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**Araştırma Makalesi / Research Article**

# Life Cycle Assessment (LCA) Case Study on Cement-bonded Particle Board Produced By Using Construction Demolition Wood Waste

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## Abstract

Construction and Demolition Waste (CDW) is currently seen as one of the most important concerns that national authorities, particularly in Turkey, which is in the process of urban transformation and located in an earthquake zone. The search for alternative secondary raw materials for industries that use wood and its derivatives as raw materials is an important issue with the decrease on forest resources. CDW consists of bulky materials such as asphalt, bricks, wood and plastic. The main purpose of this study is use of waste wood those obtained by recycling the construction and demolition wood waste (CDWW) as cellulose source in production of cement-bonded particle board (CBPP). For this purpose, alkali treatment of CDWW was carried out by using alkaline solutions at four different concentrations of 2%, 3%, 5% and 8% NaOH by using the dipping method. A new cement-bonded particle board design was made using these alkali treated CDWW. The mechanical and physical performance tests of the produced particle boards were carried out and a recipe that yield the particle board having the best results was determined and a life cycle assessment study was conducted. As the recipes were produced by holding the cement/wood (c/w) ratio stable at 2:1, the best results were obtained from the boards produced by using CDWW that treated with 2% NaOH. The modulus of rupture (MOR), modulus of elasticity (MOE) and density tests were applied to the produced boards in accordance with TS EN 310 and TS EN 323 standard, respectively. The vaules obtained as a results of MOR, MOE and density test are 10.37 N $mm^{-2}$, 6437.28 N $mm^{-2}$ and 1255.12 kg $m^{-3}$, respectively. The experimental outcomes showed acceptable mechanical and physical performance of the developed CBPP in compliance with the required standards. The feasibility of the study was evaluated by conducting LCA studies for the most effective recipe. The global warming potential (GWP) value of the recipe with the best result as a 677.11 kg $CO_2$ equivalent was found. The results of this study can be considered as an effective roadmap for sustainability in all over the world and in appling secondy raw metarial CDW management.

**Keywords:** Construction demolition waste, cement-bonded particle board, recycling, LCA

## 1. Introduction

All over the world construction industry that create massive amounts of construction and demolition wastes (CDW) is a booming industry in metropolitan cities and rapidly developing municipalities in every year (Epd, 2015). Construction and demolition waste often constitutes a remarkable portion of the total municipal solid waste in giving rise to the environment deterioration (Lu and Tam, 2013). Although current regulations require central collection and processing of construction and demolition waste, most of this waste is sent directly to landfill or thrown away randomly. Additionally, large amounts of construction and demolition waste generated from infrastructure construction have been transferred from urban areas to rural areas (Huang et al., 2018). For instance, more than 50% of waste deposited in a typical landfill come from construction, whilst about 70 million tons of waste are also arise as a result of construction and demolition activities in the United Kingdom (Sealey et al., 2001). In another research in related with Australia waste mass, revealed that almost 14 million tons of waste have been discarded to landfill each year, and it is known that 44% of it is attributed by the construction industry (Lu and Tam, 2013). In the United States of America, almost 29% of solid-waste arises from construction (Rogoff and Williams, 2012). And this wastes in landfill bring about to major amounts of air, water and soil pollution due to the production of carbon dioxide ($CO_2$) and methane ($CH_4$) from anaerobic degradation of the waste. Hence, more and more rural areas and landfill are faced with the problem of construction and demolition waste day by day (Lu and Tam, 2013) and this situation creates important environmental problems that require urgent intervention. There are two generic approaches for dealing with construction waste. As a technical point of view, environmental engineers investigate how 'hard' technologies can help reduce, reuse, or recycle construction waste (Lu and Tam, 2013). In order to ensure sustainability, it is imperative that every existing waste be recycled and re-evaluated. Construction and demolition waste is one of the heaviest and the most voluminous waste. Many of these are recyclable. It consists of many materials such as concrete, brick, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil. Considering that raw material resources are limited, construction and demolition wastes must be used especially as secondary raw materials in order to protect natural resources and the environment (Lehto et al., 2018; Öztürk, 2017). Since wood waste is considered as a recyclable and renewable resource, usage of construction demolition wood waste (CDWW) for synthesis of cement-bonded particle boards (CBPB) is a prospective upcycling option (Wang et al., 2016). The raw material need of the industry is increasing rapidly parallel to the rapid development of the industry and, the amount of waste is also increasing at the same rate. On account of the availability of raw materials is not unending and the ecosystem is not able to absorb the infinite quantities of pollutants. Therefore, environmental damages have been risen (Jacquemin et al., 2012). This situation has encouraged the birth of environmental policy (Eliceche et al., 2007) and thereby the improvement of environmental assessment methodologies to reduce the environmental footprints of product manufacturing (Jolliet et al., 2005; Telenko et al., 2008). In this way, developed life cycle assessment (LCA) is an important tool to determine the effect of a product’s life cycle and the methodology of life cycle assessment which has been applied to products is a well-established analytical method to determine environmental impacts (Jacquemin et al., 2012). The aim of this study is to investigate the use of waste wood, which is likely to be found in construction and demolition waste, as a cellulose resource in the production of cement-bonded particle board by applying alkaline treatment. Also, it is aimed to evaluate of the physical and mechanical properties of the created new boards in order to determine their performance and to make case study life cycle assesment of the newly designed cement-bonded particle board.

