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EXERGY AND LCA

Environmental profile analysis of particleboard production: a study in a Pakistani technological condition

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Abstract

Purpose Particleboard is a composite panel comprising small pieces of wood bonded by adhesives. The particleboard industry is growing in Pakistan, but there is little information on the environmental impacts associated with this product. Therefore, the aim of this study was to develop a life cycle assessment of particleboard manufactured in Pakistan and to provide suggestions to improve its environmental profile. The study covers energy use and associated environmental impacts of raw materials and processes during particleboard manufacture in the year 2015–2016.

Methods The study uses a cradle-to-gate (distribution center) life cycle assessment approach. The reference unit for this study was 1.0 m^3 of finished, uncoated particleboard. Primary data from the particleboard mill surveys were combined with secondary database information and modeled using CML 2000 v.2.05 methodology and a cumulative exergy demand indicator present in the SimaPro v.8.3 software.

Results and discussion The results reveal that urea formaldehyde resin, transportation of raw materials, and finished product distribution had the highest contribution to all the environmental impact categories evaluated. Heavy fuel oil and natural gas consumption was responsible for abiotic depletion, photochemical oxidation, ozone layer depletion, and marine aquatic ecotoxicity impacts. The rotary dryer and hot press were the most important sectors in terms of emissions from the manufacturing process. The total cumulative exergy demand required for manufacturing of 1.0 m^3 particleboard was 15,632 MJ-eq, with most of the energy usage associated with non-renewable, fossil fuel sources. A sensitivity analysis was conducted for a reduction in the quantity of urea formaldehyde resin consumed and freight transport distances.

Conclusions The results indicated that reducing the urea formaldehyde resin use and freight distances could greatly decrease environmental impacts. Most of the surveyed mills did not have emissions control systems, and most of the mills exceed the limits set by the National Environmental Quality Standards of Pakistan. Environmental impact improvements might be attained by reducing quantity of urea formaldehyde resin and transportation freight distances and by installing pollution control devices.

Keywords Cumulative exergy demand · Environmental impacts · Hotspot · Life cycle assessment · Pakistan · Particleboard · SimaPro · Wood

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Abbreviations

AD	Abiotic depletion
AP	Acidification potential
CExD	Cumulative exergy demand
CORRIM	Consortium for Research on Renewable Industrial Materials

EP	Eutrophication potential
FAE	Freshwater aquatic ecotoxicity
FSMP	Forestry sector master plan
GDP	Gross domestic product
GWP	Global warming potential
HAPs	Hazardous air pollutants
HFO	Heavy fuel oil
HT	Human toxicity
$kgCO_2e$	Kilogram carbon dioxide equivalents
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LPG	Liquefied petrol gas
MAE	Marine-water aquatic ecotoxicity
MJ-eq	Mega Joule-equivalents
OLD	Ozone layer depletion
PM	Particulate matter
PO	Photochemical oxidation
RCOs	Regenerative catalytic oxidizers
RTOs	Regenerative thermal oxidizers
TE	Terrestrial ecotoxicity
UF resin	Urea formaldehyde resin
VOCs	Volatile organic hydrocarbons
PB	Particleboard

1 Introduction

Wood panels are usually manufactured from processed wood materials bonded with synthetic adhesives and consolidated under high heat and pressure (ANSI 2009; Kouchaki-Penchah et al. 2016; Hussain et al. 2017). Common wood panels include particleboard, fiberboard, oriented strand board, and veneer-based products such as laminated veneer lumber and plywood (Silva et al. 2013a; Saravia-Cortez et al. 2013). Particleboard was initially manufactured in the 1950s using industrial wood residues generated during the production of lumber and plywood products (Puettmann et al. 2013c). Before this, these wood residues were considered waste and were disposed of either by burning or in landfill (Wilson, 2010a).

Wood-based industries are important in Pakistan. These businesses employ about 500,000 workers and their contribution to the total GDP was about 8.4% in the year 2004–2005 (ww.boi.gov.pk). The industry was started in 1965 to provide substitutes for solid wood products, which are in limited domestic supply (NMC 1990). Currently, there are more than 20 particleboard mills in Pakistan (EC-FAO Partnership Programme 2002). In 2013, the particleboard industry manufactured a total of 76,000 m^3 of particleboard or 0.1% of the total world production (www.factfish.com; FAOSTAT 2014). Particleboard is consumed internally in Pakistan and is exported to Afghanistan, Sri Lanka, Saudi Arabia, and other Gulf states in the form of furniture. The furniture industry of Pakistan consumes about 60% of the particleboard produced in the country (SEMDA 2006).

The production lines of particleboard consume huge quantity of materials and energy resources (Kouchaki-Penchah et al. 2016). During the manufacture of particleboard, carbon dioxide (CO_2), formaldehyde, volatile organic compounds (VOCs), total hydrocarbon (THC), particulate matter (PM), and other hazardous emissions are produced (EPA 2002; Doosthoseini et al. 2013; Kouchaki-Penchah et al. 2016). Thus, particleboard industry is recognized as an important source of natural resource depletion and environmental pollution; however, its contribution to economy and development is also acknowledged (Sandin et al. 2016). Therefore, the identification of sustainable options in this domain is crucial (Azapagic and Perdan 2000).

Due to increasing global warming, more attention is being paid to manufacture products with less impact to the environment and human health (Kouchaki-Penchah et al. 2016; Garcia and Freire 2014). The wood panel industry is facing increasing pressure to document and reduce the environmental burdens of their products (Silva et al. 2013a; Puettmann et al. 2013a; Hussain et al. 2014). To achieve these aims, it can be helpful to take a life cycle assessment (LCA) approach (Remmen et al., 2007). LCA is a holistic tool that can be applied to identify the most significant environmental burdens posed by the products and where they occur in the production chain (Curran, 2013; Rauf and Crawford 2015; Baumann and Tillman, 2004; Rivela et al. 2006; Silva et al. 2013a). Also, the environmental impacts of alternative products can be compared to identify the one with less impact (Robertson et al. 1997). In many cases, an LCA approach is based on a cradle to grave framework, or even a cradle to cradle approach, to include the use and potential reuse or disposal of a product. This enables a holistic consideration of the "life cycle" of the product; however, in other cases, a more limited approach (gate to gate or cradle to gate) is defined, so as to focus attention to certain phases within the life cycle (McDonough and Braungart 2002).

