

WOOD RECYCLING IN THE CIRCULAR BIOECONOMY

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Abstract:

Although most people agree that recycling materials is a good thing to do, not many of them know how materials are recycled. Wood is a prime example. It is highly likely that many people who are reading this have never thought in detail about how wood is recycled. This paper discusses the need for recycling, the current wood recycling practices, the challenges currently facing the wood recycling sector and how these challenges are being addressed.

Key words: *post-consumer, recycling, secondary raw materials, wood, fibreboards.*

INTRODUCTION

The term “recycling” is sometimes used incorrectly, for example, someone might talk about recycling beams from an old building when, what they mean is that the beams are *reused*. Recycling specifically refers to the extraction of materials from a product after it has completed a useful life cycle, so that the extracted materials can be used to make another product. The extracted materials are often referred to as secondary raw materials (SRM). Potting *et al* (2016) defined ten circularity strategies for material use and presented them in order of environmental impact. The strategy that has the least environmental impact is to refuse (strategy R0) and the strategy with the greatest environmental impact is to burn a product at the end of its life and recover the energy within it (R9). Recycling is strategy R8, so only one better than burning. The impacts come from the energy needed to extract and separate the SRM. Within the wood sector, the extracted materials rarely have the same properties as virgin wood and often have small dimensions, which limits remanufacturing opportunities.

The term “recycling” is sometimes incorrectly applied to materials that are produced as a result of processing a resource, e.g. sawdust, chips and slab wood from sawmilling operations. Materials like sawdust are by-products of processing logs; they might have a low value, but, they should not be considered as wastes. A wood-based product that has been used and is now no longer needed is a “post-consumer” product. It could be reused (R3), repaired (R4), refurbished (R5), remanufactured (R6), repurposed (R7) or recycled (R8) (Potting *et al.* 2016).

This paper will focus on the recycling of post-consumer wood.

Why should we recycle wood?

Wood is a renewable material, but this does not mean that there is an infinite supply available. If the forest resource is to be used sustainably, then the total volume of wood available is limited to the annual growth. If the volume of wood used is greater than the annual growth rate then, by definition, the forest area available for the following year will be reduced, thus the annual growth available on the following year will be smaller. Even if we lived in an ideal world where resource use matched supply, the continuing growth in population will result in a demand that is greater than the forest can produce. Improvements in silvicultural practices and tree breeding can help ensure the volume of supply is as large as possible, whereas recycling wood can reduce the demand for virgin wood.

The rate of recycling has a marked effect on the sustainability of using a given material. As an example, imagine the discovery of a new, non-renewable resource of which there are a maximum of 100 units across the planet. If we use 3 units of this resource in year 1 and increase the use in the next and subsequent years by 1%, year on year, which is approximately equivalent to the global population growth rate at the time of writing, then this new resource would be depleted in only 28 years, see Fig. 1. If 50% of the previous year’s use is recycled back into the current year’s production, then the resource would be depleted after just 50 years. It is interesting to note that the current recycling rate in Europe for many materials is 49% (Anon 2023b). New targets for recycling Construction & Demolition waste will be proposed as part of an amendment to the European Waste Framework Directive by the end of 2024. It is expected that these will be between 65 and 75%.

What will surprise many is that Fig. 1 shows that even higher recycling rates, like those proposed by the EU, do not make material use sustainable. A very commendable recycling rate of 80% would still result in the depletion in 94 years, i.e. the lifetime of some people, of this theoretical resource. This shows that it is extremely important to use less as well as recycle. This paper, however, will focus on the recycling question.

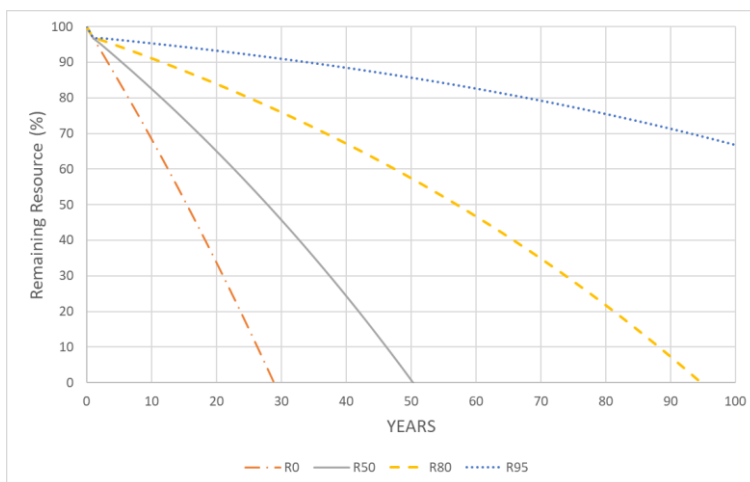


Fig. 1.