## 2. Materials and Methods

### 2.1. Material supply

Throughout this study, during the production of trial boards, used CEM I 42.5 Portland cement (OPC, Grade 42.5R, Fineness 2.5%, Specific gravity 3.11 g cm$^{-3}$, Initial and final setting times are 150 and 220 min respectively., Aluminum sulfate ($Al_2(SO_4)_3$) is used as binder whereas, sodium silicate ($Na_2SiO_3$), dolomite ($CaMg(CO_3)_2$), fly ash are used as additive, Sodium hydroxide (NaOH) used for alkali treatment. All these compounds were obtained from the Research and Development Laboratory of Tepe Betopan A.Ş. Aluminum sulphate is solid, colorless and has a density of 1.71 g cm$^{-3}$. In addition, when it is in the form of 2% solution at 20ºC its pH value is between 2.5-3. Sodium silicate is supplied as a colorless, clear viscous liquid. While the bome value at 20°C is 39-41, the viscosity value is between 75-300 cp. Its density at 20°C was reported to be between 1360-1390 g cm$^{-3}$. The specific gravity of fly ash is 2.01 and its chemical composition is $SiO_2$ (58.5%), $Al_2O_3$ (25.48%), $Fe_2O_3$ (5.86%), CaO (1.47%), MgO (2%, 22), $SO_3$ (0.11%), $K_2O$ (4.04%), $Na_2O$ (0.59%), KK (1.19%), $Cl^-$ (0.011%). As the chemical composition of fly ash, the total of $SiO_2$, $Al_2O_3$, $Fe_2O_3$ is 89.69%. While the molecular weight of sodium hydroxide is 40 g mol$^{-1}$ and the other features are as like these extra pure, density 2.13 g cm$^{-3}$ (20°C), assay >= 98.0%, Sodium Carbonate ($Na_2CO_3$) <= 0.5%, Sodium Chloride (NaCl) <= 0.02%, Iron (Fe) <= 0.001%). In addition, the fresh wood (FW) supplied to be used in the control experiment was obtained from the Betopan factory of Tepe Betopan A.Ş. This wood was subjected to chipping process in the Betopan Factory production line and chipped wood sieved to pass through the 3 mm sieve. Then it was taken and used in the experimental studies. As to construction and demolition wood waste which is the main purpose of this study, was obtained from by collecting from different construction waste sites in Ankara location. Firstly, chipping process was applied to CDWW. In this study, the average thickness was tried to be kept constant between 0.40-0.55 mm and wood chips passed through the 3mm sieve. By virtue of this method, stability of the waste wood to be used in the cement bonded particle board samples was tried to be ensured.

