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Rossella Corrao · Tiziana Campisi · Simona Colajanni · Manfredi Saeli · Calogero Vinci *Editors*

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Contents

Wood Industry Wastes Valorisation and Reuse for a Greener Architecture

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Abstract. This study is part of a PhD research supported by PNRR aimed to provide concrete actions to implement greener constructive practices in response to the EU Green Deal and the demand of sustainability in construction. In particular, this paper analyses how wastes from the wood industry can be reused for applications in construction, in light of the circular economy (CE) and the industrial symbiosis. The analysed wastes derive from various processes and their heterogeneous nature often makes their incorporation into novel products complex. Additionally, they may contain contaminants, such as glues or chemicals, that may limit the reuse options or require special handling procedures. However, by addressing these issues through appropriate manufacturing processes and sustainable practices, wood waste reuse can offer significant environmental benefits, such as reducing wastes quantity and saving natural resources, or technological benefits by bringing innovation and sustainability to the sector. Once wood assortments' manufacture was briefly outlined, the various types of waste resultant from each processing phase are analysed to explore possible recycling opportunities and identify challenges and prospects for more efficient, rational, and sustainable management. The study proposed here, focuses on the analysis of materials, products and systems that reuse wastes from the wood industry and the possible applications in construction. Among these, for example, thermoacoustic panels, polymer-based biocomposites, wood-cement panels and blocks are discussed. Furthermore, attention is given to microlaminated wood technology, currently considered a technological implementation to traditional laminated wood. Finally, the crucial role of wood waste recycling as a CE approach is underlined, emphasizing the fundamental contribution to environmental sustainability, the mitigation of climate change, and the creation of new markets and jobs in the construction context.

Keywords: Wood Waste · Circular Economy · Industrial Symbiosis · Environmental Sustainability · Innovative Materials

1 Introduction

The increasing abuse of energy use on a global scale, has recently generated serious concerns about the depletion of non-renewable natural resources and the disastrous environmental impacts, such as increasing CO_2 emissions and massive air pollution,

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global warming, and the decline of the ecosystems [1]. Furthermore, the rapid expansion of the population globally is undeniably contributing to an increased demand for further energy resources. At the same time, a growing awareness is spreading on the need to address issues related to wiser resource use, product manufacture, and waste management [2]. Worldwide, the industrial activities, for example, produce significant quantities of waste annually, which pose significant challenges in terms of management, treatment and disposal, resulting in huge financial losses and immense energy and environmental impacts [3]. In order to face the waste problem and reduce its impact on the environment, the European Union (EU) has established ambitious objectives for recycling and reducing the use of landfills [4] to promote a circular transition, encouraging products reuse, recycling and extension of life cycle, in order to minimise waste production and, conversely, maximise efficiency in resources use. In this sense, the EU has issued a number of regulations and incentives aimed at achieving efficient waste management objectives, including the Waste Directive (Directive 2008/98/EC) and the Waste Catalogue (Directive 2000/532/EC), including a complete list of waste categories, divided by type based on the industrial sector of origin, and the Action Plan for the circular economy. Therefore, the Circular Economy (CE) principles "reduce, reuse, recycle", are becoming the focus of increasingly stringent policies promoted by governments in the EU and globally [5]. Moreover, such perspective is not only aimed at promoting environmental sustainability but also at creating new economic opportunities, encouraging innovation, and the creation of new markets and jobs. Currently, the concept of "waste" is moving from a simple object to be eliminated to a resource to be managed and valorised. This innovative approach is based on fundamental principles such as minimising waste, extending the useful life of materials and products and improving efficiency in the use of resources [2, 6]. The strategic importance of the adoption of practices related to CE is reflected in various sectors, among which construction emerges, as highlighted by the recent Eurostat report that highlights the central role of the sector in the generation of solid waste in the EU, contributing significantly to 36% of the total [7]. For example, the widespread use of bio-based materials in the construction sector represents a deep evolution and innovation, beyond a high-value opportunity, with the potential to bring numerous benefits. Since, these materials are inherently renewable, they are also capable of capturing CO_2, which is subsequently long-term stored in biomass as a by-product of the building process [8]. Carbon removal from the atmosphere, and its subsequent immobilization in biomaterials, contribute positively to the Earth's climate and actively participate in the mitigation of climate change [9]. Consequently, to achieve the objective of carbon neutrality by 2050, Italy is oriented towards a substantial green transition. That implies the adoption of targeted actions that can establish a new model of sustainable and circular development aimed to protect resources, reduce pollution, and combat climate change, in line with the objectives of the Green Deal, the Blue Deal, and the Agenda 2030 [2]. In this context, the use of low carbon content materials, such as wood, is becoming increasingly relevant. Although this is one of the oldest building materials and waste from the production of timber assortments has been reused for centuries, the wood industry still produces significant quantities of wastes and by-products whose amount, treatment, and disposal could be quite complicated. Therefore, promoting their recycling is extremely important as it could bring significant benefits, especially in architecture, beyond including the reduction of deforestation and green-house gas emissions. Therefore, the development of novel materials and more sustainable products, together with an alternative use of such wastes, could represent a valid strategy to increase the sustainability of products in various sectors, and especially in construction, bringing benefits both at an environmental and economical level [3, 10]. The remainder of this paper follows: Sect. 2 discusses wood waste types, generation, and main characteristics. In Sect. 3, usual wood waste management and disposal procedures are described, including the regulatory frameworks and the associated environmental impacts. In Sect. 4, innovative strategies for reusing wood waste into building materials and products are reported, focusing on both innovation and limits, before the paper is concluded in Sect. 5.