Indicators result from the life cycle impact assessment phase (Guinee 2001). Some of the impacts have a localized environmental effect (e.g., eutrophication and photochemical smog), whereas the others have global effect (e.g., ozone depletion and global warming) (Azapagic and Perdan 2000). Exergy can be defined as the maximum amount of useful work which can be done by a system or energy flow as it comes to equilibrium with a reference environment (Rosen and Dincer 2001). Exergy can be an indicator for the formulation of an efficient energy policy since its accounts not only for the quantity but also for the quality of the energy sources (Herva, 2011; Hovelius and Hansson, 1999). Application of the exergy indicator in the environmental impacts assessment of the industrial processes and products and its usefulness to quantify the optimal use of energy in the processes has been explored (Banat and Jwaied 2008; Zhu et al. 2005; Hau and Bakshi 2004a).

LCA can play a role in environmental policy when assessing the environmental impacts of the production process (Kouchaki-Penchah et al. 2016). It can also be a tool for identifying opportunities to increase efficiency and reduce cost (Rivela et al. 2006). Developed countries are conducting LCA research to support the needs of their industries and to reduce their greenhouse gas (GHG) emissions (Lee et al. 2004; Kim and Song 2014). However, there is no published LCA of the particleboard manufactured in Pakistan, whereas several studies have been conducted for other countries such as the USA (Puettmann et al., 2013b; Wilson 2008), Spain (Rivela et al. 2006), Brazil (Silva et al. 2013a), Australia (Tucker et al. 2009), Portugal (Garcia and Freire 2012), and Iran (Kouchaki-Penchah et al. 2016). The main differences of particleboard production in Pakistan and these other countries are the sources of wood materials and energy consumption in the mill. Wood wastes and industrial residues from forest operations and sawmills are the main sources of wood materials to manufacture particleboard in the USA, Europe, and Portugal. However, in Pakistan, most of the wood materials are obtained in the form of round logs from forests and farmland plantations. With respect to fossil fuel consumption as a source of thermal energy in the particleboard manufacturing process, most of the countries reported consumption of natural gas and wood residues, whereas particleboard mills in Pakistan also used heavy fuel oil (HFO) along with the other fuels.

2 Global overview of the life cycle assessment of particleboard production

Wilson (2010a) conducted an LCA of particleboard produced in the USA that examined different processes within the manufacturing operation. The results revealed that the on-site activities contributed only 15% to the overall carbon footprint. Most of the carbon footprint was due to extraction, processing, and delivery of wood residues, urea formaldehyde (UF) resin and chemicals, fossil fuels, and electricity to the mill. The carbon stored in the final particleboard product more than offset the carbon footprint of the production process and thus leaves a net carbon flux of −898 kg CO_2 (i.e., net carbon storage) (Tables 1, 2, 3, and 4). An update to that report (Puettmann et al., 2013a) showed that forest resources resulted in fewer emissions than manufacturing processes such as drying, boiling, and pressing processes. In that study, the carbon footprint of 1.0 m^3 particleboard production was calculated to be 376 kg CO_2e, whereas its carbon stock was −1289 kg CO_2e, leaving a net carbon flux of −913 kg CO_2 (Table 4). The authors further investigated the environmental performance of particleboard manufacture using the TRACI 2.0 impact assessment model. For the global warming potential (GWP) indicator, about 73% of the (CO_2 equivalent) emissions were associated with the particleboard mill processes, with 23 and 4% of emissions from wood residue production and forest operations, respectively. Proportions were similar for other impact categories, including acidification, eutrophication, and smog (Table 5).

Tucker et al. (2009) conducted a life cycle inventory (LCI) for forest and wood products in Australia. In that case, a small portion of the raw material to produce 1.0 m^3 particleboard was sourced from logs (72 kg), with the balance from wood residues (650 kg) (Table 4). Rivela et al. (2006) conducted a comprehensive LCA of particleboard in Spain. The production chain was divided into three subsystems, i.e., wood preparation, board shaping, and board finishing. The results indicated that the potential for damage to human health was mainly produced at the board finishing subsystem. The main contribution to this category was energy consumption (Table 5). Kouchaki-Penchah et al. (2016) published an LCA of particleboard manufacturing in Iran. The results were that most of the environmental impacts were associated with the UF adhesive and the fuels and electricity used (Table 5). Silva et al. (2013a) conducted an LCA of medium density particleboard in Brazil, considering the forest and industrial production phases separately. The authors determined that the manufacturing phase was responsible for most of environmental impact, except for eco-toxicity, where glyphosate herbicide applied during forestry operations was the main contributor (Table 5). HFO as a source of thermal energy and UF resin used as a synthetic binder were identified as the main "hotspots"—the components of the manufacturing process associated with the greatest environmental burdens. Silva et al. (2014a) also conducted a study on LCA of particleboard manufactured with sugarcane bagasse residues in Brazil. Sugarcane bagasse is an important agro-industrial residue of sugar manufacturing which can be utilized to manufacture composite products. The results indicated that the hotspots were mainly associated with the particleboard manufacture subsystem, which was responsible for 24–100% of the environmental burdens (Table 5).

Vertima and Ellio (2016) conducted LCA of "NU green soya" particleboard produced by Uniboard in Quebec, Canada. The results revealed that raw material acquisition had the largest contribution to both the environmental impacts (80%) and energy consumption (60%) of the production chain of NU green soya particleboard manufacture. In addition, the raw material acquisition was also responsible for 67% of the life cycle water intake. The authors concluded that NU green soya particleboard is better than climate neutral material, because of its more net carbon flux than the carbon footprint; however, it has more carbon footprint and less net carbon flux as compared to wood-based particleboards (Tables 5, 6, and 7).