### 2.2. Alkali treatment

The alkaline treatment was carried out according to the dipping method using sodium hydroxide solutions at different concentrations. Before the experimental study, the moisture value of CDWW was determined according to the TSE EN 322 standard. Weight of dry wood sample was calculated via this determined value and it was subjected to alkali treatment for 24 hours in NaOH solution at 2%, 3%, 5% and 8% concentrations, at a dry wood-solution ratio of 1:10. At the end of this period, the samples were washed with pure water until the pH value of the drained water decreased to 7. After this stage, it was conditioned and kept in laboratory conditions to be used in the production of CBPB.

### 2.3. Production of boards

Cement-bonded particle board production was carried out by using fresh wood, constuction and demoliton wood waste, and alkali treated constuction and demoliton wood waste. A large laboratory mixer was used to mix all materials homogeneously. Wood materials is placed into the mixer first. Then, aluminum sulfate, sodium silicate, dolomite and fly ash required for the production of cement-bonded particle board are added. Finally, the binder component cement is added to the mixture and mixed until a homogeneous mixture is achieved. It is aimed to make 10 mm cementitious particle board from this mixture. In line with this goal, the homogeneous mixture was poured into the mold and its surface smoothed (a 500x200 mm mold was used in the production process under laboratory conditions). Then the prepared mixture was taken, and then mixture was pressed by applying a 40 kg cm$^{-2}$ pressure. After production of CBPB with this method, the created CBPB were subjected to curing process period as follows. For this, CBPB are kept in a hot water bath with a temperature of 80 $^{o}$C for 10 hours. At the end of this period, the boards are removed from the hot water bath and left in laboratory conditions for 10 days to set. After the boards were set by air curing, experiments were carried out to determine the physical and mechanical properties of the plates in accordance with TSE standards.

### 2.4. Experimental test

The modulus of rupture and modulus of elasticity values of the trial board were determined in accordance with the principles described in the TS EN 310 standard. In addition, the densities of the boards was determined in accordance with the principles given in TS EN 323 standard.

### 2.5. Life cycle assesment case study

The life cycle assessment technique was performed to estimate the effect of the developed new CBPB product on the environment. Environmental impact of CBPB production was assessed by using the standard LCA techniques recommended by ISO 14040–14044 (ISO 14040, 2006; ISO 14044, 2006). In this study, open LCA software version 2.0 was used to evaluate the global warming potential (GWP) and cumulative energy demand (CED) of the particle boards prepared by using fresh and waste woods. Obtained results were compared to determine the usability of the waste woods in particleboards production. In additional, LCA studies of three different CBPB were carried out. These are defined as follows;

Study 1: CBPB prepared by using fresh wood.

Study 2: CBPB prepared by using construction and demoliton wood waste.

Study 3: CBPB prepared by using construction and demoliton wood waste that having the best mechanical and physical properties after alkali treatment.

In order to conduct an LCA study, it is necessary to know origin and supply method of the raw materials and the types and quantities of utilities used during the production phase. In addition, detailed information is required during the service life of the product maintenance-repair procedures applied during the its usage phase and the disposal process after the end of service life. For these reasons, in this study, it was decided to choose the cradle-to-gate method since sufficient data quality could not be provided after the product was produced (due to differences in climatic conditions, product lifespan and disposal conditions vary according to the development level of the countries). This method includes the stages of raw material supply, transportation and manufacturing. Because of the fact that the thickness and dimensions of the boards may vary, 1 m$^{3}$ volume was chosen as the unit function. In the cradle-to-gate method, calculations were made using ecoinvent v3.7 database on the amount of raw materials, the amount of utilities such as natural gas, electricity and water usage, suppliers and transportation data by distance, used by Tepe Betopan company in the process during 2022. In addition, since the CDWW used in the study were supplied from Ankara, calculations were carried out based on the farthest Ankara distance in LCA transportation calculations. Environmental impact results were evaluated using the Impact2002+ method.

