fibers

Review

Developments in the Recycling of Wood and Wood Fibre in the UK: A Review

Morwenna J. Spear *, Athanasios Dimitriou, Simon F. Curling and Graham A. Ormondroyd

BioComposites Centre, Bangor University, Bangor LL57 2UW, UK; a.dimitriou@bangor.ac.uk (A.D.); s.curling@bangor.ac.uk (S.F.C.); g.ormondroyd@bangor.ac.uk (G.A.O.)
* Correspondence: m.j.spear@bangor.ac.uk

Abstract: There is great interest in using bio-based materials to reduce the climate impact of materials. Similarly, there is an increased focus on the circular economy and recycling of materials to increase material efficiency and reduce waste. In the case of wood waste, this provides a cluster of benefits but has led to a high demand for the reclaimed material. This review provides updates on several technologies where wood fibre recycling and products from recycled wood fibre are breaking into new markets, including wood fibre insulation products, wood plastic composites, oriented strand boards, and fibreboards. Emerging technologies, such as the ability to recycle medium-density fibreboards, in addition to the more commonly recycled solid wood or particleboard, will allow for a new set of options within the wood cascading chain. Looking ahead, there are likely to be advances in new composite products, as well as other feedstock materials derived from reclaimed wood, such as nanocellulose, pyrolysis oils, or wood polymers reclaimed from the wood feedstock. This review arose from an investigation into the wood recycling sector in the UK. So, the horizon scanning exercise presented here considers the needs and challenges that may arise, if the volume of recycled wood fibre can be increased, in an already highly active market. Such developments would permit an increase in the manufacture of new-generation long-service-life products to enhance carbon storage, and potentially a shift away from bioenergy generation.

Keywords: waste wood; recycled wood; cascade; wood-based panels; wood composites; carbon storage

Academic Editors: Pratheep Kumar Annamalai and Stuart G. Gordon

Received: 31 December 2024
Revised: 3 February 2025
Accepted: 13 February 2025
Published: 15 February 2025

Citation: Spear, M.J.; Dimitriou, A.; Curling, S.F.; Ormondroyd, G.A. Developments in the Recycling of Wood and Wood Fibre in the UK: A Review. *Fibers* **2025**, *13*, 23. https://doi.org/10.3390/fib13020023

1. Introduction

Wood has demonstrated circular economy principles for many years. Initially, post-industrial waste wood (shavings, chips, and sawdust) was used in wood-based panels by the early 1990s, with the recycling of post-consumer waste wood into panel products becoming more widely accepted during the 1990s [1–4]. More recently, options for recycling the wood-based panels themselves have been considered [5–7], and the range of sorting and cleaning technologies has increased [8]. There has also been a steady investigation of options for novel products derived from recycled wood. While early wood-based panels papers may confuse post-industrial waste wood with recycled wood from post-consumer or demolition origins, this is now such a standard practice that the use of industrial co-products as feedstock is no longer included within recycled wood statistics.

Recycled wood has grown in prominence, with the FAO statistics for 2023 indicating that Europe collects the greatest volume of post-consumer waste wood for recycling (76.8%), within which Germany (19.7%), France (15.6%), and the UK (11%) are the largest contributors [9]. Sweden, Italy, The Netherlands, Austria, and Norway also fall within the top 10 global producers of post-consumer waste wood. China is the second largest producer of waste wood globally (17.1%) and the Republic of Korea ranking eighth (3%), giving Asia a 23.1% share of the global total. Sweden, Belgium, the Netherlands, Germany, and Austria all import significant quantities of this recycled wood (over half a million tonnes each in 2023) [8]. These figures reflect a market that has expanded rapidly.

Wood-based panels are a common destination for recycled wood. In the UK, in 2022, 1.0 million tonnes (29%) of wood from post-consumer waste was processed into wood-based panels, and a further 1.2 million green tonnes of sawmill residues were used (34%, post-industrial), alongside 1.2 million green tonnes of roundwood timber (35%). The remaining 3% was from imported material (0.09 million tonnes) [10]. This principle of approx. one-third from each source has continued for a considerable time in the UK, reflecting the well-established practice. Recently, there has been increasing interest in the quantities of end-of-life timber recycled, in order to consider the duration of carbon storage and the contribution of the circular economy to mitigating climate change [11]. Forster et al. [12], for example, highlighted the need to increase circularity in order to drive decarbonisation.

Developments in the UK and Europe, during the first two decades of this century, have centred on reducing the quantity of wood entering landfill, and, in parallel, there has been an increased use of biomass for energy. Both of these factors have dramatically altered the wood recycling sector in the UK, with a dramatic shift from 2009, when a significant proportion went to landfill [13], to the present day, where this quantity is negligible.

There has been a marked change in the quantities of waste wood being used as bioenergy. For example, in 2008, only 250,000 tonnes went into biomass energy [14], compared to 2.73 million tonnes in 2023 [15], an eleven-fold increase. This increase in wood for biomass energy has allowed the lower-quality recycled wood to be utilised (for example, treated or painted materials). However, the option for multiple life cycles of the wood fibre prior to its ultimate fate in energy recovery would be beneficial for the circular economy.

The quantity of recycled wood which is converted into products is more stable. The largest is still particleboard, with a slight decrease to 1.0 million tonnes in 2023 [10] (in 2009 it was 1.2 million tonnes, which is very close to current values). The use of recycled wood in other uses, such as animal bedding and mulches, has also remained stable; for example, 390,000 tonnes went into animal bedding in 2008, and 350,000 tonnes in 2023. Thus, the additional material generated by deflection away from landfill appears to have been almost entirely consumed by the rapid growth of the biomass energy sector in the UK.

These days, the circular economy is often proposed as a solution to reduce our extraction of virgin resources and to improve the efficient use of the materials that we have in the technosphere [16–18]. The European Parliament has recently endorsed cascading of wood to promote the circular economy and climate change mitigation benefits within the RED III (Renewable Energy Directive III) legislation [19]. This is an acknowledgement of balance within and between climate change mitigation strategies. Even though timber is a renewable biobased material, recycling is still a valuable step as even renewable materials can become scarce, if the growth rate is lower than the market demand [20]. There is growing recognition, and even concern, that demand for wood resources will far outstrip supply by 2050 [21]. In future, competition between forest, farming, and other uses for the available land area and competition for timber are likely to increase. There will be a need for strategic choices in land management and resource efficiency [12,22–24]. In particular, competition between the bioenergy sector and the wood-based panel sector is anticipated [8,25,26].

2. UK Waste Wood Markets

The latest Wood Recyclers Association (WRA) statistics for 2023 show that, of the 4.5 million tonnes of waste wood handled, 4.408 million tonnes were processed and used in the UK [15]. In terms of destinations, large-scale biomass energy plants used 63% of the wood processed, i.e., 2.73 million tonnes. Panel products took 22% of the recycled wood, i.e., 963 thousand tonnes. This is a decrease compared to 2022, partially related to the closure of one particleboard factory. A further 8% went into animal bedding, i.e., 350,000 tonnes. In addition, 5% of the recycled wood was exported, due to demand for bioenergy in Europe.

The increased share of recycled wood going into bioenergy between the first decade of the century and current is dramatic. For example, in 2007 panel products were 60% of the market supplied, and biomass and energy only 12.6%. At the time the total handled was lower, just under 2 million tonnes [14]. By 2009, 566 thousand tonnes of the total 2.2 million tonnes of waste wood went into bioenergy [13], i.e., the quantity had doubled in two years. The current 63% of recycled wood entering bioenergy is a reversal of fortune, reflecting a strong shift in the market.

Ormondroyd et al. [27] noted that the municipal wood waste gathered from Wales and from the highly active recycling regions of England were located close to existing wood-based panel manufacturers, indicating the connection between market pull and waste infrastructure. Good wood waste collection provides an easy route to the next generation of wood products. By 2023, the utilisation of waste wood has reached a higher level of competition with a complex web of transactions between local authorities, waste handling companies, and panel mills or biomass energy producers, meaning that this geographical trend is less evident.

Nguyen et al. [28] pointed out that, in Europe, the energy utilisation of waste wood tends to exceed materials uses such as wood-based panels, with some countries having 85–95% of waste wood enter energy applications (e.g., Sweden, Switzerland, Norway, the Netherlands, and Finland). This is now increasingly the case in the UK.

Landfill ceased to be the default option for waste wood in the UK during the 2010s, when a sequence of increases in landfill tax were implemented [13,29]. The quantity of wood entering landfill decreased dramatically. Current UK waste statistics report wood as 0% of landfill intake materials, which can be interpreted as a negligible or undetectable quantity [30]. The most likely remaining reason for wood entering landfill is the very small quantities that are too intimately mixed with other wastes for segregation, for example, as a small component within an electrical appliance or household object. Other traces of wood waste may occur in the household waste stream where the quantities are perceived by the consumer to be too small to justify a trip to the household waste recycling centre. But, it should be noted that the use of landfill itself has diminished in the UK, as the incineration of household waste with energy recovery has become a common approach for the non-recyclable fraction of the waste stream in many regions.

3. Wood Collection, Segregation, and Processing Routes

3.1. Waste Sorting

In order to segregate and process wood waste more efficiently and optimise the split into appropriate grades, there has been an increase in the number of hubs across the UK handling, sorting, or storing wood waste. This was prompted by work by WRAP and the WRA in the 2010s that highlighted the need for increased collection facilities and a consistent set of criteria to ensure best use of the range of qualities of material [31,32]. The result was a widely adopted set of grades, from A to D, as shown in Table 1.

Table 1. Grades of waste wood within the UK system, derived from [33].

