Embodied Energy of Plywood – A gate to gate study

Prakash Vijay Kumar[1*], Sujatha Dhanpal[1], Uday D Nagammanavar[1], Mamatha B Sehagiri[1], Kiran M Chandrojirao[1], K. Ch. Varadarajulu[1], Ramkumar V Ramamoorti[1]

{vijayp@icfre.org, sujathad@icfre.org, udaydn@gmail.com}

Plywood and panel Products Technology division Institute of Wood Science and Technology, Malleshwaram Bengaluru 560003

Abstract. Global warming and climate change are the environmental challenges that has intensified awareness of the ecological impacts of products throughout their lifecycle. This has driven consumers, architects, and builders to favour sustainable materials, often termed "green building materials." For a product to qualify as green, it must have minimal environmental impact and low embodied energy which could be assessed thorough Life Cycle Analysis (LCA). This study examines the gate-to-gate life cycle assessment of plywood manufacturing in India. Findings indicate that plywood offers significant environmental benefits compared to materials like steel, aluminium, and concrete. Plywood stores net carbon which was absorbed by wood during its growth retaining it throughout the life. Unlike conventional materials, which emit carbon during production, plywood only releases absorbed carbon when incinerated at the end of its life. Thus, plywood is classified as a green building material, supporting carbon neutrality and sustainability in construction industry.

Keywords: Embodied energy, Life Cycle Analysis, Green building material, Carbon Storage, Plywood.

1 Introduction

Wood is environmental friendly, aesthetically pleasing and products from wood are energy efficient compared to competing materials such as steel, concrete and plastic [1]. Not only beingone of the oldest and most commonly utilized building material but also renewable and biodegradableoffers wood substantial environmental advantages throughout its life cycle compared to other materials and stands out for its positive environmental attributes[2]. It can be sawn into timber as well as can be converted into composites viz. particle board [3], Block board [4], Flush door [5]and also structural panels viz. Laminated veneer lumber (LVL) [6] etc. to economically enhance its performance for various end use applications. Ever increasing population and development activities have put tremendous load on the forests which is the main source of timber [4] for a wide range of applications including construction. Uncontrolled commercial logging has resulted in numerous ill effects giving rise to global warming and climate change due to which stringent forest policies are in place today in most of the countries to check deforestation [7] as a result of which the availability of timber form

FPCS 2024, November 13-14, Bengaluru, India

DOI 10.4108/eai.13-11-2024.2355683

forest is limited and wood based industries are dependent on trees outside forest (TOF). Due to non-availability of timber a considerable number of wood based industries are being operated below their installed capacity [8]. To support wood based industries in terms of raw material, even agriculture by products are being utilized for producing panels like particleboard in Malaysia [9]. In India the demand for wood based panels are ever increasing [10] and the supply of timber raw material is not in pace with the demand [11]. Fast growing plantation timber species are studied for their suitability for panel manufacturing [12] and also comparative studies are being conducted among fast growing plantation timber species [13] to point out the most productive species in Indian climatic conditions so that the supply of timber raw materials may be improved for squeezing the demand and supply gap for raw material. These studies has resulted in a good number of panels successfully manufactured from fast growing plantation timbers species [7]. The wood based industries in India are managing to survive on the timber available outside forest, secondary species and other lesser known Indian hardwoods. Conservation oriented forest management policies and total ban on commercial logging from natural forest has led the panel industry in India to a situation of shortage of traditional timber raw material which is used for manufacturing wood based panels. The industry is dependent on imported timber species to some extent as a source of raw material [14].With this scenario of timber raw materials at hand for wood based industries, the need of the hour is to make efficient utilization of the available timber resources by adopting corrective measures in the production practices so that wastage can be minimized to enhance the timber recovery in the form of finished products.

In the recent past, environmental issues have gained an increasing priority both among producers and consumers. Today manufacturing industries are faced with stringent environmental policies and changing market trends in which consumers are more environmental conscious[15].[16]has observed that environmental issues have gained public awareness in most countries, besides global warming, other key-words in the ecological discussion are: resource management, environmentally friendly energy supply systems, eco-toxicology and human health etc. [16] has opined that the industries are more towards the sustainable management of natural resources which includes both minimal consumption of materials (renewable or non-renewable) and the protection/conservation of the environment, energy saving, improved use of materials, reuse & recycling, emission control etc. which are key measures that helps in achieving the goal of sustainability.

