

Gate to gate life cycle assessment of plywood manufacturing in India

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Abstract: A gate-to-gate life cycle assessment (LCA) study was conducted for 1 cubic meter (m³) of finished plywood with density 600 kg/m³ for four different plywood manufacturing facilities based on their location, production capacity and the variety of products manufactured. Primary data on inputs (raw materials, energy consumption, etc.) and the outputs (plywood and the byproducts) were collected through questionnaires by interacting with staff working in different sections of the production plants. Primary data collected were used to simulate the plywood manufacturing process in GaBi (software for LCA) and secondary data was sourced from the GaBi professional database 2011 to ascertain its environmental impacts in terms of material use and emissions. Primary energy demand, greenhouse gases (GHG) and other organic and inorganic emissions have been determined for various processes involved in plywood production. Carbon dioxide (CO₂) emissions broken down by individual processes as biogenic and fossil emissions and also (CO₂) sequestered during each process by the way of output product have also been carefully assessed. Major electrical energy consumption is found to be in veneer peeling, veneer drying, and hot pressing of plywood, whereas veneer drying is found to be thermal energy intensive, which gives impetus to develop energy-efficient veneer dryers with automation. Material recovery varies from factory to factory for various reasons, such as the quality of the logs, the skills of the laborers/machine operators, etc. The highest material recovery of all the factories considered in this study is found to be 63%, which is a clear indication of ample scope for improvements. Variation in the electrical and thermal energy was observed for different production facilities, mainly due to the production practices and extent of mechanization involved. It is inferred from the study that compared to other materials, viz., steel, aluminum, etc., plywood stores a net amount of carbon than emitted during its manufacture, which is mainly attributed to wood, a biogenic material that absorbs CO₂ from the atmosphere and is the major raw material for plywood manufacturing, and hence plywood can be regarded as a green building material.

Keywords: life cycle analysis; green building material; carbon storage; plywood; greenhouse gases (GHG)

1. Introduction

The construction industry contributes significantly to greenhouse gas (GHG) emissions, responsible for almost 40% of total carbon emissions [1]. Wood-based panels are products used in various applications with the potential to replace energy-intensive materials while promoting carbon sequestration. Wood products when biogenic carbon sequestration is considered have a negative global warming potential (GWP) [2]. Wood is one of the oldest renewable resources used by human beings, serving as a key building material for centuries [3]. Apart from being known as pro-environment and natural material, wood possesses the quality of good aesthetics and energy efficiency compared to materials like steel, concrete, and

plastics, etc. [4], which is an added advantage in the market, which is driven by sustainability and environmentally friendly materials. Wood has an edge over its competitors in terms of embodied energy, i.e., energy required to produce a unit quantity of material; e.g., one ton of plywood requires 1.5 million Kcal of energy, whereas concrete, steel, and aluminum require 2.15, 12.68, and 50.51 million Kcal, respectively. Wood can be sawn into timber as well as converted into composites such as particleboard [5], block board [6], flush door [7], and structural panels, viz., laminated veneer lumber (LVL) [8], etc., to enhance its performance economically depending on its end-use applications. Increasing populations have put a tremendous load on natural forests, which are the main source of timber [6] for a wide range of applications, including construction. Unregulated commercial logging has resulted in many ill effects, giving rise to global warming and climate change, due to which stringent forest policies are in place to check deforestation [5], as a result of which the availability of timber from natural forests is limited, and industries now, to a great extent, depend on trees outside forests (TOF). Due to the non-availability of timber, many wood-based industries are being operated below their installed capacity [9]. To support wood-based industries in terms of raw material, even agricultural residues and byproducts are being utilized for producing composites like particleboard in Malaysia [10]. Demand for wood-based panels is ever increasing in India [11], and the supply of timber raw material is not in pace with the demand [12], which has led to a scenario of timber raw material shortage. Fast-growing plantation timber species are studied for their suitability for panel manufacturing [13]; also, comparative studies are conducted among fast-growing plantation timber species [14] to point out the most productive species in Indian climatic conditions so that the supply of timber raw materials can be improved, thereby squeezing the demand and supply gap for raw material. 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 as to minimize the wastage and to enhance the timber recovery in the form of finished products, thereby reducing its impact on the environment.

2. Plywood and its manufacturing

Plywood is a veneer-based structural wood composite mainly used in the furniture and construction industries [15–17]. Plywood manufacturing includes peeling a wooden log into veneers, clipping these veneers to eliminate the defects, drying the veneers, gluing, assembling, hot pressing the assembly, and trimming and sanding. A pictorial flow chart of plywood manufacturing is shown in **Figure 1** below.



Figure 1. Plywood manufacturing process.

A brief description of each process in plywood manufacturing is given below.

- a) **Debarking**—Logs prior to peeling are debarked, i.e., the removal of bark. Else any foreign objects such as stones and iron implants such as nails present in the log shall chip off the peeling knife.
- b) **Peeling**—Debarked log is subjected to peeling during which, based on the adjusted peeling lathe settings, veneers of required thickness are peeled and rolled for subsequent handling without causing any damage.
- c) **Veneer clipping**—A ribbon of veneer is now clipped to the required dimensions for further processing. The size of the panel generally is 4 feet \times 8 feet. However, the veneers are clipped by giving an allowance of 1 inch on all sides for final trimming.
- d) **Drying**—Green logs peeled will yield veneers of higher moisture content ranging from 60%–90%. For applying glue, the required moisture content is about 6%–8% maximum, and hence the wet veneers are dried using either a band dryer or roller dryer. Efficiency of the drying process is crucial, as this is an energy-intensive process.
- e) **Gluing and assembling**—Veneers dried to the required moisture content are then applied with a suitable adhesive based on the end-use application. Care is taken to apply the optimal quantity of adhesive to the veneer surface, as both high and low rates of gluing are not desirable, which brings down the quality of the final panel. Adhesive-coated veneers are then assembled with the grain direction in any two consecutive veneers being orthogonal to each other. Assembly of the panel will be higher than the target thickness of the panel for accommodating compression loss, which occurs during hot pressing.
- f) **Hot pressing**—The assembled veneers are subjected to elevated temperature and applied specific pressure (pressure per unit area of the panel), which depends on the adhesive used. Pressing time basically depends on the final thickness of the panel.