A simple model of resource depletion and the impact of resource recycling: R0 = no recycling; R50 = 50% of previous year's production recycled into the current year; R80 = 80% recycling rate; R95 = 95% recycling rate.

How do we currently recycle wood?

It would seem that where there is legislation or guidance documents on the use of recovered wood that these documents classify recovered wood into four categories. Some of these are compared in

Table 1. There is little difference between the definitions of the cleanest grades (AI and A) and also of the most contaminated grades (AIV, Grade D and Class C). There are, however, some differences in the definitions and uses of the "middle" grades. Either of the middle two grades can be recycled to particleboard in Britain and France, but the AIII grade can only be used to particleboard if most of the finishes have been removed previously, which is impractical to do.

Table 1

A comparison of different grades of recovered wood used across Europe

| German Waste Wood Ordinance (2002) | | British PAS 111 (2012) | | The French Market ¹ | |
|------------------------------------|------------------------------------------------------------------------------|-------------------------------|-------------------------------------------------------------------------------|--------------------------------|--------------------------------------------------------------------------------------|
| Grade | Abridged Description | Grade | Abridged Description | Grade | Description |
| AI | Waste wood in its natural state or only mechanically worked | Grade A "Clean" recycled wood | Packaging waste, scrap pallets, packing cases, and cable drums. | Class A | Packaging waste |
| AII | Bonded, painted, coated, lacquered ... with no halogenated organic compounds | Grade B Industrial feedstock | Building and demolition materials and domestic furniture made from solid wood | Class B | Building and demolition materials and domestic furniture, can include panel products |
| AIII | Waste wood with halogenated organic compounds in coatings | Grade C Fuel | Flat pack furniture made from board products | DEA ² | Flat pack furniture made from board products |
| AIV | Waste wood treated with wood preservatives | Grade D Hazardous | Fencing, transmission poles, railway sleepers, | Class C | Recovered wood classified as hazardous |

¹The *Référentiel de classification des déchets bois* (Glet-Labeyrie and Deroubaix 2022) proposes two B grades (BR1 and BR2) that are differentiated by the type of burning system that they might fuel, even though both can be used for particleboard manufacture. DEA can be present in both BR1 & 2.

²Déchet bois d'Elément d'Ameublement, which translates as wood waste from furniture components and is largely accepted to contain a lot of panel products, especially particleboard.

| | | | | | |
|--|--|-------|-----------------|--|-------|
| | | waste | cooling towers. | | waste |
|--|--|-------|-----------------|--|-------|

Post-consumer wood products tend to be bulky and of low value. It is logical, therefore, for recycling companies to grind old furniture into particles to ease the storage and transport of recovered wood. Once converted to particles, the options for recycling are limited to particleboard manufacture, animal beddings, landscape uses, e.g. mulches, and so on.

The only reliable data on the use of recovered wood is that collected by particleboard manufacturers, who are large consumers of recovered wood. A particleboard manufactured in Europe currently contains on average 43% recovered wood (EPF 2023). This represents 8.58 million tons of dry recovered wood or 10.55 million tons of recovered wood on the market because post-consumer wood chips have an average moisture content of about 23% (Edo et al. 2016). It is fair to say that without particleboard manufacture the wood economy would be much less circular.

Collecting and processing waste is big business. Multi-national companies like Veolia and Suez are involved in all aspects of collecting, storing, processing and selling waste. They are often sub-contracted by local authorities to take care of the municipal waste generated in their areas. Put very simply, the business model is that companies like Veolia are paid to collect waste by the producer, they then extract the SRM from the waste and sell them to companies as raw materials. It is in the recycling company's interest to maximise the recovery and quality of SRM. Obviously, mixed waste requires more effort to process than a single waste type, e.g. solid wood. Bins specifically for wood can be found on construction and demolition sites and at companies across Europe. Unfortunately, it is rare to find bins for specific wood product types, e.g. solid wood or wood composites. Some wood processing companies who produce large volumes of processing residues, say more than 40t per month, and who have a particleboard manufacturer with 150 km might send their residues directly to a particleboard factory rather than a recycling company like Veolia. In many cases, particleboard manufacturers buy from recycling companies who will have partially shredded and cleaned the recovered wood according to agreed specifications.