It is claimed that wood products require low production energy and creates few pollutants during production. In service, energy benefits are claimed based on the relatively high insulation value of wood in a structure and it is also claimed to be easily recycled. Wood products have the potential to play a major role in the development of a sustainable environment, particularly through the integration of material and energy flows in the construction sector with those in the forestry, energy, industrial and waste management sectors. The life cycle of wood building materials includes the growth of trees, the harvest of woody biomass from plantations, production of wood-based products, utilization and maintenance of the building, and the disassembly and end of-life management of the wood material [17]. [18] has observed that the idea to assess environmental impacts of wood products arose during the early 70^{th} of the last century as a result of the two oil crisis. Consequently, early research and case studies focused on energy consumption during production process. This was followed by extension of interest towards covering more environmental aspects and integrating the complete life cycle of wood products. During the sixties and seventies of the last century, environmental policy mainly focused on the reduction of emissions to land and water.[19] has recorded that the life cycle assessment (LCA) studies on forestry and wood products have generated international attention. In 2004, the Consortium for Research on Renewable Materials (CORRIM) published several wood product and forestry lifecycle inventories (LCIs) documenting the environmental performance of wood building materials from forestry operations through building construction and use known as the "CORRIM" reports, these extensive LCIs were the first publically available LCI studies covering US forestry and wood products production that followed international standards. Australia has also completed an extensive LCI database on forestry and wood products following the model of CORRIM Phase I LCI[20]. At a time when the wood industry is rethinking how they grow, manage, and produce products originating from forests, LCA studies produce the scientific information that documents the quantitative environmental impacts of their operations and prepares the industry for future "green" marketing opportunities.

If to be explained briefly, LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by:

1. Compiling an inventory of relevant inputs and outputs of a product system;
2. Evaluating the potential environmental impacts associated with those inputs and outputs;
3. Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

The current interest in LCA comes from government, industry, consumer and environmental groups.

Environmentally cleaner as well as energy efficient and waste sensitive wood based panels are gaining popularity in the current scenario. Society has become concerned about the issue of natural resources depletion and environmental degradation. Many industries have responded to this awareness by providing "green" products using "greener processes.

2.1 Gate to Gate LCA of Plywood

Plywood is a building material made of thin layers of wood known as veneers glued together with adhesives [21]. Veneer products, such as plywood and laminated veneers have been developed as an alternative to sawnwood as this method allows small logs from plantations and unimportant species to be utilized for high value commercial products[6]. Veneer products have various advantages over conventional solid wood such as increased dimensional stability, uniformity and higher mechanical strength, improved stress-distributing properties, reduced processing cost, availability in larger sizes, and better appearance [22].

Materials like plastic, metal and concrete etc. requires a lot of energy for extraction of raw materials andmanufacture. Moreover, these materials will result in a net carbon emission and is said to have a positive carbon footprint whereas the wood is said to have a negative carbon footprint because of the carbon dioxide from air which was taken up the original living tree remains in the final product unless incinerated and the emissions associated with harvesting, transporting and processing of wood products are small compared to the total amount of carbon stored in the wood. This means that even when energy used for harvesting, transport and processing are taken into account, there is a net storage of carbon in wood. In any industry, the three top operating expenses are often found to be energy (both electrical and thermal), labour and materials, of all thesethe energy component is expensive and thus energy management function constitutes a strategic area for cost reduction.LCA study of plywood reveals the energy requirement for conversion of wood into plywood which can be compared with conventional non-wood constructional material like steel, aluminium, cement, asbestos or plastics.Any production unit of building component releases carbon dioxide due to burning of various types of fuel. Conversion of raw material into products mechanically through input of energy, always results in emission of harmful gases and release of pollutant effluent. The study is expected to reveal the impact of production of plywood compared to other panels such as asbestos, steel and concrete etc.

2.2 Goal of the Study

Goal of study is to examine the environmental impact of plywood manufacturing in terms of carbon footprint, electrical and thermal energy consumption during various production stages focusing gate-to-gate approach.

2.3 System Boundaries for gate to gate plywood production

This study has taken into account the inputs and outputs at plywood facilities starting from the raw material arrived at the gate through manufacturing of plywood and delivery at the gate. The upstream and downstream activities beyond the gate i.e. energy spent in raising the plantations, maintaining, harvesting and transport the same at the gate is not taken into consideration. In the same way, the energy spent in utilizing, maintaining and end of life and corresponding emissions are not taken into considerations. Figure 1 summarizes the system boundaries for gate to gate life cycle assessment of plywood.