- g) Trimming and sanding—Unloaded hot-pressed plywood is then allowed to cool and stabilize, after which it is trimmed on all four sides for final dimensioning. The panel is finally subjected to sanding to obtain smooth surfaces on both sides.

Product standard (India):

Plywood (MR/BWR grade): IS:303/2006.

Product standard in India for plywood: IS: 303-2006 (MR (Interior)/BWR (Exterior)).

Binder type: Urea formaldehyde and phenol formaldehyde resin-based adhesive as per IS: 848/2006.

Raw material used:

- a) Base material: Wood in the form of green log and veneer with 6%–8% moisture
- b) Phenol formaldehyde: Resin polymer with approximately 50% non-volatile, 1%–2% free formaldehyde, a very small quantity of free phenol, and the rest water, with sodium hydroxide at 6%–8% by weight of phenol.
- c) Urea formaldehyde: Resin approximately 50% solid content, 1%–3% free formaldehyde, traces of urea, and rest water.
- d) Extender: Any one or more of the following components: coconut shell flour, groundnut cake powder, wheat flour.
- e) Insecticide: Organic chloro phosphate, copper sulphate, sodium dichromate, boric acid.
- f) Hardener: acid salts.

3. Life cycle assessment

Life cycle assessment is a perfect tool to address the scope of improvements in production practices of any product to enhance the efficiency and promote sustainability. The product life cycle starts from the extraction of raw material, processing them into finished goods, the service period, and the end of life, including the possibilities of reuse or recycling. Each stage in a product life cycle has its own inputs, outputs, and impact on the environment. Life cycle assessment (LCA) methodology is found to be a valuable tool to analyze systematically the impact that a product or service has on the environment [18]. Details of inputs (energy, raw material consumption) and output (products, by-products, air emissions, landfill, etc.) can be drafted down, which provides ample opportunities to enhance the process efficiency and to reduce the environmental impacts by minimizing the wastage. The LCA study is to be governed by the standards set by the International Organization for Standardization (ISO) as in ISO 14040 (2006) and ISO 14044 (2006). The results of LCA are always with respect to a unit quantity known as the functional unit of the product under consideration. Inputs and outputs corresponding to 1 unit of the product manufactured at optimal conditions and minimal impact on the environment can be considered as a benchmark which can be used as a reference to compare and optimize the performance of the other production facilities. The quality of the raw data collected from a production facility on the usage of various resources and corresponding outputs shall define the accuracy of the outcome of an LCA study.

4. Goal and scope

4.1. Objective

The goal of the study comprises understanding the environmental impact in terms of carbon footprint and energy consumption during various production stages of plywood manufacturing based on a gate-to-gate approach. The study also includes assessment of carbon footprint in terms of biogenic sequestration, i.e., intake of CO₂ by wood logs, carbon storage in finished plywood composites, carbon dioxide emission (fossil and biogenic) due to consumption of electricity and use of thermal energy during production processes. The study also involves comprehensive energy mapping for various processes during the production of plywood in Indian manufacturing conditions.

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

- a) Veneering (logs peeled into veneer sheets and dried).
- b) Application of phenol-formaldehyde/urea-formaldehyde resin to the dried sheets.
- c) Assembling of glue-coated veneers.
- d) Hot pressing of assembled veneers.
- e) Finishing (trimming, sanding and stacking).

This study determines energy demand, product carbon footprint, i.e., carbon dioxide emissions for each process of plywood production. The LCA methodology applied to this study comprises the evaluation of the environmental impact of various activities associated with the production of plywood employing a gate-to-gate approach.

4.2. Functional unit

For this study, one cubic meter (1 m³) of a finished plywood sheet was selected to be the functional unit. The functional unit helps in scaling the results conveniently for different quantities of products.

The specifications of the product are as mentioned below:

- a) Average thickness of product—10.45 mm.
- b) Average size of product—2.97 square meters (m²).
- c) Moisture content in finished plywood is approximately 8 percent.
- d) Quality standard: Interior and exterior as permitted in IS:303/2006.
- e) Binder type: Urea formaldehyde and phenol formaldehyde resin-based adhesive as per IS: 848/2006.
- f) Technical data of MR & BWR grade plywood: Mechanical strength properties and bond strength as determined at erstwhile IPIRTI (now IWST) laboratory as per IS: 1734 (Pt I to Pt 14).

4.3. System boundary

The **Figure 2** below summarizes the system boundaries for the gate-to-gate life cycle assessment of plywood manufacturing and **Figure 3** gives the schematic representation of system boundary.