Table 1 Life cycle inventory of inputs/outputs to produce 1.0 m^3 of particleboard in Pakistan during 2015–2016

Products	Value	Unit/m^3	Weighted coefficient of variation (CVw)
Particleboard	1	m^3	
Material resources and fuels			
Groundwater	1.30E+01	L	60.69%
Municipal water	5.00E+00	L	38.65%
Wood logs, average Pakistan value	7.75E+02	kg	39.66%
Urea-formaldehyde (U/F) resin, 65% solids	9.30E+01	kg	40.82%
Urea scavenger	5.00E+00	kg	29.35%
Paraffin wax	6.48E+00	kg	78.00%
Ammonium sulfate, as N	1.67E+00	kg	58.44%
Electricity, at grid	1.83E+02	Kwh	34.50%
Diesel	1.15E+00	L	49.50%
Petrol/gasoline	7.10E-01	L	56.70%
Natural gas	4.00E+01	m^3	44.54%
Heavy fuel oil	1.83E+01	L	51.90%
Wood waste combusted in boiler/dryer	7.00E+00	kg	52.90%
Sander dust (wood fuel)	2.90E+01	kg	44.40%
Wood fuel	6.00E+00	kg	50.1%
Wood residue/log transport, combination truck, diesel power	3.36E+02	t km	49.17%
U/F resin transport; combination truck, diesel power	1.13E+02	t km	21.83%
Wax, urea and ammonium sulfate transport, combination truck, diesel power	1.03E+02	t km	28.26%
Finished product distribution to the markets, combination truck, diesel power	8.47E+02	t km	18.92%
Emissions to air			
Particulate matter (PM)	3.03E-02	mg	82.00%
CO	3.08E-02	mg	67.00%
NhO_x	6.40E-03	mg	41.00%
SO_x	1.03E-03	mg	64.00%
Waste to treatment (disposal, solid wastes, specified (hazardous) to unspecified treatment)			
Batteries	6.69E-03	kg	89.14%
Air filters	9.35E-04	kg	47.34%
Oil filters	1.77E-03	kg	82.25%
Lubricants/solvents	2.50E-02	kg	19.68%
Fluorescent lamps	6.87E-04	kg	35.33%
Wiping clothes	7.28E-03	kg	42.17%
Rubber tires, etc.	5.18E-02	kg	56.35%
Paper, cardboards, etc.	1.51E-02	kg	46.62%
Toner	1.33E-03	kg	84.47%

3 Life cycle model and inventory

3.1 Objectives of the study

The objectives of this study were threefold: first, to collect data from Pakistan on particleboard production and determine the material flow, energy use, and emissions to air, soil, and water from the manufacturing process; second, to investigate various environmental impacts in terms of GWP, ozone layer depletion (OLD), abiotic resource depletion (AD), acidification potential (AP), eutrophication potential (EP), photochemical oxidation (PO), freshwater aquatic ecotoxicity (FAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), and human toxicity (HT); and third, to suggest improvement opportunities by assessing alternative production scenarios.

Table 2 Emissions inventory data for important hazardous substances and its most effective sources in the particleboard manufacture process

Hazardous substance	Compartment	Unit	Total	Most effective sector
Benzene	Air	g	7.67	Hot press, HFO, and diesel fuel
Benzene	Water	mg	772.05	Hot press, HFO, and diesel fuel
Carbon dioxide, fossil	Air	kg	747.12	Rotary dryers, fossil fuels
Carbon monoxide, fossil	Air	kg	1.26	Rotary dryers, fossil fuels
Formaldehyde	Air	g	95.35	Vacuum pump, hot press, rotary dryers
Formaldehyde	Water	g	4.74	Vacuum pump, hot press, rotary dryers
Hydrocarbons, aliphatic, alkanes, cyclic	Air	mg	62.73	Rotary dryers, hot press
Hydrocarbons, aliphatic, alkanes, unspecified	Air	g	6.73	Rotary dryers, hot press
Hydrocarbons, aliphatic, alkanes, unspecified	Water	mg	448.60	Rotary dryers, hot press
Hydrocarbons, aliphatic, unsaturated	Air	g	1.13	Rotary dryers, hot press
Hydrocarbons, aliphatic, unsaturated	Water	mg	41.42	Rotary dryers, hot press
Hydrocarbons, aromatic	Air	g	11.40	Rotary dryers, hot press
Hydrocarbons, aromatic	Water	g	2.05	Rotary dryers, hot press
Hydrocarbons, chlorinated	Air	mg	58.24	Rotary dryers, hot press
Hydrocarbons, unspecified	Air	mg	2.38	Rotary dryers, hot press
Hydrocarbons, unspecified	Water	g	2.38	Rotary dryers, hot press
Methane, fossil	Air	kg	1.91	Fossil fuels, rotary dryers
Methanol	Air	g	33.47	Hot press, hammer mill, vacuum pump, rotary dryer
Methanol	Water	g	2.00	Hot press, hammer mill, vacuum pump, rotary dryer
Nitric oxide	Air	µg	6.4	HFO fuels, rotary dryers, hot press
Nitrogen oxides	Air	kg	2.92	HFO fuels, rotary dryers, hot press
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	g	707.55	Hot press, hammer mill, vacuum pump, rotary dryer
Ozone	Air	g	1.40	Hot press, hammer mill, vacuum pump, rotary dryer
PAH, polycyclic aromatic hydrocarbons	Air	mg	90.93	Rotary dryers, hot press
PAH, polycyclic aromatic hydrocarbons	Water	mg	44.70	Rotary dryers, hot press
PAH, polycyclic aromatic hydrocarbons	Soil	ng	31.30	Rotary dryers, hot press
Particulates	Air	µg	30.37	Flakers, hammer mill, rotary dryers, sander dust
Particulates, < 2.5 µm	Air	g	370.74	Flakers, hammer mill, rotary dryers, sander dust
Particulates, > 10 µm	Air	g	547.85	Flakers, hammer mill, rotary dryers, sander dust
Particulates, > 2.5 and < 10 µm	Air	g	197.37	Flakers, hammer mill, rotary dryers, sander dust
Phenol	Air	mg	25.18	Hot press, vacuum pump
Phenol	Water	g	1.19	Hot press, vacuum pump
Propane	Air	g	18.25	Hot press, vacuum pump
Cadmium	Air	mg	112.32	Fossil fuels, hot press, rotary dryers
Cadmium	Water	mg	731.99	Fossil fuels, hot press, rotary dryers
Cadmium	Soil	mg	1.57	Fossil fuels, hot press, rotary dryers
Sulfur dioxide	Air	kg	2.60	Fossil fuels, hot press, rotary dryers
Sulfur monoxide	Air	µg	1.03	Fossil fuels, hot press, rotary dryers
Sulfur oxides	Air	g	2.13	Fossil fuels, hot press, rotary dryers
Urea	Water	µg	7.44	Hot press
VOC, volatile organic compounds, unspecified origin	Water	g	1.21	Flaker, hammer mill, rotary dryers, hot press