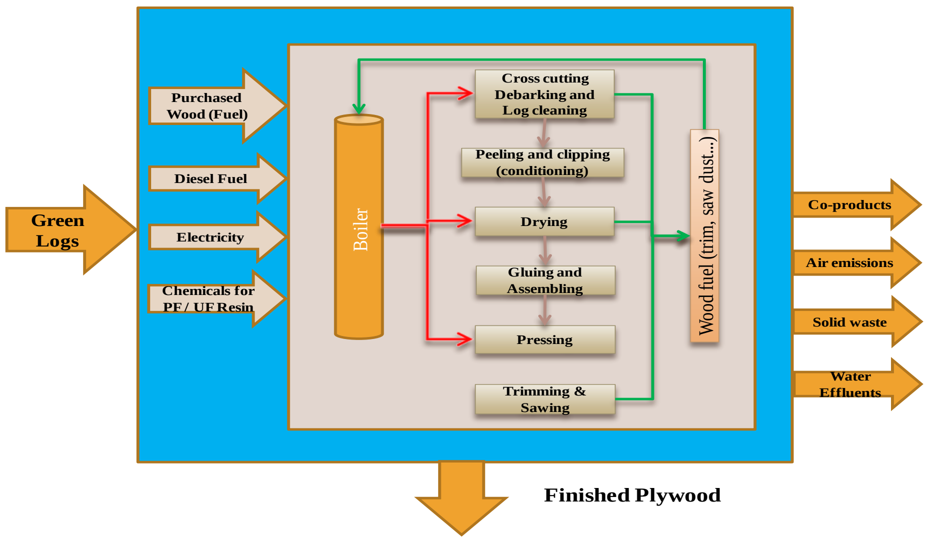

Fig.1. - System boundaries for plywood life cycle assessment

From the figure it is clear that whatever wood waste viz. sawdust, trim waste, odd size veneer generated within the manufacturing facility is utilized as fuel to run the boiler to generate thermal energy required for veneer drying and hot pressing of plywood. Flow chart for plywood manufacturing is shown in figure 2.

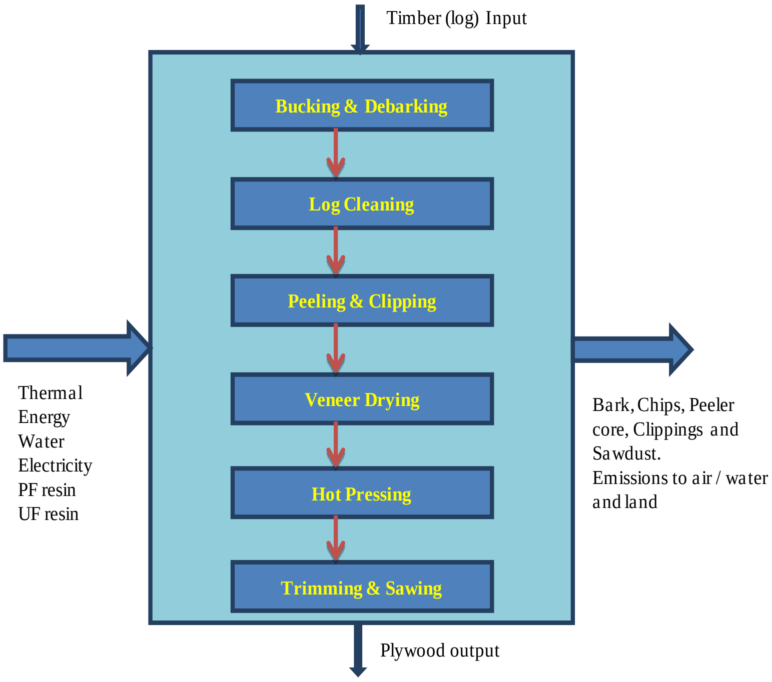

Fig. 2 Flow chart for plywood life cycle assessment

2.4 Scope of the Study

The scope of the study includes following processes which constitute plywood production:

- Logs are peeled into veneer sheets and dried
- Phenol-formaldehyde / Urea-formaldehyde resin is then applied to the dried veneers
- These veneers are stacked with grain orientation at right angles in successive layers
- The stack is put into a hot press where pressure and heat are applied to consolidate the glue coated veneers into a panel.
- The cured panel is then unloaded from the press, allowed to stabilize and trimmed to standard sizes.

2.5 Functional Unit

The functional unit helps in scaling the results conveniently for different quantities of products.

Results of this study is quantified for 1 m^3 of finished plywoodwhich is considered to be the functional unit.

The specifications of the product are as mentioned below:

- Average thickness of product- 12 mm.
- Average Size of product - 2.67 sq. m
- Moisture content approximately 8 percent in finished plywood.
- Indian standard governing the quality of plywood – IS: 303.

2.6 Plywood production was modelledin Gabi4 a LCA software, based on:

a) Primary process data on energy and materials consumption as well as measured direct emissions which was collected from four manufacturing sites.

b) Calculated emission using emission factors for emissions from diesel combustion and electricity and direct carbon dioxide emissions related to materials (fuel wood and woody biomass).

c) Upstream data were utilized by GaBi (software for LCA studies).

Plywood production consists of several processing stages. Though the practices are different in different plywood manufacturing facility processes involved in converting the timber in to plywood remains the same. Material conversion during various stages of plywood manufacturing is shown in figure 3.