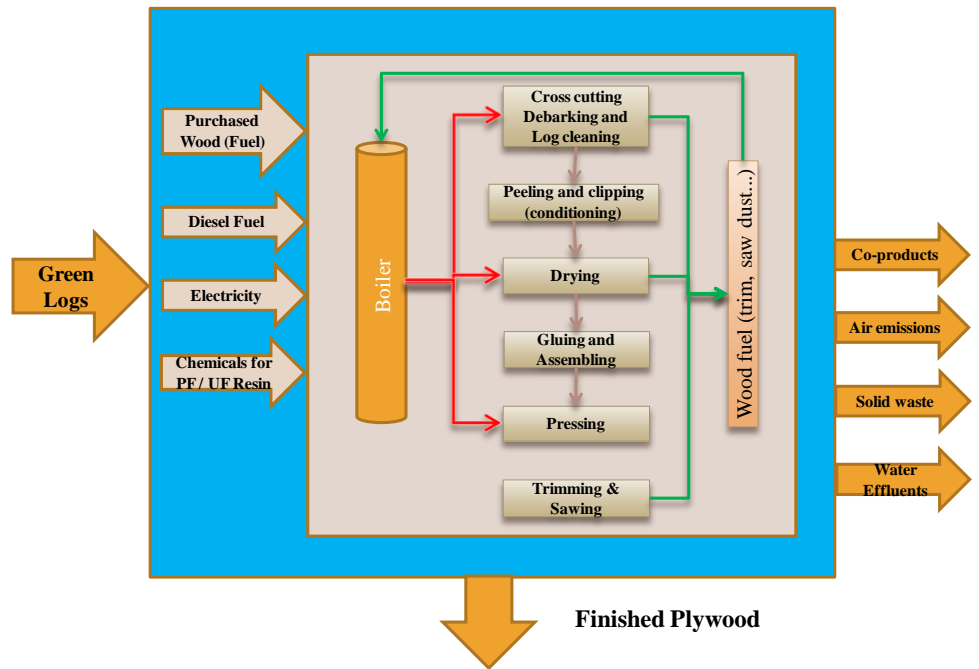


Figure 2. System boundaries for plywood life cycle assessment.

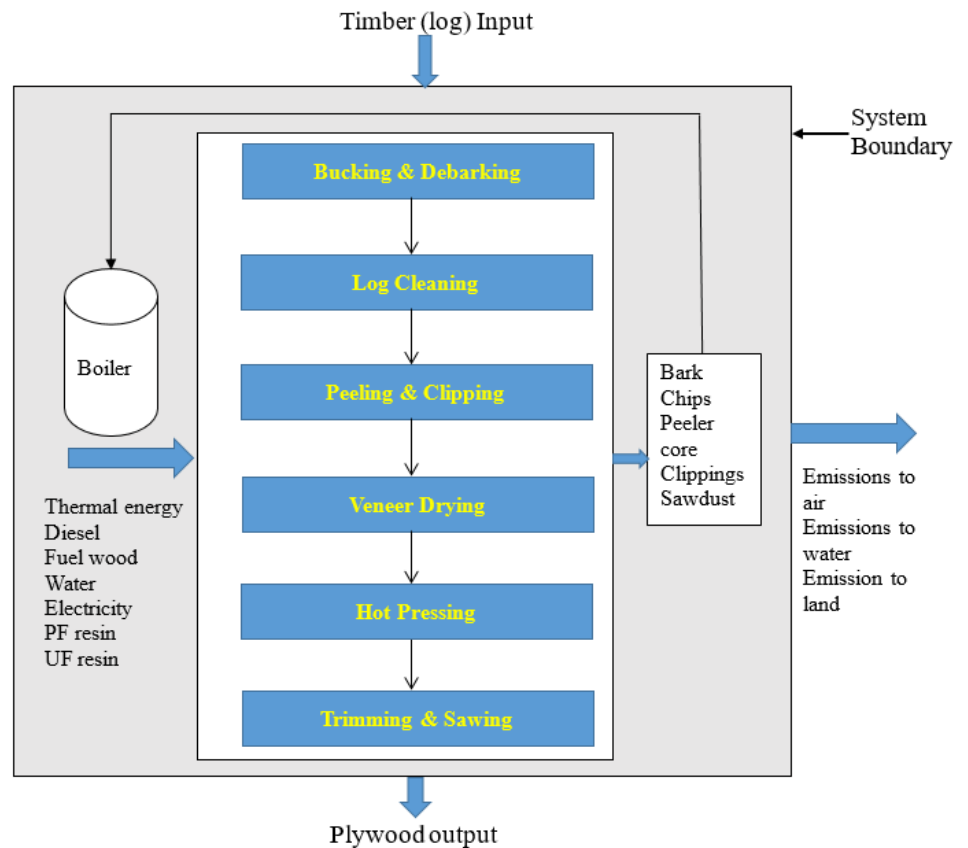


Figure 3. System boundaries for plywood life cycle assessment.

Activities that have been excluded from the assessment are:

- (1) Cultivation of tees in plantations.
- (2) Harvesting and delivery of timber and other raw material to the factory gate.
- (3) Construction of factory and capital equipment, etc.

- (4) Since the study employs a gate-to-gate approach, shipping of the plywood, its service, and end of life are not considered.
- (5) Energy consumption due to employee's transport and human labor.
- (6) Energy requirement for producing chemical raw materials used for plywood manufacturing.
- (7) Land use/noise impacts are excluded in the study; this shall not provide insights on occupational hazards of the human resources working in the facility.

4.4. Data quality

a) Data collection

Data on which this study is based were collected by visiting and interacting with concerned individuals and competent authorities of plywood mills. Four different plywood mills were visited for data collection. Mills were selected based on the geographical area, production capacity, level of automation involved, and variety of products. Out of four mills, one mill purchased veneer, whereas the other peeled partly and purchased the rest, whereas the remaining two mills peeled veneers in-house.

b) Fuels and energy—Upstream data

National averages for fuel inputs and electricity grid mixes were obtained from the GaBi 4 database 2011. Datasets on Indian average mixes for fuels (e.g., diesel) and electricity were used for this study.

c) Raw and process materials—Upstream data

Primary data for the log wood were collected from Indian plywood manufacturers. Data for all other upstream raw materials were obtained from the GaBi 4 database 2011.

d) Emissions to air, water and soil

Air emission data associated with the production of the plywood were also monitored and assessed for 1 m³ of plywood. Similarly, wastewater effluent quality was analyzed, and various parameters were evaluated for 1 m³ of plywood.

