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Review

Circular Economy of Construction and Demolition Wood Waste—A Theoretical Framework Approach

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Abstract: A considerable amount of construction and demolition wood waste (CDWW) is generated, mostly landfilled, contributing to severe environmental effects. The management of CDWW is a significant challenge as it is a hazardous contaminated waste. In this context, the circular economy (CE) concept is a solution as it comprises waste minimisation and efficient recovery of resources. Although much research is found in the literature on CDWW end-of-life management, research on CE implementation considering every life cycle stage is still scarce. In this review, we endeavour to integrate CE in CDWW to identify the waste management strategies involved in the life cycle phases. The databases were searched from 2009 to 2020 and were analysed using CiteSpace version 5.7.R1 software. Forty-nine articles were identified, and the six life cycle stages were explored. The analysis shows that CE for wood waste is essential and has greater growth potential. While the LCA studies are limited to environmental viewpoints, combining economic and social perspectives is necessary for sustainable development. Overall, based on the research findings, a theoretical framework was proposed. This study, as a consequence, promotes the application of recycled wood into multiple valuable products and thus encourages waste management to boost CE and sustainability.

Keywords: construction demolition wood waste (CDWW); life cycle phases of wood; circular economy (CE); sustainability; end-of-life products

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1. Introduction

Construction and demolition waste (CDW) are solid wastes, such as building debris, rubble, concrete, aggregate, steel, bricks, timber, and site clearance mixed-materials from the construction and demolition or renovation industry [1–3]. These wastes are generated from land excavation; construction; residential, commercial, or industrial site clearance; demolition; or renovation of buildings [4]. The construction industry is an important economic sector contributing to a country's GDP (gross domestic product). However, this sector has a significant environmental impact as it consumes substantial natural resources, uses energy to release pollutants and greenhouse gases (GHGs), and generates a massive quantity of waste [3,5,6]. CDW contributes to the most significant waste stream each year: nearly 30–40% of total solid wastes are generated globally [7]. This considerable amount of CDW creates adverse environmental impacts. As a result, the reduction, reuse, and recycling of CDW is a worldwide priority.

1.1. Amount of CDWW Generation

A tremendous amount of timber waste is generated worldwide during construction, demolition, and renovation. Timber waste is considered the second leading element of CDW, contributing at least 20–30% of the total CDW stream (Construction and Demolition Recycling Association (CDRA) USA (United States of America)). The wood waste products from all 28 EU (European Union) countries account for around 50.2 million tons (MT) [8]. In the USA, approximately 55.75 MT of wood waste was produced in 2020 [9–11]. Furthermore, in the UK (United Kingdom), 4.5 MT of wood waste was generated in 2021, of which around half a million tons were landfilled [12]. In Germany, about 11.9 MT of wood waste was generated in 2015, of which CDWW accounts for 26.7%. In 2020, Hong Kong produced 20.72 MT of CDWW [13]. According to the 2008 Wood Waste Report, 1781 kt of wood waste is generated annually all over Australia [14]. Sustainability Victoria reported that the amount of waste wood collected from C&I (commercial and industrial, mainly from packing pallets) and C&D (construction and demolition) waste streams during 2013–2014 was 505 kt, of which 165 kt was recovered, and 340 kt was sent to landfills [15]. The latest data on wood waste was published in 2018 in a report prepared by Blue Environment Pty Ltd. and Randel Environmental Consulting [16]. This report showed that in 2018–2019, Australia generated 2311 kt of wood waste. The C&D sector's share as the second largest wood waste producer was nearly 799 kt (25.8%), surpassed by C&I with almost 1524 kt (64.3%). Table 1 summarises the CDWW generation in different countries. It is estimated that around 10–15% of the timber used in new construction goes to the waste stream. Overall, in an annual global estimation, CDWW accounted for about 10% of all waste material dumped into landfills ("The Importance of Wood Recycling in C&D Management" UK, 2018).

Table 1. CDWW generation in different countries.

County	CDWW	Year
The USA	55.75 MT	2020
UK	4.5 MT	2020
EU-28 countries	50.2 MT	2018
Australia	2,311,000 tons	2018–19
Victoria (Australia)	511,000 tons	2013–2014
Germany	11.9 MT	2015
Hong Kong	20.72 MT	2020

MT (million tons).

In the previous literature, many research works have been found considering recycling and reusing concrete, aggregate, and steel individually [17–21]. Recently, research approaches have been made to recycle timber from the CDW stream [22]. Yet still, wood recovery and recycling rates are considerably lower than other CDW materials, for example, concrete (82%) and steel (98%). CDW alone generates a tremendous amount of wood waste and disposable solid wood materials yearly. In addition, wood is an organic material. When landfilled, an anaerobic decomposition occurs in the soil, which releases a significant amount of greenhouse gas (GHG) (such as carbon and CH_4) into the environment [23]. As a result, managing such a large amount of CDWW has become a global concern and challenge. Due to the COVID-19 pandemic, there is a shortage of virgin materials and their severe impacts on the environment, which requires a proper wood waste management plan and circularity in the life cycle of CDWW. This circularity can contribute to the conservation of forest resources and bring sustainable development [24,25]. Thus, the circular economy (CE) concept can be adopted, which is considered an efficient tool that contributes to economic, social, and environmental benefits.

1.2. Types of Wood Waste

There are three types of wood waste: untreated timber waste, engineered wood waste, and preservative-treated or painted wood waste. All these types of wood wastes are found in construction, renovation, or demolition activities.

1.2.1. Untreated Wood Waste

Untreated wood waste refers to waste that has not been treated with preservatives. This waste usually comes from 'softwood' or 'hardwood'. These timbers are high quality and used in building framing [26]. Softwood is generally harvested from coniferous trees such as pines or firs, while hardwood derives from trees with broad leaves, such as eucalyptus, oak, and walnut.

1.2.2. Engineered Wood Waste (EWW)

Several engineered wood products (EWP) are used in the construction industry, such as plywood, oriented strand board (OSD), laminated veneer lumber (LVL), glue-laminated timber, particleboard, and medium-density fiberboard (MDF) [27]. These products are manufactured using wood flakes, chips, fiber, or veneers. Resin or adhesive bonds these elements to form various products, including basic structural materials [26]. EWP is used widely in the construction industry, resulting in a vast amount of EWW generation.

1.2.3. Preservative-Treated or Painted Wood Waste

Preservative-treated wood refers to the wood coated or painted to improve the products' quality, such as increasing product durability and resistance to spoiling by biological agents—such as fungi, insects, and animals. Some preservatives commonly used for wood treatment are copper chromium arsenic (CCA), alkaline copper quaternary (ACQ), light organic solvent preservatives (LOSP), or creosote [27]. Usually, softwood is treated with CCA. However, a small amount of hardwood is also treated for various uses. Wood products are also painted with lead-based paint, which is highly hazardous to the environment and is still noticed in the CDW waste stream.

1.3. Physical Form of Wood Waste

In the construction and demolition stages, wood waste is found in various physical forms, including off-cuts, shavings, sawdust, slabs, and bars [14], as shown in Figure 1. These wastes also contain different fastenings such as nails, hinges, nail plates, framing anchors, etc. Wood shavings, including fragments, can be of variable size. Sawdust particles that are variable in size, ranging from coarse particles to flour, can cause health hazards [14]. Off-cut wastes are irregular in form and are not always suitable for reuse [14]. The collection, transportation, and storage of wood waste occupy a large volume due to the irregularity and non-uniformity in their shape and structure. Another major issue related to wood waste management is preservative-treated wood in the waste stream, which is hazardous and requires a separate management process to recover. This hazardous waste makes the sorting and recycling process more complicated [27].

Figure 1. Represents different forms of wood waste.

1.4. Circular Economy (CE) and Wood Waste

The past century has seen the global demand for wood increase dramatically [28]. This increase is due to rapid population growth, urbanisation, and worldwide industrial development. Therefore, more attention needs to be paid to critical matters such as energy use, consumption of raw materials, and waste management practices. The life cycle of wood begins from raw material extraction to end-of-life disposal, which is a linear process in which a considerable amount of waste is generated. Hence, it is crucial to implement the CE in the whole life cycle of wood to achieve sustainable development. CE is an economic model (Figure 2) that aims to minimise raw material input, waste generation, emission, and energy by promoting the circularity of the material through 3R principles (reduction, reuse, and recycling). It is a regenerative system in which resource input, waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This process can be achieved through waste minimisation in the design stage, prevention, reduction, maintenance, repair, reuse, and recycling [29]. The main principles of a circular economy are avoiding waste generation, improving resource recovery, increasing the use of recycled materials, better managing material flow for the benefit of the environment, economy, and society, and supporting innovation (Figure 2). For sustainable development, balanced integration of economic performance, social inclusiveness, and environmental resilience is crucial to the benefit of current and future generations [30].