3.2 Reference unit

Consistent with other studies, the reference unit chosen was 1.0 m^3 of finished uncoated particleboard. All input and output data were expressed in terms of this reference unit based on the mass of products and co-products, in accordance with ISO protocol (ISO 2006) and Pakistan Standard Industrial Classification (PSIC 2010). The density of particleboard manufactured was usually 750 kg/m^3 with a moisture content of 2–5%. The bending strength of the Pakistani particleboard

Table 3 Comparative environmental impact assessment of the two proposed scenarios for transportation with the baseline scenario I

Impact category	Measurement unit	Baseline scenario I impacts[a]	Scenario II (25% reduction) impacts	Change due to scenario II in impacts (%)	Scenario III (50% reduction) impacts	Change due to scenario III in impacts (%)
Abiotic depletion (AD)	kg Sb eq	6.059	5.614	7.54	5.173	15
Acidification potential (AP)	kg SO_2 eq	3.343	3.124	7	2.907	14
Eutrophication potential (EP)	kg PO_4- eq	0.610	0.560	8	0.511	16
Global warming potential (GWP100)	kg CO_2 eq	552.000	490.624	11	430.033	22
Ozone layer depletion (OLD)	kg CFC-11 eq	0.0001	0.00009	10	0.00007	20
Human toxicity (HT)	kg 1,4-DB eq	384.032	356.000	7	327.576	14
Freshwater aquatic ecotoxicity (FAE)	kg 1,4-DB eq	135.315	126.377	7	117.525	14
Marine aquatic ecotoxicity (MAE)	kg 1,4-DB eq	256,717.37	242,982.00	5	229,388.81	10
Terrestrial ecotoxicity (TE)	kg 1,4-DB eq	3.178	3.062	4	2.947	8
Photochemical oxidation (PO)	kg C2H4 eq	0.247	0.237	4	0.226	8

[a] Baseline scenario I represents the results of the present study

ranges from 14 to 16 N/mm^2, internal bond strength ranged from 0.3 to 0.4 N/mm^2, and delamination strength is 1 N/mm^2. Similarly, the board thickness tolerance and length and width tolerance are ±0.2 and ±0.25 mm, respectively (www.sunlightwood.net.pk).

3.3 The particleboard production process

Particleboard is a composite wood panel product manufactured from particles derived from logs or wood processing residues bonded by adhesives (ANSI 1993). According to the demands of the customers, a variety of particle sizes are used and board thicknesses manufactured. For instance, the typical particle sizes are 4880 × 2440 mm or 2440 × 1220 mm, whereas the board thickness can range from 4 to 25 mm in Pakistan (SMEDA 2006). Each particleboard industry has its specific process settings; however, the general process flow is common to all of them (Fig. 2).

3.3.1 Delivery and storage of wood materials

The particleboard industry in Pakistan is unusual in that the main raw material supply is in the form of roundwood (logs), not wood processing residues such as sawdust or planar shavings, as is usual in other countries. Logs are brought to the factory normally by large and medium trucks. Initially, the logs and residues are sorted by size and moisture content and stored outdoors at the factory.

3.3.2 Debarking

Bark is considered an impurity in particleboard; therefore, it is usually removed before particle production and sent to the boiler for energy recovery. However, in Pakistan, most of the particleboard mills convert the entire log (including bark) into wood particles. This degrades the quality of the final particleboard product and is the main reason that particleboard produced in Pakistan is generally of inferior quality.

3.3.3 Particle production and storage

The quality of the final particleboard product depends on the moisture content and shape of wood particles. The logs are cut by chippers, hammermills, and shaving machines into small (particle) sizes. Oversized particles are screened out sent back for further breakdown. The particles of varying sizes and moisture content are placed in different silos. Smaller particles are placed on both the surfaces (outside layers) for smoothness, whereas the coarser particles are concentrated in the core (inside layer) for strength, thus making a layered structure of the particleboard.

3.3.4 Screening

A set of screens sorts the particles by size. The screens separate the desired size particles for use in the face and core layers. Undersized particles, called fines, may be utilized as wood fuel in the dryers.

3.3.5 Drying

The particles are passed through dryers of either single-pass or triple-pass configuration, where they are dried by hot exhaust gas from burners. When entering the dryers, particles have up to 100% moisture content on an oven dry weight basis and are dried down to 3–5%. The dryers are fueled by natural gas or sander dust. The dryers often produce particulates and VOC emissions. Particles are dried to different levels of moisture content, with drier particles used in the interior layer.