## 3. Results and Discussion

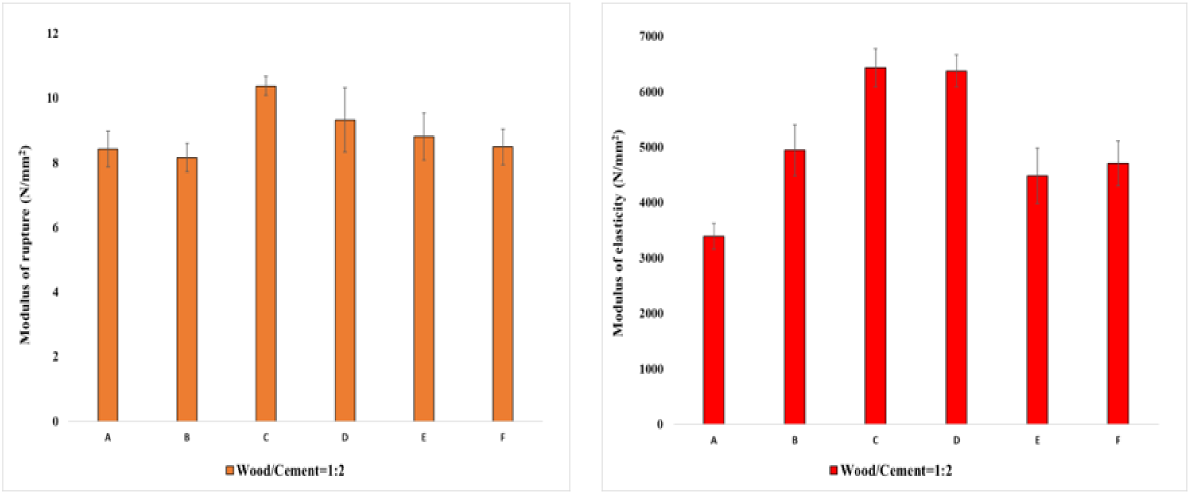
### 3.1. Experimental results

The general contents of the new designed cement-bonded particle boards for this study and their experimental test results according to standards (TS EN 310; TS EN 323) are presented in Table 1. In all produced CBPB wood-cement ratio of 1:2 was used and optimum design of the experimental studies is to maximize the MOE, MOR and density. Figure 1 illustrates that average modulus of rupture and modulus of elasticity values (with error bars) of produced cement-bonded particle boards prepared by using both fresh wood and construction and demolition wood waste and their relationship with each other.

**Table 1**. Content of the produced boards and experimental test results

| **Specimen Name** | **Content of Board** | | **Test Results** | | |
|---|---|---|---|---|---|
| | **Wood Type** | **Alkali Treatment** | **MOR (N/mm$^2$)** | **MOE (N/mm$^2$)** | **Density (kg/m$^3$)** |
| A | FW | % 0 NaOH | 8.42 | 3394.44 | 1188.59 |
| B | CDWW | % 0 NaOH | 8.16 | 4944.72 | 1251.83 |
| C | CDWW | % 2 NaOH | 10.37 | 6437.28 | 1255.13 |
| D | CDWW | % 3 NaOH | 9.32 | 6380.13 | 1259.46 |
| E | CDWW | % 5 NaOH | 8.81 | 4487.21 | 1261.77 |
| F | CDWW | % 8 NaOH | 8.49 | 4705.97 | 1269.23 |

According to the test results (Table 1), while board C has the highest MOR value of 10.37 N mm$^{-2}$, board B hads the smallest MOR of 8.16 N mm$^{-2}$. The highest MOR value is obtained for boards prepared by using CDWW treated with 2% NaOH, while the lowest MOR value was obtained for particle board prepared by using the untreated CDWW. In addition, the board C had the maximum MOE value of 6437.28 N mm$^{-2}$ while board A had the least MOE of 3394.44 N mm$^{-2}$. This highest MOR value is above the minimum standard of 9 N mm$^{-2}$ specified by standard (TS EN 634-2) for general for commercial and industrial purpose particle boards. Morover, MOE value for commercial and industrial particle boards is specified as at least 4000 and 4500 N mm$^{-2}$ for Class 1 and Class 2 boards, respectively according to the standard (TS EN 634-2). This obtained highest MOE value in this study fulfilled the TS EN standard requirement. Thereby, it could be said that the board (created by using %2 NaOH alkali treated CDWW) that meet these values can be used for structural purposes.