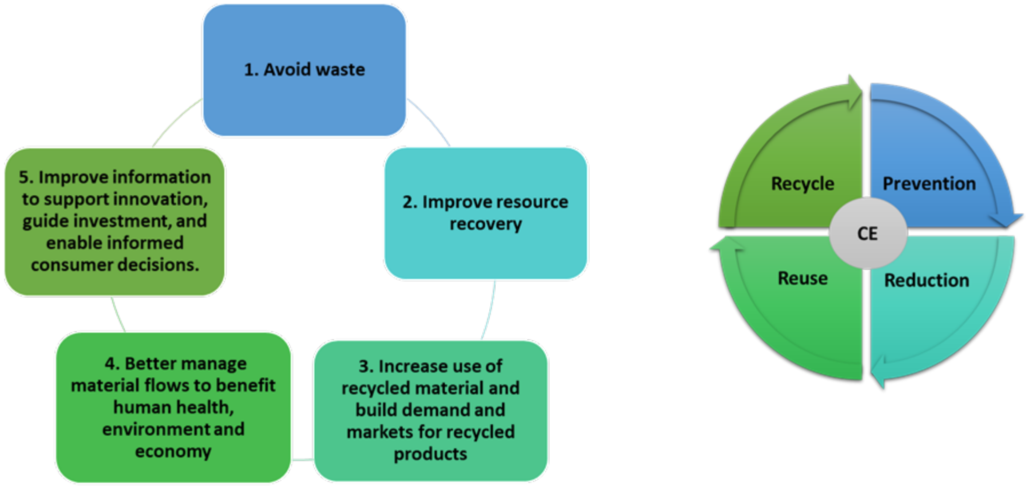

Figure 2. Circular economy principles.

The concept of CE has been gaining acceptance in the last years, both in national and international spheres, aiming to optimise how organisations produce and consume. However, the circular economy model for the timber waste recycling industry is still growing, and the transition process is in its initial phase [31]. Although wood is plentifully used worldwide, its potential involvement in CE has received less attention in the past. Current practices are mostly limited to low-value uses, such as mulch or firewood. However, there are enormous possibilities for wood waste to be recycled as value-added products [32]. Therefore, the CE for wood waste in every life cycle stage is not yet widespread, pointing to a gap yet to be investigated comprehensively.

2. Research Methodology

This study is divided into two parts. Firstly, analysis of existing literature and research trends and gaps in the light of wood waste management, LCA studies, and CE using CiteSpace software. Secondly, developing a theoretical framework based on the existing CE opportunities for wood waste. The wood waste management strategies of six life cycle stages and CE options through waste reduction, reuse, and recycling are represented through this framework. In the previous literature, CE approaches for wood waste are not accumulated in the life cycle stages. Most of the works of literature are based on end-of-life waste management practices [33–37]; hence, there is a gap to explore for a theoretical framework that abridges six life cycle stages and CE for wood waste management. This framework can be used as a guideline for CE implementation for wood waste. The following flow diagram (Figure 3) highlights the overall methodology adopted in this study.

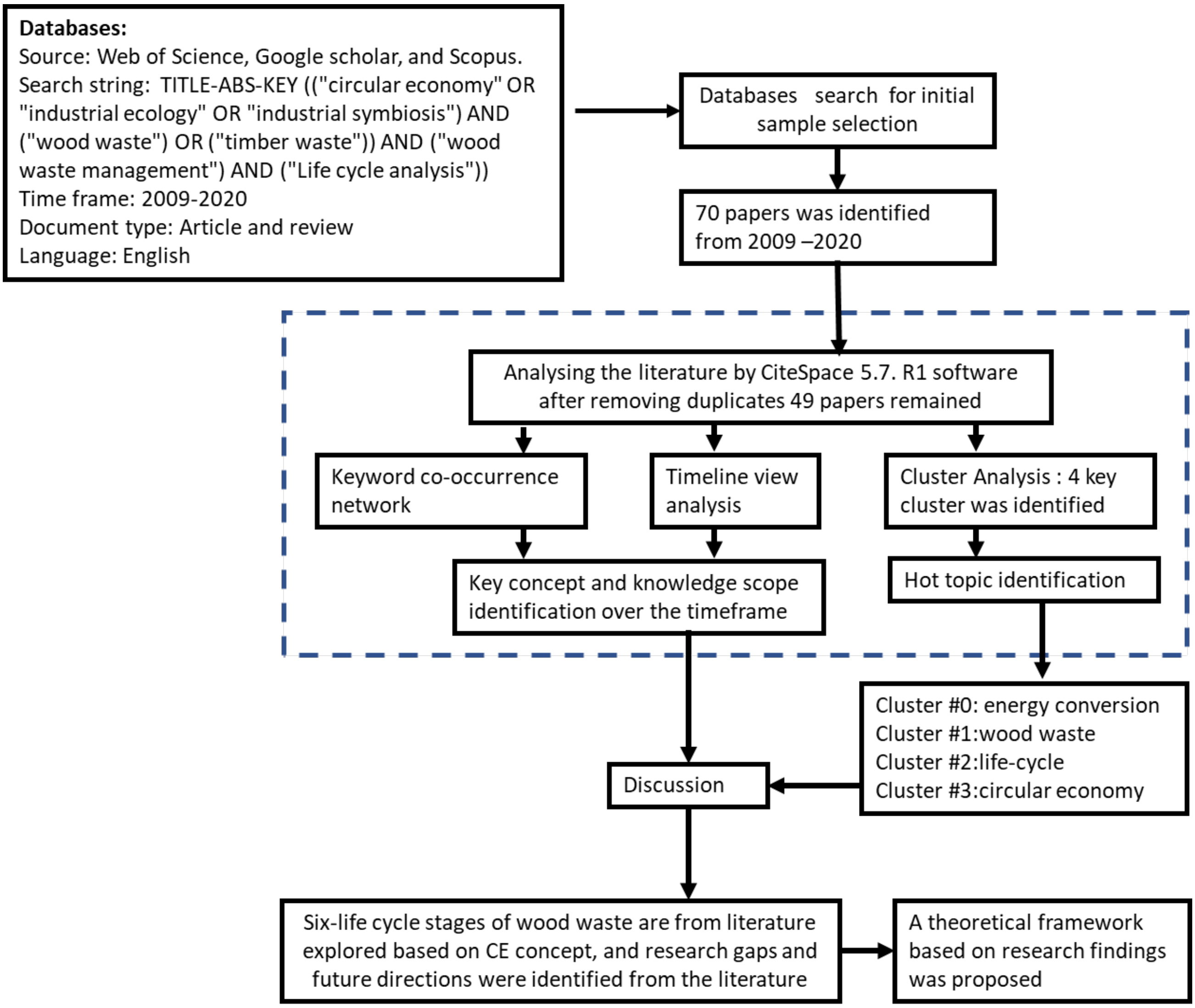

Figure 3. Flow diagram of the literature search and data analysis procedure.

2.1. Literature Selection and Analysis Procedure

The literature selection and analysis procedure consist of four steps. The first step is identifying the literature in the databases, called initial sample selection, as shown in Figure 4. The second step was searching the literature using the following Boolean search string: TITLE-ABS-KEY ((“circular economy” OR “industrial ecology” OR “industrial symbiosis”) AND (“wood waste”) OR (“timber waste”)) AND (“wood waste management”) AND (“Life cycle analysis”)) as mentioned in Table 2.

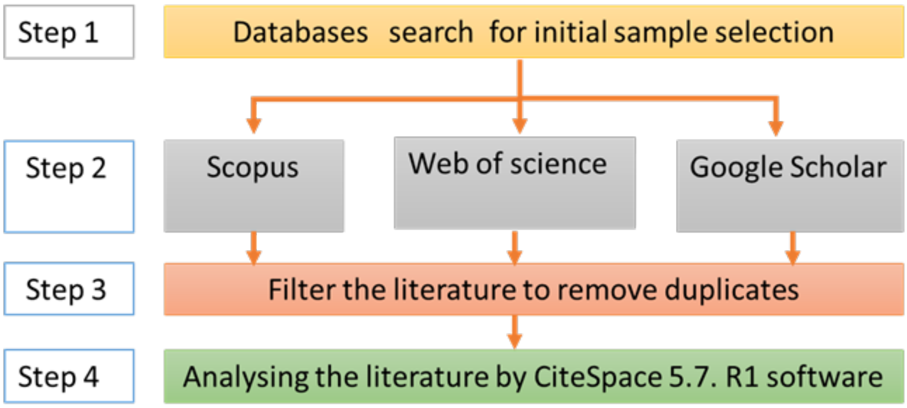

Figure 4. Literature selection and analysis procedure.

Table 2. Database search procedure for this study.