Table 4 Comparative analysis of resource inputs and carbon emissions, storage, and net carbon flux for 1.0 m^3 particleboard manufacturing globally

Name of country	Wood residues (kg)	UF resin (kg)	Paraffin wax (kg)	Ammonium sulfate as a catalyst (kg)	Urea scavenger (kg)	Sander dust (kg)	Wood fuel (kg)	Electricity (kWh)	Natural gas (m^3)
LCA of PB manufacture in the USA	672	68	2.5	0.72	2.9	25	2.1	157	30
LCA of PB manufacture in the USA	703	68	2.5	0.72	2.9	25	2	158	30
LCA of MDP in Brazil	725	72	5.47	1.38	NA	NA	NA	141	NA
LCA of PB manufacture in Spain	666	67.94	2.13	0.74	NA	NA	NA	105	NA
LCA of PB manufacture in Iran	1360	80	2.5	0.5	0.2	41	48	159	83
LCA of PB manufacture from bagasse in Brazil (m^2)[a]	27	1.5	0.15	0.023	NA	NA	NA	93.11	NA
LCA of PB manufacture from pine wood shavings in Brazil (m^2)[b]	35.41	1.5	0.15	0.023	NA	NA	NA	68.65	NA
LCI of PB production in Australia	721	65	9.85	NA	NA	NA	1549 (MJ)	145.61	722 (MJ)
LCA of NU green soya PB in Canada	601	27	1	24	24	NA	6507 MJ	481 (MJ)	NA

Name of country	Diesel (L)	Petrol (L)	HFO (L)	LPG (L)	Water (L)	Carbon footprint (kg CO_2e)	Carbon store (kg CO_2)	Net carbon flux (kg CO_2)	References
LCA of PB manufacture in the USA	0.26	0.021	NA	0.33	304	392	−1290	−898	Wilson (2010)
LCA of PB manufacture in the USA	0.32	0.021	NA	0.33	304	376	−1289	−913	Puettmann et al. (2013)
LCA of MDP in Brazil	1.7	NA	13.7	NA	175	NA	NA	NA	Silva et al. (2013)
LCA of PB manufacture in Spain	NA	NA	NA	NA	19.69	NA	NA	NA	Rivela et al. (2006)
LCA of PB manufacture in Iran	61 (MJ)	NA	NA	NA	180	NA	NA	NA	Kouchaki-Penchah et al. (2016)
LCA of PB manufacture from bagasse in Brazil (m^2)[a]	134.66 (kwh/m2)	NA	NA	NA	0.0745	NA	NA	NA	Santos et al. (2014)
LCA of PB manufacture from pine wood shavings in Brazil (m^2)[b]	157	NA	NA	NA	0.0745	NA	NA	NA	Santos et al. (2014)
LCI of PB production in Australia	15.95 (MJ)	NA	85.65 (MJ)	63.56 (MJ)	NA	NA	NA	NA	Tucker et al. (2009)
LCA of NU green soya PB in Canada	NA	NA	NA	NA	7311	407.6	−1039	−631.7	Vertima and Ellio (2016)

NA data not available in the literature

[a] Data not available

[b] Santos et al. (2014) applied square meter functional unit for their LCA study of PB only

Table 5 Potential environmental impacts caused by 1.0 m^3 particleboard manufacturing reported globally

Name of the country	GWP (kg CO_2e)	AP (kg SO_2eq)	EP (kg PO4- eq)	PO (kg C2H4 eq)	AD (kg Sb eq)	TE (kg 1, 4-dB eq)	OLD (kg CFC-11 eq)	HT (kg 1, 4-dB eq)	MAE (kg 1, 4-dB eq)	FAE (kg 1, 4-dB eq)	References
LCA of particleboard production in the USA	375.67	215.47	0.1299	37.44	0.97	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	Puettmann et al., 2013a)
LCA of particleboard production in Brazil	333.28	2.4	0.132	0.28	0.98	82.8	NA[a]	6.71E-07	NA[a]	NA[a]	Silva et al. (2013a)
LCA of particleboard production in Spain	0.33	6	6	NA[a]	225.1	115.1	NA[a]	32	NA[a]	NA[a]	Rivela et al. (2006)
LCA of particleboard production in Iran	433	1.82	0.13	0.49	4.13	1.76	0.00007	155.77	81,951.11	32.19	Kouchaki-Penchah et al. (2016)
LCA of particleboard manufacture from bagasse (1.0 m^2)[b]	74.42	42.22	81.42	24.76	2692	NA[a]	NA[a]	7,800,000	NA[a]	NA[a]	Silva et al. (2014a)
LCA of particleboard manufacture from pine wood shavings (1.0 m^2)	168.06	95.24	183.68	25.71	3984.7	NA[a]	NA[a]	7,847,000	NA[a]	NA[a]	Silva et al. (2014b)
LCA of NU green soya particleboard in Canada	440	1.54	0.96	25.7 (kg O_3 eq)	NA[a]	NA[a]	3.2E-05	NA[a]	NA[a]	NA[a]	Vertima and Ellio (2016)
LCA case study of sugarcane bagasse addition to particle board manufacturing in Brazil	319	2.49	0.207	0.344	0.0004	10.4	2.5E-06	1.96E-06	NA[a]	NA[a]	Silva et al. (2014a)

GWP global warming potential, *AD* abiotic depletion, *EP* eutrophication, *PO* photochemical oxidation, *AP* acidification potential, *TE* terrestrial ecotoxicity, *OLD* ozone layer depletion, *HT* human toxicity, *MAE* marine aquatic ecotoxicity, *FAE* freshwater aquatic ecotoxicity, *NA* data not available in the literature

[a] Data not available

[b] Santos et al. (2014) applied square meter functional unit for their LCA study of PB only

Table 6 Comparative environmental impacts assessment of baseline results with the results obtained by 25% reduction in the UF resin consumption

Impact category	Unit	Baseline scenario I impacts (93 kg UF resin)[a]	Scenario II impacts at 70 kg UF resin (25% reduction in UF resin)	Decrease in environmental impacts (in percent)
Abiotic depletion (AD)	kg Sb eq	6.059	5.421	10.52
Acidification potential (AP)	kg SO_2 eq	3.343	2.897	13
Eutrophication potential (EP)	kg PO_4- eq	0.610	0.530	13
Global warming potential (GWP100)	kg CO_2 eq	552	490.000	11
Ozone layer depletion (OLD)	kg CFC-11 eq	0.0001	0.00009	10
Human toxicity (HT)	kg 1,4-DB eq	384.032	331.000	14
Freshwater aquatic ecotoxicity (FAE)	kg 1,4-DB eq	135.315	116.195	14
Marine aquatic ecotoxicity (MAE)	kg 1,4-DB eq	256,717.37	216,322.738	16
Terrestrial ecotoxicity (TE)	kg 1,4-DB eq	3.178	2.597	18
Photochemical oxidation (PO)	kg C2H4 eq	0.247	0.215	13