Fig. 2.

A delivery of recovered wood. Note the low packing density and the pile of chips in the background.

The transport of post-consumer wood to recycling centres is often relatively inefficient because of the low bulk density of wood waste, see

Fig. 2. To facilitate the storage and subsequent transport, the wood is chipped or shredded, see Fig. 3. Hand picking to remove larger non-wood materials, e.g. mattresses, plastic and metal furniture etc., is done to improve the quality of the chips and minimise damage of shredding machines. Hydraulic operated grabs are often used to pick out these large contaminants rather than man handling pieces. The grabs are also used to initially crush the larger pieces so that it is easier to feed into the shredding machines.



Fig. 3.

A typical recycling centre. (A) a small pile of finely shredded furniture waste. (B) coarse shredded furniture waste. (C) furniture waste before shredding. (D) Class B wood before shredding. The shredding machine is super-posed to the foreground.

Shredding is often conducted in two steps. The first is a coarse shredding that breaks the post-consumer products into large pieces, which might be 10cm or more in size, see (B) in Fig. 3. This step drastically reduces the volume of the recovered wood. The metal removal systems will also remove some of the ferrous metals present. The second shredding, which is often carried out with the same machine but with different operating parameters, so that the wood is broken down to smaller pieces. Fig. 4 shows average particle size distributions after sampling and analysing 62 plies of recovered wood distributed over France by the EcoReFibre³ project. Most particles collected from Coarse piles, i.e. those that have passed only once through the shredding machine, remain on an 8 mm sieve at the end of a sieving step and only 6% are able to pass through a 4mm sieve. In contrast, the Refined samples are made up of many smaller particles. Generally, particleboard manufacturers take delivery of refined recovered wood. They will, however, grind it further to produce the particles needed to make particleboard.



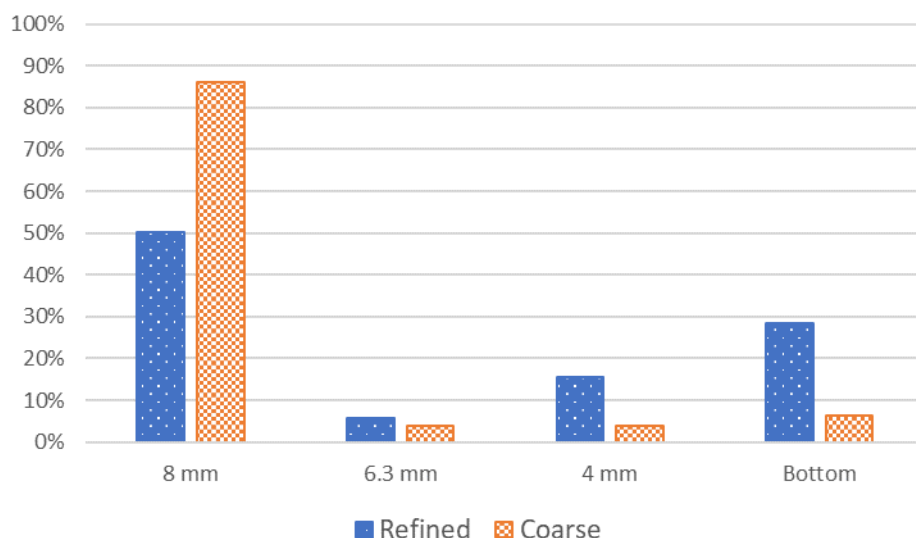
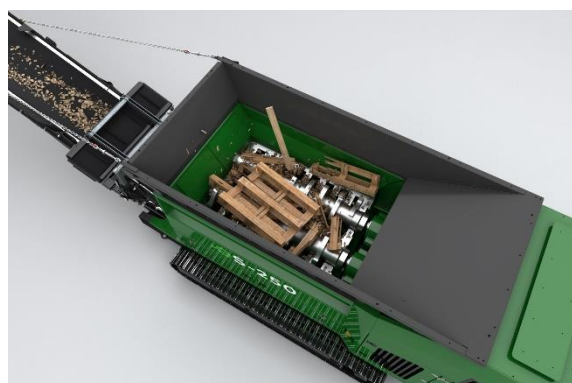


Fig. 4.

Particle size distribution of recovered wood samples collected across France, from June 2022 to August 2023, as part of the EcoReFibre project.

The most common shredders used are one of two main types: slow turning, high torque, cutting shafts or highspeed rotation hammer mills, see 5. Slow turning shredders are particularly suited to pre-shredding bulky material and hammermills are proficient in reducing pre-shredded material. Either machine can, however, process bulky and particulate materials.