Resource	Search Titles	No of Papers
Scopus	TITLE-ABS-KEY ((“circular economy” OR “industrial ecology” OR “industrial symbiosis”) AND (“wood waste”) OR (“timber waste”)) AND (“wood waste management”) AND (“Life cycle analysis”))	20
Web of Science	TITLE-ABS-KEY ((“circular economy” OR “industrial ecology” OR “industrial symbiosis”) AND (“wood waste”) OR (“timber waste”)) AND (“wood waste management”) AND (“Life cycle analysis”))	31
Google Scholar	All in title: “Wood” OR “Timber” waste (“circular economy” OR “industrial ecology” OR “industrial symbiosis”) OR (“Life cycle analysis”)	19
	Total literature	70
	After filtering the duplicates	52
	After full reading and analysis of the final portfolio	49

It was seen from the search history that CE in wood waste is an emerging topic. Much literature is found focusing on CDWW recycling and CE practices. There are 20, 31, and 19 papers in Scopus, Web of Science, and Google Scholar, respectively, related to wood or timber waste management, LCA (life cycle analysis), and CE practices of wood or timber waste. The literature was searched from September to December of 2020, considering the papers published since 2005. However, the wood waste research that was found from 2009 to 2020 was directly or somehow linked with the circular economy. Before this timeframe, articles are based on waste management and LCA analysis, focusing primarily on environmental impacts.

The third step was filtering the literature to remove duplicates. The filtering was conducted according to the following criteria:

- The duplicate literature was excluded using the reference management software CiteSpace 5.7.R1. After the removal of duplicates, 52 remained.
- After reading and analysing the abstracts, keywords, and titles, only the studies related to wood waste management, LCA, and CE of wood waste were included. Consequently, 49 articles remained for further analysis and investigation.

2.2. Mapping the Content through CiteSpace Software

The ultimate step of this methodology is mapping the content of the chosen literature through CiteSpace 5.5.R1 to find the research trends over time. CiteSpace is an open-source Java application that visualises and analyses scientific literature trends, enabling scientific visualisation of the knowledge domain [31]. This software helps visualise the scientific literature network through nodes and links [38]. The nodes refer to the journals or articles, whereas the links represent their co-relations. This software provides several types of scientometric analysis—such as cluster analysis, network links analysis, co-occurrence of keywords or terms, citation burstiness analysis, author's co-citation, and literature co-citation analysis—which helps in understanding and interpreting research trends.

This study imported relevant references from Web of Science and Scopus into CiteSpace. After removing duplicate contacts through CiteSpace and reading the abstract and keywords, 49 articles are retained for final analysis. Initially, the co-occurrences of the terms network are created through CiteSpace, which helps to map the critical concept in the field of CDWW research and the potential knowledge gap in this field. Based on this co-occurrences network, the frequency of different terms from various articles was observed and documented to identify possible knowledge in CDWW research. Then, an article co-citation network was generated to find the critical articles in this field. After that, the frequency of co-cited articles and keywords was assessed by the modularity index created by the software (Figure 5a). The timeline analysis was then performed to identify the article's chronological features and knowledge over the timeframe (Figure 5b) [32]. Then, cluster analyses were performed with articles with similar interests and topics to find the current research direction and future research trends (Figure 6). According to the research findings, a theoretical framework of CE implementation in every life cycle stage of CDWW is proposed (Figure 7). The knowledge, such as fundamental research topics, trends, and future research opportunities based on major clusters analysis obtained from this scientometric analysis, are summarised in Figure 8.

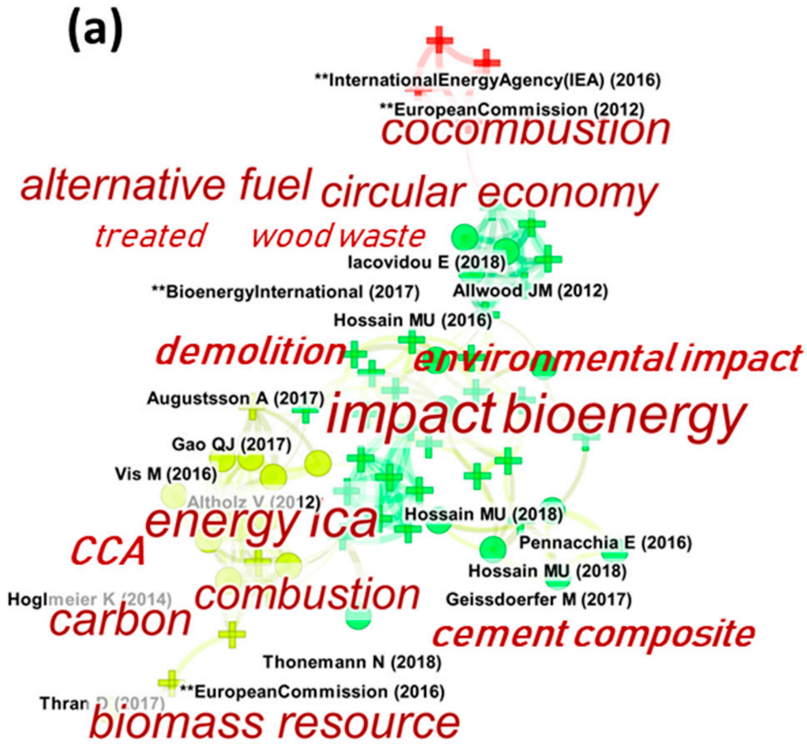

Figure 5. *Cont.*

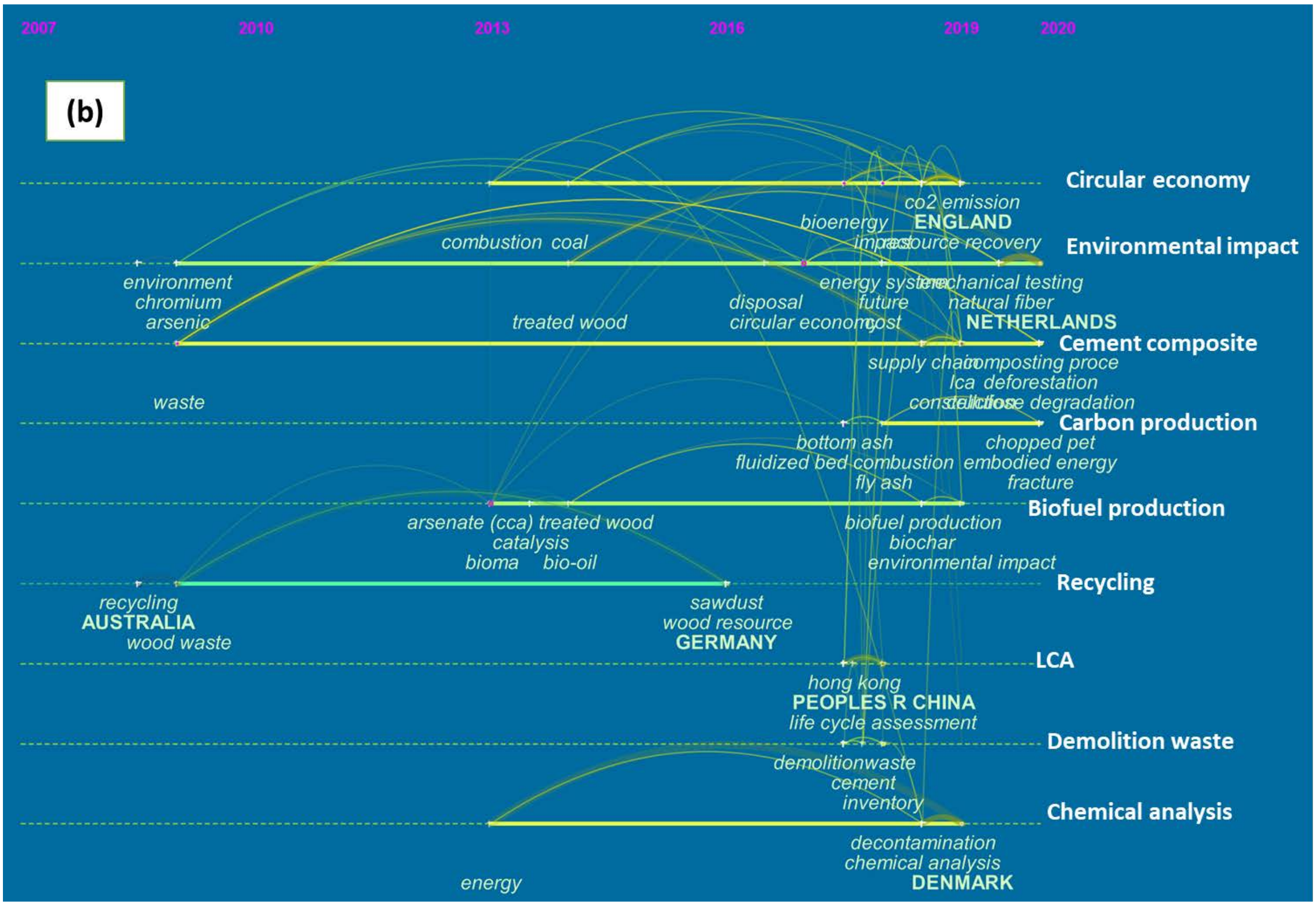

Figure 5. (**a**) The most common keywords in the network, and (**b**) the timeline view (2007–2020) of the keywords and countries in the network (** emphasises the co-occurrence of keywords from the literature).