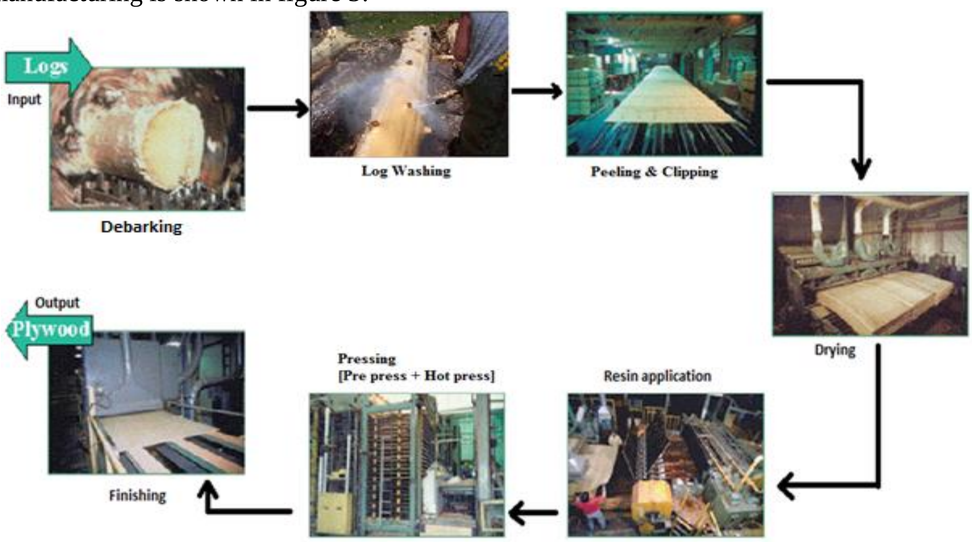

Fig. 3 Stages of material conversion in Plywood Production

Since manufacturing units at four different locations of country was selected for this study, a general model was developed as shown in figure 4 so as to maintain the uniformity of the study.

2.7 Raw material used

1. Base material: Wood in the form of veneer with 4-6% moisture
2. Phenol formaldehyde (BWR grade panel)**:** Resin polymer with approximately 50% non-volatile, 1-2% free formaldehyde, very small quantity of free phenol and rest water, sodium hydroxide 6-8%.
3. Urea formaldehyde (MR grade panel): Resin approximately 50% solid content, 1-3% free formaldehyde traces of urea and rest water.

4. Extender: Any one or more of the following components: coconutshell flour, ground nut cake powder, wheat flour.
5. Preservative: Organic chlorophosphate.

3 Plywood Manufacture

Timber logs are debarked and cleaned. Too dry logs or high density logs are boiled for heat treatment. Logs are peeled to ribbon of veneer which are clipped to desired size eliminating defects. Veneers are then dried to desired moisture content. Dried veneers are segregated into face (top and bottom) glue core and parallel core. Glue core veneers are glued with amino or phenolic resin based adhesive and veneers (glued and non-glued) are laid in definite fashion on metal caul plates.

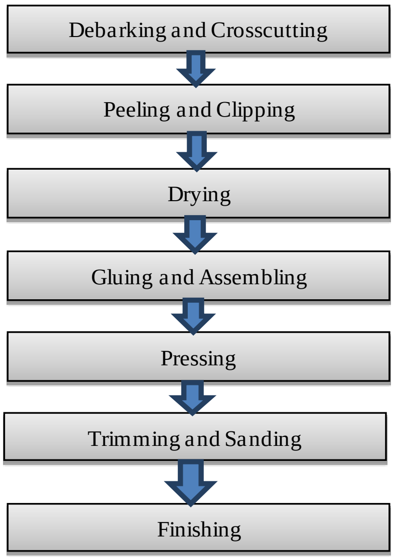

Fig.4 Model Developed for LCA of Plywood

The assemblies are hot pressed under high pressure during which the resin polymer undergoes irreversible reaction forming network holding the veneer in place to give sheet/material. Finally, plywood sheets are trimmed to definite size and sanded on the surface and stored before dispatch for market.

The material flow for plywood product is shown in figure 5 below. The material flow illustrates various processes beginning with the receiving of wooden logs at the factory gate. The log is then debarked and converted in to veneer. After drying of veneer, it is assembled using glue and other additives. Assembled veneer is then pressed under elevated temperature and pressure to get unfinished plywood which is then trimmed on all the four sides to get the finished plywood. This finished plywood if required, is then treated with suitable chemicals to enhance termite resistance, borer resistance properties to get the finished plywood. Final treatment of assembled plywood results in the finished plywood product which is then transported out of factory gates.