		Notes
Category A	Pre-consumer waste wood and untreated wooden packaging Clean untreated wood	The main sources for this type of wood are the distribution, packaging, and retail industries (e.g., pallets, packing cases, cable drums), as well as offcuts from the wood machining industries. The wood can be contaminated with nails, screws and plastics; however, the processors generally screen these out. The wood can contain minor amounts of surface paint, but these are commonly water-based and non-toxic. This is the preferred material for animal bedding applications, but can also be used by the panelboard industry, in non-IED Chapter IV biomass, or in the manufacture of briquettes and pellets.
Category B	Business waste Treated non-hazardous	This can include Category A wood and demolition wood and material from waste transfer stations. It can, therefore, include solid wood furniture. This grade of wood can be contaminated with plastics, paints, glass, grit, non-hazardous coatings, and glues. This is the preferred material for the particleboard industry but can also be used for IED Chapter IV biomass.
Category C	Municipal waste wood Treated non-hazardous	This can include Categories A and B but is primarily sourced from municipal collections, transfer stations and HWRCs. This category often contains wood-based panels from flat pack furniture and DIY products. It can include some treated wood (non-CCA and no creosote). It can be used in panelboard manufacture or burnt. Due to the presence of the water-based preservatives any incineration needs to be in a boiler compliant with Chapter IV of the Industrial Emissions Directive. This category is a 'waste' according to Waste Management Regulations.
Category D	Hazardous waste wood Treated hazardous Category C and track works, fencing and transmission poles	This category includes waste wood from hydraulic engineering (e.g., from docks) or from industrial applications (e.g., cooling towers, or woodblock flooring), and from boats, carriages, and trailer beds. Can also be waste wood treated with CCA or creosote (i.e. includes telegraph poles, agricultural fencing, etc). The wood can contain all the contamination found in Category C, but the presence of CCA (Copper Chrome and Arsenic) preservatives and creosote is the main criterion. It must be segregated and consigned to sites permitted to handle hazardous wood.

The grades were developed by the Wood Recyclers Association and have been refined as the waste wood handling sector has matured [33]. The difficulties of separation and classification (relating to the unknown provenance and history of the wood) are largely handled by the route that the wood takes entering the recycling system and the improved recognition and testing of the wood that is deemed potentially hazardous. The largest challenge remains when handling wood waste at household waste recycling centres (HWRCs, for domestic waste) as the wide range of products being disposed of makes recognition difficult. A testing programme in 2019–2020 indicated that the percentage of hazardous waste entering HWRCs was so low that it could be considered insignificant (0.06%). A follow-up round of testing was initiated in 2023 to provide additional evidence [34].

A guidance document was released in November 2021, giving clear examples of wood types commonly handled at HWRCs, and which ones are most likely to potentially contain hazardous wood, requiring further testing [35]. Potentially treated wood that pre-dates 2007 is typically assessed to reflect the withdrawal of CCA from sale in 2006.

Clean, sorted demolition wood features quite high up in the waste wood hierarchy, in Category B. Strict limits are set on the amount of coated and treated timber that is allowable in the timber mix. If it includes wood that is deemed treated hazardous, i.e., is likely to exceed the limits on preservatives, the timber is downgraded to Category D timber. It is then handled as hazardous waste with specialist disposal. A Regulatory Position Statement (RPS 250) was in place until 2023 for construction and demolition waste, and a new RPS 291 covers 'amber waste' in England. This allows temporary storage of this waste wood while it undergoes the WRA testing mentioned above.

One concern at waste handling hubs is the flammability of wood chip piles, if stored for prolonged periods. This is due to microbial action within the chip pile, leading to a build-up of heat. As a result, both the Environment Agency and the local Health and Safety Executive are very strict about the size of wood waste piles. One reason for such piles having developed is the fluctuation of wood waste prices; in order to achieve the best possible prices in the wood industry some storage is needed. In other cases, the market for Category C and D wood has been poor, leading to a backlog of low-quality material when a given operator ceases trading.

3.2. Industry-Adopted Regulations

It is common for many industries to specify the quality requirements for their feedstock materials, and this is also the case for waste wood entering the panel mills. The panel industry (primarily particleboard) uses a significant amount of waste wood in their manufacturing process; however, the wood has to be clean and free from chemical contamination before it enters the factory. A clear picture emerged early on about the acceptable levels of heavy metals and contaminants that might relate to existing wood treatment agents from the first use of a product [27]. Other aspects of the specification may include the size and form of the timber, the grit content, and the moisture content.

Work in this area started in 2000, when the Wood Panel Industries Federation (WPIF) in the UK recognised the increased use of waste wood in manufacturing wood-based panels. They developed an industry standard (WPIF/UKFPA/1-2000) which was based around the strictest European Standard to consider allowable metals content at the time, BS EN 71 or 'The Toy Standard' [36]. This standard prescribed the heavy metal content limits for materials used in the manufacture of toys. In 2004, a Publicly Available Specification (PAS 104, [37]) was published, governing contaminant levels, followed by an updated WPIF guidance document in 2005 to cover the manufacture of particleboard, MDF, and OSB in the UK. The limits have been incorporated into the PAS 111 standard for processing waste wood, with an additional restriction on the total heavy metal compound content of 4000 mg/kg dry matter [31]. The WPIF standard was also adopted by the European Panels Federation, as shown in Table 2, with revisions over the past 15 years [38].

Whilst the standard was written to protect the panel board industry's interests and ensure that panels were able to supply to all industries, it initially prevented the use of most demolition waste wood streams and instigated the sector's dependence on clean waste wood. Since this time, much work has been undertaken to analyse timber waste streams and demonstrate the decrease in heavy metal content with the transition from older-generation to new-generation timber preservative treatments [34]. The clear but stringent specification on contaminants has led to excellent quality control of waste wood intake for the industry and driven development of best practice in segregation. As a result, there have been many innovations in the processing steps for recycled timber as it enters the panel manufacturers.

Table 2. The maximum allowable quantities of contaminants permitted in wood-based panels manufacture [38].

Contaminant	Limit (g/kg)
Arsenic (As)	0.025
Cadmium (Cd)	0.050
Chromium (Cr)	0.025
Copper (Cu)	0.040
Lead (Pb)	0.090
Mercury (Hg)	0.025
Fluorine (F)	0.100
Chlorine (Cl)	1.000
PCP	0.005
Creosote	0.0005

3.3. Screening and Cleaning for Wood-Based Panel Mills

Recycled wood in the UK is frequently shredded as the first stage in conversion to a feedstock for use. The shredded material can then be segregated by size and ferrous metals removed using an overband magnet. This works well for the larger and better liberated metal components, but small ferrous metal pieces may remain if well embedded into wood particles. In some systems these are detected visually to return into the shredder or removed using technology such as the rare earth drum magnet and eddy current separator [39]. Entrapped metals are removed using the drum magnet, whereas non-ferrous metals can be removed using the eddy current separator (with an alternating magnetic field). A further metal detector may be installed above the belt for transport to the secondary shredding step.

In many systems, sieving occurs using a variety of screens and sifting tables. Vibrating conveyors may also be used to segregate material by size during movement through the process. In some mills, it is important to ensure that plastics and low-density materials are also removed from the recycled wood feedstock. This can be achieved using various technologies, some based on screens with rollers to flick the lightweight, bulky plastics off the top of the chip. Other systems can use advanced sensor technology to detect plastics optically and eject them from the current of chipped wood. One example is the Cyclops system from PAL [40]. Garcia et al. [8] report the combinations of X-ray, near-infrared (NIR), and hyperspectral sensing technologies, where both NIR and hyperspectral methods are combined with principal component analysis (PCA) to aid recognition. In Italy, where 50% of panels are to be made from recycled material by 2030, Fantoni have demonstrated separation technologies on an MDF line—where excellent segregation and cleaning is required [41]. This used a quarter of a million tons of furniture-grade recycled material and a system developed by Steinert.

A wide range of separating and cleaning technologies exist—some are applied at the dry end, and others may be used at the wet end. For example, a wet system may use density difference to separate stones, grit, and metals from the wood chips, which float across the surface of a tank of water, while the denser contaminants drop to the bottom. This can be a suitable step to elevate furnish moisture content shortly before resination and pressing, or prior to refining (which uses wet chips). Dry-end systems might be used as the chips leave the shredding and screening stage.

Technologies can include kinetic systems, using momentum and air resistance to govern segregation; pneumatic systems, agitating particles through a vertical system of screens; and gravimetric systems, based on density within a cyclone-type structure [42].

3.4. Cleaning Wood for Recycling

After physical separation, in certain grades of recycled wood, the chemical contaminants within the wood may remain a challenge, especially for treated timber contained within household waste (Category C) or within construction and demolition waste (Category B). The obviously treated materials (e.g., fencing panels) may be visually identified and removed prior to shredding to minimise the need for segregation later within the process and deflected into Category D. However, it would be desirable to find cleaning treatments, either chemical or biological, that can remove the contaminants and enable this feedstock to be returned into new products.

In the context of particleboard, the feedstock must be sufficiently clean. Potential contaminants include adhesives, coatings, additives, and chemical treatments. Researchers have long considered methods for sampling and quantification of contaminant levels and their influence on board properties [43,44]. Hydrolysis is the most commonly proposed method for deactivation of urea formaldehyde adhesive bonds [5,45], as discussed later, but other adhesives may prove more challenging—for example pMDI, MUF, and PF resins are resistant to hydrolysis and deliberately selected to provide moisture resistance in certain products. Many additives, e.g., waxes and hydrophobising agents, are of low toxicity and, thus, of limited benefit to remove, but could alter the bond formation within next generations of product. Coatings are a complex group—ranging from paints and stains or varnishes through to solid laminates or polymers which can be identified and removed by physical methods. The larger challenge is associated with preservative treatments and fire-retardant treatments [8,46].

Helsen and Van den Bulck [47] considered the specific case of CCA-treated timbers, and identified chemical extraction, bioremediation, electrodialytic remediation, and thermal destruction as options. This particular grade of treatments posed multiple challenges, including the possibility for arsenic release, or hazards associated with chromium if in certain valent states, as well as the potential formation of dioxins and furans during combustion reactions. However, the quantity of CCA-treated timber within the waste stream is diminishing as the use of this treatment agent was restricted in Europe in 2006 [48].

Chemical cleaning treatments, solvent systems, biological treatments, and liquefaction have been tested to remove preservative treatment chemicals from the wood. In some cases, the technology has focused on the reclamation of the copper, chromium, and arsenic and conversion to a form suitable for re-use as a wood treatment chemical [49,50], although this is of lower interest in Europe where such treatments are not permitted. The use of organic acids has been demonstrated to be effective in removing copper-based treatments [46,51,52], especially citrate ions. Shiau et al. [53] demonstrated that citric acid extraction gave a steep chromium and arsenic removal when the pH was dropped to 3.5.

