam material	Ergun and Ergun, 2024

In 2022, the market volume of activated carbon was approximately 5.8 million metric tons worldwide (Statista, 2024). In such a large market, utilizing biological waste, especially wood and citrus residues, for the production of activated carbon offers a cost-effective solution while enhancing environmental sustainability. This approach not only improves waste management but also creates an alternative to traditional carbon sources, meeting industrial demand.

Conclusion

Mechanical and thermal pre-pretreatments proved to be a versatile technique for enhancing the utilization of citrus and wood waste. These pre-treatments can transform citrus and wood waste into a wide range of products, from food additives and functional foods to activated carbon and biofuels. This versatility highlights the potential of pre-pretreatments as a key technology for addressing the challenges associated with waste management and promoting a circular economy.

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