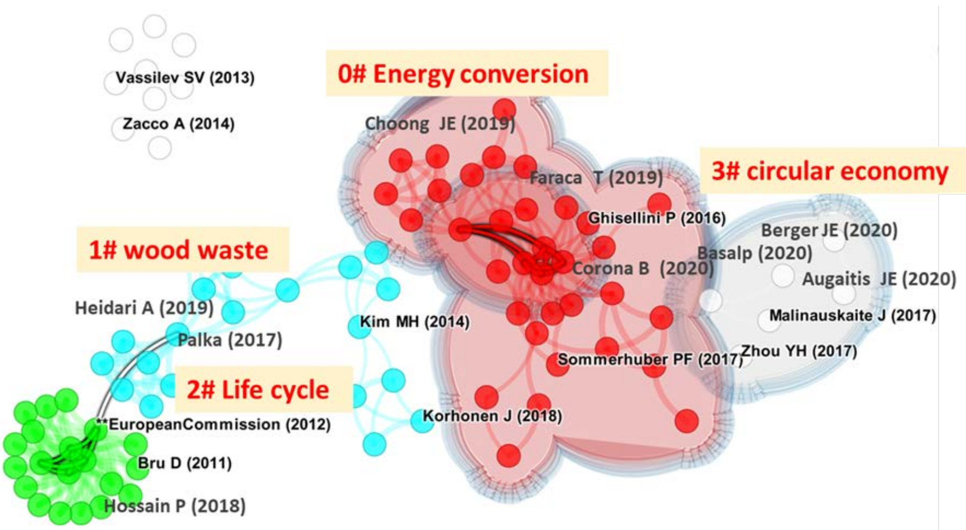

Figure 6. Illustrating different clusters found by CiteSpace on wood waste (** emphasises the co-occurrence of keywords from the literature).

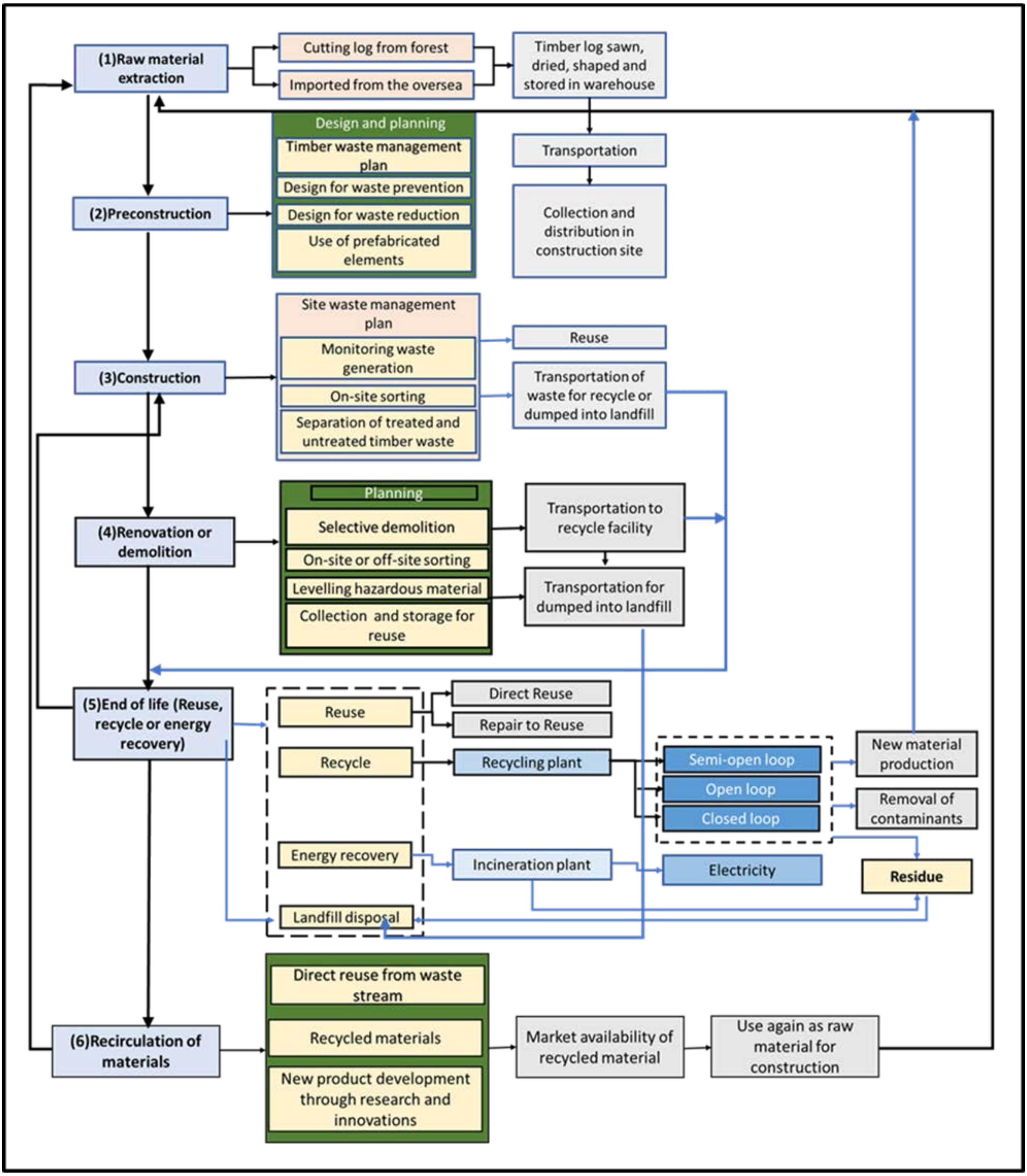

Figure 7. A framework for life cycle stages of CDWW toward a circular economy.

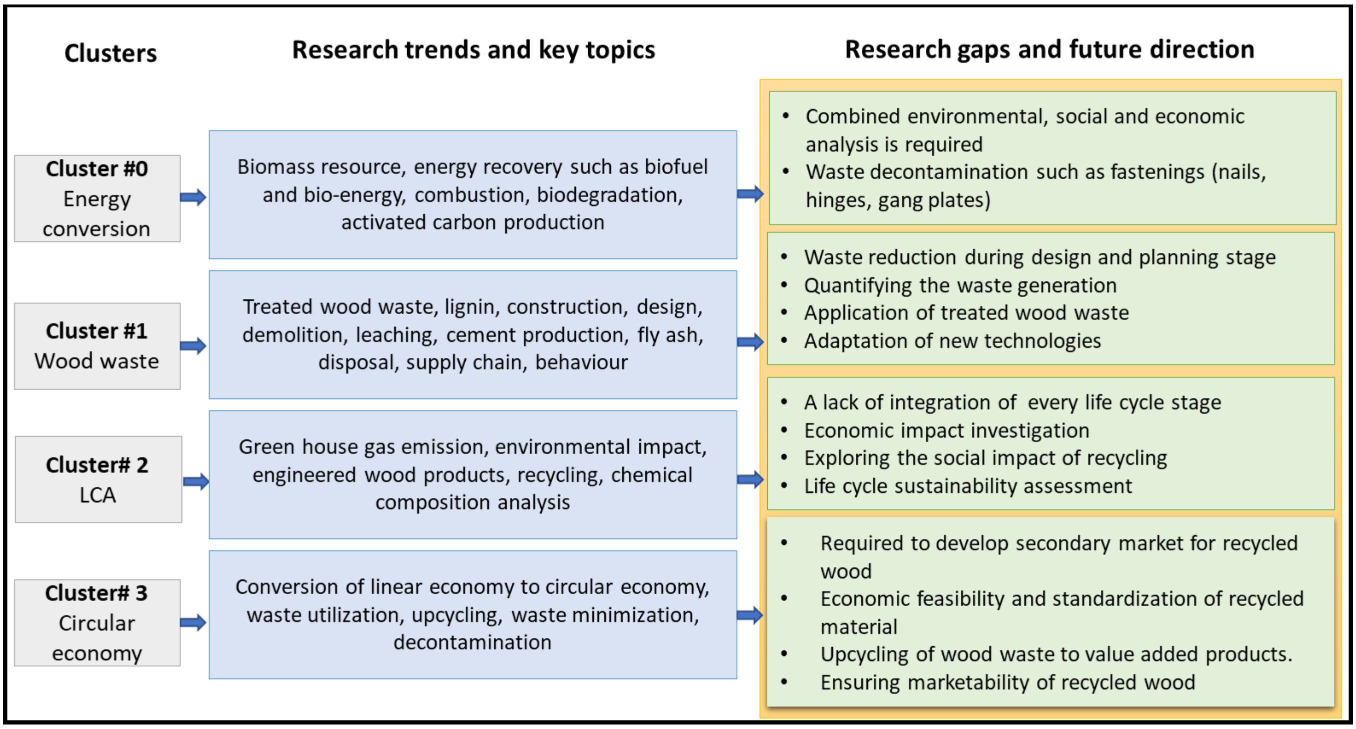

Figure 8. Research trends and research gaps in the CDWW.