[a] Baseline scenario I represents the results of the present study

3.3.6 Blending

In this process, urea formaldehyde resin, catalyst, paraffin wax, and scavengers are added to the dried particles. The resin acts as a binder and its dosage plays a vital role in the stability of the final product. The most common resins used are UF, phenol formaldehyde (PF), and melamine formaldehyde (MF). However, urea formaldehyde resin (UF resin) is the least expensive and is clear when reacted and is thus the dominant adhesive used (GDC 2004; AWPAI 2004). For particleboards in which more moisture resistance is desired, either polymeric isocyanate or melamine urea formaldehyde resins may be used. Paraffin wax is added to improve the water resistance of the boards. Catalysts control the rate of resin-curing during the pressing process. Scavengers also may be added in the blending step to reduce formaldehyde emissions from the process. The aqueous solution of resin and other additives is sprayed through nozzles onto the particles in rotating drums.

3.3.7 Mat forming

After blending, the particles are spread on a tray or conveyor to form a mat. The mat is generally multiple layers (three or five) comprising face and core layers. The size of particles and their resin and moisture contents are controlled for each layer to acquire desired board characteristics.

3.3.8 Hot pressing

Formed mats are moved into multi-opening hot presses that consolidate the mat and react the resin. Often, the mat is pre-pressed before the hot press to decrease the thickness. The presses work at adequate temperature (140–220 °C) and pressure (2–5 MPa) to cure the resin and obtain the desired final thickness of the board. Due to the high temperature and resin curing, hazardous air pollutants (HAPs), particulates, and VOCs are emitted to the air. If there are emission control devices, i.e., regenerative thermal oxidizers (RTOs),

Table 7 Summary of subcategories related to CExD indicator and associated hotspots in particleboard production

Sub-category	Measurement unit	Total	Most effective sectors/hotspots
Non-renewable, fossil	MJ-eq	12,504.86	UF resin, paraffin wax, HFO, urea scavenger, natural gas, transport, diesel
Renewable, biomass	MJ-eq	1455.38	Wood wastes, wood fuel, and sander dust burned in dryers, UF resin
Renewable, potential	MJ-eq	782.49	Electricity, UF resin, and transportation
Renewable, water	MJ-eq	458.14	UF resin production and urea scavenger
Non-renewable, nuclear	MJ-eq	246.63	UF resin, HFO, urea scavenger, natural gas, transportation
Non-renewable, metals	MJ-eq	159.33	Urea scavenger, transport, paraffin wax, ammonium sulfate
Non-renewable, minerals	MJ-eq	25.40	Transport, electricity, waste mineral oils
Total	MJ-eq	15,632.23	

Table 8 Ecoinvent database v.3.0 and associated processes in SimaPro v.8.3 software applied for environmental impacts modeling in the present study

Inputs category/activity	Process followed from the SimaPro v.8.3 software	Project database
Metals\Non ferro\Transformation	Copper cake {GLO}| treatment of | Alloc Def, S	Ecoinvent 3—allocation, default—system
Diesel fuel consumption	Diesel {RoW}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Purchased electricity	Electricity, high voltage {RoW}| electricity production, hydro, run-of-river | Alloc Def, S	Ecoinvent 3—allocation, default—system
Heat\Wood\Transformation	Heat, central or small-scale, other than natural gas {RoW}| heat production, mixed logs, at furnace 100 kW | Alloc Def, S	Ecoinvent 3—allocation, default—system
Heat\Wood\Transformation	Heat, central or small-scale, other than natural gas {RoW}| heat production, mixed logs, at furnace 30 kW | Alloc Def, S	Ecoinvent 3—allocation, default—system
Fuels\Oil\Fuel oil	Heavy fuel oil {RoW}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Fuels\Natural gas	Natural gas, high pressure {RoW}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Chemicals\Organic	Paraffin {GLO}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Chemicals/Organic	Urea formaldehyde resin {RoW}production | Alloc Def, S	Ecoinvent 3—allocation, default—system
Fuels\Oil\Petrol	Petrol, unleaded {RoW}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Finished product distribution/marketing	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
UF resin transport to PB mill	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Wood logs transport to PB mill	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {GLO}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Wastes sent to landfill	Tyre wear emissions, lorry {RoW}| treatment of | Alloc Def, S	Ecoinvent 3—allocation, default—system
Chemicals\Fertilizers (inorganic)	Urea, as N {GLO}| market for | Alloc Def, S	Ecoinvent 3—allocation, default—system
Waste\Transformation\Electronics waste\Others	Used fluorescent lamp {GLO}| treatment of | Alloc Def, S	Ecoinvent 3—allocation, default—system
Waste\Transformation\Electronics waste\Others	Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical treatment | Alloc Def, S	Ecoinvent 3—allocation, default—system
Waste\Transformation\Incineration Hazardous waste	Waste mineral oil {RoW}| treatment of, hazardous waste incineration | Alloc Def, S	Ecoinvent 3—allocation, default—system
Waste\Transformation\Others	Waste paper, unsorted {RoW}| treatment of, sorting | Alloc Def, S	Ecoinvent 3—allocation, default—system
Waste\Transformation\Incineration\Municipal incineration	Waste textile, soiled {RoW}| treatment of, municipal incineration | Alloc Def, S	Ecoinvent 3—allocation, default—system

regenerative catalytic oxidizers (RCOs), and biofilters, then these devices treat these emissions in the particleboard factory.

3.3.9 Cooling

After pressing for 2–6 min, the hot boards are then transferred to a rotating wheel to cool the boards, equilibrate the moisture content, and stabilize the resin curing process. Some air emissions may be released at this point.