Data for all upstream materials, electricity and energy carriers were obtained from the GaBi 4 database 2011. These datasets include all the inputs and outputs for all materials, energy, and emissions (including emissions that may contribute to toxicity impacts).

e) Cut-off criteria

For the material and energy input to the gate-to-gate data, no cut-off criteria were applied as it was intended to capture the complete material input.

f) The following cut-off criteria were applied in the study to all upstream data:

- i) Mass—If a flow is less than 2% of the cumulative mass input to the foreground processes of the model, it may be excluded, provided its environmental relevance is not a concern.
- ii) Energy—If a flow is less than 2% of the cumulative energy input to the foreground processes of the model, it may be excluded, provided its environmental relevance is not a concern.
- iii) Environmental relevance—If a flow meets the above criteria for exclusion yet is thought to potentially have a significant environmental impact, it is included. Material flows that leave the system (emissions) and whose

environmental impact is greater than 2% of the whole impact of an impact category that has been considered in the assessment are to be covered. This judgment will be done based on experience and documented as and when necessary.

The sum of the excluded material flows must not exceed 5% of mass, energy or environmental relevance. The cumulative mass and energy inputs to the plywood were assessed based on the data collection by the institute.

g) Data quality requirements

Data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., are there any unreported emissions?), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, time period, technology). To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistency, upstream LCA information from the GaBi LCI database were used. This upstream information from the GaBi LCI database is widely distributed and used with the GaBi 4 software. The datasets have been used in LCA models worldwide for several years in industrial and scientific applications for internal as well as critically reviewed studies. In the process of providing these datasets, they have been cross-checked with other databases and values from industry and a scientific point of view.

h) Precision and completeness

- i) Precision: The relevant foreground (gate-to-gate) data is primary data for plywood manufacturing sites in India. All upstream data is consistently GaBi professional data with precise documentation.
- ii) Completeness: All relevant, specific processes for the different options are considered and modeled to represent each specific situation. All upstream processes are taken from the GaBi databases (GaBi 4 documentation).

i) Consistency and reproducibility

- i) Consistency: A qualitative assessment of whether the study methodology is applied uniformly to various components of the analysis was conducted. To ensure consistency, only primary data of the same level of detail and upstream data from the GaBi databases are used. While building up the model, cross-checks concerning the plausibility of mass and energy flows are continuously conducted. The provided primary data of the technology representatives was checked and recalculated. Conservative assumptions were made, and efforts taken to get them as consistent as possible were applied so that the results remain valid.
- ii) Reproducibility: The reproducibility is given for internal use since the owners of the technology provided the data and the models are stored and available in a database. Sub-systems are modeled by “state of art” technology using data from a publicly available and internationally accepted database. For the external audience, it is possible that no full reproducibility in any degree of detail will be available for confidentiality reasons. However, experienced experts will easily be able to recalculate and reproduce suitable portions of the life cycle system as well as key indicators.

j) Geographic coverage

The geographical coverage of this study covers the manufacturing site of

plywood in India. For gate-to-gate aspects, Indian boundaries wherever possible have been adapted, and other datasets were chosen from the EU in cases where no Indian datasets were available for chemicals. For plywood production, data generated and collected at erstwhile IPIRTI (now ICFRE-IWST) was used for modelling purposes.

k) Time coverage

Standard data available with the institute, which is recent and relevant (not more than 5 years old), and data collected during a factory visit by the scientists or data provided by a competent authority in the factory form the base for this study.

As a measure of data quality, it was reported whether the data were measured, calculated, an average value, or estimated. In addition, the origin of the data was documented. Wherever possible, measured data from the facilities were utilized.

l) Plywood production was modelled based on:

- i) Primary process data on energy and materials consumption as well as measured direct emissions was collected by erstwhile IPIRTI (now ICFRE-IWST) from manufacturing sites.
- ii) Calculated CO₂ emission using emission factors for CO₂ emissions from diesel combustion and electricity and direct carbon dioxide emissions related to materials (fuelwood and woody biomass).
- iii) Emission of formaldehyde was measured directly in the factory using calibrated handheld devices. Effluent was collected and analyzed at the erstwhile IPIRTI (now ICFRE-IWST) laboratory, Bangalore.
- iv) GaBi upstream data was fetched wherever necessary.

5. Selection of LCIA methodology and types of impacts

The CML 2001 method (activities by translating emissions and resource extractions into a limited number of environmental impact scores) has been selected for evaluation of environmental impacts developed by the Institute of Environmental Sciences, Leiden University, Netherlands. These indicators are scientifically and technically valid. Furthermore, they are relevant from the environmental point of view and provide a multi-criterion approach to the environmental issues. These indicators are widely used and accepted by the international community of LCA experts [4,10,18,19–23].

A set of environmental indicators was investigated, including the following inventory flows and environmental impact categories: primary energy (electrical and thermal) demand, global warming potential, etc.

Land use and noise: Other impacts such as land use and noise are not considered relevant for this study. The robustness of each impact category has been classified from LO (Low) to HG (High). These reliability indicators are qualitative, and based on our own expert judgment, they aim both at strengthening the credibility of the results and stressing the necessary precautions that need to be taken when interpreting results. The current study focuses on product carbon footprint and energy analysis of plywood from a gate-to-gate perspective. Hence, global warming potential and primary energy demand indicators will be assessed.

6. Software and database

The LCA model was created using the GaBi 4 software system for life cycle engineering, developed by PE International AG. The GaBi database provides life cycle inventory data for several of the raw and process materials obtained from the upstream system.

Interpretation:

The results of the LCI/LCIA are interpreted according to the goal and scope. The interpretation addresses the following topics:

- Identification of significant findings.
- Understanding the environmental impact of plywood manufacture, focusing on gate-to-gate assessment.
- Conclusions, limitations, and recommendations should state the appropriateness of the definitions of the system functions, the functional unit, and the system boundary.

Databases used:

The description of the inventories of materials in the study is described in this section. **Table 1** below shows the materials and energy along with the description of the inventory.

Table 1. Lifecycle inventories of materials and energy.

