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Wood cascading: a brief review on principles, impacts and limitations

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ABSTRACT

Cascading is a principle that enhances resource efficiency by utilizing wastes and recycled materials to maximize total biomass availability within a specific system. It adheres to the principles of a circular economy by minimizing waste and mitigating the environmental effects of wood-based composites. The cascading of wood is a method that prioritizes sequential and multiple utilizations of wood to optimize its lifecycle prior to final disposal or energy recovery. This brief review examines the basics of wood cascading and its advantages for enhancing resource efficiency, diminishing environmental impact, and advancing circular economy objectives by reducing waste and maximizing material value. This brief review clearly delineates the limitations and issues encountered by wood cascading. The future of wood cascade presents significant opportunities for enhancing resource efficiency and reducing environmental impacts.

Keyword: Cascading, Circular Economy, Environmental Impacts, Resource Efficiency

1. Introduction

The notion of cascading resource use refers to the progressive repurposing of a single resource unit for several high-value uses prior to its ultimate disposal. According to Vis et al. [1], cascading use is defined as “*the efficient utilization of resources by using residues and recycled materials for material use to extend total biomass availability within a given system*”. Figure 1 showed the principle and concept of cascade use of a given resource, first proposed by Sirkin and ten Houten [2]. The objective of resource cascading is to improve resource usage efficiency through the successive reuse of a single resource unit for several high-grade material applications, culminating in final disposal. As shown in Figure 1, at every cascading stage, the quality of the resources deteriorates but material life is extended after several times of use.

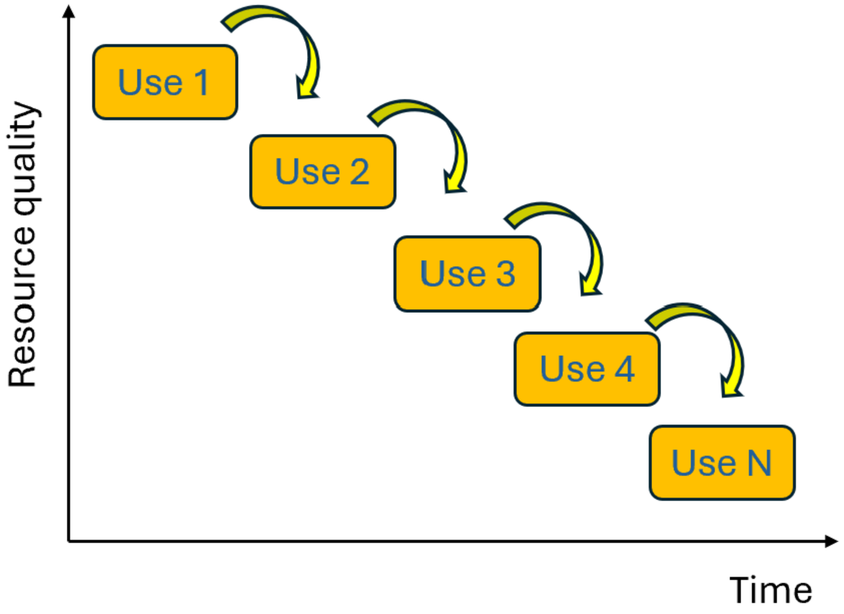

Figure 1. The principle of cascading, Adapted from Sirkin and ten Houten [2].

Odegard et al. [3] has defined the concept of cascading into three types, which is in time, in value and in function (Table 1).

Table 1. Types of cascading concept [3-4]

Cascading types	Details
In time	The biomass’ life span is extended through subsequent use; the alternative that provides the most flexibility at the end of its lifespan should be chosen. Paper recycling is a common example.
In value	Optimizing cascading in time can be achieved by cascading in value to guarantee the most possible value is attained while selecting among alternatives, hence maximizing the value across the whole life cycle. An illustration is the utilization of straw for ethanol production, which can subsequently be employed to manufacture polymers, offering advantages relative to its original purpose.
In function	The term 'cascading in function' refers to co-production, which can be accomplished through the utilization of a bio-refinery. Co-production refers to the simultaneous generation of various functional outputs (e.g. protein, oil, and an energy carrier) from a singular biomass source, hence optimizing overall functional utilization. An exemplary case is a grass refinery. For example, grass can be a good bioenergy resource to simultaneously generate into multiple products such as bioethanol, biogas, charcoal, pellets and for heat and power generation [5]. Subsequently, cascading in function is succeeded by cascading in value or time.