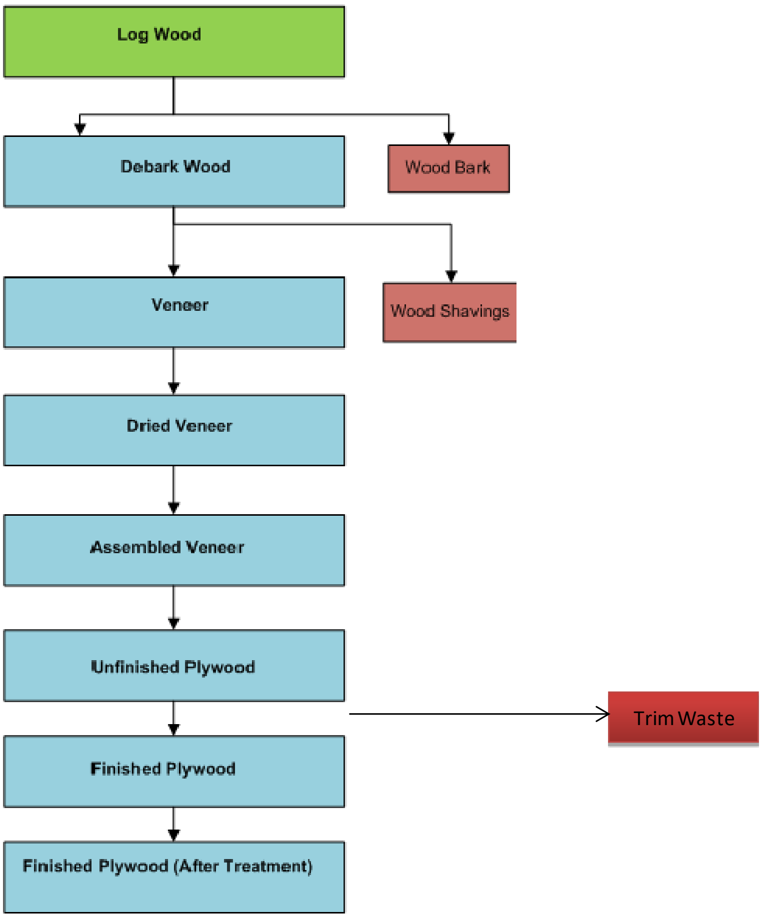

Fig. 5.- Material flows for plywood production

4 Procedure

In this study four factories were studied, i.e. data were collected from four different factory premises, for honouring the non-disclosure agreement signed during the data collection from the factories and for the sake of understanding these factories are labelled as factory A, B, C and D. Factory A does not have any peeling lathe hence do not peel veneers and only purchases the veneers and processes it in to plywood. Whereas factories B, C and D peel veneers internally i.e. Logs are purchased and the veneering is done in the factory itself. Data collected from these factories includes the raw material consumption such as veneers, timber, chemicals viz. phenol, formalin etc. and energy consumption such as electrical and thermal energy etc. output of finished products, co-products and effluents were also collected. These data were used as inputto the model developed in Gabi 4 the software tool used for LCA studies and simulated. The output thus obtained are discussed below.

5 Result Analysis

A comprehensive gate to gate Life Cycle Assessment study has been conducted for 1 m^3 of finished plywood. This study has examined the environmental impact of plywood production process employing gate-to-gate approach. The study is based on primary data collected from manufacturers which includes material and energy consumption data for individual processes. A detailed model was prepared using GaBi 4 software and secondary data was sourced from GaBi 4.4 professional database 2011.

The study has allowed to determine carbon dioxide emissions for individual processesas well as broken down into biogenic and fossil emissions; wherein biogenic emission is due to burning of wood waste and fossil emission is due to generation of electricity which is consumed at the factory. Carbon dioxide sequestered during each process in the way of output product has also been carefully assessed. Table 1 gives the electrical energy consumed at different process in all the factories, it can be clearly seen that the drying of veneers consumes more energy than any other process inferring that drying is an energy intensive process. Table 2 gives the thermal energy consumed in drying and pressing and again from the table it is clear that drying of veneers consumes more thermal energy than pressing of glued veneers in to plywood.

Table 1 Electrical energy consumption in MJ at different processes for Manufacture of 1 m^3 of Plywood

Factory	Debarking and cross cutting	Peeling and clipping	Drying	Gluing & assembling	Pressing	Trimming & sanding
A	-	-	70.142	22.65	43.55	24.72
B	3.43	147.24	159.8	118.3	98.45	88
C	2.8	58.01	75.94	34.02	80.89	41.1
D	5.8	114.52	68.38	44.5	64.31	30.67

Table 2 Thermal energy consumption in MJ for Manufacture of 1 m3 of Plywood

Factory	Drying	Pressing
A	3934.2	983.55
B	5415.11	1353.77
C	5058.56	1264.64
D	4053.5	1013.37

Table 3 Emission in Kg for Manufacture of 1 m^3 of Plywood

Factory	Fossil	Biogenic
A	58.45	722.29
B	223.32	994.18
C	106.27	929.24
D	107.53	744.19