Material	Description of the inventory	Source	Representativeness
Log wood [Renewable primary products]	Log wood		India
Boric Acid [Operating materials]	Boric acid		RER
Copper sulfate [Inorganic intermediate products]	Copper sulphate		RER
Formalin (37% Formaldehyde) [Organic intermediate products]	Formaldehyde solution	GaBi 4.4	Germany
Phenol (hydroxy benzene) [Organic intermediate products]	Phenol solution	Database	RER
Power [Electric power]	Electricity power	2006	India
Sodium dichromate [Inorganic intermediate products]	Sodium dichromate		RER
Sodium hydroxide (100%; caustic soda) [Inorganic intermediate products]	NaOH; caustic soda		RER
Urea (agrarian) [Agro chemicals]	Urea		India

7. Results analysis

Four plywood manufacturing units/mills were visited for data collection. Due to a non-disclosure agreement (NDA), the names of the units/mills shall be masked with identities as follows.

- Unit I—Situating in North east region shall be denoted as NE.
- Unit II—Situating in South India and shall be denoted as S.
- Unit III—Situating in North India and shall be denoted as N1 (veneer purchased).
- Unit IV—Situating in North India and shall be denoted as N2 (veneer partly purchased and rest peeled).

Figure 4 Depicts the flowchart of the model developed for LCA of plywood

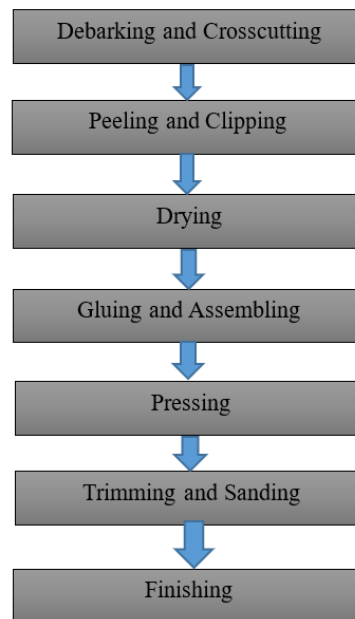


Figure 4. Model developed for LCA of plywood.

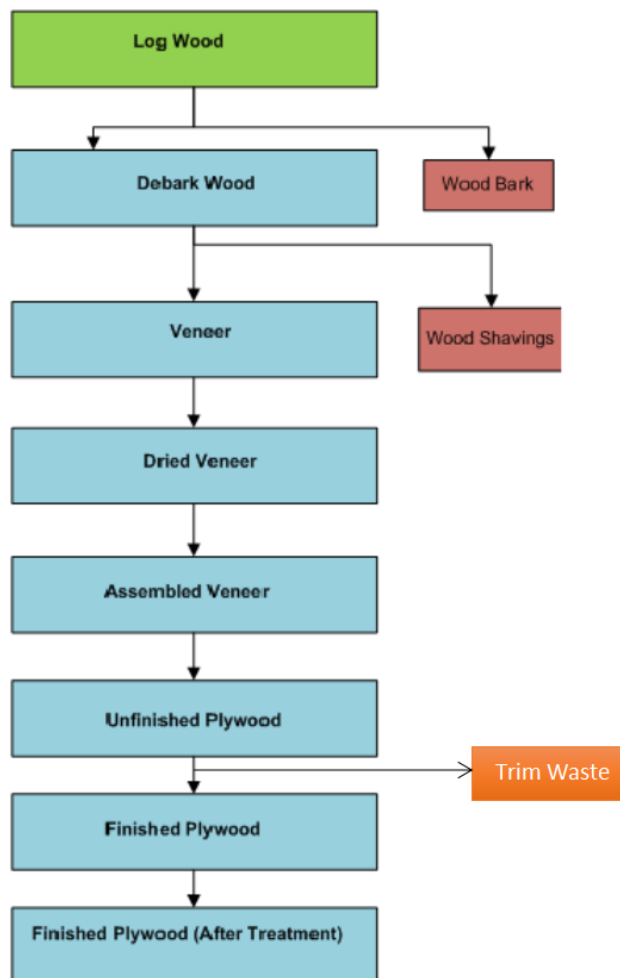


Figure 5. Material flows for plywood production.

The material flow for the plywood product is shown in **Figure 5**. The material flow illustrates various processes beginning with receiving logwood at the factory

gate. The wood is then debarked and converted into veneer. After drying of veneer, it is assembled after applying glue and other additives. Assembled veneers are then pressed under elevated temperature and pressure to get unfinished plywood, which is then trimmed on all 4 sides to get the finished plywood. This finished plywood is then treated with suitable chemicals to enhance resistance to bio-degradation (optional). Final treatment of stacked plywood results in the finished plywood product, which is then transported out of factory gates. **Table 2** summarizes the inputs and outputs of LCA for producing 1 m³ of plywood.

Table 2. Inputs and outputs for gate-to-gate lifecycle analysis of 1 m³ of finished plywood.

Inputs			
Materials	Units	SI unit per m³	
Log wood [Renewable primary products]	kg	859.39	
Carbon dioxide sequestered (biogenic) [kg CO ₂]	kg	2379.1	
Formaldehyde (37%; methanol) [Organic intermediate products]	kg	27.52	
Phenol (hydroxy benzene) [Organic intermediate products]	kg	27.52	
Sodium hydroxide (100%; caustic soda) [Inorganic intermediate products]	kg	5.41	
Urea (agrarian) [Agro chemicals]	kg	18.76	
Boric acid [Operating materials]	kg	0.19	
Copper sulfate [Inorganic intermediate products]	kg	0.44	
Sodium dichromate [Inorganic intermediate products]	kg	0.63	
Purchased			
Wood waste purchase [Waste for recovery]	kg	193.72	
Electrical use			
Power [Electric power]	MJ	297.53	
Fuel used			
Thermal energy (MJ) [Thermal energy]	MJ	6333.6	
Water used			
Water [Water]	kg	25	

Table 2. (Continued).