2 Materials - Wooden Wastes: Processes and Types

It is essential to clarify the difference between the two key words "wood waste" and "waste wood". The former is commonly used to indicate pieces of wooden material that is not suitable for construction for various reasons, such as structural limitations or the origin from residual constructive elements or even temporary structures (i.e. formwork). This designation also applies to lumber from pallets, used in the industry of transportation, and other by-products of the woodworking process. In the case of low-quality wood, contaminated wood or wood from low-quality wood species, the term "waste wood" is used instead [11]. It is well known that wood, that is resulting from the trees vegetative activity, is characterised by trunk's primary and secondary growth, mostly highlighted by the formation of concentric annual rings. This material is extremely versatile, easily workable, and biodegradable; it shows significant advantages in construction, furniture and production of everyday objects. Also, as known, wood is mainly made of hemicellulose (20–30%), cellulose (40–50%), and lignin (20–30%) [12]. These proportions could slightly differ between the various wooden species, returning distinctive chemical-physical behaviours, appropriate for different applications in construction [13]. Wood characteristics also include good mechanical performance, low density, low thermal and acoustic conductivity, and a great pleasant appearance. All of that has always made wood a perfect material for many architectural and construction applications, with a long history over the centuries. Starting from load-bearing structures, it is widely exploited thanks to its lightness and resistance which make it ideal for the construction of robust structural frames. Even in the contexts of finishing, decoration and furniture, as renewed excellence in Italy, wood still plays a predominant role for floors, coverings, walls, ceilings, and other architectural and engineering details [14]. Since the beginning of the 21st century, there has been a significant increase in wood utilisation not only for traditional and well-known uses, but also for novel applications such as energy product, smart building material, and chemicals [15]. Such increase in demand is evidently followed by waste production rise, resulting from the processing phases and from wood-based products having reached their end-of-life. Therefore, valorising and recycling such considerable resource could represent an abundant and economically advantageous source of raw material for novel products manufacture in light of CE and sustainability. The production process of wood-based building elements, as well as furniture and architectural products in general, generate considerable quantities of wastes. In fact, the manufacturing chain, from the forest to the sawmill/carpentry, includes a sequence of operational phases that generate waste of various nature, as shown in Table 1 where the main waste products produced by different generative processes are reported. The felling phase, which marks the transition from a living tree to a sturdy trunk, requires not only advanced technical skills, but also rigorous compliance with consolidated rules of practice to guarantee a clean cut and a controlled harmless fall. In that phase, timing is fundamental, especially in the quiescence period (usually December-March) when the tree is less vulnerable to external attacks and the reduced sap give greater resistance to the material. Subsequently, branches and bark are eliminated by limbing and debarking, manually or mechanically. These represent the first wastes that currently, after being reduced to powder, are generally used as natural fertiliser. Furthermore, the most effective use for twigs is as fresh wood chips, a traditional use originated in Canadian Quebec under the name of "*Bois Raméal Fragmenté*" (BRF). In fact, it is a green wood chip produced from small and medium-sized branches, used in agriculture for mulching and enriching the soil [16]. Afterwards, the following phases are shredding, that consists in cutting the trunks into smaller pieces to facilitate handling and moving to sawmill, and vaporising, to eliminate impurities and other substances that could attract parasites. Having reached the sawmill, a fundamental phase is the stacking when each piece of trunk is, firstly, examined and selected based on its physical characteristics, then is dried and seasoned to balance the inner humidity and let the material properties set. At this stage, both natural and artificial accelerated curing systems can be used to ensure an optimal quality of the final product. Finally, to market the wood, a crucial phase is cutting into selected sizes such as, for example, beams, strips, and boards. There are different cutting techniques applied to obtain the greatest number of pieces with the least possible wastes generation. However, such stage of the process is estimated to cause the largest amount of waste, including sawdust, shavings, and clippings [17]. Furthermore, among these, piles of sawdust are particularly abundant, since the use rate of such waste is considerably lower than that of the others (bark, branches, shavings, and clippings). At the end, wooden products are treated based on specific requirements, such as, for instance, the application of antiseptics and protection against fire [18]. It must be observed that wood wastes, from various sources including construction, generate a considerable environmental impact. Indeed, approximately 20% of construction and demolition waste consists of wood [19]. Sectors such as agriculture and forestry also produce wood waste, such as, i.e., dried fruit shells, straw, or branches. The pulp and paper industries contribute with chips and clippings as per wood waste; while the food sector largely exploits wooden pallets or crates for transportation constituting additional wood waste. Similarly, other manufacturing sectors can generate wood waste during the processing phases. Furthermore, commercial activities such as food services (i.e. restaurants) can generate additional wood waste through packaging, wooden utensils, food waste. Having that in mind, it is evident how such diversification of waste sources highlights the importance of adopting sustainable management practices to encourage responsible use of these materials for an improved CE and sustainability that can be also applied to the construction sector [20].