Electrokinetic processes have been investigated at the bench scale; for example, Sarahney et al. [54] demonstrated the removal of 74% of chromium, 97% of the copper, and 88% of the arsenic from CCA-treated timber. The electrokinetic process was enhanced with an oxalic acid–EDTA solvent mixture.

Bioremediation offers a sustainable approach to removing inorganic wood preservatives like heavy metals from treated wood, mitigating ecological risks and human hazards [55]. This process uses microorganisms to break down or transform contaminants into less harmful substances [56]. Xing et al. [55] reviewed three main direct bioremediation options: fungal bioremediation, bacterial bioremediation, and non-living bio-sorbents. It has been suggested that the decontaminated wood can be reused in products such as particleboard [57]; however, there can be strength and toughness loss, depending on the organism deployed and treatment conditions.

Work with bacteria such as *Lactobacillus* and *Streptococcus* shows some potential [58] but may require several days to achieve metal removal. The laboratory study used milled wood powder so that it may generate material that is better suited to wood plastic composite production than particleboard. Milling was shown to be unnecessary for bacterial fermentation by *Bacillus licheniformis* when oxalic acid was used as a pre-treatment [59]. Enzymatic systems such as pectinolytic and cellulolytic from *Bacillus* and *Pseudomonas* spp. may assist in releasing copper, chromium, and arsenic from wood [59].

Some researchers have investigated the production of cleaned chips for future reuse [60,61]. The pilot scale work by Coudert et al. produced wood chips with a significantly reduced copper content from CCA, ACQ, MCQ, and copper-azoletreated woods [61]. Up to 97.5% of the arsenic, 87.9% of the chromium, and 96.1% of the copper present in CCA treated wood was removed by the three-step leaching process. The particles were sufficiently clean for compost production but only suitable for use in particleboards if mixed with clean wood chip at 10 to 50% of the chip feedstock (US regulations).

It is clear that while approaches for chemical or physical cleaning upgrading methods for treated wood exist, none have yet become a reality due to economic constraints. The move from small-scale to industry-level applications has not yet taken place. Cleaning could benefit the particleboard manufacture from recycled timber, opening potential for lower-quality material to enter a material second life rather than combustion. It could also lead to new options and products if the cleaning process leads to a transformation of state (e.g., pyrolysis oils and nanocellulose).

4. Cascading Use of Wood and the Circular Economy

Innovative thinking on the recovery and recycling of materials can lead to materials 'cascading' through many life cycles before the material is rendered only suitable for incineration and (hopefully) energy recovery [62,63]. The aim of the waste reduction measures, and the philosophy of cascading use of materials, is to reduce the quantity of waste reaching landfill. The initial diversion of timber away from landfill is largely complete in the UK, but the cascade can continue to be refined and developed. More recently, the concept of cascading has become a key part of the approach to optimising choices in the wood value chain to enhance carbon storage and to reduce GHG emissions—both necessary to mitigate climate change [12].

An ideal material cascade for waste wood may be to move from primary use in structural timber, furniture, pallets, etc., into a second use within particleboard; thereafter, the particleboard may be recycled once or more into new generations of particleboard, finally leading to a tertiary product or use for energy recovery (Figure 1). During this process, some losses will occur at each step, e.g., non-recoverable off-cuts of particleboard, painted material, and material too degraded for recycling. Most of these small portions will reach landfill or incineration, some may decompose in the environment, and a few pieces may also reach new artisan or alternative applications.

For the timber cascade system it is possible to use the model to estimate residence time within the wood products pool, relating to carbon storage benefits (greenhouse gas removal and storage) within the wood products sector [11,64]. This has become a subject of intense interest and has renewed efforts to enhance the recycling and reuse of wood, to move wood through different product lives down the cascade, prolonging the time period for which the sequestered atmospheric carbon remains in solid form, removed from the atmosphere [64].

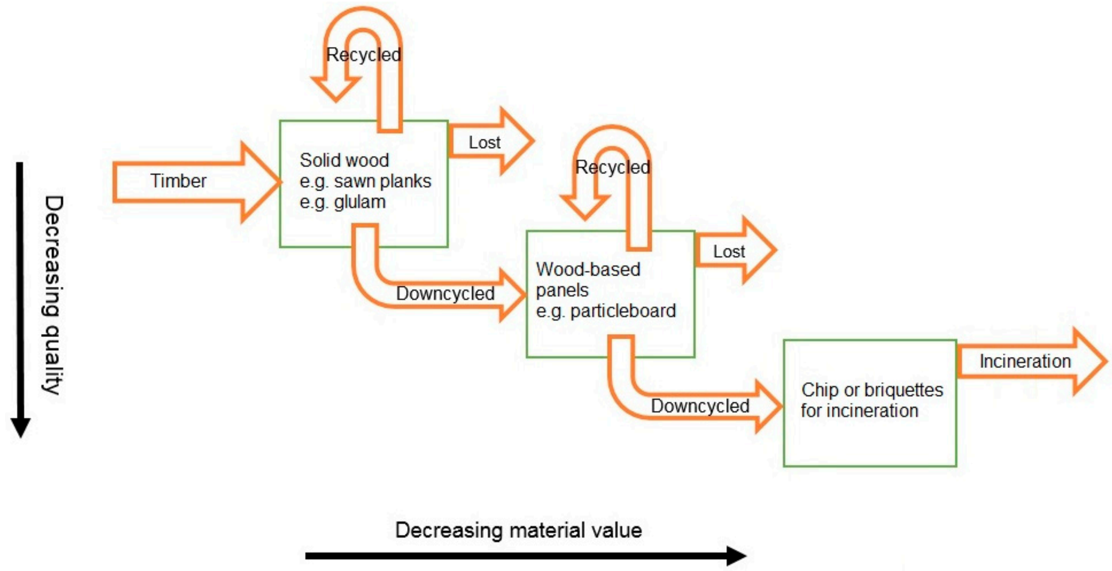

Figure 1. Simplified cascade diagram for wood.

Some researchers have promoted the idea that there should be multiple passes through each tier of the cascade, for example, with structural timber being reused into engineered wood composites such as CLT and glulam before they pass onwards into the wood-based panels tier [65]. This is a good concept; however it is important to remember that probability functions apply at all tier levels. For example, in converting solid wood into glulam, there will be shavings and offcuts passing directly to the wood-based panels stage or incineration stage; even with the primary life of the timber, the log is split into planks and co-products (sawdust, shavings, and chips), which pass to other tiers directly. Thus, the cascade is a complex network rather than a linear waterfall (Figure 2).

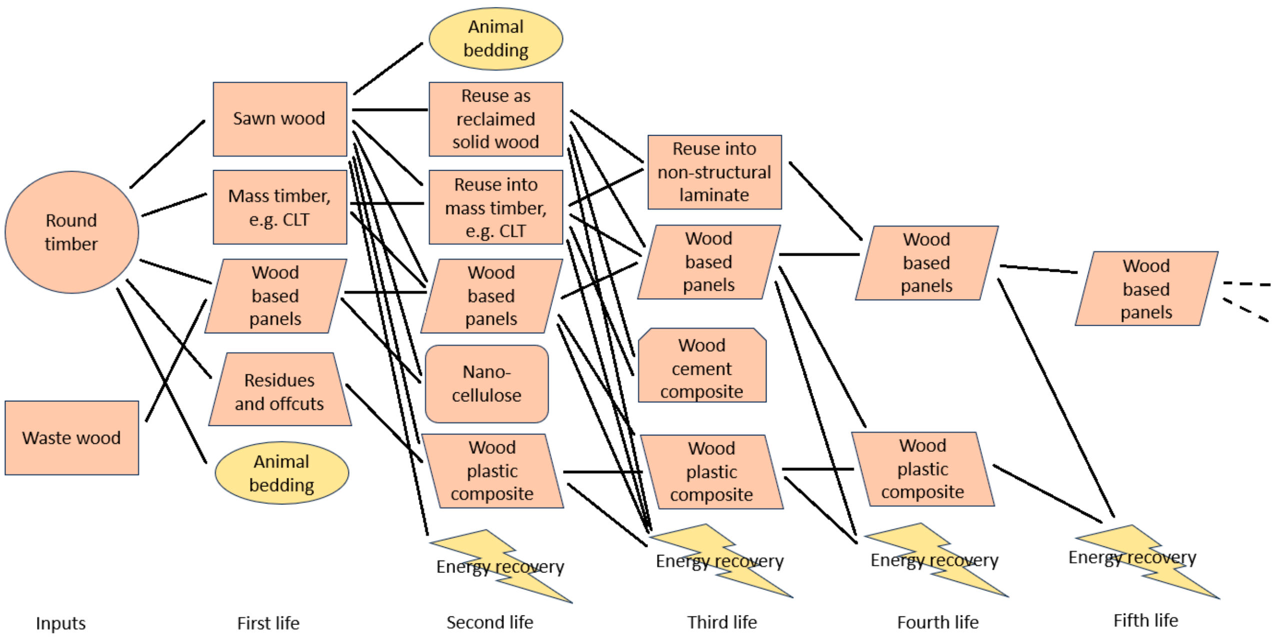

Figure 2. Simplified network of pathways for wood during recycling, reuse, and energy recovery.

5. Most Commonly Used Recycling Options

5.1. Mulches, Animal Bedding, Play Surfaces, and Cat Litter

For waste wood in the UK, two markets which use the cleanest grade of wood are found in agriculture (as bedding for livestock or for equine applications such as arenas and gallops) and in horticulture (as mulch). These are long-standing markets and the quantity of material entering these products is relatively stable, with only Category A wood accepted. Once the mulch or equine surface material is produced, the wood has a relatively short lifespan and moves rapidly to landfill, composting, or degradation in service.

Another minority product is wood pellet cat litter. This also requires high cleanliness of wood feedstock, so it can only be formed from a small proportion of the available recycled wood resource. The cat litter product also has a short residence time.