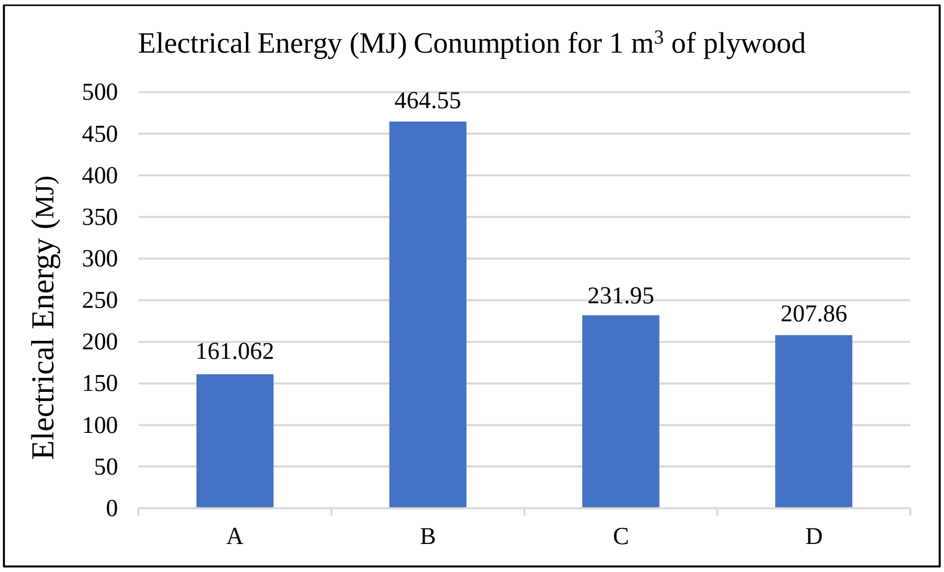

Fig. 6 Factory wise electrical energy consumption in MJ.

Key findings from the gate-to-gate study reveal that 618.324 mega joule (MJ) or 171.75 Kilo watt (kWh) of electrical energy is consumed for producing 1 m^3 of finished plywood while 2528.84 MJ of thermal energy is required for production of 1m^3 of plywood. Total carbon dioxide sequestered is 2684.987 kg CO_2. The biogenic carbon dioxide emission is 1171.2 kg while fossil carbon dioxide emission is 49.477 kg due to electricity consumption at various stages of plywood production.

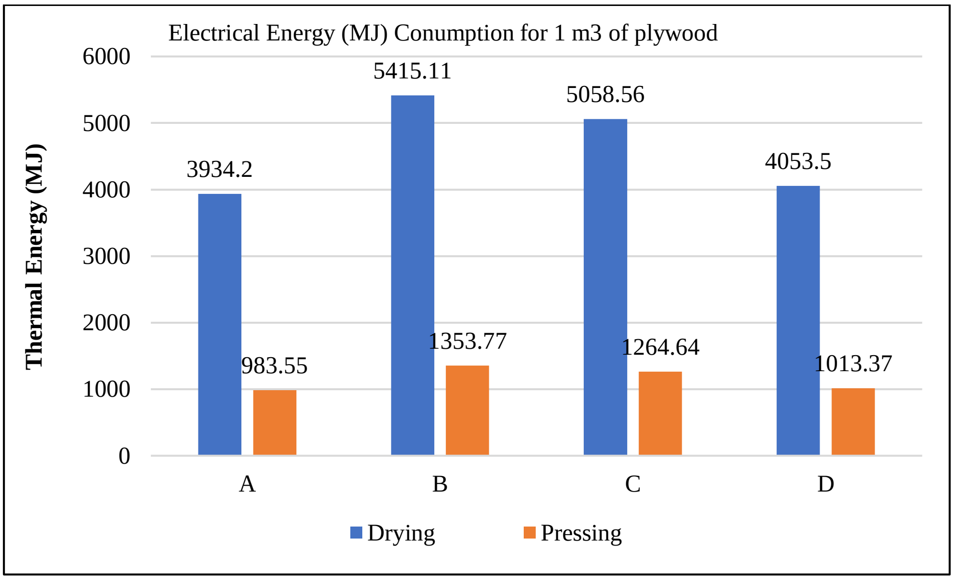

Fig. 7 Factory wise electrical energy consumption in MJ

Table 4 Net sequestered in Kg for Manufacture of 1 m^3 of Plywood

Factory	Sequestered	Emission	Net Sequestered
A	1754.94	-786.9	968.04
B	2427.4	-1227.8	1199.52
C	2057.66	-1042.37	1014.79
D	2.79.1	-897.35	1481.75

The study has also revealed that 1821 kg of net carbon dioxide is sequestered in 1 m^3 finished plywood. This figure has been arrived at by considering the carbon dioxide in the log wood (1910.312 kg CO_2) which is the raw material and then adding any additional carbon dioxide sequestered during the production process (1074.4 kg during drying and 1008.15 kg during pressing due to purchased wood waste used for thermal energy generation) and subtracting biogenic carbon dioxide emission resulting due to consumption of biomass (1171.2 kg during drying and 49.477 kg during pressing) and also subtracting the released due to generation of electricity using diesel (equivalent to 1 cubic meter of plywood).