Table 1. Main wood wastes from different manufacturing processes

Waste and by-product	Generative process	Description
Bark	Peeler	Trunk outer layer removed during peeling
Branch	Cutting with saws or pruning	Trees branched parts, often cut during various processing
Shavings	Processing with saws or cutters	Small fragments of wood resulting from various processing
Cuttings	Various phases	Small pieces left over from manufacturing processes
Sawdust	Cutting with saws	Thin slices of wood cut during processing
Packaging	Packaging manufacture	Wooden materials used as packaging
Dried fruit shells	Nut processing	Woody fruit shells
Straw	Vegetable fibres processing	Vegetable fibres manufactured from straw processing
Beam, strips and boards	Cutting and processing of structural elements	Larger pieces of wood used in construction
Residues from planing	Planer	Small fragments generated during planing
Unused trunk	Selecting and cutting	Unsuitable parts of the trunk removed during selection
Wooden dust	Processing with sanders	Small fine particles produced during sanding
Wooden ash	Various processing	Volatile particles produced during various processing

3 Wastes from Wood: Issues of Management and Disposal

Considering the widespread use of wood worldwide and in a number of industrial sectors, including construction, it is essential managing appropriately all the productive chain up to recovery and disposal. Consequently, if wood, regardless of its domestic or industrial origin, cannot be recycled in appropriate centres for further reuse, it is crucial to dispose it in compliance with current Regulation 2014/955/EU, in the absence of others at national/local level [21]. More particularly, that regulation establishes a precise legal framework for the control on recycling and recovery operations of waste at both a domestic and industrial level. Accordingly, if the wood waste cannot be appropriately recycled, it is sent to waste-to-energy plants for the production of heat. However, it must be said that such (unfortunately common) procedure certainly causes the loss of material that is potentially suitable for recycling. At the same time, it generates CO_2 and other polluting gas emissions into the atmosphere. Moreover, very often wood wastes contain additives such as glues, paints, and finishes that could act as pollutant, together with contaminating materials such as glass, plastic, and metals. Hence, the regulation distinguishes the wood wastes into the categories A, B and C, based on the degree of cleaning, or treatment, of the material: A - clean or lightly treated wood; C - presence of potentially dangerous substances; B: includes all wastes that cannot be classified as A or C wood (i.e. those containing glues, paints and veneers). That heterogeneity further complicates recycling processes. As a result, current wood waste management strategies are mainly based on (1) landfill, (2) energy recovery, and (3) material recovery [17]. In any case, disposition of in landfill is strongly discouraged because, beyond permanently taking up space, the processes of degradation/decomposition produce unpleasant odours and releases methane and CO_2 [22]. In some underdeveloped regions, such as Ghana and Nigeria, a high rate of wood waste disposal in landfill is observed due to the limited capacity of downstream industries to absorb and reuse the generated wastes. The engineered wood, pulp, and paper industries reuse only about 36% of their waste, leaving considerable amounts to be disposed or incinerated [23]. For example, in Zimbabwe the timber industry is estimated to be responsible for 50–80% of waste production [24]. Although it is theoretically possible to recycle up to 60% of the incoming raw wood as a finished product, currently only the 40–45% of round wood is completely recovered, often for the permanence of obsolete technologies and/or machineries, generating further waste loss. These include, approximately, 10% bark, 5% sawdust, and 45% clippings and chips [25]. Furthermore, there is an unquantified waste resulting from timber harvesting, pruning or thinning activities, such as clippings, trunks and treetops, which are generally used as firewood, cellulose, or artificial textile fibre. Just for example, the foliage (municipal waste) can be used in paint factories to produce colours and in herbal medicine, while the roots can be used for the production of briar used in pipes manufacture, or again, in herbal medicine for infusions, medicine, and chemistry [26]. Furthermore, among the appropriate practices of management for pallets and other wastes deriving from demolition and fruit crates, the reduction of volume by crushing or shredding can be considered, always followed by a deep cleaning, to eliminate any ferrous residue, and further refining by reducing its dimensions. The final disposal stage involves drying and firing in special furnaces to eliminate both the CO_2 and the residual moisture, followed by packaging according to the intended use [27].

4 Experimental - Reusing Wood Wastes in Building Products

In the current regulatory panorama, the possibility of integrating wastes' percentages into new building products is highly promoted and encouraged in light of the CE approach. That, revolutionary for the contemporary building sector, has radically changed the way these waste materials are perceived and managed: instead of the past practice of mixing with synthetic binders to satisfy the required performances, nowadays wastes reuse is maximised to minimise the environmental impact [28]. In this context, it is also crucial to respect the Minimum Environmental Criteria (MEC), promoting solutions that could guarantee more sustainable resources management and the reduction of the overall environmental impact [29].

During time, the profound transformation of the construction methods and technologies has generated a significant amount of wastes deriving from disused elements. In example, the diffusion of laminated wood in architecture represented a significant evolution of the traditional constructive systems in solid wooden members. This product, in fact, has proven to be an innovative construction solution, with diversified applications in the load-bearing structures of residential, commercial, and public buildings. Its characteristics, such as a deep flexibility in design, good thermo-acoustic performance, and especially superior mechanical resistance and notable durability, if compared to traditional solid wood, made, and still make, it a technologically advantageous choice. Furthermore, the advancement of technologies in the wood sector, such as engineered wood and treated wood, have further expanded the possibilities in architecture, allowing the generation of increasingly complex structures [30]. A further recent innovation in the field have led to significant technological advancement through the application of "microlaminated wood", also known as Laminated Veneer Lumber (LVL), that is composed of thin layers of laminated wood. The LVL optimises the use of the material by exploiting smaller elements, allowing an efficient reuse of wastes from other processes, or lower quality woods, especially in panels manufacture [31]. As an example, the commercial system STEICO LVL is reported in Fig. 1. Its production line includes diaphragms for floors and roofs which perform the dual function of load-bearing panel and bracing diaphragm. Furthermore, the LVL also offers versatility in special applications, such as use for curvilinear elements, highlighting its adaptability to more specific design needs [32].