5.2. Wood-Based Panels

Wood-based panels have been one of the most significant options for recovered wood for a long time, with the bulk of usage in particleboard. Vis et al. [63] indicated that the recycled wood entering particleboard varied between 100% in Italy; 50% in Belgium, the United Kingdom, and Denmark; 15–30% in Germany, France, and Spain; and 0% in Switzerland. The proportion in the UK has diminished in the past few years as demand for bioenergy has increased. The production of wood-based panels in the UK in 2022 was 3.5 million m^3 using 1.0 million tonnes of recycled wood, but 1.2 million green tonnes of roundwood and 1.2 million green tonnes of sawmill residues [10]. However, panel production remains an important part of the circular economy for wood materials in many European countries, as reflected in the recent European Parliament statement [19].

While particleboard is the most common panel to contain recycled material, there is scope to produce medium-density fibreboard (MDF) as well. This product uses pressurised refining technology to transform chips of recycled wood into thermomechanical pulp fibres (TMP). However, it is essential that the feedstock is sufficiently clean and free from solid contaminants (metals and inorganics). After refining, the TMP fibre can be used to form MDF or other fibreboards such as high-density fibreboard (HDF) or hardboard.

There is also limited scope for incorporating recycled wood into other panels such as oriented strand board (OSB), as demonstrated by the recent development of a five-layer OSB panel by Kronospan, produced in Luxemburg. However, the strands that are used to form the OSB need to have a long thin shape, allowing good transfer of load for this structural panel product. To recycle solid wood into strands for OSB would require a different stranding process, and while it is not impossible to imagine, it has not been widely investigated. Again, this relates to concerns about the contamination of recycled wood with solid particles, which could damage the cutting knives, or concerns about the suitability of infeed material. In the most common demolition practice wood is broken up during demolition rather than removed sequentially in long lengths. Large fractures at multiple points in the timber would reduce the potential yield of strands for OSB.

Consumption of panel products in the UK is significantly larger than manufacture capacity: 1.25 million m^3 plywood (100% import); 3.38 million m^3 particleboard and OSB (30% import); and 1.69 million m^3 MDF and fibreboard (53% import) in 2022 [10]. Based on strong demand, there is scope for expansion and for this to incorporate additional recycled feedstock. Wood-based panels, therefore, represent a substantial market for recycled wood and recycled fibre if recycling practices continue to develop, and feedstock is sufficiently clean.

5.3. Recycling Wood-Based Panels into New Wood-Based Panels

Hydrolysis can be used to break down urea-formaldehyde (UF) resins in wood panel waste, liberating the chips or fibres [5,45,66]. This process can also help mitigate the release of formaldehyde in the next generation of product. Various factors such as temperature, pressure, and steam ratio can affect the hydrolysis process [67,68].

Whilst this has been the subject of research for some years [5,69], one company has recently commercialised a technology to recover fibres from MDF panels and return these fibres back into MDF manufacture. MDF Recovery have patented technologies for the separation of fibres from boards and have proven their use in the remanufacture of MDF boards with similar board properties and emission profiles to those of virgin boards [6]. This technology is now scaled up and commercially available [70]. A parallel development has been the use of steam and pressure to hydrolyse the resin, and Unilin are trialling the technology at their mill in France [71].

An alternative approach is mechanical disintegration, although this is reported to degrade the size and quality of the particles [7]. Surface-laminated panels present an additional challenge and were studied by Hong et al. [72]. Four different laminate types on MDF were investigated in a hydrolysis system. The recycled fibre was used in the core of three-layer MDF panels, and their properties evaluated. The lowest strengths were seen for the polyester coating laminates, and it was suggested this might relate to the different alkaline buffer capacity of this laminate type affecting resin cure [72].

The literature suggests a lack of research on the production of plywood and OSB from wood waste [28,73]. This is because of difficulty in processing wood waste into suitable veneers for plywood or strands for OSB. The process would be at great risk of contaminants shattering any blades used in slicing the veneers of strands. Complex sorting would be required to ensure suitable material was prepared for strand manufacture if OSB production were to be pursued. Further research could address this challenge, as contaminant recognition and removal technologies continue to advance. However, the idea of recycling OSB into new panels of OSB is limited by the resins that are most commonly used in this panel type being resistant to hydrolysis. OSB is typically an exterior product or used in humid environments, so water-resistant resin types are used, preventing recycling through the hydrolysis-based technologies [45].

It would also be beneficial to evaluate the economic viability of innovative recycling and processing methods to maximise adoption and contribution to a circular economy in the timber industry.

5.4. Wood for Biomass Energy or Heat

The other primary option for disposal of waste wood is burning for energy recovery. It was noted above that this is currently the destination of 63% of the UK's recycled wood [15]. There has been steady policy support for renewable energy generation within the UK (from the UK Renewable Energy Strategy in 2009 up to the current Clean Power 2030 action plan). Wood as a fuel contributes to electricity generation and heat generation. The Biomass Strategy indicates that biomass contributed to 11% of the UK's electricity supply [74]. While not all of this is from recycled wood, it indicates the scale of expansion which has occurred in the sector in the past decades.

Many energy generation systems can handle only clean wood or clean agri-crop residues such as straw, miscanthus, and short rotation coppice. However, there has been expansion in the number of sites licenced to handle waste wood. Such incinerators operate with greater controls and measures to control emissions from burning timber containing preservative treatments, paints, or other potentially problematic components and are compliant with Chapter IV of the Industrial Emission Directive.

In addition to the industrial electricity and heat systems, some recycled wood can be incorporated into pellets and briquettes for the consumer market. Kindling might also be formed from short lengths and narrow dimension solid wood residues. All of these options require clean recycled wood to ensure the wood fuel is not harmful. Heavy metals, such as CCA-treated wood would not be suitable within the domestic wood pellet stoves or wood burning stoves commonly used by the public.

However, reliance on burning waste wood for energy recovery may be premature, in that it cuts short the options for materials cascading through multiple uses prior to eventual incineration [56]. This topic will be further considered later as it provides the context in which the different recycling options operate.

6. Emerging Practice in Reusing or Recycling Timber

6.1. Reuse in Construction

There is growing interest in the process of reclaiming solid wood for recycling into first generation products such as glulam and CLT [65,75,76]. However, this requires the solid wood to be removed from buildings in a form that does not decrease its length or cause damage. This returns to the key themes when developing markets for waste wood from construction—detection and removal of fasteners and fixings, and potential contamination from paints or treatments used during the first life of the product.

A portion of reclaimed wood is recovered during demolition, if particularly old or valuable, and then stored and marketed by salvage merchants, and specialist architectural dealers. In the majority of cases, however, demolition teams prefer to break wood up during demolition, rather than deconstruct the building to reclaim the timber. The exception is where the client specifically requests the deconstruction method, or where the value of the timber beams or trusses is sufficiently high to make it worth the cost.

The focus on material shortages and circular economy principles has led to new research to use reclaimed demolition wood for new applications. One example is the manufacture of CLT and glulam from reclaimed timber [65,75]. This requires good metal detection prior to resawing into the new unit dimensions for the lamellae. It has also been demonstrated that timing and storage are essential to being able to respond rapidly when timber is available and to hold stocks until sufficient material is gathered for manufacture of the laminated timber.

6.2. Wood Fibre Insulation

The emergence of technologies for recycling MDF into a fibrous feedstock [70] opens the opportunity for wood fibre insulation to use this recycled fibre. A company in Wales is working with MDF Recovery to develop a loose fill product, Pillo, with excellent thermal insulating properties [77]. The product could be deployed in timber framed housing panels or as a cavity wall insulation option. Previous studies have considered the use of sawdust and shavings, or the creation of wood fibre from chipped waste, or used paper fibre [78,79].

6.3. Wood Plastic Composites

Wood plastic composites (WPCs) are a blend of wood particles or wood fibres in a thermoplastic matrix. WPCs often use virgin timber or sawdust from primary manufacture to ensure a consistent chemical composition and particle dimensions to aid uniformity in manufacturing. The feedstock can be sawmill residues, and hardwood material is preferred, to minimise the off-gassing of terpene volatiles which would occur from softwood timbers [80]. Such feedstocks also help to ensure consistent particle sizes and easy milling. In some cases co-location of WPC manufacture with existing wood processing industries is beneficial, if these are generating sawdust or planer shavings as waste. However, there is scope to consider WPCs as a destination for reclaimed timber if of suitable quality and species. However, the softwood carcassing timbers which dominate construction and demolition wood would be less desirable.

Polymer matrices for WPCs include polyethylene, polypropylene, PVC, or polystyrene or may increasingly include biopolymers such as polylactic acid (PLA) or thermoplastic starch. The exact formulations depend on the manufacturer and technology employed. Each manufacturer has their own range of different target markets and properties, relating to the polymer characteristics. The largest market is extruded decking planks and cladding sections, and this has become well established [80].

As for other applications, the presence of solid contaminants in some grades of recycled wood will present a challenge to the milling equipment [27]. If metal or inorganics pass through the milling stage, they present a further risk to the compounding equipment, extruders, and moulding equipment. Many of the contaminants can be removed using metal detection, and screening systems for removing non-ferrous metals and inorganic particles. Such technologies have evolved greatly in recent decades, as discussed above.

The other contaminants present in recycled wood, such as paint, varnish, or treatment products and glues, may contribute additional considerations [27]. For example, if the organic contaminants degrade in the high temperature of the process, or give off gases. Also if the contaminant causes chemical interactions to occur, or lead to a reduction in compatibility between the particles and the polymer matrix. It is reported that the glues and other contaminants present gave poorer results for recycled wood than virgin wood in a study that considered a wide range of wood and paper wastes as feedstock for WPCs [81]. A study using relatively clean recycled wood, which was finely milled for WPC manufacture showed strength properties which were very similar to the WPC using virgin wood; however, the water absorption for the recycled fibre was higher [82].