3. Result and Discussion

3.1. Keyword Co-Occurrence Network and Timeline View Analysis

The primary content of the literature surveys is denoted through keywords and reveals the progression of research trends over time. The keyword co-occurrence network in Figure 5a represents 84 nodes and 232 links. The timeframe of the data inputted is 2005 to 2020, and the time slice for this analysis is set to two years. In this network map, keywords that occur more than twice in the publications were selected in this paper. The size of the keywords is proportional to their frequency. The most frequently co-occurring keywords are “alternative fuel”, “bioenergy, “biomass”, “combustion”, and “circular economy”, as illustrated in Figure 5a.

The timeline view illustrated the similar keywords re-occurring from 2005 to 2020 (Figure 5b). The time zone views clearly stated that England, China, Netherlands, Denmark, and Germany had been committed to timber waste management research (Figure 5b).

Therefore, the hot topics in timber waste research are: (a) circular economy, (b) environmental impact, (c) wood cement composite to produce particleboards, (d) carbon production, (e) biofuel production, (f) upcycling, (g) life cycle assessment, (h) demolition waste, and (i) chemical analysis.

Between 2009 and 2020, timber research commenced with waste-to-energy conversion through biofuel and bioenergy generation. Since then, chemical analysis for decontamination of CCA-treated wood [39] and life cycle analysis to reduce environmental impacts have become focal points for researchers [40–43]. Therefore, recycling, reusing, and engineered wood products from recycled materials in particleboard, glue-laminated timber, and activated carbon production research are seen in the literature [44–47]. In the last decade, an emphasis away from a linear economy to a CE has been prominent as a research trend for timber recovery [43,48,49]. Current research on timber waste predominantly focuses on upcycling wood waste and developing engineered wood materials from recycled wood transition to implement the circular economy in this sector.

3.2. Cluster Analysis

The cluster analysis can divide the collected literature into several structured clusters to discover the research pattern according to the learning domain in CiteSpace. The cluster analysis transforms the collected data into a visual distribution of cited references. Figure 6 shows the document cluster network analysis generated by CiteSpace with 239 nodes and 721 links. The data frame is from 2005 to 2020, and the time slice is set to one year. In Figure 6, nodes represent cited references, and the link between two nodes represents a co-citation relationship. The assorted colors of each cluster indicate other cluster groups.

This analysis recognises four major clusters: wood waste, circular economy, life cycle, and energy conversion, as shown in Figure 6. The clusters modularity is 0.578 (modularity > 0.5), and silhouette is 0.6108 (silhouette > 0.5), indicating the structure made by clustering is substantial. The cluster size indicates the number of cited references in each cluster. The silhouette identifies the homogeneity of the cluster. It ranges between 0 and 1 to indicate the lowest to highest homogeneity of the clusters. The details of these clusters are characterised in the following Table 3. The largest cluster is Cluster #0 energy conversion which allocates the wood waste to the energy conversion network. Cluster #1 represents the wood waste management and recycling networks, and Cluster #2 life cycle analysis.

Table 3. Represents the cluster size, silhouette, and top keywords.

	Size	Silhouette	Top Keywords
#0 Energy conversion	10	0.7121	Time-dependency; quality; resource cascading; combustion process; resource recovery; environmental impacts; wood waste-derived fuel; biomass
#1 Wood waste	9	0.6361	Recycling; reverse logistics; waste management; biomass; waste treatment
#2 Life cycle	8	0.5033	CO_2 emission; waste treatment; life cycle assessment; dynamic life cycle assessment (LCA); global warming potential (GWP)
#3 Circular economy	12	0.6193	Cement production; particleboard; downcycling; techno-environmental feasibility; circular economy

In Clusters #0, #1, and #2, wood waste management focuses on energy generation, life cycle studies, and end-of-life scenario studies. The waste-to-energy section focuses on electricity generation from biomass and environmental impact assessment. In European Union, cascading utilisation of post-consumer wood waste was analysed by Faraca, Tonini and Astrup [50]. Their study demonstrated that rating quality instead of quantity in wood waste management (sorting, separation, collection) could ensure substantial savings from GWP (global warming potential). Recently, wood waste combustion as a boiler fuel was assessed by Corona et al., 2020 [48]. They focused on the LCA of heat and power generation from wood waste. Potential ecological impacts analysed were climate change, acidification, particulate matter, freshwater eutrophication, human toxicity, and cumulative energy demand.

Choong et al., 2019 presented waste-to-energy generation in a biomass-fired power plant using wood waste from the Malaysian perspective [37]. They concluded that wood waste-to-energy conversion is a sustainable approach to reducing GHG emissions. Several LCA studies have confirmed that recycled wood waste can be used for sustainable energy generation [40,41,51–53]. Bais-Moleman et al., 2018 [54] assessed the utilisation of recycled wood waste for energy generation to reduce greenhouse gases (GHGs) based on 28 member states. Some LCA studies have focused on energy generation from direct biomass burning in China [55], the US (United States) [56], and France [57]. However, most of these LCA studies have only been conducted on the environmental implications.

Recent literature has focused on activated carbon production from waste wood [46]). The LCA methodology was applied to identify the energy requirements and an environmental footprint to quantify and compare the potential ecological impacts of bio-oil and activated carbon production from eucalyptus wood waste [46]. Similarly, Kim et al. [44]

used LCA to analyse the environmental benefits of activated carbon production from wood wastes compared to landfill disposal. Their study discovered that the activated carbon production from 1 ton of waste wood could provide an environmental benefit of 163 kg CO_2-eq. in reducing GWP compared to the same amount disposed of in landfills.

Particleboard manufacturing is the most popular wood waste utilisation practice found in the literature among engineered wood products. Numerous LCA studies have been conducted on the environmental perspectives of particleboard production [36,45,47,58–60]. According to a study by Azambuja et al. [61], CDWW can be successfully utilised to produce the inner layer of medium-density particleboard. Rivela et al., 2006 [59] showed that recycling ephemeral wood structures in particleboard production is environmentally beneficial compared to energy generation. Merrild and Christensen (2009) and Kim and Song (2014) derived similar conclusions for utilising recovered wood for particleboard production while focusing on GWP.

Another study in Brazil was conducted by Silva et al., 2015 [62], which focused on substituting UF resin for MUF for particleboard production. The study used LCA to conclude that MUF contributes less to photochemical oxidation and human toxicity than UF. Another study in China was carried out on the LCA of plywood manufacturing from a cradle-to-gate perspective to identify environmental performance and sustainability [63]. This study covers the life cycle stages, including raw material preparation, manufacturing, and processing.

Table 4 summarises the critical literature on CDWW management and LCA articles. The previous studies separated wood waste management (collection, sorting) and end-of-life (reuse, recycle practices) studies. LCA studies regarding production with recycled materials often dropped the management stages, such as separation and collection steps. There is a lack of integration in the recycling system of CDWW that covers details of the process in every life cycle step. Most studies focus on the environmental aspects of recycled wood used in particleboard production or energy generation. Therefore, systematic wood cascading is still emerging. The economic and social perspectives were not mentioned much in the LCA studies. Only one study in Germany combined the life cycle assessment (LCA) and life cycle costing (LCC) for recovered solid wood from construction into glued-laminated timber (GLT) products and compared environmental and economic impacts with the incineration of salvaged wood [49]. Their results indicated that recycling recovered wood into GLT products is environmentally and economically viable and can produce value-added products. Recycling further shows up to 29% lower environmental impacts and 32% lower costs than incineration.

Table 4. Shows some important literature on Clusters #0, #1, and #2.

References	Study Direction	Country	Application
[48]	LCA—environmental impacts	European countries	Waste wood combustion as boiler fuel.
[37]	LCA—environmental impacts	Malaysia	Waste-to-energy conversion as a sustainable approach and capacity to reduce GHG emissions.
[46]	Environmental impacts using LCA	Australia	Bio-oil and biochar production using a fast pyrolysis process.
[49]	LCA+LCC	Germany	Recovered wood waste from construction into glue-laminated timber (GLT) products.
[42]	Environmental impacts from LCA	Hong Kong	Construction wood waste is used to manufacture wood panels and power generation.
[54]	Environmental impacts	European Union	Recycling wood waste for biofuel production and developing the bio-economy sector to achieve climate change mitigation.

Table 4. *Cont.*

References	Study Direction	Country	Application
[44]	Environmental impacts using LCA	USA	Recycling wood residue to produce activated carbon and energy to reduce GHGs.
[62]	Environmental impacts using LCA	Brazil	MUF contributes less to photochemical oxidation and human toxicity impacts than UF.