Fig. 1. a: load-bearing panel; b: counter-wind diaphragm. © 2018, STEICO LVL.

Starting from these concepts and using the keywords "wood waste", "wood waste in building materials" and "management of wood waste", an analysis of the recent scientific and technological literature was conducted using the Scopus database. From this analysis it can be observed that a considerable number of papers were published in the last two decades and that the interest of the scientific community is continuously increasing, also in light of the topics of CE and sustainability. In Figs. 2, 3 and 4 the numbers of scientific papers published on the Scopus database in a time span of approximately 24 years are reported.

From the temporal analysis of the documents shown in Figs. 2, 3 and 4, which differ in terms of keywords and related number of reported papers found, it is noted that the trend is always positive, meaning the number of the dedicated studies on the topic is rising

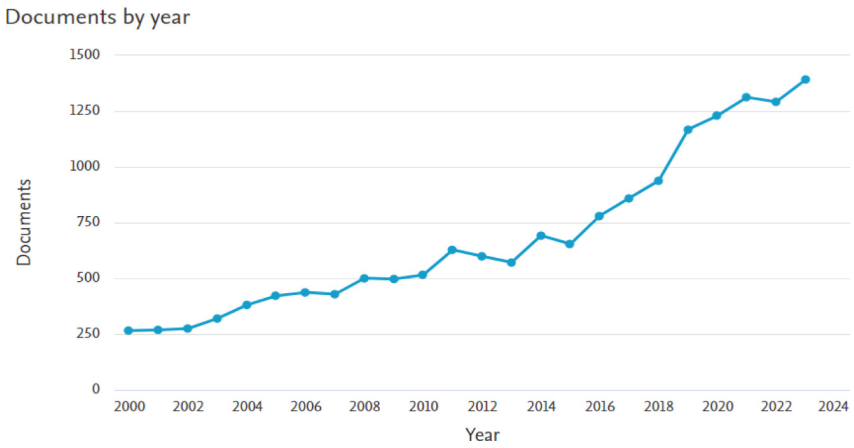

Fig. 2. Papers number trend published on Scopus, years 2000–2023. Keywords “wood waste”. © Data from Scopus 2024.

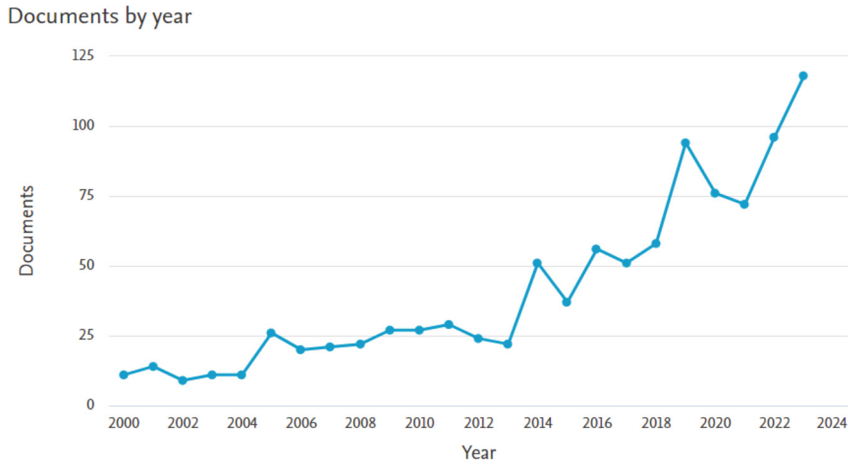

Fig. 3. Papers number trend published on Scopus, years 2000–2023. Keywords “wood waste in building materials”. © Data from Scopus 2024.