Outputs		
Materials	SI units	SI unit per m³
Wood bark [Waste for recovery]	kg	25.78
Peeler core [Materials from renewable raw materials]	kg	85.93
Wood shavings [Biomass fuels]	kg	51.56
Waste veneer [Waste for recovery]	kg	17.18
Saw dust [Waste for recovery]	kg	4.286
Trimmed plywood [Materials from renewable raw materials]	kg	22.5
Finished plywood [Materials from renewable raw materials]	kg	600
Emissions & effluents		
Acetaldehyde (Ethanol) [Group NMVOC* to air]	kg	0.00569
Acrolein [Group NMVOC to air]	kg	361×10^{-07}
Boron [Inorganic emissions to fresh water]	kg	1.78×10^{-06}
Carbon dioxide Emission (biogenic) [kg CO ₂]	kg	1171.2
Carbon dioxide Emission (Fossil) [kg CO ₂]	kg	107.53
Chromium (unspecified) [Heavy metals to fresh water]	kg	0.83×10^{-03}
Copper (+II) [Heavy metals to fresh water]	kg	1.78×10^{-06}
Formaldehyde (methanol) [Group NMVOC to air]	kg	1.2284×10^{-02}
Methanol [Group NMVOC to air]	kg	0.0788
Nitrogen oxides [Inorganic emissions to air]	kg	3.3046×10^{-02}
Particulates: unspecified, from stack [Production residues in life cycle]	kg	1.62×10^{-01}
Phenol (hydroxy benzene) [Group NMVOC to air]	kg	0.784×10^{-03}
Sulphur dioxide [Inorganic emissions to air]	kg	0.0564×10^{-03}
Suspended solids, unspecified [Particles to fresh water]	kg	1.3
VOC (unspecified) [Organic emissions to air (group VOC)]	kg	1.41×10^{-01}
Thermal energy		
Thermal energy (MJ) [Thermal energy]	MJ	5066.88
Waste water		
Waste water-treated [Production residues in life cycle]	Kg	25

Note: * NMVOC—Non-methane volatile organic compounds.

For assessment of environmental impacts during the production of plywood using a gate-to-gate approach, the environmental impact due to material is excluded. Electric and thermal energy consumption for plywood production broken down for various processes is shown in **Figures 6** and **7**, respectively. **Table 3** gives summary of inputs and outputs for gate-to-gate lifecycle analysis of 1 m³ of finished plywood. The total electricity consumption is in the range of 161.02 MJ to 589.22 MJ for the complete production process of every cubic meter of plywood, whereas the total thermal energy consumption is in the range of 6147.2 MJ to 8461.12 MJ.

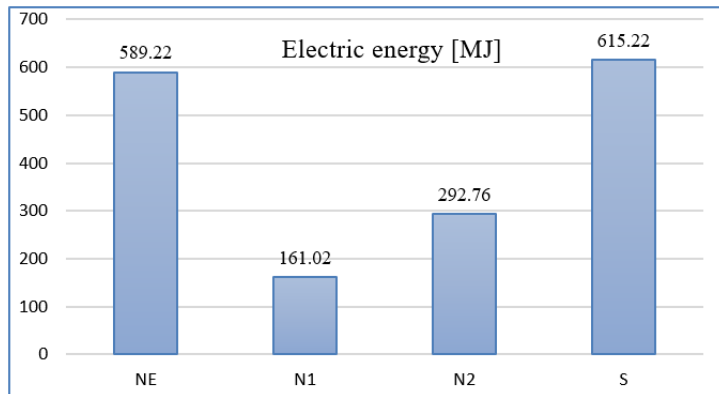


Figure 6. Unit-wise electric energy consumption for the production of 1 m³ of plywood.

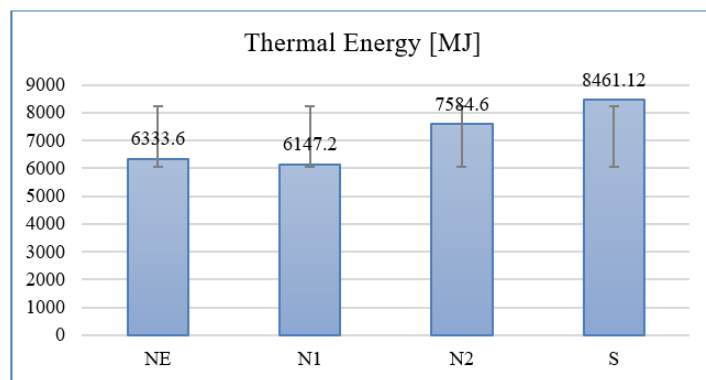


Figure 7. Unit-wise thermal energy consumption for the production of 1 m³ of plywood.

Table 3. Inputs and outputs for gate-to-gate lifecycle analysis of 1 m³ of finished plywood.

Name of the unit	Timber input [kg]	Product output [kg]	Power requirements		Carbon dioxide emitted/sequestered		Net Carbon dioxide sequestered [kgs]
			Electric power [MJ]	Thermal power [MJ]	Carbon dioxide sequestered [kgs]	Carbon dioxide emitted [kgs]	
NE	1265.48	600	589.22	6333.6	1475	897.35	578.48
N1	1005.13	615	161.02	6147.2	1382.05	786.9	595.15
N2	1094.5	612	292.76	7584.6	1385.49	1042.87	343.12
S	1291.19	600	615.22	8461.12	1553.23	1227.88	325.35

Table 4. Electrical energy required for different wood composites.