3.3.10 Sanding

The cooled panels are moved to the sander to provide the desired surface smoothness and precise and uniform panel thickness. Sander dust produced during this process is sent back to the production line to recycle it as furnish or it is utilized as a fuel in the dryers. Particulate emissions are go to cyclones and baghouses, if installed.

3.3.11 Sawing

The large boards are sawn into specific lengths and widths according to the customers' requirements. Trimmings are hammermilled into particles and sent back to the production process as feedstock. The boards are now ready to be stacked and shipped.

3.3.12 Associated activities

Other processes include combustion to produce heat and energy for running the processes of board manufacture. The boilers are usually fired with natural gas, wood residues, or oil fuels. These combustion processes release carbon monoxide (CO), CO_2, and other gases into the air. Electricity and natural gas are consumed to operate the emission control systems. The logs and other raw materials are transported by trucks from various places to the particleboard mills.

3.4 Life cycle inventory and data quality assessment

In the present study, data on particleboard manufacture were acquired from eight particleboard factories in Pakistan. The questionnaire survey covered the transport and usage of inputs such as wood logs, fossil fuels, purchased electricity, and additives, through the production of the particleboard at the mill. This approach is a cradle-to-gate approach; however, we also considered the transportation of finished particleboard to the distribution centers, because most of the particleboard mills with large production capacities are in the northwestern part of Pakistan (the Khyber Pakhtunkhwa province) (Fig. 6). Thus, finished product distribution is an important component of the particleboard production chain in Pakistan and our study is a cradle-to-gate (distribution center) approach as shown in Fig. 1. Particleboard mills were visited to collect the required data through surveys and interviews with mill managers and workers. Data regarding production capacity, manufacturing processes, fossil fuels and electricity use in the mill, total distance traveled by the mill fleet, and the amount of waste generated were provided by the mill officials. Information about the wood species consumed and their moisture content were reported by wood buyers hired by each mill. Average values for transport distances were estimated by the mill managers for primary and secondary raw materials and finished product distribution (Fig. 2).

This study covered the production period 2015–2016. Production-weighted average values were calculated from the information provided by the eight particleboard mills surveyed (Table 1). The data quality assurance and assessment of the collected data included reporting of the variation of the dataset in the form of the weighted coefficient of variation (CV_w). This method is also included in the "CORRIM guidelines for performing life cycle inventories on wood products" (Puettmann et al. 2014). The coefficient of variation (CV) defines the variability of the data series by dividing the standard deviation by the mean (Abdi 2010). To be consistent with the documented production-weighted average values (Eq. 1), the weighted standard deviation was calculated (Eq. 2). Furthermore, the CV_w was calculated and documented for individual values by using Eq. 3 (Puettmann et al. 2014; Toshkov 2012; NIST 1996).

$$\bar{x}_w = \frac{\sum wx}{\sum w} \quad (1)$$

$$\mathrm{Sd}_w = \sqrt{\sum_{i=1}^{N} W_i \left(X_i - \overline{X}_W\right)^2 x \frac{N'}{\left(N' - 1\right)\sum_{i=1}^{N} W_i}} \quad (2)$$

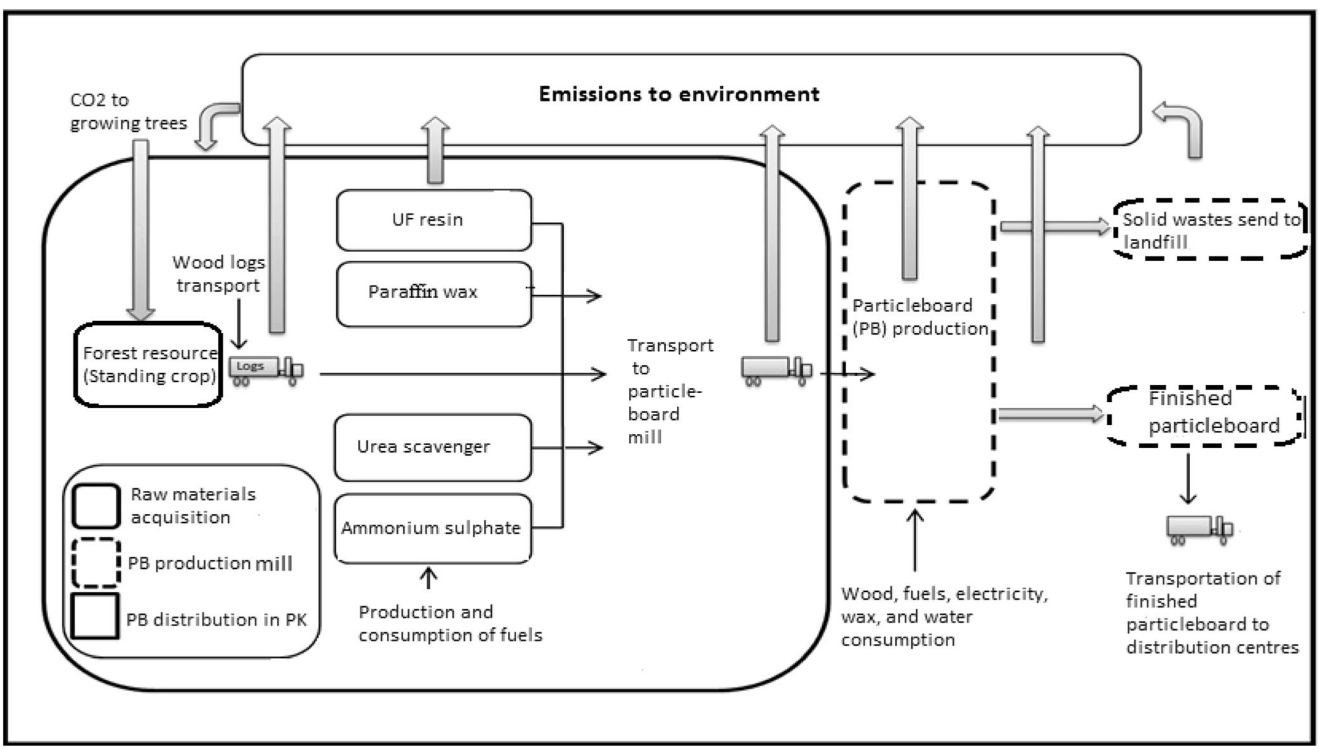

Fig. 1 System boundary of the particleboard (*PB*) manufacturing life cycle model, cradle-to-gate (distribution center) perspective