continuous interest. From 2000 to 2023, in fact, around 16.660 scientific documents were produced dealing with the reuse of “wood waste” in general (cf. Figure 2). Obviously, the enormous number is explainable by the extremely vast option of applications in various disciplines. “Wood waste in construction materials” appears in about 1000 documents in total (cf. Figure 3). Furthermore, from (Fig. 4) approximately 700 documents in total deal with the “management of wood waste” in a broader sense. This dynamic indicates a growing interest in the sector, with variations that may reflect changes in the scientific scenario or, possibly, issues related to the timing of the magazines. Table 2 reports the products currently produced and marketed exploiting wood residues. A sort of scientific (and technological) evolution is evident on the market considering the wastes’ diffusion

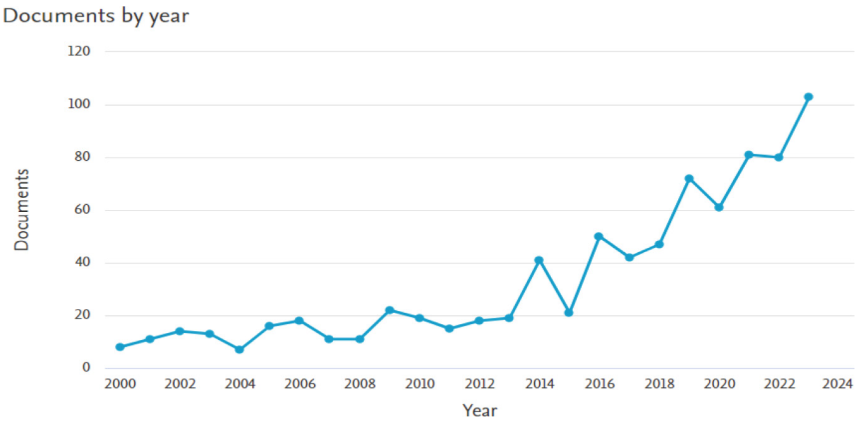

Fig. 4. Papers number trend published on Scopus, years 2000–2023. Keywords "wood waste in building materials". © Data from Scopus 2024.

(i.e. sawdust, chips and bark) that is currently used in the manufacture of high-density wood fiber panels, such as chipboard and Medium Density Fiberboard (MDF) [33]. These materials not only influence the structural design and the construction itself, but also play a crucial role in the energy sector, contributing to the production of bioenergy through combustion or gasification processes. It is important to observe, however, that the most critical factor in recycled wood-base materials performance is represented by the glue used, i.e., in chipboard, plywood, fiberboard, etc. As an example, recent studies showed that the presence of just 6 wt.% of urea glue can cause a reduction of up to 50% in the shear resistance of plywood panels [11]. Wood fiber-based thermo-acoustic panels, also, are made following complex processes involving the activation of the natural wood resin through controlled vapour injection. These panels possess excellent thermo-acoustic insulation properties and are notably versatile, while composites based on natural materials, such as wood-fibers or cellulose, are particularly suitable for injection and extrusion processes. These composites, mainly made up of natural fibers and polymers (polyethylene, polypropylene, polyvinyl chloride, etc.), offer a wide range of applications in architecture, allowing specific additives admix. However, it is essential to consider chipboard panels possible limitations due to flammability, as they burn quicker than the solid wood for the higher density and the used resins. Nonetheless, to mitigate that, it may be appropriate to evaluate the use of fireproof materials or the application of protective coatings [34]. Wood-cement panels and blocks are a combination of wood fibers and Portland cement that represent a stable and durable building solutions with considerable structural strength [35]. Finally, the pellets, using various grinded wastes, do not use specific industrial binders but the natural lignin as a natural binding agent, activated by hot pressure. This materials diversification offers flexible solutions capable of satisfying a wide range of constructive requirements [36].

However, there are still enormous quantities of wood waste, that are not reused and, hence, are landfilled or incinerated, causing significant environmental impact [37, 38]. The wood waste combustion, in fact, generates great quantities of ash and residual substances that are responsible for environmental damage, ecological challenges, and

Table 2. Commercial products that currently use wood waste. Leone et al., 2024.