Courtesy of RENTEC



Courtesy Of Stedman Machine

Fig. 5.

A slow turning shredder is shown on the left and a high speed hammermill shaft on the right.

The metal present in bulky wood products in the form of nails, screws and fixings is not removed before shredding. Some of the metal, and other non-wood components, will be separated from the wood because of the shredding operation. In general, the finer the grinding the greater the separation of wood from non-wood components. The efficiency of the subsequent cleaning, i.e. separation steps, determines the quality of the wood coming out. Almost all cleaning methods are based on physical properties like size, form, density, and magnetism. Sorting out non-wood contaminants is rarely 100% efficient and so it should be done several times, e.g. at the recycling centre and at the particleboard manufacturing site.

Innovative technologies are being introduced by companies like Dieffenbacher, IMALPAL and Tomra (TOMRA 2022) to improve the sorting of recovered wood via sensors. A wide range of sensors are being proposed that use colour, image analysis (size and form), near infrared (NIR) (Mancini and Rinnan 2023), induction (Friedrich et al. 2022), X-ray, and X-ray fluorescence (XRF) (Hasan et al. 2011). The signals from these different sensors are being used to identify contaminants and also differentiate between distinct types of wood product, for example to differentiate between particleboard and fibreboard.

Table 2

A summary of non-wood contaminants often found in recovered wood.

| | | | | |
|--------------------------|-------------------------------------------|-----------|--------------------------------------------|------------|
| Ferrous metal | Nails, screws, hinges | Magnetism | Magnet | Easy |
| Inorganic | Sand, stones, concrete, glass | Density | Stone traps, wind sifting, flotation tanks | Easy |
| Non-ferrous metal | Handles, edgings | Magnetism | Eddy-current drum ⁴ | Quite easy |
| Organic | Plastic, rubber, textiles, strings, ropes | Density | Wind sifting, flotation tanks | Difficult |

Despite the initial cleaning conducted at the recycling centres, the recovered wood received by particleboard manufactures will still include a wide range of non-wood components as outlined in Table 2. The recovered wood cleaning towers found at particleboard factories still largely rely on sorting via physical properties. Once cleaned, the recovered wood can be reduced to the size of chips needed for particleboard manufacture.

Hammermills like those shown in Fig. 5 can be used but require careful setting. More often, a particleboard mill will have a hammermill only for larger pieces after initial sorting. A commonly used machine is the knife ring flaker, which takes its name from the ring of knives that cut the particles to a predetermined length and thickness, see Fig. 6. A knife ring flaker can cut good quality chips for the core layer, i.e. they should be long relative to their thickness and have smooth surfaces. Of course, a range of particle sizes will exit the machine and the finer ones will be used for the surface layer.

Recovered wood is increasingly being used for the surface layers of particleboard. The evidence for this is that more than 70% of the wood used by particleboard manufacturers in Italy, UK, Belgium and Denmark is recovered wood (EPF 2023). Surface layer particles should be fine to give a smooth, hard surface to the panel after hot-pressing. Impact mills, which are like knife ring flakers except the outer knife ring is replaced with a ring on screens and anvils of assorted designs. The one shown in Fig. 6 has a central anvil and screens either side. The size and shape of the holes in the screen determines the form and dimensions of the fines produced. The screens and anvils are also optimised with regard to the input material, i.e. its size, species, moisture content etc.

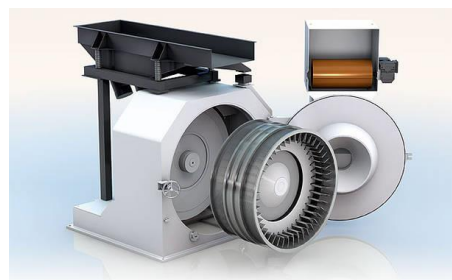


Fig. 6.

Left a ring of knives waiting to be inserted into a knife ring flaker and right, an impact mill. Both images courtesy of Hombak.