Cluster #3, as shown in Figure 6, summarises the circular economy-related journals on wood waste. In the literature, some approaches to upcycling, reusing, and recycling wood waste have the potential for circular economy implementation. The circular economy practices are addressed by European countries (Netherlands, Norway), Brazil, and Hong Kong, as mentioned in Table 5. For sustainable production and consumption, wood-based bio-concrete, wood–plastic composites, wood–wool cement board, and particleboard were produced [43,64–66] from recycled plastic and wood to minimise waste, decrease environmental effects, preserve natural resources, and support the CE.

Table 5. Summary of the study indicating CE practices in the literature.

References	Country	CE Practice
[66]	Brazil	Circular economy implementation for wood waste as CO_2-sink in bio concrete.
[67]	Poland	Application of wood waste loose-fill building insulation.
[65]	Netherland	Wood–plastic composites from recycled plastics (electronic waste) and recycled particleboard.
[64]	European Union	Recycling plastic and wood wastes as wood–plastic composite contributes to CE through new product development.
[50]	Denmark	Cascading utilisation of post-consumer wood waste into particleboard.
[68]	Brazil	Recycling of wood waste and epoxy-based ink-waste as adhesive to produce particleboard.
[43]	Hong Kong	Upcycling of wood waste into cement-bonded particleboard.
[45]	USA	Recycling wood residue to produce particleboard and energy aims to reduce GHGs.
[69]	Norway	Upcycling of wood waste and plastics of electronic waste into wood–plastic composite to produce particleboard.
[70]	Brazil	Reuse OSB, MDF, and plywood residue mixture into small handmade objects.
[39]	Canada	Recycling of CCA-treated wood waste: extraction of arsenic, chromium, and copper, an opportunity to utilise treated wood waste.
[71]	Australia	Wood waste management generated from the wooden furniture manufacturing sector focusing waste management practices and strategies to increase sustainability.

Another approach for wood waste utilisation as a potential filler for loose-fill building insulation was proposed by Augaitis et al., 2020 [67]. They used diverse types of wood waste—such as uncleaned and cleaned pinewood sawdust, bark, and hemp shives—and immobilised them in polyurethane foam to produce a biocomposite. Different performance testing was conducted with obtained products and found recycling the wood waste as an insulation material is an appropriate approach that contributes to the CE of wood waste [67].

Again, a resource cascading utilisation of wood waste into wood cement composite board was studied by [65]. Wood strands were sourced from wood pallets and demolition wood waste. They used up to 30% recycled wood waste to substitute spruce materials in wood–wool cement boards. They studied the mechanical properties, leaching measurement, and chemical compatibility of the composites to ensure the possibility of recycling wood waste as a building material. It was found that wood from pallets is an excellent choice for composite because it contains less contamination and is a similar structure to spruce, which is industrially used in cement board manufacture. However, the construction and demolition of wood wastes are very contaminated; therefore, they are most challenging to manufacture composite. Another problematic issue of manufacturing these composites was preparing wood strands from waste wood. Although wood cement composite is a new way for CE practice, it requires more investigation to design a sustainable composite.

Another study addressing the cascading utilisation of wood waste was conducted by Faraca, Tonini, and Astrup 2019 [50]. They used post-consumer wood waste to produce wood chips which can be utilised in wood-based panels. The study revealed that post-consumer wood waste could be utilised up to 100% (depending on countries), dramatically contributing to circular economy practice through particleboard manufacturing instead of sending it to landfills. An environmental and technical feasibility study of upcycling wood waste into cement-bonded particleboard in Hong Kong was conducted by Hossain et al., 2018 [42] using LCA methodology. They compared recovered wood from construction in particleboard production with alternative landfill and energy generation treatments. Their study mentioned that energy generation is beneficial over the recycling scenario due to greenhouse gas emission savings from substituting fossil fuels. In Brazil, again, technical feasibility and environmental aspects of particleboard were made with wood waste and epoxy-based ink-waste as the adhesive conducted by Souza et al., 2018 [68] using LCA. Kim and Song also proposed particleboard manufacturing from wood waste [45]. Their study found that particleboard manufacturing from wood waste provides benefits by reducing GHG emissions compared to virgin material use. These studies are contributing to CE through new product development from wood waste.

Wood–plastic composite and another CE practice for wood waste were proposed by Baslp et al., 2020 [64]. This study successfully demonstrated wood–plastic composite manufacturing using industrial scale post-consumer bulky plastic and wood wastes. To manufacture the composite, wood flour and polypropylene or polyethylene-based recycled plastics are used in which wood flour contains 30% of the weight of the composite. Surface morphology, tensile strength, flexural strength, and density of recycled composite were observed. Their study concluded that these recycled wood–plastic composites could substitute virgin material, contributing to the valorisation of waste material by upcycling. Another study of upcycling wood waste and plastics from electronic waste into wood–plastic composite to produce particleboard was proposed by Sommerhuber, Wang, and Krause [69].

An Australian study by Daian and Ozarska explored the current and future wood waste reduction and recycling scenario generated by the Australian furniture industry. This study aimed to advise small and medium enterprises (SMEs) of the Australian furniture industry to consider wood waste as a resource instead of a problem. Recycling and reuse opportunities for turning wood waste into value-added products are highlighted in this study, contributing to CE Abreu, Mendes, and Silva's proposal of making small decorative objects from plywood and medium-density fibreboard residue can avoid dumping these residues [70]. This research contributes to CE by reusing wood waste.

CCA-treated wood waste is a significant concern as it contains hazardous chemicals often found in the wood waste stream. To eliminate this problem, a study proposed by Janin et al. [39] was through an inexpensive method of the leaching process, where arsenic, chromium, and copper from CCA-treated wood be removed. This study reveals a new option of recycling CCA-treated wood waste with little cost. This study addressed the decontamination of treated wood waste cost-efficiently, which can be considered a CE approach to utilising treated wood waste. Therefore, it is evident that CE-related opportunities apply to wood waste. The leading, recurring means seem to be developing new materials from wood waste. However, most of these applications are developed on a laboratory scale. There is a need to implement CE practice industrially.

4. Discussion

In the literature, CE opportunities are found to reduce, reuse, and recycle wood waste. Waste reduction during the design and planning stage is crucial for minimising waste generation. For cascading utilisation of wood waste, it is necessary to estimate the recycling materials. As economic profit plays a key role in enhancing the secondary materials market in the construction industry, there is a need to develop secondary markets for CDWW recycled materials. Another issue is a lack of standards that guarantee the quality of recycled material which is a potential barrier to the market development of secondary materials. Sometimes, the higher prices of secondary materials over virgin raw materials discourage consumers from buying secondary materials. For implementing CE in CDWW recycled materials, we need to develop the materials cost-effectively, matching the standard of virgin materials. This process requires more research and innovation in this CDWW sector. This study proposes a conceptual framework based on the literature studies to implement CE for CDWW. This framework could guide professionals to expand their knowledge and work further to achieve a CE for CDWW. Moreover, CE can be adopted to integrate environmental, social benefits, and economic opportunities for CDWW.

4.1. A Theoretical Framework for CDWW

A theoretical framework has been proposed in this paper to achieve a circular economy concept for CDWW, considering the six life cycle stages, as shown in Figure 7. These stages will highlight the existing literature and strategies applicable to wood waste.

4.1.1. Raw Material Extraction

In this framework (Figure 7), the first stage is raw material extraction harvested from the forest. Forests perform critical economic and ecological functions as they provide goods and livelihoods and protect our ecology. Our world had around 3870 million hectares of forest in 2000, and this forest covers 30% of our land area [72]. For timber industries, raw materials are primarily sourced from forests to decrease our forests daily [73,74]. The world leaders in wood production and export are Canada, the USA, Sweden, Finland, Germany, Russia, and Brazil. They produce 31, 19.5, 18.5, 16, 14.5, 14, and 11 billion kgs of wood annually [75]. This raw wood is supplied to industries for producing industrial round wood, wood-based panels, engineered wood products (EWP), sawn timber, wood-based platelets, paper, pulp, furniture, and other products for global economic growth [76].

In the construction industry, wood-based panels, framing, and EWP are primarily used as raw materials. Harvesting wood from the forest as raw material improves the economy, but it also presents a profound environmental impact and biodiversity loss. If the circular economy concept (the 3R principle consisting of reduction, reuse, and recycle) can be utilised for timber waste, the pressure on virgin materials can be reduced significantly.

4.1.2. Pre-Construction Phase

This stage is incredibly significant to achieving a circular economy, as this will contribute to proper waste prevention and reduction planning. Therefore, an effective timber waste management plan (TWMP) considering waste prevention and reduction in the pre-construction stage is essential [77,78]. No such goal is available in the industry, which requires consideration before any construction project. Construction contractors play a vital role in minimising waste generation. Engineers and architects of construction projects can help predict the precise amount of required raw materials to prevent waste generation. An appropriate TWMP can be helpful for different stakeholders for the reduction of waste generation.