Name	*Description*	*Image*
Chipboard panels	Untreated wood scraps, compressed and glued together to form a single and resistant panel	
Fibre panels	Fine sawdust, shavings and other wood residues Divided into categories such as LDF, MDF and HDF, undergo initial shredding, drying and pressing at high temperature and pressure	
Oriented Strand Board (OSB)	Layers of fibers binded with resins with lower environmental impact than formaldehyde. The targeted orientation of the fibers gives these panels greater strength and durability	
Wood fiber thermo-acoustic panels	Produced using water vapour and natural wood resins. With thermal insulation, heat storage and sound insulation properties	
Wood-based composites	Composites made from natural fibers and plastic polymers such as polyethylene, polypropylene, and polyvinyl chloride, offer a wide range of applications, with the possibility of adding specific additives	

(*continued*)

health problems, particularly if they are not managed correctly [39, 40]. Furthermore,

Table 2. (*continued*)

Name	*Description*	*Image*
Woo-cement panels and block	Combine wood fibers with Portland cement, generating solid and durable construction options	
Laminated Veneer Lumber (LVL)	Formed by thin layers of laminated wood; represent an evolution oft he traditional laminated wood, as it uses smaller elements to optimize the material use to effectively use waste from other processes or lower quality wood	
Pellet	Obtained by grinding various waste without the addition of specific binders. Using lignin as a natural binding agent, they are hot pressed to form small cylinders used in various applications	

a significant wood waste percentage, that is currently used as fertiliser, can cause soil pollution for the presence of heavy metals [41, 42].

Therefore, to mitigate these problems numerous studies propose alternative uses for these wastes from wood. For instance, wood ash deriving from wooden residues and by-products (such as chips, sawdust, and bark) combustion for energy generation, has been tested in cementitious materials for an improved performance and sustainability [43]. However, many factors including the combustion temperature, the type of kiln, and the hydrodynamics, as well as the tree species, can influence the qualitative and quantitative characteristics of the generated ash, hence the final material performance. Indeed, a combustion above 1000 °C causes carbonates and bicarbonates decomposition, reducing their alkalinity and the subsequent reactivity [44]. Despite this, wood ash still remains a widely used secondary cementitious material for its high calcium content and the hydraulicising property [45]. In addition, various studies conducted on partial Portland replacement with ashes in concretes, mortars and pastes, showed significant improvements in terms of mechanical strength, i.e. compressive resistance over 33 MPa [44]. These – and other - results fall within the parameters established by the technical standards, highlighting the potential of wood ash as a sustainable alternative in architecture, and in construction in general [46, 47]. Wood fibers have also been tested in gypsum paste [48–50]. In particular, the obtained mortars had been enriched with shavings or sawdust from demolitions in order to improve thermo-acoustic insulation properties. Results clearly showed that increasing the wood waste quantity, the conductivity (λ) significantly reduced, from 0.45 to 0.33 W/mK, with a 27% decrease [48]. Despite such improved energy performance, the resulting superior lightness causes a consequent reduction in mechanical resistance, although the minimum observed value never falls below 1 MPa [51]. Also, fibers from waste furniture panels manufacture were used to stabilise the excess of binder