(a) (b)

**Figure 1.** Modulus of rupture and modulus of elasticity values of produced boards

The purpose of the alkali treatment is to dissolve and remove partially alkaline soluble components such as resins, hemicelluloses, lignin and pectin on the wood surface from the structure of the wood in order to clean and activate the surface of the wood (Altun et al., 2013). This could be attributed to reduction of surface impurities (noncellulose substances or cellulose-binding materials), including hemicellulose, lignin, oil, waxes, and other inorganic substances, which have potential to adversely affect the adhesion between the waste wood fiber and matrix (Alawar et al., 2009; Bergander and Salmen, 2002; Wong et al., 2010; Setswalo et al., 2019). As a consequence, this situation can be explained as a main reason of increase of mechanical properties (MOR and MOE values) of CBPB prepared by using alkali treated waste wood in this study.

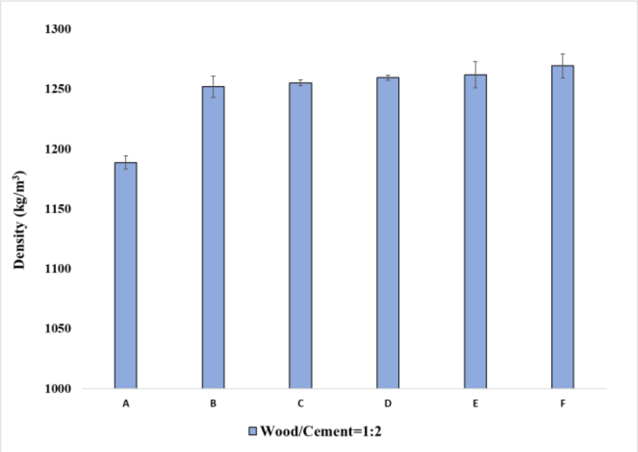


**Figure 2.** Density values of produced boards

Figure 2 reveals the average density values (with error bars) of produced cement-bonded particle boards by using both fresh wood and construction and demolition wood waste. In this study the density of CBPB made with CDWW is higher than those made with fresh wood. Maximum and minimum density values belonging to boards are 1269.23 kg $m^{-3}$ and 1188.59 kg $m^{-3}$, respectively (Table 1). While these were obtained for the boards treated with 8% NaOH with CDWW and were obtained for the boards prepared by using FW, respectively. It has been observed that alkali treatment generally increases density. However, no significant increase or decrease was observed in the density values. This can be explained by the compatibility of alkali-treated wood with cement in general. The main reason of these results could be attributed to the higher board-compaction ratio and fewer void spaces inside the boards (Nasser et al., 2016; Almeida et al., 2002). According to the standard (TS EN 634-2) specifies density value at least 1000 kg $m^{-3}$ for commercial and industrial purpose particle boards. As a natural consequence, all boards in this study meet this value and so can be used for structural purposes.