This brief review concentrates on wood cascading, examining its economic implications, environmental impacts, limitations, and problems.

2. Wood cascading

The cascading concept aligns with the circular economic principle by reducing waste and the environmental impacts of wood-based composites. In a review by Mair and Stern [6], the authors reported the difference between cascading utilization (CU) of wood and circular economy (CE). First, CU emphasizes the usage of bio-based materials such as wood while CE considers a diversity of resources. Secondly, CU normally refers to the utilization of resources from high- to low-value products, hence the term “cascading”. Meanwhile, CE refers to a concept where the resources are kept in the system and minimize the use of primary resources, thus creating a circular loop. However, the authors reported that the cascading use of wood perfectly fits into the CE concept, and that CU is a part of the CE. According to Campbell-Johnson et al. [7], CU is able to ease the pressure on the ecosystems and reduce environmental impacts by maximizing the usage of the resources. Several studies have proved that CU could significantly reduce the environmental impacts by reducing net greenhouse gas (GHG) emissions [8]. Also, CU could help to increase carbon stock [9] and delay emission resulting from incineration or decomposition of wood at the end of products lifetime [10].

Wood cascading can be classified into single stage or multiple stage [11]. In a single stage cascade, the wood is processed into a product and then ends up incinerated for energy purposes. Meanwhile, for multiple stage cascade, the wood is processed into a product and is used at least once before being disposed of or incinerated for energy generation [11]. Figure 2 summarizes the essential processes of wood cascade. Initially, the wood will be employed in high-value applications, such as construction or furniture, where its mechanical capabilities are maximally utilized [12]. At the conclusion of its lifecycle, wood can be repurposed into composite materials such as particleboards and medium-density fiberboards, which are capable of undergoing several recycling iterations [13]. The latter phase is the production of lower-value items, such as paper liners, utilizing recycled wood resources that may exhibit reduced mechanical capabilities [14]. Ultimately, when the wood is no longer suitable for reuse or recycling, it is burnt for energy recovery, so concluding the cascade [15].

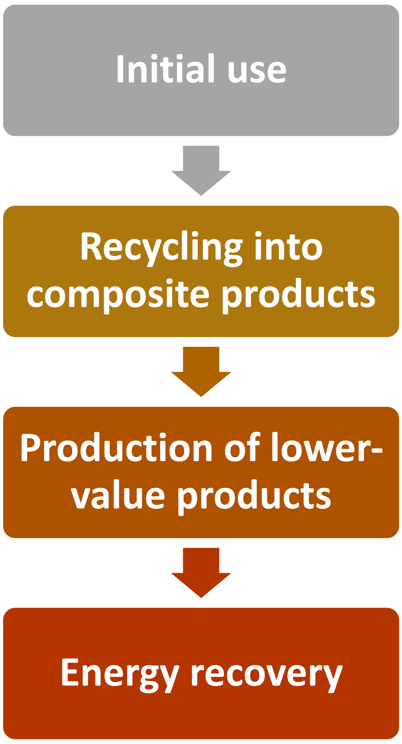

Figure 2. Key stages of wood cascading

Wood cascading strictly follows 3 principles, namely appropriate application, lifetime extension and quality conservation [16]. The first principle, appropriate application, refers to the application of wood should be kept at the highest possible quality. In another word, it discourages the use of wood from trees directly for pulp and paper. The second principle, lifetime extension, means that the lifetime of the same unit of wood was extended over several stages of cascading to different products. The third principle is to minimize the quality loss for the next cascading stage as every stage reduces the dimension of the wood. The recovered or recycled wood should be kept in as large dimensions as possible [17]. The positive effects of cascading use can be maximized had these three principles been strictly adhered to.

However, wood-based composite is a chemically complex material. Chemical contaminants, primarily adhesives, tend to limit the cascading potential of wood-based composites. Until now, the majority of cascading wood use has been limited to a single-stage cascade model, which is particleboard. It means that wood is only processed into one product (particleboard) before it is used to generate energy. Due to the strict requirement for contaminant-free raw materials, multiple-stage cascade models are frequently difficult to implement, for example, in fiberboard. As a result, research and development to increase the utilization of used panels other than particleboard is critical to expanding the capabilities of multi-stage cascading.