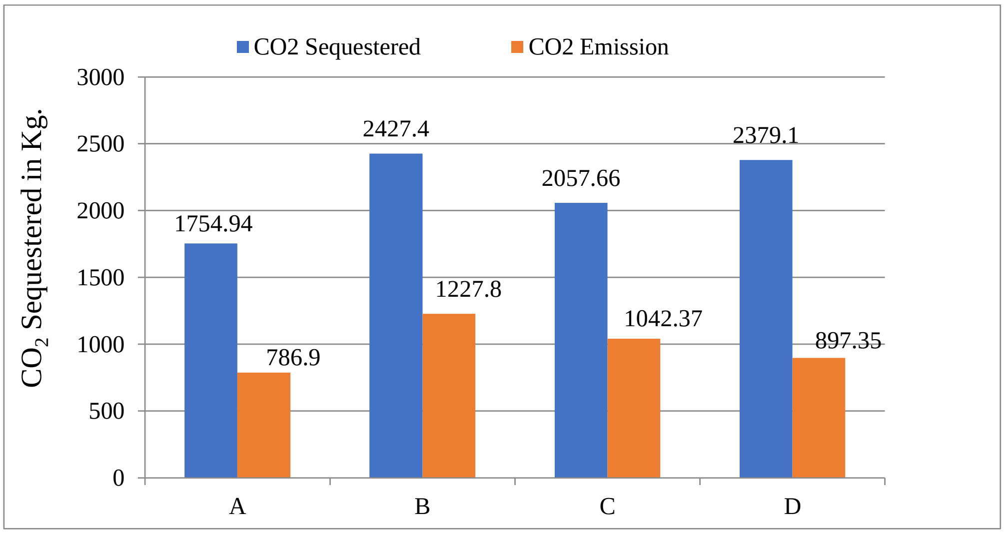

Fig. 8 Carbon dioxide emission and sequestered for manufacturing 1m^3 Plywood.

6 Conclusions

Detailed examination of the plywood production process and associated energy consumption reveals that electricity consumed for plywood production has significant influence on the environmental impact. It is for this reason that electricity conservation measures are highly important and well-implemented measures can substantially contribute in reducing the overall primary energy demand. Some of the suggested measures are avoiding idling of machines and use of electrical equipments with higher efficiency. Variable voltage variable frequency(VVVF) drives, when employed for electric motors have proven to be highly efficient compared to conventional methods.

Inspection of results presented in this study reveals that drying of veneers is an energy-intensive process accounting for significant percentage of total energy demand and subsequently contributing to global warming potential. It is for this reason that moisture content in the veneers prior to drying assumes heightened importance, operating the drier with full capacity at all times shall ensure efficient usage of thermal energy. Drier efficiency needs to be given due attention to ensure that it operates in the most energy efficient manner. Boiler efficiency is also critical as considerable amount of thermal energy is used for plywood production.

Plywood production process involves significant wastage of wood at various stages such as peeling & clipping and trimming & sanding. Yield improvement can effect saving of raw materials and increase plywood output for unit input of log wood. Reduction of wastage will also result in reduced energy consumption as the quantity of output is increased for the same input energy and raw material which will, in turn reduce the environmental impact.

Production of plywood requires several chemical agents such as formalin, urea, phenol, boric acid, copper sulphate etc. Replacing these with eco-friendly alternatives can be looked upon to make plywood eco-friendlier.

Since the plywood production has a negative carbon foot print. i.e. production of plywood locks a net amount of carbon dioxide in the finished product. It is a carbon negative or climate positive panel and hence, it may be regarded as green building material compared to other building materials such as steel, concrete, aluminium.

References

[1] M. R. Milota, C. D. West, and I. D. Hartley, "Gate-to-gate life-cycle inventory of softwood lumber production," *Wood Fiber Sci*, vol. 37, pp. 47–57, 2005.

[2] V. R. Ramkumar, N. Anand, V. Prakash, D. Sujatha, and G. Murali, "Experimental study on the performance of fiber-reinforced laminated veneer lumber produced using Melia dubia for structural applications," *Constr Build Mater*, vol. 417, p. 135325, 2024, doi: 10.1016/j.conbuildmat.2024.135325.

[3] V. Prakash, D. N. Uday, D. Sujatha, and M. C. Kiran, "Physical and Mechanical Properties of Particle Board from Lops and Tops of Melia dubia," *Int J Sci Res*, vol. 6, no. 5, pp. 2319–7064, 2015, [Online]. Available: www.ijsr.net

[4] M. P. Singh, V. Prakash, D. N. Uday, D. Sujatha, and M. C. Kiran, "Block Board from Melia dubia," *Int J For Wood Sci*, vol. 7, no. September, pp. 96–100, 2020.