An early example of recycled wood as a feedstock for WPC materials used the sawdust from MDF and particleboard manufacturing plants [83]. This fine material may be less desirable for other products where sawdust is typically used. The sawdust was added at different percentages and the properties compared with virgin MDF and particleboards (rather than with WPC made from virgin wood). Comparison with generic data for WPC materials [80] indicates that the modulus of elasticity (2.5–3.0 GPa), modulus of rupture (25–35 MPa), and unnotched impact strength (400–550 J/m) values obtained at 60% fibre loading were within the expected range for uncompatibilised WPCs [27]. The WPC made using MDF sawdust performed better than the WPC containing particleboard sawdust, which was attributed to the fibrous quality of the MDF sawdust [83]. Similar results might be expected if waste MDF was segregated and the fibre recycled into a WPC product. The method of separation appears significant, with slightly higher tensile and impact properties achieved for WPC made with fibre separated by the thermo-hydrolytic method compared to fibre from mechanical separation [84]. Similarly, recycled newsprint and other paper fibres have been used to form WPC materials with improved properties, relating to the fibrous rather than particulate character of the filler [85].

A more recent study considered Tanalith E-treated wood flour within a PLA matrix for WPCs. The presence of the preservative treatment led to enhanced resistance against decay fungi (*Trametes versicolor* and *Coniophora puteana*) in decay tests; however, the water resistance of samples containing both treated and untreated wood was poor [86].

The research on the use of waste wood in WPC manufacture is limited, and focus has been on WPCs using recycled plastics. There appears to have been relatively little activity to commercialise a product in this area, but it remains a potential option for the use of recycled wood. The recurring theme of cleaning the timber from contaminants must be taken into account.

6.4. Wood–Cement Composites

Wood–cement composites are a panel for structural and building-related applications, which use Portland cement as the binder and the wood particles of various dimensions and shapes [87–89]. The panels have been used for thermal and acoustic insulation and for structural applications due to their fire resistance or termite resistance [88–92].

In an early study on possible re-use options for CCA-treated wood in Florida, cement-bonded particleboards and wood–cement composites were identified as having potential for several reasons. The wood may reduce the density of the pure cement, giving better insulating properties, while the cement may contribute to the stabilisation of the metals within the wood, minimising potential for leaching [93]. Other studies have assessed the properties of cement-bonded wood composites manufactured with demolition wood [90,94,95]. The leaching of copper and arsenic was greatly reduced for Portland cement composites, including CCA-treated wood particles; however, chromium remained leachable [96]. Schmidt et al. [97] indicated that CCA-treated wood had greater compatibility with the cement than untreated wood, with greater resistance to fibre pull-out.

A more recent study considered the hygrothermal properties of a wood fibre–cement system as permanent formwork for a structural system [98]. However, the wood used was shavings, i.e., post-industrial material, rather than post-consumer recycled wood. Wang et al. [99] considered wood that had been used as formwork in construction as a feedstock for cement-bonded particleboard materials and demonstrated that lightweight panels could be achieved by the suitable choice of admixtures that prompted crystal formation within the wood cells.

It is most likely that particleboard is the most suitable format to accommodate recycled wood, as this reduction technology is better developed. However, Qi et al. [95] showed that MDF can be recycled into wood–cement composites with good results. Wood wool has also been formed from waste wood to demonstrate the potential in wood wool–cement boards (WWCBs) [100]. WWCBs are widely accepted due to the lower density and higher sound and thermal insulation achieved through use of wood wool. The heat flow was identical for the recycled and the raw wood wool in WWCBs, although the mechanical properties of the strands were different. This led to a slight decrease in WWCB panel strength as the proportion of recycled wool increased and fresh strands decreased.

Some recent studies on wood cement composites have highlighted the beneficial effect of wood as a low carbon material to reduce the emissions or increase the carbon storage of the cement or concrete [101,102]. This may provide renewed impetus to developments within this area.

6.5. Extraction of Nanocrystalline Cellulose from Wood Waste

Cellulose nanocrystals (CNCs) have diverse applications in fields such as bioplastics, composites, and biomedical materials [103]. Waste MDF has been identified as a potential source for extracting CNCs through sequential chemical degradation processes [104,105]. This method involves fractionating the MDF and isolating the CNCs. Couret et al. [105] used MDF waste fibres and other fibres from processes that replicate recycled wood fibre feedstocks to evaluate the effect of adhesives present on the nanocrystal generation process. The cellulose recovery yield was good for all four fibre types; however, in the MDF fibre types, a small percentage of the adhesives or non-wood starting material were still present in the nanocrystalline cellulose sample at the end of the process. TEM revealed good quality nanocrystals from all feedstocks.

6.6. Pyrolysis of Decontaminated Wood

Decontaminated wood waste can be pyrolyzed to produce biocrude, an alternative energy source, and biochar [106]. Partial liquefaction is a novel system which may offer particle cleaning for recycling into panel products [107]. It is reported that this technology is of interest for handling wood wastes or logging residues [108]. Both pyrolysis oils and solid residues (charcoal or biochar) are typically generated. Solid wastes must be shredded and dried prior to pyrolysis, which is compatible with existing wood waste handling infrastructure. Recent trends appear to favour the use of wood as a co-feedstock when using pyrolysis to dispose of plastics and car tyres [109].

Biochar can be produced from treated wood. This be used for various purposes like improving soil conditions, where it stores the sequestered carbon, and for applications in adsorption, electromagnetic, and energy battery fields [55]. The characteristics and efficiency of biochar depend on factors such as the pyrolysis process, residence time, and reaction temperatures.

7. Challenges and Opportunities

7.1. Competition Effects

The predicted future global shortage of wood and biomass [21] means that much attention has been directed towards the materials circular economy and recycling. This has brought significant progress in reclamation and waste handling, sorting, and cleaning, as reviewed above. It has also supported growth in the use of recycled wood in many applications, but in particular, wood-based panels and biomass energy. It is reported that the wood panels sector is feeling the pressure from the widespread consumption of biomass for energy—including in the UK, where a very large number of installations compete for woody biomass and agri-residues alongside waste wood. It is reported that the proportion of clean (Category A) waste wood entering wood panels has diminished while Categories B and C has increased [110]. Competition for resource is likely to remain a challenge for the future.

7.2. Benefit of Carbon Storage

In the context of the competition for biomass, it makes sense to remember that recycling wood contributes substantial benefits to greenhouse gas mitigation, through the storage of biobased carbon in products. The storage of carbon in harvested wood products (HWPs), and, most notably, in long life applications such as construction timber, is increasingly recognised. The European Council recently greenlighted a certification framework for carbon removals, including storage in products [111]. In the UK, the carbon storage potential of wood products is also receiving attention [112]. The potential to store carbon extends into the second, third, or multiple lifespans of the wood, if it can be recycled into new products that are, in turn, recyclable (for more examples, see Figure 2). With this in mind, it is interesting to consider the duration effect for the most common destinations of recycled wood.

The Category A recycled timber is highly sought for the animal bedding, landscaping, and play surfaces sector. Yet, in this application, the residence time is relatively short. It would be similarly short for cat litter or other related products. The emerging option of structural products using secondary timber, such as CLT or glulam, would offer a lifespan of decades—depending on building type and design—if this becomes widely adopted. It is already prompting calls to revise our concept of wood cascading to acknowledge that cycling can occur even at the first stage in the sequence [65]. Wood–cement composites from recycled timber could also offer long lifespans, if a product were commercialised.

It appears that wood-based panels are the area which has received the greatest attention for carbon storage calculations [11,113]. Wood-based panels are increasingly drawing on Category B and C material, with some use of Category A material when it is available. The residence time for some panel products in the home is shorter than structural timber; however, if plywood and OSB are used in structural elements, such as flooring cassettes or wall panels, they may remain for the life of the building, like the softwood joists [11]. On the other hand, particleboard and MDF are predominantly used in fitted kitchens and other furniture, which have a shorter retention period. It is estimated that the average household replaces their fitted kitchen every 15 years [113]. For some items, such as flat pack wardrobes, the product life is estimated as being considerably shorter, possibly as low as 5 years [114]. Spear [11] proposed simple estimates of durations and combinations for the residence time of wood-based panels to combine into recycling scenarios. This led to a potential residence time of 150 ± 40 years if a structural panel such as OSB is recycled into structural-grade particleboard. A combined lifespan of 125 ± 27 years was suggested for a joinery panel recycled into structural wood panels or a structural panel being recycled into a joinery panel such as MDF. Shorter examples involved panels used in other sectors, including shop fitting and packaging, as the total pool of wood-based panels serves a broad range of markets. Such suggestions rely on continually emerging service life data, but it is clear that enhancing the options for recycling post-consumer particleboard and MDF products will provide an additional life prior to final disposal. Brunet-Navarro et al. demonstrated that carbon storage increases linearly for extending the product life, but exponentially if the recycling rate is increased [115].

Enhancing the options for the re-use of MDF into novel products such as nanocellulose would also lead to a storage benefit [105]. Couret et al. [113] simulated the potential volumes of MDF waste available for nanocellulose production, based on 2012 MDF waste wood levels. The development of new markets to take MDF into alternative products would extend the number of options for recycling a challenging material. If the current recovery of TMP fibres from MDF for use in insulation products for buildings gains popularity, then the expected service life of the recycled insulation will be decades. This would enhance the wood products pool for carbon storage through the large quantity required per dwelling as well as the long duration of product use.

7.3. Lower Carbon Footprint

Utilising recycled timber for fillers or particleboard manufacturing significantly reduces carbon emissions and global warming potential (GWP). The use of recycled wood requires less energy to process into panels than raw timber, as the material is drier [1,12]. Products, such as door cores and particleboard made from recycled wood, can have a lower carbon footprint than its fresh wood counterpart [73,116,117]. Forster et al. showed that Scope 1–3 emissions were substantially reduced in scenarios where the cascading of wood was employed, compared to business as usual [12].

8. Conclusions

While some product groups that use recycled wood have changed little over the past two decades in the UK, the market has matured considerably. The strict grading categories selected early in the evolution of recycled wood usage in wood-based panels in the UK have led to continued and substantial advances in the segregation and cleaning technologies. However, there is still scope for further innovation, such as the cleaning of the chemically treated wood, which is currently assigned to Category D (destined for controlled disposal to minimise the risk to the environment). As competition for the resource intensifies, there will be a need to optimise material flows to deliver a balance of benefits to society and the environment.