### 3.2. Life cycle assesment of CBPB production

LCA studies carried out in Study 1 (prepared using FW), Study 2 (prepared using CDWW) and Study 3 (prepared using alkali treated CDWW using 2% NaOH solution) were given in this section. In this study, the total global warming potential of new created cement-bonded particle boards, made by using the cradle to gate method, and its distribution in terms of raw materials, transportation and production are shown in detail in Figure 3. In addition, cumulative energy demand of these boards are shown in Figure 4. Approximately 85% of the GWP values in the studies came from the raw material supply (Figure 3). The main reason for this situation can be explained as the high environmental burden of the raw materials used in the process (Debnath et al., 2022). In addition, the GWP values of transportation is almost 4%, while that of production is 10% in this study. As a result of the LCA study, it was determined that the highest environmental impact was the raw material and it was emphasized that the importance of the use of secondary raw materials was vital. In the production of CBPB, which is a composite material, it has been observed that cement has a high effect on GWP, especially since it is the binding material. GWP values in this study are listed as Study 1, Study 3 and Study 2, from highest to lowest, respectively. These values are 733, 677 and 657 kg $CO_2$ eq, respectively. The fact that the highest value is in Study 1 is due to the use of fresh wood, which is the primary raw material. The fact that the lowest value is in Study 2 can be attributed to the fact that the environmental burden of waste wood is reduced by using it as a secondary raw material in the process instead of storing it in landfills and burning it. Additionally, the fact that Study 3 is higher than Study 2 can be attributed to the alkaline treatment with NaOH and the $CO_2$ emission of the NaOH production process. Therefore, CDWW provided an alternative solution for CBPB by creating a substitute for fresh wood and reduced the GWP value of new created CBPB.

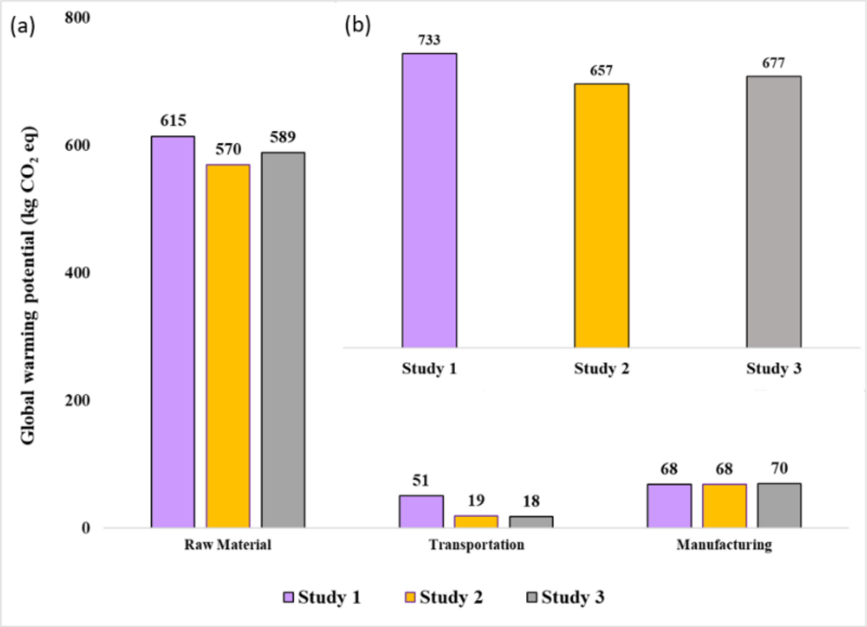


**Figure 3.** Life cycle assessment of new created CBPB from cradle to gate (a) contents of GWP (b) total GWP

The cumulative energy demand values in this study was obtained in parallel with the results of global warming potential values (Debnath et al., 2022). And so, while the peak value was obtained from Study 1 and the lowest value was acquired from Study 2. Again, in parallel with the GWP values, the CED value of Study 3 is higher than Study 2, while a lower value is compared to Study 1. The energy values of Study 1, Study 2 and Study 3 were found as 5392 MJ, 4174 MJ and 4818 MJ, respectively (Figure 4). Compared to Study 1, the cumulative energy demands of the new designed CBPBs produced with a secondary raw material, which is CDWW, decreased by 22.6% and 10.6% for Study 2 and Study 3, respectively. This situation showed the importance and potential of sustainability and circular economy.