[5] V. Prakash, D. N. Uday, D. Sujatha, V. K. Chawla, and M. C. Kiran, "Suitability of Melia dubia for Manufacture of Flush Door," *Int J Sci Res*, vol. 10, no. 10, pp. 644–648, 2021, doi: 10.21275/SR211005154104.

[6] D. K. M. C. N. Prakash, V; Uday, D N; Sujatha, "Laminated Veneer Lumber (LVL) from Fast Growing Plantation Timber Species Meliadubia," *Int J Sci Res*, vol. 8, no. 4, pp. 1721–1723, 2019.

[7] V. Prakash *et al.*, "Panel products from Melia dubia," *Indian For*, vol. 148, no. 12, p. 1259, 2022, doi: 10.36808/if/2022/v148i12/166520.

[8] S. Setunge, K. K. Wong, and M. Jollands, "Economic and environmental benefits of using hardwood sawmill waste as a raw material for particleboard production," *Water, Air, Soil Pollut Focus*, vol. 9, no. 5–6, pp. 485–494, 2009, doi: 10.1007/s11267-009-9224-z.

[9] S. Jusoh, K. Nordin, and M. A. Jamaludin, "Gate-to-Gate Life Cycle Analysis of Particleboard Production in Malaysia," pp. 481–486, 2013.

[10] Upadhayay V K and Mohanty B N, "Trends and perspectives of Indian wood based panels," *Asian J Curr Eng Maths*, no. April, 2016, doi: 10.15520/ajcem.2016.vol5.iss2.51.pp35-40.

[11] R. S. Chauhan, D. B. Jadeja, N. S. Thakur, S. K. Jha, and M. S. Sankanur, "Selection of Candidate Plus Trees (CPTs) of Malabar Neem (Melia dubia Cav.) for Enhancement of Farm Productivity in South Gujarat," *Int J Curr Microbiol Appl Sci*, vol. 7, no. 05, pp. 3582–3592, 2018, doi: 10.20546/ijcmas.2018.705.414.

[12] K. T. Parthiban, S. Dey, N. Krishnakumar, and A. Das, "Wood and plywood quality characterization of new and alternate species amenable for composite wood production," *Wood Fiber Sci*, vol. 51, no. 4, pp. 424–431, 2019, doi: 10.22382/wfs-2019-040.

[13] Dhiman RC and Gandhi JN, "Comparative performance of Poplar , Melia and Eucalyptus based agroforestry systems," *Indian J Agrofor*, vol. 19, no. 2, pp. 1–7, 2017.

[14] V. Prakash, M. P. Singh, D. N. Uday, D. Sujatha, M. C. Kiran, and N. Murthy, "Indian Timbers for Veneering - A Review," *Indian For*, vol. 147, no. 5, p. 431, 2021, doi: 10.36808/if/2021/v147i5/154878.

[15] D. R. J. Murphy, "Review of Information on Life Cycle Analysis of Tropical Timber Products," vol. 04, no. August, p. 66, 2004.

[16] B. Solberg and A. Frühwald, "Life-cycle analysis : a challenge for forestry and forest industry : proceedings of the International Workshop organised by the European Forest Institute and the Federal Research Centre for Forestry and Forest Products, 3-5 May 1995, Hamburg, Germany," in *Proceedings of the InternationalWorkshop organised by the European Forest Institute and the Federal Research Centre for Forestry and Forest Products*, Arno Frühwald and Birger Solberg, Ed., Hamburg, 1995, p. 278.

[17] R. Sathre and S. González-García, "Life cycle assessment (LCA) of wood-based building materials," *Eco-Efficient Constr Build Mater Life Cycle Assess (LCA), Eco-Labelling Case Stud*, pp. 311–337, 2013, doi: 10.1533/9780857097729.2.311.

[18] F. Werner and K. Richter, "Wooden building products in comparative LCA: A literature review," *Int J Life Cycle Assess*, vol. 12, no. 7, pp. 470–479, 2007, doi: 10.1065/lca2007.04.317.

[19] M. E. Puettmann and J. B. Wilson, "Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials," *Wood Fiber Sci*, vol. 37, no. 2001, pp. 18–29, 2005.

[20] J. B. Wilson, "Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon," *Wood Fiber Sci*, vol. 42, no. SUPPL. 1, pp. 107–124, 2010.

[21] E. M. Hlaing and A. M. Lwin, "A Study on Analysis of Product Quality Problems in Plywood Production of No Plywood Factory in Myanmar," vol. 6, no. 1, pp. 1739–1744, 2021.

[22] C. Tenorio, R. Moya, and F. Munoz, "Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing Gmelina arborea trees," *J Wood Sci*, vol. 57, pp. 134–139, 2011, doi: 10.1007/s10086-010-1149-7.