The service life of wood-based panels (i.e., residence time in the built environment) is a strong benefit when recycling wood into the wood panel product group. Storage durations for some panel products are as long as the structural timber, especially in the case of timber frame housing systems. The same information can also support a case for recycling wood fibre within MDF panels or into insulation products to achieve further extension of the residence times, and an increased environmental benefit.

Traditional wood and timber recycling methods are often considered to lead to downcycling, producing materials of lower quality than the original. The common applications include energy generation, particleboard production, and animal bedding. Yet the hierarchy contains surprises, as the wood-based panels that use material from Categories A, B, and C can have considerable value as forms of carbon storage and offer further recycling cycles. The emerging option of MDF recycling, now demonstrated at scale, is a clear example of how even previously hard-to-recycle panels can enter the recycling chain. In future, it may be necessary to consider much more complex models of the different cascading routes within a network of recycled wood using options.

To transition to a better integrated circular economy in the timber industry, greater awareness of the suite of panel products and their range of qualities and service lives will enhance decision making. In addition, there is scope for new innovation, either into advanced recycling and cleaning methods or for the creation of higher-value products from recovered wood. If a price premium becomes associated with certain applications, this could assist the economics of novel cleaning methods, thereby improving recycling rates. Chemical systems to remove preservative treatments have been demonstrated but require effort to scale up or a pull through from the market to utilise the cleaned wood. One option that could take cleaned wood and generate a premium is cellulose nanocrystals. A different option is pyrolysis oils as a feedstock for adhesives and wood treatments.

Author Contributions: Conceptualisation, M.J.S. and G.A.O.; investigation, M.J.S., A.D. and G.A.O.; resources, G.A.O.; writing—original draft preparation, M.J.S., G.A.O., A.D. and S.F.C.; writing—review and editing, M.J.S., G.A.O. and S.F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Welsh Government under grant number: SFIS 081.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Earl, H.E.; Elias, R.M. Technical advantages of utilising recycled wood in particleboard production. In Proceedings of the Wood—The Ecological Material: 4th European Symposium, Stockholm, Sweden, 22–23 September 1997; pp. 115–117.
2. Franke, R.; Roffael, E. Recycling of particle- and medium density fibreboards (MDF) Part 1. On the hydrolysis resistance of cured UF-resins on particle- and fibreboards. *Holz Als Roh-Und Werkst.* **1998**, *56*, 79–82. (In German) [CrossRef]
3. Olofsson, T. Refining technology for low grade materials including urban waste wood. In Proceedings of the Third European Panel Products Symposium (EPPS3), Llandudno, UK, 6–8 October 1999; pp. 155–163.
4. Saukkonen, S. Cleaning recycled urban waste wood materials for panelboard processes. In Proceedings of the Third European Panel Products Symposium (EPPS3), Llandudno, UK, 6–8 October 1999; p. 176.
5. Wood Based Panels Technology Cost Action E49. *Wood Based Panels: An Introduction for Specialists*; Irle, M., Barbu, M., Thoemen, H., Inggris, G.B., Sernek, M., Eds.; Brunel University Press: London, UK, 2010.
6. Bartlett, C. MDF: Closed loop recycling—Enhancing supply chain value. In Proceedings of the International Panel Products Symposium 2015, Llandudno, UK, 7–8 October 2015; pp. 83–88.
7. Wronka, A.; Kowaluk, G. The influence of multiple mechanical recycling of particleboards on their selected mechanical and physical properties. *Materials* **2022**, *15*, 8487. [CrossRef] [PubMed]

8. Garcia, R.; Calvez, I.; Koubaa, A.; Landry, V.; Cloutier, A. Sustainability, circularity, and innovation in wood-based panel manufacturing in the 2020s: Opportunities and challenges. *Curr. For. Rep.* **2024**, *2024*, 10420–10441. [CrossRef] [PubMed]
9. FAO. FAOSTAT: Forestry Production and Trade. 2024. Available online: https://www.fao.org/faostat/en/#data/FO (accessed on 28 December 2024).
10. Forest Research. *Forestry Statistics 2023*; Forest Research: Roslin, UK, 2023. Available online: https://www.forestresearch.gov.uk/tools-and-resources/statistics/publications/forestry-statistics/forestry-statistics-2023/ (accessed on 9 December 2024).
11. Spear, M. The benefits of circular economy approaches in the wood panels industry on the magnitude of harvested wood products (HWP) storage. In Proceedings of the International Panel Products Symposium (IPPS 2023), Llandudno, UK, 3–4 October 2023; pp. 23–40.
12. Forster, E.J.; Healey, J.R.; Newman, G.; Styles, D. Circular wood use can accelerate global decarbonisation but requires cross-sectoral coordination. *Nat. Commun.* **2023**, *14*, 6766. [CrossRef]
13. WRAP. *Wood Waste Market in the UK, Summary Report, Project Code MKN022*; Poyry Forest Industry Consulting Ltd.: Oakville, ON, Canada; Oxford Economics Ltd.: Oxford, UK, 2009; p. 37.
14. WRA. Wood Recyclers' Association Waste Wood Market Statistics 2007. 2008. Available online: http://www.woodrecyclers.org (accessed on 21 February 2011).
15. WRA. Over 97% of UK Waste Wood Processed in 2023. 2024. Available online: https://woodrecyclers.org/over-97-of-uk-waste-wood-processed-in-2023/ (accessed on 9 December 2024).
16. Sirkin, T.; Houten, M.T. The cascade chain: A theory and tool for achieving resource sustainability with applications in product design. *Resour. Conserv. Recycl.* **1994**, *10*, 213–277. [CrossRef]
17. UNECE FAO. Circularity Concepts in Forest-Based Industries. Geneva Timber and Forest Study Paper 49. 2021. Available online: https://unece.org/info/Forests/pub/367742 (accessed on 1 August 2024).
18. Yang, M.; Chen, L.; Wang, J.; Msigwa, G.; Osman, A.I.; Fawzy, S.; Rooney, D.W.; Yap, P.-S. Circular economy strategies for combatting climate change and other environmental issues. *Environ. Chem. Lett.* **2023**, *21*, 55–80. [CrossRef]
19. EPF. EPF Applauds Cascading Use of Wood with EU Legislation. 2023. Available online: https://europanels.org/press-release-epf-applauds-cascading-use-of-wood-in-eu-legislation/ (accessed on 28 December 2024).
20. Winder, G.M.; Bobar, A. Responses to stimulate substitution and cascade use of wood within a wood use system: Experience from Bavaria, Germany. *Appl. Geogr.* **2018**, *90*, 350–359. [CrossRef]
21. FAO. Global Forest Sector Outlook 2050: Assessing Future Demand and Sources of Timber for a Sustainable Economy. 2022. Available online: https://openknowledge.fao.org/server/api/core/bitstreams/9f646b14-28d2-496e-9728-0b1c281339b5/content (accessed on 20 December 2024).
22. Birdsey, R.; Duffy, P.; Smyth, C.; Kutz, W.; Dugan, A.J.; Houghton, R. Climate, economic and environmental impacts of producing wood for bioenergy. *Environ. Res. Lett.* **2018**, *13*, 050201. [CrossRef]
23. Lee, H.; Brown, C.; Seo, B.; Holman, I.; Audsley, E.; Cojocaru, G.; Rounsvell, M. Implementing land-based mitigation to achieve the Paris Agreement in Europe requires food system transformation. *Environ. Res. Lett.* **2019**, *14*, 104009. [CrossRef]
24. Soimakallio, S.; Kalliokoski, T.; Lehtonen, A.; Salminen, O. On the trade-offs and synergies between forest carbon sequestration and substitution. *Mitig. Adapt. Strateg. Glob. Chang.* **2021**, *26*, 4. [CrossRef]
25. Hope, E.; Gagnon, B.; Avdic, V. Assessment of the impact of climate change policies on the market for forest industrial residues. *Sustainability* **2020**, *12*, 1787. [CrossRef]
26. Auer, V.; Rauch, P. Wood supply chain risks and risk mitigation strategies: A systematic review focusing on the Northern Hemisphere. *Biomass Bioenergy* **2021**, *148*, 10601. [CrossRef]
27. Ormondroyd, G.O.; Spear, M.J.; Skinner, C. The opportunities and challenges for re-use and recycling of timber and wood products within the construction sector. In *Environmental Impacts of Traditional and Innovative Forest-Based Bioproducts*; Kutnar, A., Muthu, S.S., Eds.; Springer: Berlin/Heidelberg, Germany, 2016; pp. 45–104.
28. Nguyen, D.L.; Luedtke, J.; Nopens, M.; Krause, A. Production of wood-based panel from recycled wood resource: A literature review. *Eur. J. Wood Wood Prod.* **2023**, *81*, 557–570. [CrossRef]
29. DEFRA. *Wood Waste Landfill Restrictions in England: Call for Evidence*; DEFRA: London, UK, 2013.
30. Gov.uk. Official Statistics on Waste. 2024. Available online: https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste (accessed on 28 December 2024).
31. *PAS 111:2012*; Specification for the Requirements and Test Methods for Processing Waste Wood. British Standards Institute: London, UK, 2012.
32. WRAP. *The Business Case for Wood Waste Collection Hubs*; WRAP: London, UK, 2012.
33. WRA. WRA Grades of Waste Wood. 2023. Available online: https://woodrecyclers.org/wp-content/uploads/WRA-Grades-of-Waste-Wood.pdf (accessed on 20 December 2024).