Application of BIM for Waste Prevention and Minimization

Building information modeling (BIM) can be used to estimate exact forecasts of waste generation. Through BIM, the detailed composition of waste materials can be calculated at the early design stage [79–82]. Accurate estimation of material used during the design stage plays a significant role in waste management and prevention by determining waste generation, reusability, and recyclability of recoverable materials at the end-of-life stage. Furthermore, BIM in the design stage helps manage infrastructure throughout its life cycle, including demolition, reuse, and recycling in CE implementation [82].

Application of Prefabricated Elements

Another popular term for wood waste prevention is using prefabricated elements in construction [83–85]. The prefabricated products are formed, assembled, and prefinished in factories and then utilised in the construction sites, which is a labour incentive but an effective process for minimising the waste stream during construction [78,86]. In residential building construction, most contemporary buildings contain broken veneer timber-framed structures in which wall framings, roof trusses, studs, rafters, and joints are prefabricated. The prefabricated elements can reduce labour costs and site waste generation, such as off-cuts, sawdust, and shavings. The literature highlighted that the prefabrication technique could reduce timber waste from 65% to 80% [78,86].

4.1.3. Construction and Operation Phase

In this phase, adopting a site waste management plan (SWMP), as shown in Figure 7, consists of monitoring, sorting, collection, and storing of waste materials are the essential steps toward waste reduction, recycling, and reuse [87–89], which are necessary to achieve a circular economy. Wood is an organic material that decomposes very quickly in the environment. Therefore, obtaining durable material with a longer life cycle from wood waste is challenging. Wood waste also contains various qualities and compositions of untreated, treated, or engineered wood and contaminated wood with other products [26]. Proper monitoring and handling of the waste stream helps to avoid contamination. However, to ensure the quality of recovered material, sorting waste wood into various categories is a significant challenge as it requires labour and space, which is not always enough. Different sorting techniques are available such as manual and online sorting (e.g., X-ray fluorescent, laser-induced breakdown spectroscopy). It is seen from the literature that existing sorting processes are not efficient in removing impurities from wood waste. A substantial percentage of other constituents remain in wood waste—such as metals, cementitious materials, or plastics—affecting the quality of the final product [24]. Therefore, a need exists to develop an efficient sorting technique for waste wood, a prerequisite for ensuring quality wood in the reuse and further treatment in the recycling process.

4.1.4. Renovation or Demolition Phase

The majority of CDWW is generated from the demolition sector. In recent decades, wood-based material has been highly demandable and enormously used in construction activity. For example, one-fourth to two-thirds of products in the USA are wooden products utilised in building construction [90]. Demolition or deconstruction projects generate more waste (10 times higher) than construction projects [91]. In this stage, the matter of concern is that mixing several types of waste with CDWW makes it harder to separate. Even renovation and demolition projects produce a considerable EWW of varying qualities and categories, making it even harder to sort and separate [39].

The construction stage, sorting, collection, and separation of untreated wood waste and EWW is a great challenge for renovation or demolition stages. Specially engineered or treated wood may contain hazardous material and is extremely hard and expensive to recycle [92]. As a result, most of this material is dumped, which has a severe environmental impact. In this regard, selective demolition through the stepping out process can be utilised for timber collection from those buildings. House components—such as flooring, timber beams, roofing, and cladding—can be extracted and used again in constructing new buildings. In this context, strategies (Figure 7)—such as demolition audit, planning; selective demolition; and proper sorting and labelling of treated, untreated contaminated, or hazardous waste—can be fruitful for a circular economy [79,89,93,94].

4.1.5. Reuse Recycling or Energy Recovery

Reuse of Wood Waste

As shown in Figure 7, material reuse is regarded as one of the utmost waste management and recirculation practices in the circular economy concept. It is cost-effective and environmentally friendly [79,81,95]. The reuse of MDF, plywood and OSB residue to produce small decorative objects was proposed by Abreu, Mendes, and Silva 2009 [70]. However, in the case of wood waste reusability, direct reuse may not always be accepted because of the lack of material standards, which leads clients to doubt the quality of reused materials [80]. Some wood-based products—for instance, formworks, pallets, wood-frame structures, beams, window framing, and doors—are reused in the building sector [78]. Moreover, it is necessary to develop a standard for reused material and the market by engaging all stakeholders, such as contractors, engineers, architects, companies of demolition and renovation, and consumers, to implement a circular economy.

Recycling of Wood Waste

Like reuse, recycling is a fundamental step towards a circular economy, as shown in Figure 7. It contributes to the recovery of the material from impurities; reduces the energy intake of manufacturing processes; reduces pressure on virgin materials, and alleviates economic, social, and environmental burdens. Each year, a vast quantity of wood waste from the construction renovation or demolition stage is transported to the recycling plant after sorting. Wood is preferred as valuable structural material compared to concrete and steel, which raises its use in the construction industry. Sawn wood waste contributes a significant percentage to the CDWW stream. These wastages are pre-treated to remove impurities [96]. After that, a suitable recycling process (e.g., semi-open, open, or closed loop) (Figure 7) is chosen to develop new material. For CDWW, recycling practices are still inefficient, resulting in a tremendous amount of wood waste being dumped into landfills legally or illegally without environmental protection [89]. Only 20–30% of CDW is estimated to be recycled globally (World Economic Forum, 2016). The average recycling rate in the EU, UK, France, Spain, Germany, Australia, US, and China are 46%, 89.9%, 47.5%, 37.9%, 34%, 38–40%, 70%, and 5%, respectively [78,80,97,98]. Recycling contaminated wood waste is complex and costly. Even engineered wood product (EWP) contributes a large amount of waste to the CDWW stream [27]. EWP contains chromium, copper, arsenic, LOSP, lead, and boron, which are hazardous to the environment and particularly challenging to remove during recycling [27,92]. However, few studies proposed decontamination of treated wood waste cost-efficiently, which needs to be implemented on an industrial scale [39]. Considering CDWW recycling, more attention must be given to generating new materials according to the standard.

Energy Recovery

If wood waste is not recycled, it could be repurposed directly through combustion or conversion to gaseous or liquid fuel or burned to produce energy or power (Figure 7) [99]. Several waste-to-energy conversion technologies are available such as thermochemical technologies, which use elevated temperatures, including pyrolysis, gasification, and incineration. On the other hand, biochemical technology with low temperatures includes carbonisation, physicochemical technologies, etc. A substantial amount of timber waste is used in energy industries; for instance, in the Netherlands, a massive amount of wood waste created from CDW is fuel for power plants and heat generation [2]. In Canada, about a million tons of wood waste pellets exported to the EU are used as fuel in power plants and hot water generation [100]. In Scotland, wood waste is used as boiler fuel for producing steam for turbines [101]. Wood waste is also used for electricity generation. However, it is stated that the wood waste used for energy generation is responsible for higher GHG emissions, which are 55% higher than the burning of biogas for electricity production. In this concern, wood waste is not suggested for energy generation [24]. As a result, to achieve better economic benefits without compromising environmental issues, there is still room for improvement in wood waste used for energy generation in the CE concept.

Dumping to Landfill

The last phase of wood waste turns to landfill (Figure 7), where biodegradation of wood ensues. The wood structure contains cellulose, hemicellulose, and lignin, where cellulose and hemicellulose decompose quickly. However, lignin in timber is resistant to biodegradation in an anaerobic environment and can persist for exceedingly prolonged periods [102]. Wood waste emits methane, carbon dioxide, and nitrous oxide, potential components of GHGs. EWW contains hazardous materials—such as CCA, lead-based paint, or chromium—which cause the leaching of hazardous elements to the environment, delivering severe health concerns. Thus, contamination is the main hindrance to sending wood waste to landfilling [27,101]. Landfill disposal needs to be restricted to implement the circular economy in wood waste because it undermines energy recovery and requires compensation for the process. Many governments—such as Sweden, Austria, and Germany—have already banned wood waste landfilling, while many others have discouraged landfilling through taxation [103,104].

Transport of Waste Material

The transport types and distances situate the economic benefits of reuse, recovery, and recycling over landfilling. Suppose the transport and distance cost is more than landfilling. The stakeholders may prefer dumping waste materials to landfilling, overlooking the environmental impacts. Therefore, economic benefit plays a crucial role in developing secondary materials for the construction industry.

4.1.6. Marketability of Developed Material from CDWW

The wood waste from construction renovation or demolition is recovered by reusing, recycling, or energy recovery as input material for other industries. Recycled wood or recovered products from wood waste have mixed use in the circular economy for sustainable development activities, as shown in Figure 8. The improvement in wood engineering design has privileged the durability of end products and made them environmentally friendly. Markets for recycled wood include landscaping mulch, bedding material, boiler fuel, fibers for composite board products, press wood pallets, pellets, animal bedding, EWP, and other building materials. It must be emphasised that various utilises of wood waste involving distinct qualities and properties are prerequisites for circular economy implementation. Hence, sustainable design must be considered while designing new products from waste [105]. The developed materials from CDWW are available for further use as raw materials. They are divided into the following types: recycled and recovered materials, materials developed from CDWW research, and innovation.