Once the wood has been reduced to chips and fines for the core and surface layers respectively, it is dried. It is estimated that approximately 62% of the energy needed to make a particleboard is spent on drying the wood (FAO 1990). A significant advantage of recovered wood over virgin wood is that it is much dryer. For example, a long-term study of waste wood intended for burning in Sweden (Edo et al. 2016) measured an average moisture content of 23% between 2008 and 2013. The current average moisture content observed by the current EcoReFibre project (data collected since June 2022) is 18% ± 8%, which is significantly lower, but 60% of the samples have been collected during summer months. Virgin wood sources for particleboard manufacture include small diameter logs, which have a high proportion of sapwood and the outer parts of trees, i.e. sapwood, in the form of slab wood, sawmill chips and sawdust. Dinwoodie (1981) states that the moisture content of softwood sapwood ranges from 116% to 167% and hardwood sapwood

⁴ Non-ferrous metals are ejected by passing them through a rapidly changing alternating magnetic field (Smith, Nagel and Rajamani 2019)

from 68% to 84%, so considerably higher than recovered wood. The dryer recovered wood is normally mixed with virgin wood before entering the drier to reduce the risk of fire and explosion.

It is difficult to differentiate between virgin and recovered wood particles once they exit the drier because they now have similar moisture contents. Experience has shown that particles derived from solid recovered wood can be used in the same way as those from solid virgin wood. Of course, recovered wood not only consists of solid wood, as there are other products present including plywood, OSB, particleboard and a range of fibreboards. The recovered wood collected so far for the EcoReFibre project has been found to consist of the following fractions: 59.0% solid wood; 32.9% panel products; 4.1% fibreboard; and 4.0% non-wood.

Recovered wood includes wood from many sources and there is always a risk that a preservative treated piece of wood is accidentally placed in the wrong bin. Therefore, the particleboard industry wrote its own standard in 2002 that defined maximum permitted concentrations for certain metals, see

Table 3. These were derived from EN 71-3 Toy standard of 1995 for Modelling clay and finger paint (EN 71-3 1995), and these are toys which could be placed in children's mouths and so were the most stringent values at the time. EN 71-3 has been updated and now includes requirements for wood-based toys and the permitted maximum values of which are higher than those chosen by EPF (European Panel Federation). The EPF decided to adhere to the extremely low permitted levels that it set in its industry standard in 2002. By comparison, the industry standard is strict because it defines the maximum permitted concentration in the particleboard, while the EN 71-3 measures the migration of elements from the toy and so the concentrations in the toy could be much greater. Surprisingly, Germany is the only European country to have legally binding legislation that defines concentration limits for the metals in wood that will be recycled and these are shown in

Table 3.

Table 3

The heavy metal concentration limits (mg/kg) defined by various standards that are relevant to particleboard

| Standard | As | Cd | Cr | Cu | Hg | Pb |
|-------------------------------------------------|----|----|-------------------------------------------------------|------|-----|----|
| EN 71-3 Safety of toys (1995) ^A | 25 | 50 | 25 | - | 25 | 90 |
| EPF industry standard (2002) | 25 | 50 | 25 | 40 | 25 | 90 |
| Waste Wood Ordinance (Altholzverordnung) (2002) | 2 | 2 | 30 | 20 | 0.4 | 30 |
| EN 71-3 Safety of toys (2021) ^B | 47 | 17 | 460 (Cr ^{III}) 0.053 (Cr ^{VI}) | 7700 | 94 | 23 |

^A Values for modelling clay and finger paint.

^B Values for Category III materials, which includes Wood, fibre board, hard board and other solid materials.

To place these limits in perspective, the limit for Cu would be reached in a 50x50mm square of particleboard if it contained a hair of copper wire that weighs only 0.001g. Here in lies a problem, the metals Cr, Cu and Pb are used in construction in solid form such as stainless-steel screws for Cr, electrical wire and pipes for Cu and flashings for Pb. Consequently, it is possible to obtain extreme concentrations for these elements. Although there are statistical techniques for removing outlier values it is proposed, instead, to use the median rather than the mean values for metal concentrations.

Currently the industry's ability to sort out fibreboard from the wood waste stream is limited. This fact is important because the particles generated from chipping fibreboards are far from ideal in terms of form, surface quality and integral strength, i.e. fibreboard particles break easily, see Fig. 7.

To maximise mechanical properties, particles for the core layer should have a high aspect ratio, i.e. they should be long relative to their thicknesses. The fibreboard particles highlighted in Fig. 7 have a low aspect ratio. In addition, they have rough surfaces with high specific surface which probably allows them to absorb a disproportionate quantity of adhesive. Ideally, the adhesive should be uniformly distributed and so if a fibreboard particle takes more than its fair share then other particles, elsewhere in the mattress, will not have enough adhesive, thus creating zones of weakness.



Fig. 7.

A photograph of particles prepared for the core layer of a particleboard with three fibreboard particles highlighted.