34. WRA. WRA Launches Tests to Confirm Hazardous Wood Treatments Diminishing in Household Waste Stream 2023. Available online: https://woodrecyclers.org/wra-launches-tests-to-confirm-hazardous-treatments-diminishing-in-household-waste-wood-stream/ (accessed on 20 December 2024).
35. WRA. Waste Wood Assessment Guidance for the UK Waste Wood Industry, Version 2, November 21. 2021. Available online: https://woodrecyclers.org/wp-content/uploads/WRA-Waste-Wood-Assessment-Guidance-V2-November-2021.pdf (accessed on 9 December 2024).
36. *BS EN 71-5:1993*; Safety of Toys. Chemical Toys (Sets) Other than Experimental Sets. British Standards Institute: London, UK, 1993.
37. *PAS 104*; Wood Recycling in the Panel Board Manufacturing Industry. British Standards Institute: London, UK, 2004.
38. EPF. EPF Standard for Delivery Conditions of Recycled Wood. 2018. Available online: https://europanels.org/wp-content/uploads/2018/09/EPF-Standard-for-recycled-wood-use.pdf (accessed on 18 December 2024).
39. Bunting. Separating Metal when Recycling Wood. 2024. Available online: https://www.bunting-redditch.com/separating-metal-when-recycling-wood/ (accessed on 20 December 2024).
40. Imalpal. Cyclops—All in One. 2024. Available online: https://www.imalpal.com/prodotti/cyclops-all-in-one/ (accessed on 20 December 2024).
41. Anon. 250,000 tons of Sorted Waste Wood for the Longest MDF Press in Europe. 2022. Available online: https://www.recycling-magazine.com/2022/06/28/250-000-tons-of-sorted-wood-waste-for-the-longest-mdf-press-in-europe/ (accessed on 28 December 2024).
42. Instalmec. Cleaning of Wood. 2024. Available online: https://www.instalmec.it/en/wood/plants (accessed on 20 December 2024).
43. Irle, M.A.; Fru, C.; Maher, K.; Ormondroyd, G.A. Measurement of contaminants in recycled wood and products made from recycled wood. In Proceedings of the Seventh European Panel Products Symposium, Llandudno, UK, 8–10 October 2003; pp. 208–218.
44. Fru, C.; Irle, M.A.; Maher, K.; Ormondroyd, G.A. A protocol for the sampling of recycled wood and resulting chipboard for contamination analysis. In Proceedings of the Seventh European Panel Products Symposium 2003, Llandudno, UK, 8–10 October 2003; pp. T1–T3.
45. Lubis, M.A.R.; Hong, M.K.; Park, B.D. Hydrolytic removal of cured ureal-formaldehyde resins in medium-density fibreboard for recycling. *J. Wood Chem. Technol.* **2018**, *38*, 1–14. [CrossRef]
46. Lopes DJ, V.; Stokes, E.C.; dos Santos Bobadilha, G. The use of chemical and biological agents in the recovery of heavy metals from treated woods—A brief review. *BioRes* **2019**, *14*, 2287–2299. [CrossRef]
47. Helsen, L.; Van den Bulck, E. Review of disposal technologies for chromated copper arsenate (CCA) treated wood waste, with detailed analyses of thermochemical conversion processes. *Environ. Pollut.* **2005**, *134*, 301–314. [CrossRef]
48. PCA. Summary on Present Situation Regarding Pre-Treated Timber. 2003. Available online: https://www.property-care.org/news/pre-treated-timber (accessed on 20 December 2024).
49. Gezer, E.D.; Cooper, P.A. Factors affecting sodium hypochlorite extraction of CCA from treated wood. *Waste Manag.* **2009**, *29*, 3009–3013. [CrossRef] [PubMed]
50. Janin, A.; Zaviska, F.; Drogui, P.; Blais, J.F.; Mercier, G. Selective recovery of metals in leachate from chromated copper arsenate treated wastes using electrochemical technology and chemical precipitation. *Hydrometallurgy* **2009**, *96*, 318–326. [CrossRef]
51. Kartal, S.N.; Imamura, Y. Chemical and biological remediation of CCA-treated waste wood. *Wood Res. Bull. Wood Res. Inst. Kyoto Univ.* **2003**, *90*, 111–115. Available online: https://core.ac.uk/download/pdf/39187289.pdf (accessed on 28 December 2024). [CrossRef]
52. Chen, S. *A Green and Novel Technology for Recovering Copper and Wood From Treated Wood Waste—Part 1*; Document No IRG/WP/15-50309; International Research Group on Wood Preservation: Viña del Mar, Chile, 2015.
53. Shiau, R.J.; Smith, R.L.; Avellar, B. Effects of steam explosion processing and organic acids on CCA removal from treated wood waste. *Wood Sci. Technol.* **2000**, *34*, 377–388. [CrossRef]
54. Sarahney, H.; Wang, J.; Alshawabkey, A. Electrokinetic process for removing Cu, Cr and As from CCA-treated wood. *Environ. Eng. Sci.* **2005**, *22*, 642–660. [CrossRef]
55. Xing, D.; Magdouli, S.; Zhang, J.; Koubaa, A. Microbial remediation for the removal of inorganic contaminants from treated wood: Recent trends and challenges. *Chemosphere* **2020**, *258*, 127429. [CrossRef] [PubMed]
56. Besserer, A.; Troilo, S.; Girods, P.; Rogaume, Y.; Brosse, N. Cascading recycling of wood waste. *Polymers* **2021**, *13*, 1752. [CrossRef] [PubMed]
57. Mohajerani, A.; Vajna, J.; Ellcock, R. Chromated copper arsenate timber: A review of products, leachate studies and recycling. *J. Clean. Prod.* **2018**, *179*, 292–307. [CrossRef]
58. Chang, Y.C.; Choi, D.B.; Kikuchi, S. Enhanced extraction of heavy metals in the two-step process with the mixed culture of *Lactobacillus bulgaricus* and *Streptococcus thermophiles*. *Bioresour. Technol.* **2012**, *103*, 477–480. [CrossRef] [PubMed]

59. Clausen, C.A.; Smith, R.L. Removal of CCA from treated wood by oxalic acid extraction, steam explosion and bacterial fermentation. *J. Ind. Microbiol. Biotechnol.* **1998**, *20*, 251–257. [CrossRef]
60. Kartal, S.N.; Clausen, C.A. Leachability and decay resistance of particleboard made from acid extracted and bioremediated CCA-treated wood. *Int. Biodeterior. Biodegrad.* **2001**, *47*, 183–191. [CrossRef]
61. Coudert, L.; Blais, J.-F.; Mercier, G.; Cooper, P.; Gastonguay, L.; Morris, P.; Janin, A.; Reynier, N. Pilot-scale investigation of the robustness and efficiency of a copper-based treated wood wastes recycling process. *J. Hazard. Mater.* **2013**, *261*, 277–285. [CrossRef] [PubMed]
62. Hill, C.A.S. *An Introduction to Sustainable Resource Use*; Earth Scan: London, UK, 2011.
63. Vis, M.; Mantau, U.; Allen, B. *Study on the Optimised Cascading Use of Wood*; Publications Office: Brussels, Belgium, 2016.
64. Hill, C.; Norton, A.; Kutnar, A. Environmental impacts of wood composites and legislative obligations. In *Wood Composites*; Ansell, M.P., Ed.; Woodhead Publishing: Cambridge, UK, 2015; pp. 311–333.
65. Breidenbach, J.; Rose, C.M.; Quinn, P.; Stegemann, J.A. Cascade Up: Extending the life of reclaimed solid wood through reuse in the manufacture of mass timber products. In Proceedings of the WSE 2024, Edinburgh, UK, 23–24 October 2024.
66. Fu, Q.; Zhang, B.; Wang, X.-M.; Cloutier, A.; Rousiere, F.; Bouffard, J.F. Thermo-hydrolytically recycling of urea-formaldehyde resin-bonded particleboard laminated particleboards. *BioResources* **2022**, *17*, 647–6859. [CrossRef]
67. Gibier, M.; Sadeghisadeghabad, M.; Girods, P.; Zoulalian, A.; Rogaume, Y. Furniture wood waste depollution through hydrolysis under pressurized water steam: Experimental work and kinetic modelization. *J. Hazard. Mater.* **2022**, *436*, 129126. [CrossRef] [PubMed]
68. Savov, V.; Antov, P.; Panchev, C.; Lubis, M.A.R.; Taghiyari, H.R.; Lee, S.H.; Kristak, L'.; Todorova, M. The impact of hydrolysis regime on the physical and mechanical characteristics of medium-density fibreboards manufactured with recycled wood fibres. *Fibers* **2023**, *11*, 103. [CrossRef]
69. Kearley, V.; Goroyias, G. Wood panel recycling at a semi industrial scale. In Proceedings of the 8th European Panel Products Symposium, Llandudno, UK, 13–15 October 2004; pp. 1–18.
70. Bartlett, C.; Balarin, L. MDF Recycling—The commercial reality. In Proceedings of the International Panel Products Symposium 2023, Llandudno, UK, 3–4 October 2023; pp. 13–14.
71. Unilin. World First: A Second Life for MDF and HDF Panels with Our Brand New Recycling Technology. 2021. Available online: https://www.unilinpanels.com/en/blog/recycling-mdf-hdf-new-technology (accessed on 20 December 2024).
72. Hong, M.-K.; Lubis, M.A.R.; Park, B.D.; Sohn, C.H.; Roh, J. Effects of surface laminate type and fiber content on properties of three-layer medium density fibreboard. *Wood Mater. Sci. Eng.* **2018**, *15*, 163–171. [CrossRef]
73. Amarasinghe, I.T.; Qian, Y.; Gunawardena, T.; Mendis, P.; Belleville, B. Composite panels from wood waste: A detailed review of processes, standards, and applications. *J. Compos. Sci.* **2024**, *8*, 417. [CrossRef]
74. Gov.uk. Biomass Strategy 2023. Available online: https://www.gov.uk/government/publications/biomass-strategy (accessed on 20 December 2024).
75. Rose, C.M.; Bergsagel, D.; Dufresne, T.; Unubreme, E.; Lyu, T.; Duffour, P.; Stegemann, J.A. Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties. *Sustainability* **2018**, *10*, 4118. [CrossRef]
76. Llana, D.F.; Iniguez-Gonzalez, G.; de Arana-Fernandez, M.; Ui Chulain, C.; Harte, A.M. Recovered wood as raw material for structural timber products. Characteristics, situation and study cases: Ireland and Spain. In Proceedings of the 2020 Society of Wood Science and Technology International Convention, Online, 12–15 July 2020; pp. 117–123.
77. Anon. W Howard and MDF Recovery Agree UK and Ireland Licensing Deal. 2023. Available online: https://www.mdfrecovery.co.uk/w-howard-and-mdf-recovery-agree-uk-and-ireland-licencing-deal/ (accessed on 20 December 2024).
78. Cetiner, I.; Shear, A.D. Wood waste as an alternative thermal insulation for buildings. *Energy Build.* **2018**, *168*, 374–384. [CrossRef]
79. Lafond, C.; Blanchet, P. Technical performance overview of bio-based insulation materials compared to expanded polystyrene. *Buildings* **2020**, *10*, 81. [CrossRef]
80. Spear, M.J.; Eder, A.; Carus, M. Wood polymer composites. In *Wood Composites*; Ansell, M.P., Ed.; Woodhead Publishing: Cambridge, UK, 2015; pp. 195–249.
81. Migneault, S.; Koubaa, A.; Perre, P. Effect of fiber origin, proportion, and chemical composition on the mechanical and physical properties of wood-plastic composites. *J. Wood Chem. Technol.* **2014**, *34*, 241–261. [CrossRef]
82. Sommerhuber, P.F.; Welling, J.; Krause, A. Substitution potential of recycled HDPE and wood particles from post-consumer packaging waste in Wood-Plastic Composites. *Waste Manag.* **2015**, *46*, 76–85. [CrossRef] [PubMed]
83. Chaharmahali, M.; Mirbagheri, J.; Tajvidi, M.; Najafi, S.K.; Mirbagheri, Y. Mechanical and Physical Properties of Wood-Plastic Composite Panels. *J. Reinf. Plast. Compos.* **2010**, *29*, 310–319. [CrossRef]
84. Bütün, F.Y.; Sauerbier, P.; Militz, H.; Mai, C. The effect of fibreboard (MDF) disintegration technique on wood polymer composites (WPC) produced with recovered wood particles. *Compos. Part A* **2019**, *118*, 312–316. [CrossRef]