Recycled and Recovered Materials

From recycled wood of CDWW, several materials or products can be manufactured, which have good demand in the market. CE can usually be implemented using this recycled wood as raw material for the construction industry or as input material for other sectors, contributing to generating new employment (Figure 8) [106]. For example, recycled wood is further processed to manufacture a new product. Composite wood products using this waste are composite pallets, door cores, etc., while recycled wood particles and fibers are used to manufacture new panel products. Different valuable products can be produced from waste wood—such as veneers lumber, chips, fibers, papers [107,108]; and a variety of building materials—including plywood, laminated veneer lumber, glue-laminated timber, particleboard, wood–plastic composite, wood–cement composite, and fibreboard [45,64,65]. Playground fibers are also available in the market, made from untreated wood waste and used by schools, parks, or homeowners as ground covering slides and jungle gyms.

Contaminated wood waste after recovery from impurities is also used as sawdust, shavings, and chips. Furthermore, wood waste is used as composting, providing carbon to micro-organisms, aiding moisture retention, and reinforcing the material for a more solid structure. This waste is also used to provide organic matter to topsoil or increase the quality of other lower-quality soils—landscape mulch is used as a ground cover material for controlling weeds and preventing moisture from the earth.

Developed Products from CDWW Research and Innovation

For economic growth, many researchers are engaged in optimising wood-waste recycling to produce higher value-added materials through hydrolysis, gasification, pyrolysis, heat treatment, chipping, and pulping process (Sui and Chen, 2014). Research and innovative works are found in the literature for developing wood waste-based value-added products.

Higher load-bearing strength and the higher strength-to-weight ratio of wood make it viable for widely applied building materials. Based on these properties, some research work is conducted using wood waste. An experiment conducted by Thandavamoorthya revealed that waste wood chips mixed with cement increase the compressive strength of building materials [109,110]. It is also stated that hardwood can be used as a structural material as a replacement for reinforced concretes [111]. Another study with contaminated wood waste can produce high-performance cement-bonded particleboard that is eco-friendly and presents excellent compatibility [43]. Moreover, different composite materials and thermal and noise insulating products are made using CDWW [49,64,65,67].

4.2. CE Adaptation for Environmental, Economic, and Social Benefits

Circular economy approach implementation can bring environmental, economic, and social benefits for CDWW towards sustainability.

4.2.1. Reduction of GHG Emissions and Deforestation

Reduction, reuse, and recycling of wood waste reduce virgin material consumption and GHG emissions and bring economic and social benefits [97]. The carbon dioxide intensity in the atmosphere is increasing. In 2017, the estimated carbon dioxide concentration in the air was 405 ppm, and it is assumed that it will be 450 ppm in 2050 and 750 ppm in 2100 (IPCC, 2017). Several studies have confirmed that about 20% of this carbon is discharged from deforestation, including wood harvesting. In this context, recycling wood waste for biofuel production and developing the bio-economy sector help mitigate climate change [8].

4.2.2. Mitigating Climate Change

Several studies suggested that developing new materials from wood waste recycling reduces GHG emissions substantially [48,50]. Some other studies also concluded with a similar concept and observed that it is necessary to enhance wood waste utilisation to develop valuable products that will mitigate climate change by reducing the consumption of natural resources [44,45]. With the development of a wood waste market, the forests' overall health would improve and prevent biodiversity loss. Thus, the material's circularity can be achieved to reduce the environmental impact of wood waste landfilling [112]. Therefore, the results obtained from the literature recommended further applications of CDWW towards CE and lessening landfill disposal that would restore forest resources through wood waste management [46].

4.2.3. Economic Benefits

The utilisation of CDWW brings an ecological balance to the environment and economic benefits [49]. Several studies have demonstrated that—for producing new products—the use of recycled wood is technically feasible and an economically viable project [49]. The framework mentioned above (Figure 8) clearly states that there are vast opportunities to reuse or develop new materials from CDWW for market entry and economic development. Recycling wood waste can create an inexpensive renewable material source to enhance economic growth and create employment opportunities. Different value-added materials can be produced from CDWW, which helps avoid landfill costs and space costs. Finally, government support for establishing market opportunities and a robust supply chain network with CDWW recycled products is crucial to enhancing chances and implementing CE. Economic development with CDWW has also guaranteed the continued sustainability of the forest reserve in emerging economies.

4.2.4. Social Benefits

In the literature, works on CDWW focus on the environmental and economic benefits. However, no study has analysed CDWW's potential contributions to social benefits. Eventually, the success of sustainable construction must embrace the collaborative development of three significant dimensions of sustainability (economic, environmental, and social) in an integrated way [113]. Therefore, all participants in the construction industry must pay attention to ecological and economic benefits and social concerns. Major participants involved in waste management can be divided into two groups. One group includes the authorities, the public, and NGOs tending to minimise construction waste by reducing the environmental and social impacts. Whereas the other group comprises project clients, main contractors and subcontractors, who are more concerned about the economic benefits of managing construction waste, which is the reality in this sector [1]. Hence, along with financial and environmental aspects, the primary social factors of waste management—such as the physical working atmosphere in waste management sites, operatives' safety, and practitioners' long-term health—need to be considered for sustainable waste management in construction industries [114].

5. Research Gaps and Future Directions

Figure 8 represents the research trends and gaps obtained through Citespace software analysis. The collection, sorting, and end-of-life (reuse, recycling practices) studies are separated in the literature for wood waste management. LCA studies regarding production with recycled materials often drop the management stages, such as the separation and collection processes. There is a lack of integration in the recycling system of CDWW that covers details of the process in every life cycle step. It is seen from the literature on wood waste management that most of these LCA studies were researched from an environmental perspective. Most studies focused on the ecological aspects of recycled wood used in particleboard production or energy generation. Therefore, systematic wood cascading is limited to the downcycling of wood. The economic and social perspectives were not included much in the LCA studies.

Combining LCA, LCC, and SLCA will follow the rationale of a life cycle sustainability assessment (LCSA), where the three dimensions of sustainability considered are: environment, economy, and social aspects. Each dimension must be analysed when a product or process is developed or improved to meet sustainability criteria. LCSA supports the identification of trade-offs between the dimensions and allows for better decision-making in politics and industry [115,116]. As well as implementing CE for waste wood, there is a need to build a secondary market and standardisation for recycled wood.

6. Conclusions and Recommendations

A pragmatic shift is going on in CDW reduction, reuse, and recycling at the global level to ensure sustainable development. A considerable amount of CDWW is generated during construction, renovation, or demolition stages and is mostly landfilled, contributing to severe environmental effects. The potential environmental impact is global warming, greenhouse gas emissions, and biodiversity loss, mainly associated with deforestation, the manufacturing of wood-based materials for the construction industry, and low product recovery rates for end-of-life stages. Therefore, to reduce environmental impact, management of CDWW and improvement of recovery rate is a priority. In this situation, CE is regarded as a possible solution as it comprises environmental, social benefits, and economic opportunities in an integrated way. Several kinds of literature are found on end-of-life wood waste management. However, research on CE implementation in each life cycle stage is limited. This study bridges the six life cycle steps (raw material extraction, pre-construction, construction and operation, demolition, end-of-life (reuse, recycle, or energy recovery), and recirculation opportunities) of CDWW and finds the potential research gaps through scientometrics analysis using the timeline, keyword co-occurrence, and cluster analysis to identify potential knowledge and research trends. The core contribution of this study is to provide a theoretical framework of the life cycle stages of CDWW towards the CE concept. It also emphasises waste management and recirculation of recovered materials for market opportunities. In addition, sustainability aspects (environmental, economic, and social) of CDWW are summarised briefly. From this literature analysis, it is evident that CE for wood waste is emerging, and it can be seen that wood waste recycling will bring environmental, social, and economic benefits. However, more innovation and practical implications are required for newly developed materials from these wood wastes. Following waste management practices in every life cycle stage is essential in order to reduce CDWW generation and build the secondary market for CE implementation. From this study, the following recommendations for waste minimisation and CE implementation are made:

- While the planning for waste prevention and reduction can reduce wastage significantly, the application of BIM and prefabricated elements can reduce wastage further in the pre-construction stage.
- As demolition projects produce huge wood waste, pre-demolition audits for reusable materials, selective deconstruction, and source separation of treated and untreated wood waste can improve recovery and waste utilisation.
- The LCA studies are limited to environmental viewpoints while integrating economic and social perspectives can bring sustainable development and CE implementation.
- More studies are still required to integrate the management side (collection, sorting, separation) and end-of-life scenarios for CDWW.
- The construction industries and the government need to be proactive and evaluate the benefits of reuse, recycling, and recovery of wood waste materials to implement CE into actual practice.

If the construction industries adopt the proposed framework for CDWW management and play a vital role in managing CDWW globally, it will boost the circular economy and bring sustainable development.

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