Sl. No	Product	Electric energy MJ/m ³	Reference
1	Plywood	565	[19]
2	Laminated veneer lumber (LVL)	202	[24]
3	Medium density fiberboard (MDF)	1493	[25]
4	Particleboard (PB)	591	[22]
5	NE	589.22	Outcome of the present study
6	N1	161.02	
7	N2	292.76	
8	S	615.22	

From the **Table 4** it is understood that the electrical energy required to produce 1 m³ of plywood is 565 MJ/m³ whereas the current study reveals that the electrical energy requirement is slightly higher, i.e., 589.22 MJ/ m³ and 615.22 MJ/ m³ for the units NE and S, respectively. Unit N1 consumes less energy than the global benchmark due to the reason that veneers are purchased and not peeled, whereas N2 consumes 292.76 MJ/ m³ as the veneers are partly peeled and the rest are purchased. The reason for higher electric energy consumption is due to the level of automation involved in plywood manufacturing in the U.S. compared to human labor being employed for a major portion of processing in India. Automation not only improves the percentage of recovery but also enhances the product quality and the production of the facility. **Figure 8** represents the magnitude of CO₂ emitted and Net CO₂ sequestered by the 4 plywood units under consideration. **Table 5** gives an idea of the energy consumed for producing different types of construction materials.

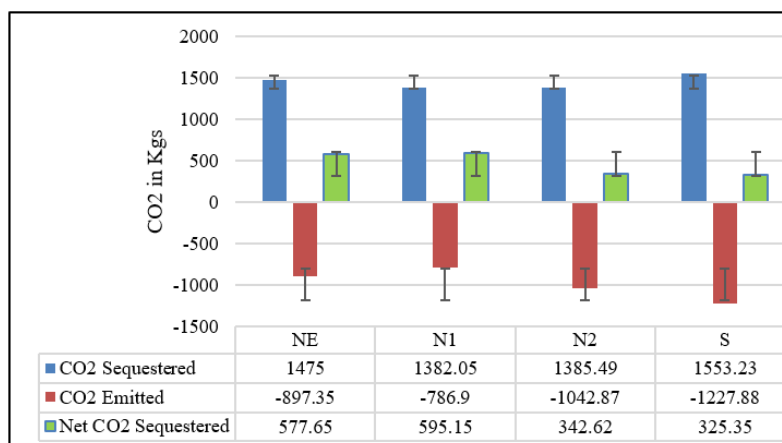


Figure 8. Unit-wise net carbon sequestered for the production of 1 m³ of plywood.

Table 5. Energy consumption for production of 1 ton of different structural material.

Commodity	Net energy required {million Kcal (oil equivalent) per oven dry ton}
Lumber	0.73
Wood fence post	1.0
Plywood	1.5
MDF	2.14
Concrete slab	2.15
Concrete block	2.21
Clay brick	2.28
Steel stud	12.68
Steel fence post	12.68
Aluminum siding	50.51
Carpet and pad	9.37

As per the above study, the minimum energy requirement to produce 1 ton of plywood in India is 2.75 million kcal.

8. Discussion

A life cycle assessment study has been conducted for 1 m³ of finished plywood. This study examined the environmental impact of the plywood production process employing a gate-to-gate approach. This is a first-of-its-kind study for plywood production in India. Primary energy demand, GHG, and other organic and inorganic emissions have been assessed for various processes involved in plywood production. The study is based on primary data collected from manufacturers by erstwhile IPIRTI (now ICFRE-IWST), 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 the GaBi 4.4 professional database 2011.

The study has allowed to determine carbon dioxide emissions broken down by individual processes as well as biogenic and fossil emissions; wherein biogenic CO₂ emission is due to burning of wood waste and fossil emission is due to electricity which is consumed at the factory. Carbon dioxide sequestered by the output product has also been carefully assessed.

Analysis have revealed deviations in input, output, total carbon sequestered in the final product (plywood) and also in energy requirement among the four plywood units under consideration. However, all variations in the chart can be explained as follows.

- 1) Material and energy (electric and thermal) consumption
 - i. Output indicates 1 m³ of plywood having a density around 600 kg/m³. Unit NE and unit S have only logs as primary raw material (biomaterial input) whereas unit N1 uses only purchased veneer (peeling is not done in-house) and unit N2 uses purchased (outside) veneer and in-house peeled veneers.
 - ii. Variation in energy requirement, i.e., in a plywood unit, major electrical energy is consumed in the peeling section where logs are converted into veneer. The lesser electric energy consumption in units N1 and N2 is reflected as peeling is totally and partly absent in these units, respectively. Unit S consumes electric energy more than that of the unit NE due to the fact that the percentage of conversion of raw material (timber logs) to finished product (plywood) is considerably on the higher side for the unit NE compared to that of unit S. Considering the thermal energy consumption, it is to be mentioned that a major part of it is utilized for veneer drying. N1 consumed the lowest thermal energy among all the units which is due to the fact that veneer is purchased from outside which is almost delivered in dry condition, requiring minimal further drying. However, N2 and S are found to consume higher thermal energy for producing the same volume of plywood which may be due to reasons like heat loss in the dryer due to discontinuous feeding of veneer into the dryer and the hot press remaining idle as the factory was found to be operated below installed full capacity. Key findings from the gate-to-gate (log to plywood) study reveal that 602.22 MJ (167.28 K·Wh) (Average) of electrical energy is consumed to produce 1 m³ of finished plywood. The lower electrical energy consumption in the case of units N1 and N2 is due to the fact that the veneer is the input and hence has not been considered for averaging. 7133.1 MJ (average) of thermal energy is required for the production of 1 m³ of plywood.