in asphalts [49]. The benefits of adding wood ash to mortars made of natural hydraulic and air limes have also been reported, demonstrating compressive strength increase, due to a more compact microstructure resulting from the binder and wood ash combination. Moreover, the hygroscopic nature of wood ash contributes to increase the ability of water retention, causing a consequently capillary absorption delay [52, 53]. Finally, wood wastes were tested in bricks manufacture also. In particular, it was observed that 30% sawdust addition resulted in lighter products, suitable for various applications in construction [54]. Wood wastes were used also for their excellent humidity and energy control, passing from 0.11 to 0.07 W/mK depending on wood particle granulometry: larger particles returned a better thermal insulation for the higher generated porosity. Furthermore, wood-lime panels showed lower water content at 60% RH, but higher at 70% RH. Consequently, in environments characterized by a hot and humid climate in summer, but cold and dry in winter, these lime-based wood panels could be more efficient [55]. A particularly interesting area of research focuses on the transformation of wood into a transparent material through various physical-chemical processes of lignin degradation. These innovative materials are proposed as valid substitution for glass, opening up new design possibilities with countless applications in architecture and engineering [56–58]. Transparent wood would not only help reducing the energy consumption deriving from fossil fuels, but would also promote the efficient transmission of sunlight inside buildings. The added low density of wood, compared to glass, would also contribute to lighter loads on the building beyond offering an improved energy efficiency and the possibility to manufacture smart windows with colourless photochromic wooden materials [59, 60]. Another area of particular interest is the development of compostable and sustainable wood-based biomaterials such as the wood-based plastic, that could help solving the problem of non-biodegradable plastic wastes [61]. Recently, a lignocellulosic bioplastic showed a high mechanical resistance, stability, recyclability and biodegradability, all at a considerable low cost. The used manufacture methodology eliminates the need to separate and isolate lignin and cellulose from wood, a cost- and energy-intensive process, to generate a homogeneous and highly viscous cellulose-lignin composite, where lignin fills the spaces within the interconnected cellulose micro/nanofibrils, resulting in a highly dense structure [62]. Moreover, the strength, lightness and durability improvement of wood waste-based products were tested through polymers impregnation or chemical treatments functionalisation. These novel high-performance wood-products could be used in applications that require greater resistance, such as the construction of large structures (i.e. wooden bridges and skyscrapers) [63]. Finally, composites based on wood waste and recycled plastic were also being studied for construction and furniture [62]. Finally, wood wastes are also gaining space in other industrial sectors, for example as a material for biomedical applications, for tissue regeneration systems, and improved medical devices. Even in aeronautics, composites based on wood waste are under development, with highly lightness, flexibility but, at the same time, resistance. Furthermore, studies are being done to make wood highly water-repellent to prevent rapid degradation in buildings [64]. Lastly, the so-called "intelligent wood" is being developed, capable of responding to environmental stimuli - such as humidity or temperature - opening up new possibilities in the advanced materials industry [65].