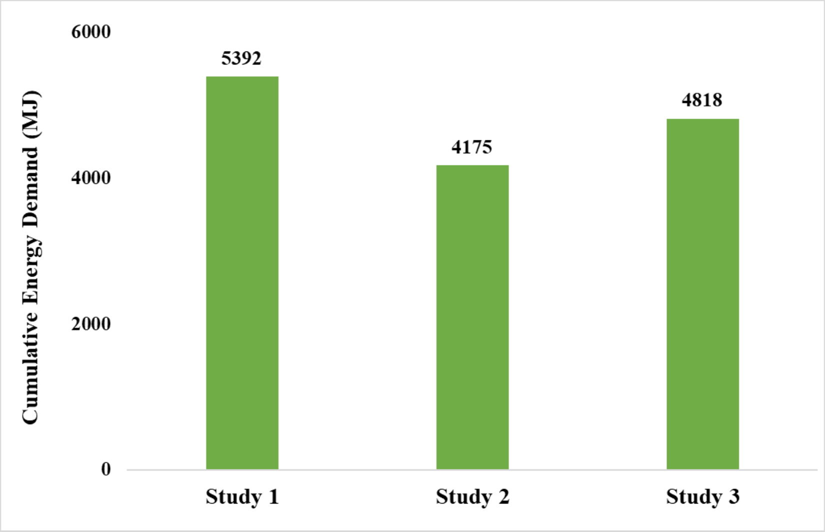


**Figure 4.** Life cycle assessment of new created CBPB from cradle to gate energy

## 4. Conclusions

The properties of new cement bonded particle boards designed by using contruction and demolition wood waste was evaluated acording to TS EN 634-2 standard. The following conclusions were drawn at the end of the research:

- While the peak MOR value was obtained from the highest board C (10.37 N mm$^{-2}$), the lowest MOR value was obtained from the B board (8.16 N mm$^{-2}$).Additionally, the highest MOE value was accurated from plate C, while the lowest MOE (6437.28 N mm$^{-2}$) value was accurated from plate A (3394.44 N mm$^{-2}$). The density values of the produced boards are generally very close to each other, and it has been observed that the density of the boards increases as the alkali solution concentration increases. It is known that the most important factor in the physical properties on the boards is the c/w ratio (2:1), and since this it is constant, the test results are very close. The experimental test results clearly showed that the positive effect of alkaline treatment on the mechanical properties of the boards. However, it was seen that the mechanical properties negatively affected as the alkali solution concentration step by step increases. Therefore, the optimum alkaline solution concentration was determined as 2% NaOH in this study, especially considering its positive effect on mechanical properties.
- Throughout this study, some assumptions was inevitably needed for carrying out comprehensive and multi-processes LCA. And so, system boundry were determined as clearly and the model of the LCA study that cradle to gate was used. In related to LCA studies, the GWP value was found as 733 kg $CO_2$ eq, while the CED value was 5392 MJ in Study 1 for the board produced using traditional fresh wood. For Study 2 and Study 3, the GWP values was 657 kg $CO_2$ eq and 677 kg $CO_2$ eq, while the CED value was 4175 MJ and 4818 MJ, respectively. Thus, whilst a decrease of 10.36% and 7.63% was achieved in the GWP value for Study 2 and Study 3, respectively, and also a decrease of 22.57% and 10.64% in the CED value was achieved. As a result, when manufacturing 1 m$^3$ CBPB by using CDWW instead of traditional fresh wood, 76 kg $CO_2$ eq and 56 kg $CO_2$ eq decreased in GWP values for Study 2 and Study 3, respectively. These values are equal to the $CO_2$ emissions released during the burning of 85.1 and 62.7 pounds of coal, respectively (EPA, 2023). Providing that the board is produced with this new method, the carbon emissions emited into nature will be decreased. In this way, this study will make an momentous contribution to both the protection of nature and sustainability.

- It was found that CDWW most promising recycled construction waste materials for composites cement-bonded particle board industries via this study. Additionally, taking into consideration that Turkey is an earthquake country and due to the massive of construction demolition wastes being welded from earthquakes, necessity of scientific studies on the recycling of these CDW.
- These results showcase that the proposed technological innovation presents a sustainability, eco-friendly, less carbon footprint and practical method option for construction and demolition wood waste.

## Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

## Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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