- 2) Carbon sequestration and percentage of material conversion
- i. Unit NE contributes significantly to carbon sequestration in the final product, which is due to the highest conversion ratio of raw material into the final product. During actual analysis it was found that the conversion ratio in unit NE is 63%, whereas in unit S it is 50%. Needless to mention that both the units use logs as raw material. Conversion ratio depends in a major way on two factors: (i) Quality of logs (ii) various stages of processing. In general, bigger girth, cylindrical logs yield good quality veneer, resulting in higher yield. Process loss depends on the quality of the veneer, the technique, and also the expertise of the machine operators where manual processing is involved. Conversion ratio is important, as this has a higher significance on the net carbon stored in the final product. Out of CO₂ emitted, the CO₂ emitted due to the burning of fuelwood, known as the biogenic component, represents a higher percentage compared to the CO₂ emitted due to the burning of fossil fuels, which can be supported by similar studies in the Pacific Northwest and Southeast, production facilities of the softwood plywood industry in the U.S. [19]. Huge variations in carbon sequestration are due to the absence of an energy auditing mandate and quality checks, which permit the unorganized plywood units to prioritize production and profits compared to the environmental concerns. Relevant policies are to be put in place to check the pollution by production units.
 - ii. Most of the Indian plywood mills run below the installed capacity, leading to higher energy consumption compared to the actual (theoretical) energy requirement to produce one-unit quantity of product (i.e., 1 m³ of plywood). Another reason for higher energy consumption is due to the miss-matching of machinery used in many units, where some machines may be of higher capacity than required for actual production in the factory. Also, due to low capacity utilization, very often, some machines run idle, only adding extra energy burden to the product. Studies revealed that net carbon dioxide sequestered varies from 325 to 595 kg for the production of 1 cubic meter of plywood, depending upon the conversion ratio achieved by the factory. Unit NE sequestered 578.48 kg of carbon dioxide in one cubic meter of product due to a higher conversion ratio (63%) compared to values in unit S (325.35 kg CO₂/m³ of plywood) due to a lower conversion ratio (50%). The higher value of carbon sequestration is (595.15 kg CO₂/m³ of plywood) for unit N1 is due to the fact that this factory uses veneer as input. The conclusion can be drawn as follows:
 - a. The production of plywood leads to net storage of carbon in the product.
 - b. Through proper technology intervention conversion ratio can be increased leading to carbon sequestration (as CO₂) up to 587 kg CO₂ per cubic meter of plywood.
 - iii. The advantage of thermal energy production in a plywood mill is that entire energy is generated from burning waste timber generated during the production of plywood. For a small factory or where peeling of logs is not done, waste wood is not sufficient to run the boiler, and firewood is

purchased from outside to feed the boiler, as in the case of unit N1. In all cases, heat energy is generated from renewable biomaterial (timber). Burning wood is considered carbon neutral as it only emits that carbon which was taken from the atmosphere during its growth. Other environment impacts such as acidification potential, eutrophication potential, human toxicity, ecotoxicity, etc. are not under the purview of this assessment.

9. Conclusions

- 1) Material recovery and emissions to air, land and water
 - i. Plywood is an engineered structural product capable of replacing products like metal (steel, aluminum), concrete, asbestos, plastic, etc. A study on carbon footprint and energy consumption reveals that plywood production and its uses have a net environmental benefit with respect to net carbon sequestration: When production of other structural material emits a substantial amount of CO₂ in air, plywood production removes CO₂ from air during the growth of wood, which is finally stored in plywood for a long period. The average life of plywood varies from 25 years to 50 years, which is the period for which carbon can be locked into plywood once it is being made. Formaldehyde emission from storage tanks, resin reactors, gluing, and hot presses are major sources of air pollution and occupational hazards. Precautionary measures like airtight containers for storage, transport of formalin through a closed system, and appropriate glue formulation can help to reduce formaldehyde emission to a greater extent.
 - ii. Production of plywood requires several chemical agents such as formaldehyde, boric acid, copper sulfate, and sodium dichromate, etc. Except for formaldehyde emission of other aldehydes or acidic gases is negligible. However, formaldehyde emission at the resin plant and gluing sections were found to be of higher orders, which causes health hazards. Constituents of preservatives, e.g., copper and chromium, are harmful to workers as well as to soil or water bodies when effluent containing preservative chemicals is discharged without treatment, and the best way to remove all the suspended and dissolved material is by treating this effluent. Recycled water can be used in a resin plant or in a boiler section for cooling purposes. Replacing harmful chemicals with eco-friendly alternatives can be looked upon, which erstwhile IPIRTI (now ICFRE-IWST) has made significant contributions to.
 - iii. A substantial amount of wood dust/sawdust is produced during the manufacture of plywood. Fine dust produced during trimming and sanding remains suspended in air and settles slowly. Sawdust from trimming contains fine particles of resin chemical. Inhaling fine dust may damage lungs and the respiratory system. Accumulation of sawdust on hair and body may cause dermatitis and hair fall. Trimming and sanding machines must be provided with a dust extraction system to keep the factory free from suspended dust. The plywood production process involves significant wastage of wood at various stages, such as peeling & clipping and trimming

& sanding. Yield improvement can affect the saving of raw materials and increase plywood output for unit input of log wood. Reduction of wastage will also result in reduced energy consumption, which will, in turn, reduce impact on the environment.

2) Energy demand

Detailed examination revealed that the electricity consumed for plywood production has a significant influence on environmental impact. It is for this reason that electricity conservation measures are highly important, and well-implemented measures can substantially contribute to reducing the overall primary energy demand. Some of the suggested measures are avoiding idling of machines and using electrical equipment with higher efficiency and employing Variable Voltage Variable Frequency (VVVF) drives for electric motors, which have proven to be highly efficient compared to conventional methods. Veneer drying is an energy-intensive process accounting for a significant percentage of total energy demand and subsequently contributing to global warming potential. A similar study [19] also suggests that combustion of wood fuel (biomass), which is comprised of wood and bark waste generated during the manufacture of plywood, forms a major source of thermal energy. It is for this reason that moisture content in the veneers prior to drying assumes heightened importance. Drier efficiency needs to be given due attention to ensure that it operates in the most energy-efficient manner with minimal losses. Boiler efficiency is to be closely monitored.

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