The fibreboard particles can be easily prised apart because the mechanical action of grinding introduces cracks in the particle. Again, this creates weak zones in a particleboard mattress wherever there is a fibreboard particle.

Manufacturers can compensate for the presence of fibreboard by adding more adhesive and/or compressing the mattress to a higher density. Both options increase production cost, which reduces the manufacturer's competitiveness in a sector that is very price conscious. Although using recovered wood reduces production costs, because it is cheaper per ton than virgin wood and it has a much lower drying cost associated with it, if the proportion of fibreboard becomes too high then the added costs of using more adhesive or making a denser panel will exceed the economic benefits of using recovered wood. If this should happen, then it would be complicated to recycle wood. Losing the ability to recycle wood via particleboard manufacture would damage the environmental credentials of wood.

The EcoReFibre project will address this challenge by develop efficient sorting machines to allow particleboard manufacturers to have access to recovered wood with low proportions of fibreboard present. This will reduce their costs, as explained above, and provide opportunities to increase the proportion of recovered wood used to manufacture particleboard. The project will also explore and demonstrate how the separated fibreboard can be incorporated into new fibreboards thus allowing fibreboard, like MDF (Medium Density Fibreboard), to be manufactured on a commercial basis with post-consumer waste fibreboard.

What about future recycling?

The estimates for the quantity of post-consumer waste wood in Europe range from 18.9 million tonnes (Gurria et al. 2020) to 33.2 million tonnes (Mantau et al. 2010). The FAO now collects and publishes data on the production of recovered wood and the total for the EU plus the UK in 2021 was 35.9 million tonnes (Anon 2023a). The European particleboard industry consumes about 20.8 million tonnes (EPF 2023). These data show that there is sufficient recovered wood to satisfy the entire needs of Europe's particleboard industry, even if the entire sector switched to using 100% recovered wood. If the higher estimates of the quantity of recovered wood are correct, then other ways of recycling post-consumer wood waste must be developed because the particleboard sector could only use 56% of the FAO estimation for recovered wood production. This was the conclusion of a consortium who founded the EU-funded CaReWood project (2014-2017) to manufacture laminated wood products from larger cross-sectioned recovered wood. The CaReWood research project showed, using real pieces of recovered wood taken from recycling centres, that for 1m³ of recovered wood with dimensions longer than 30cm, wider than 66mm, and thicker than 22mm, 0.29m³ of scantlings (laminated products) result (Irlle et al. 2018). The other 0.71m³ can be recycled in the conventional way. Although a lot more work is required to cut the lamellae and produce the scantlings, their value is

probably at least an order of magnitude higher than recycling the wood to chips. The CaReWood idea is currently being transferred to industry via the RECOWOOD project⁵ at the Ecole Supérieure du Bois (ESB).

A quick review of the wood science literature will show that recycling is currently a popular topic. A wide range of ideas on how recovered wood might be used exist. Irle and Larnoy (2023) have conceived a novel review of this literature by creating a mind map using Cmap, a free software developed by the Florida Institute for Human & Machine Cognition (IHMC 2023). Creating a Cmap, or some other mind map, is an efficient way of organising a lot of information in a logical way, which also facilitates access to the information. The aim of the Cmap is to summarise current research on recovered wood and help others develop new recycling methods. The Cmap can be accessed via the QR code below⁶ and readers are encouraged to contact the authors about any relevant articles that should be added to it.

Wood recycling requires better cleaning techniques to help extract the largest amount of clean wood. Besserer *et al.* (2021) have published a review of some of the various methods proposed by academics to decontaminate recovered wood, i.e. remove the non-wood components like adhesives and finishes. Hopefully, cleaning will become easier and more efficient as innovative technologies are introduced to the manufacture of wood products that aid recycling.

At the same time, it should be remembered that the circular strategies R3-R7 should be considered first before a wood product is recycled. New business models that encourage re-use (R3) and repair (R4) would be particularly welcome for the wood sector.

CONCLUSIONS

The last 30 years have seen the wood recycling industry grow from a time when it needed financial support from governments to a financially viable business. Recycling has become second nature in our everyday lives and is also the norm for industry. Wood recycling is big business and is well established across Europe. The manufacture of particleboard is the dominate method for recycling wood. It appears that this sector does not have the potential to use all the recovered wood generated in Europe and so other ways of using significant quantities of recovered wood must be developed. It is possible that any new recycling process might require some financial help until it achieves the economy of scale required for sustainable existence.

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⁵ scan to go to RECOWOOD website, which is in French



⁶ scan to go to a Cmap describing wood recycling

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