In wood cascading, the presence of UF residues often caused negative effects to the wood-based products [18]. During a second cross-linking step, the cross-linked glue particles do not react with a new adhesive to form a polymer network, resulting in a significant decrease in the properties of the materials formed from recycled panels [13]. Hydrolysis is often carried out on recycled materials to remove residual UF. For example, Ren et al. [19] employed hydrothermal treatment on the recycled fibers aiming to remove the UF residues. However, although the UF residues have been successfully reduced, the thermal induced degradation of fibers has inevitably reduced the properties of the composites produced. Similar result was also reported by Schild et al. [20]. Savov et al. [21] reported the effects of hydrolysis regime on the recycled MDF fibers. The authors concluded that a suitable treatment temperature and time are very important to ensure the efficiency of UF removal as well as maintain the quality of the fibers. The efficacy of the cascade products is anticipated to decline if no further resources are introduced. Therefore, one of the viable and straightforward solutions is the introduction of virgin wood to maintain its mechanical properties. However, it may not happen in the liquefaction process. Before it was disposed of for energy generation, the recycled fibers were used as liquefaction feedstock. Janiszewska-Latterini and Pizzi [22] reported that the raw materials used for liquefaction has no significant influence on the quality of the final products, which is adhesive in this study. Therefore, by extending the cascading pathway, it could keep the resources as long as possible and maximize the usage of the resources.

3. Economic implications and environmental impacts of wood cascading

This section examined the economic ramifications and environmental consequences of wood cascade. The economic ramifications are multifaceted, including resource efficiency, employment, and environmental sustainability. The sequential utilization of wood in diverse applications prior to its ultimate disposal may optimize the economic worth of a certain wood resource unit. The cascade utilization of wood prolongs the life cycle of wood products, hence enhancing resource efficiency. This indicates that the same unit of resource is retained throughout the life cycle for an extended duration. Fraanje [12] indicated that the service life of pine wood can be extended from 75 years to over 350 years by the implementation of cascade practices. A study by Taskhiri et al. [8] indicated that wood cascading can conserve up to 35% of virgin wood resources, hence advancing the circular economy. The cascade factor determines the effectiveness of wood's cascading use. A cascade factor exceeding 1.00 signifies an increased frequency of utilization of recycled materials. When the cascade factor equals 1.00, it indicates that solely wood resources from trees are utilized, with no recycled materials involved Mantau [23]. Brownell et al. [24] revealed that the cascade factor for wood in Denmark is approximated at 1.44, signifying that wood is employed about one and a half times prior to final consumption. This technique can diminish dependence on imports and foster native enterprises, so bolstering forest management and climate change efforts. Moreover, wood cascading may provide as a partial remedy to the constrained wood supply, as proposed by Szichta et al. [17]. Enhancing resource efficiency can satisfy the increasing demand for wood and contribute to a sustainable timber market. In terms of employment, wood is a crucial resource for nations reliant on wood-based industries. Nevertheless, the availability of wood resources is nearing its maximum capacity, hence constraining employment opportunities [25]. Consequently, enhancing resource efficiency would augment the wood supply capacity, potentially yielding a favourable effect on employment.

Cascading extends the utilization of wood products, thereby postponing carbon emissions and allowing trees to sequester carbon effectively [26]. Mehr et al. [27] indicated that, when comparing several cascading systems to direct incineration of waste wood, the former substantially mitigated effects by 35–59 Mt CO_2-eq over a 200-year timeframe relative to the latter. A study by Budzinski et al. [28] indicated that an improved wood product cascade can reduce greenhouse gas (GHG) emissions by around 0.2%. Taskhiri et al. [8] shown that the cascading utilization of wood might potentially decrease the global warming potential (GWP) by 15%, alongside a 4% reduction in prices. Conversely, in an alternative scenario, expenses could be diminished by up to 24%, albeit with a minimal decrease in environmental repercussions. All of this research has shown that the sequential utilization of wood yields beneficial economic outcomes and environmental effects. Nonetheless, despite the numerous advantages outlined, wood cascading entails certain trade-offs, as noted by Suominen et al. [29]. The authors indicated that heightened industrial activity could lead to higher energy consumption and greenhouse gas emissions. Consequently, it is essential to apply rigorous control on the cascading processes to alleviate these impacts.