5 Conclusions

This document has examined the challenges related to the use and management of waste-based resources, with particular attention to the wood industry in the construction and furniture sectors. Wood recycling appears to be a key element for the sustainable development of the sector, offering a wide range of opportunities to reduce environmental impact, create new markets, and contribute to climate change mitigation. The wood production process generates numerous waste materials, and effective/innovative management could maximize economic, environmental, and energy benefits. It has been emphasized how essential it is, given the reputation of such material, to have careful and sustainable management of wood waste, also in compliance with EU and Italian regulations. The analysis has highlighted that, although the current regulatory framework actively promotes Environmental Compliance in construction, there are still specific challenges often linked to the use of harmful chemicals in construction products. There are many innovative applications of wood recycling already on the market or under study, such as thermoacoustic panels, natural composites based on plastic and/or natural polymers, microlaminate products, which optimize the use of such material. Beyond the construction sector, wood recycling also shows a positive impact on other productive sectors, from paper and cardboard production to craftsmanship, furniture production, aviation, etc. However, there are still many challenges, such as managing the huge amounts of unused waste, which could cause environmental damage and threaten biodiversity. In conclusion, wood recycling not only helps to reduce a large amount of waste but also promotes environmental sustainability, pushing towards a more efficient and versatile use of this valuable material, especially in construction. Regarding the innovativeness of composite materials that reuse wood waste, it is worth noting that these materials combine environmental sustainability with functionality, using wood waste that would otherwise have been destined for landfill. This approach offers an ecological and creative solution to produce construction materials and other products. Furthermore, composite materials that reuse wood waste can be competitive in the market compared to traditional materials for several reasons, including the economic benefits derived from waste disposal cost reduction and the use of low-cost raw materials. Increasing environmental awareness and preference for sustainable products can also increase the demand for such materials, contributing to their economic competitiveness. Finally, the production costs of these materials depend on various factors, but the use of wood waste as a raw material can help keep costs relatively low compared to materials that require virgin raw materials, making them competitive in the market.

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