85. English, B.; Clemons, C.; Stark, N.; Schneider, J.P. Waste wood-derived fillers for plastics. In Proceedings of the Fourth International Conference on Woodfiber Plastic Composites, Madison, WI, USA, 12–14 May 1997; pp. 309–324.
86. Dalu, M.; Temiz, A.; Altunas, E.; Demirel, G.K.; Aslan, M. Characterization of tanalith E treated wood flour filled polylactic acid composites. *Polym. Test.* **2019**, *76*, 376–384. [CrossRef]
87. Ntalos, G.; Papdopoulos, A. Mechanical physical properties of cement bonded, O.S.B. In Proceedings of the Conference co-organized by COST Action E44–E49 Wood Resources and Panel Properties, Valencia, Spain, 12–13 June 2006; pp. 315–319.
88. Frybort, S.; Mauritz, R.; Teischinger, A.; Muller, U. Cement Bonded Composites—A Mechanical Review. *BioResources* **2008**, *3*, 602–626. [CrossRef]
89. Soroushian, P.; Won, J.-P.; Hassan, M. Durability and microstructure analysis of CO_2-cured cement-bonded wood particleboard. *Cem. Concr. Compos.* **2013**, *41*, 34–44. [CrossRef]
90. Wolfe, R.W.; Gjinolli, A. Cement-bonded wood composites as an engineering material. In Proceedings of the Use of Recycled Wood and Paper in Building Applications, Madison, WI, USA, 9–11 September 1996.
91. Papadopoulos, A.N.; Ntalos, G.A.; Kakaras, I. Mechanical and physical properties of cement bonded OSB. *Holz Roh Werkst.* **2006**, *64*, 517–518. [CrossRef]
92. Miyatake, A.; Fiujii, T.; Hiramatsu, Y.; Abe, H.; Tonosaki, M. Manufacture of wood strand-cement composite for structural use. In Proceedings of the Wood-Cement Composites in the Asia-Pacific Region, Canberra, Australia, 10 December 2000; pp. 148–152.
93. Solo-Gabriele, H.; Townsend, T. Disposal practices and management alternatives for CCA-treated wood waste. *Waste Manag. Res.* **1999**, *17*, 378–389. [CrossRef]
94. Zhou, Y.; Kamdem, D.P. Effect of cement/wood ration on the properties of cement-bonded particleboard using CCA-treated wood removed from service. *For. Prod. J.* **2002**, *52*, 77–81.
95. Qi, H.; Cooper, P.A.; Wan, H. Effect of carbon dioxide injection on production of wood cement composites from waste medium density fibreboard (MDF). *Waste Manag.* **2006**, *26*, 509–515. [CrossRef] [PubMed]
96. Huang, C.; Cooper, P.A. Cement-bonded particleboards using CCA-treated wood removed from service. *For. Prod. J.* **2000**, *50*, 49–56.
97. Schmidt, R.; Marsh, R.; Balatinecz, J.J.; Cooper, P.A. Increased wood-cement compatibility of chromate-treated wood. *For. Prod. J.* **1994**, *44*, 44–46.
98. Li, M.; Nicolas, V.; Khelifa, M.; El Ganaoui, M.; Fierro, V.; Celzard, V. Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork. *Ind. Crops Prod.* **2019**, *142*, 111784. [CrossRef]
99. Wang, L.; Chen, S.S.; Tseng, D.C.W.; Poon, C.S.; Shih, K. Value-added recycling of construction waste wood into noise and thermal insulating cement-bonded particleboards. *Constr. Build. Mater.* **2016**, *125*, 316–325. [CrossRef]
100. Berger, F.; Gauvin, F.; Brouwers, H.J.H. The recycling potential of wood waste into wood-wool/cement composite. *Constr. Build. Mater.* **2020**, *260*, 119786. [CrossRef]
101. Caldas, L.R.; Saraiva, A.B.; Lucena, A.F.P.; Da Gloria, M.Y.; Santos, A.S.; Filho, R.D.T. Building materials in a circular economy: The case of wood waste as CO_2-sink in bio concrete. *Resour. Conserv. Recycl.* **2021**, *166*, 105346. [CrossRef]
102. Ince, C.; Tayancli, S.; Deogar, S. Recycling waste wood in cement mortars towards the regeneration of sustainable environment. *Constr. Build. Mater.* **2021**, *299*, 123891. [CrossRef]
103. Grishkewich, N.; Mohammed, N.; Tang, J.; Tam, K.C. Recent advances in the application of cellulose nanocrystals. *Curr. Opin. Colloid Interface Sci.* **2017**, *29*, 32–45. [CrossRef]
104. Irle, M.; Privat, F.; Couret, L.; Belloncle, C.; Déroubaix, G.; Bonnin, E.; Cathala, B. Advanced recycling of post-consumer solid wood and MDF. *Wood Mater. Sci. Eng.* **2019**, *14*, 19–23. [CrossRef]
105. Couret, L.; Irle, M.; Belloncle, C.; Cathala, B. Extraction and characterization of cellulose nanocrystals from post-consumer wood fiberboard waste. *Cellulose* **2017**, *24*, 2125–2137. [CrossRef]
106. Kim, J.-Y.; Oh, S.; Park, Y.K. Overview of biochar production from preservative treated wood with detailed analysis of biochar characteristics, heavy metal behaviours and their ecotoxicity. *J. Hazard. Mater.* **2020**, *384*, 121356. [CrossRef] [PubMed]
107. Medved, S.; Irle, M.; Kržišnik, D.; Humar, M. Partial liquefaction as a method for remediation of recovered wood. In Proceedings of the International Panel Products Symposium 2015, Llandudno, UK, 7–8 October 2015; pp. 97–104.
108. Mohan, D.; Pittman, C.U.; Steele, P.H. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy Fuels* **2006**, *20*, 848–889. [CrossRef]
109. Wang, G.; Dai, Y.; Yang, H.; Xiong, Q.; Wang, K.; Zhou, J.; Li, Y.; Wang, S. A review of recent advances in biomass pyrolysis. *Energy Fuels* **2020**, *34*, 15557–15578. [CrossRef]
110. Kerr, A. Wood recycling at a crossroads. *Wood Based Panels Int.* **2024**, *44*, 42.
111. European Council. Council greenlights EU Certification Framework for Permanent Carbon Removals, Carbon Farming and Carbon Storage in Products. 2024. Available online: https://www.consilium.europa.eu/en/press/press-releases/2024/11/19/council-greenlights-eu-certification-framework-for-permanent-carbon-removals-carbon-farming-and-carbon-storage-in-products/ (accessed on 16 December 2024).

112. DEFRA. Timber in Construction Roadmap. 2023. Available online: https://www.gov.uk/government/publications/timber-in-construction-roadmap/timber-in-construction-roadmap (accessed on 10 November 2024).
113. Couret, L.; Irle, M.; Belloncle, C.; Cathala, B. Extracting high-value products from waste MDF. In Proceedings of the International Panel Products Symposium 2015, Llandudno, UK, 7–8 October 2015; pp. 89–96.
114. Iritani, D.R.; Silva, D.A.L.; Saavedra, Y.M.B.; Grael, P.F.F.; Ometto, A.R. Sustainable strategies analysis through Life Cycle Assessment: A case study in the furniture industry. *J. Clean. Prod.* **2015**, *96*, 308–318. [CrossRef]
115. Brunet-Navarro, P.; Jochheim, H.; Muys, B. The effect of increasing lifespan and recycling rate on carbon storage in wood products from theoretical model to application for the European wood sector. *Mitig. Adapt. Strateg. Glob. Change* **2017**, *22*, 1193–1205. [CrossRef] [PubMed]
116. Kim, M.H.; Song, H.B. Analysis of the global warming potential for wood waste recycling systems. *J. Clean Prod.* **2014**, *69*, 199–207. [CrossRef]
117. Wang, J.; Deng, N.; Cao, N.; Li, J.; Sun, J. Life cycle analysis of a novel treatment method for recycling wood processing residues into the core of wooden doors. *J. Clean. Prod.* **2023**, *415*, 137798. [CrossRef]