4. Limitations and challenges

Wood waste, upon reaching the end of its service life, is recognized for its use in recycling and energy recovery [30]. Wood waste constitutes a significant source of recyclable materials due to its annual abundance. In 2007, approximately 55 million m^3 of post-consumer wood were claimed to have been generated in the EU27 [31]. In 2012, 46% of wood waste in the EU was recycled, whereas 51% was burnt [32]. Wood waste should ideally be convertible into various wood-based composites, including oriented strand board (OSB) and medium density fiberboard (MDF). Nevertheless, the wood waste produced typically exhibits low quality, hence presenting certain technical obstacles to its utilization [33]. Consequently, particleboard is the preferred choice for recycling wood waste due to its affordability and reduced quality standards for recovered wood materials [1]. Apart from that, the wood wastes should contain minimum levels of impurities to ensure their recyclability. Table 2 enumerates the categories of contaminants that may be present in wood waste.

Table 2. Types of impurities contained in wood wastes, adapted from Faraca et al. [10]

Type of impurities	Examples
Physical	• plastics, metals, glass, textiles, soil etc.
Chemical	• finishes, paints, oils for aesthetics purpose • binders, adhesives, gluing agents for structural integrity • preservatives for extended biological durability period • phosphorous and brominated flame retardants

The presence of these contaminants, especially harmful ones, may adversely affect the recycling process, preventing it from being clean. Faraca et al. [10] revealed that the types and concentrations of contaminants vary greatly based on the type and source of wood waste. Therefore, the authors proposed the necessity of separating collecting, sorting, and handling to enhance resource quality. The recycling processes for wood waste necessitate improvements, including enhanced sorting techniques and methods for eliminating residual impurities [13]. Consequently, the expenses associated with sorting, processing, and logistics have obviously risen. Due to this reason, in regions outside Europe, especially in developing nations, existing legislation frequently fails to facilitate the effective recycling of wood waste, hence constraining the quantities that can be repurposed [34]. Or even worse, majority of those countries does not have policies that support cascading practices. For instance, the USA and Canada do not have a cascading policy in place that governs wood utilization in the forest products industry [35]. Consequently, innovation and regulatory reform are essential to establish a stronger foundation for wood cascading practices.

In addition to the previously described obstacles, a review by Nguyen et al. [36] has explicitly detailed the difficulties associated with waste wood conversion and the recycling of wood composites. Nguyen et al. [36] identified three categories of obstacles in wood waste recycling: i) pollutants and sorting methods, ii) characteristics of recycled wood products, and iii) formaldehyde emissions. Consistent with Faraca et al. [10], the authors consider contaminations in wood waste to be a primary impediment to an efficient recycling process. Meanwhile, although numerous sorting technologies are under development, there is a necessity for the creation of new and more efficient sorting procedures that can be industrially implemented. Nguyen et al. [36] indicated that the mechanical qualities of recycled wood-based products, including particleboard, MDF, and OSB, diminished. Furthermore, the formaldehyde emission of the wood-based panel composed of wood waste particles escalated, likely attributable to the residual UF resin present in the wood waste. Hydrothermal treatment is necessary to diminish formaldehyde emissions. Hydrothermal treatment effectively eliminates toxic chemicals from preservative-treated and painted wood by converting it into a mixture of hydrocarbons, such as substituted benzenes and phenolics, while recovering metals like chromium, copper, and arsenic in an acidic aqueous phase. The procedure dechlorinates pentachlorophenol to levels below detection limits [37]. In summary, waste wood is a heterogeneous resource, presenting numerous challenges that must be addressed for its effective utilization in the wood cascade process.

5. Conclusions

The future of wood cascade offers substantial prospects for improving resource efficiency and mitigating environmental consequences. Cascading can enhance sustainability in the circular economy by maximizing wood utilization throughout many product cycles. Although the cascade strategy has various advantages, it is essential to reconcile them with the necessity for additional wood production to satisfy increasing demands, so guaranteeing a sustainable and robust wood economy. Future wood use must prioritize enhancing waste wood processing, optimizing cascading opportunities, and assuring high-quality wood reuse to enhance climate change mitigation and reduce particulate matter generation. Furthermore, creating a sustainable framework for cascading wood is essential for optimal resource utilization, taking into account cost-effectiveness, environmental consequences, and market viability.

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