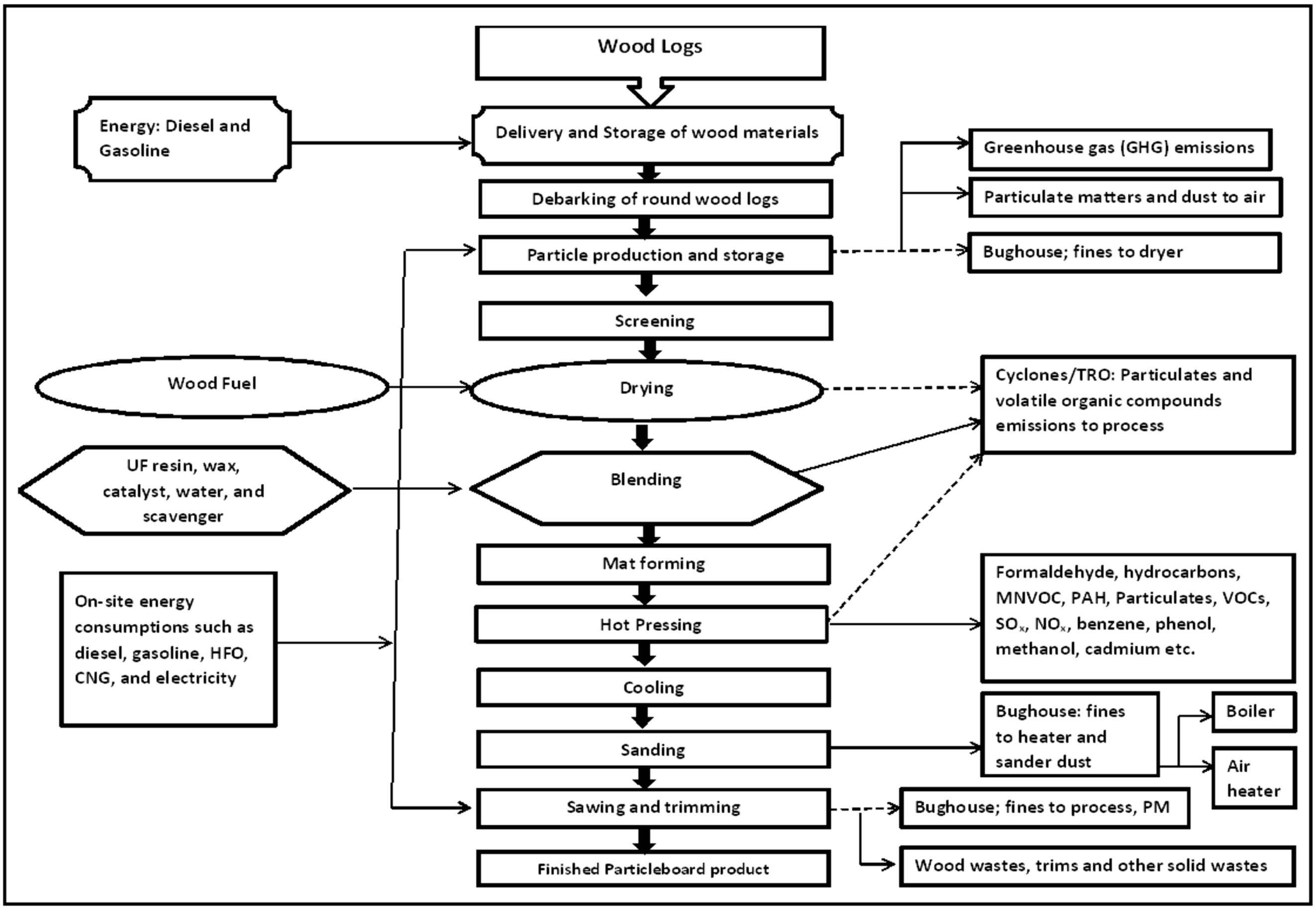

Fig. 2 Flow sheet diagram of a typical particleboard manufacturing process

$$CV_w = \frac{Sd_w}{\bar{x}w} \quad (3)$$

Secondary data for emissions to air were provided by the Khyber Pakhtunkhwa Environmental Protection Agency (KP-EPA), Pakistan. The eight factories surveyed were assumed to be representative of the "state of the art" of the Pakistani particleboard manufacturers; they collectively produced 45,832 m^3 of particleboard in 2015–2016, representing 60% of the total Pakistani particleboard production. Specific and reliable data for the forest production stage were not available for the particleboard production process in Pakistan. Most of the trees for particleboard production are grown naturally on marginal lands (Clark 1990) or along the field belts without any additional inputs of fertilizers or water. The carbon footprints from fossil fuel combustion and electricity generation were estimated using the Intergovernmental Panel on Climate Change (IPCC) emission factors and methodology (IPCC 2006) present in the SimaPro v.8.3 software. Secondary LCI data for the other materials and activities were taken from the literature (Ecoinvent 2004; KP-EPA 2015). Table 1 exhibits the life cycle inventory of 1.0 m^3 of particleboard manufacture in Pakistan. The transport freight distances and weight of wood logs were directly reported from the drivers/operators of the trucks. Generally, the logs were transported in medium trucks with a payload up to 10–20 metric tonnes, covering an average distance of 336 km by road. The UF resin and other raw materials (paraffin wax, urea scavenger, and ammonium sulfate catalyst) were transported by small trucks with a payload up to 7–10 t, traveling an average of 113, and 103-km road distance, respectively. Likewise, the finished particleboard is distributed by large trucks with a payload up to 30 t covering an average distance of 847 km.

As generally done in LCA studies, personal activities such as workers commuting to and from the factory workstation and capital infrastructure were excluded from the system boundary of this study. Wood wastes produced during the wood particle formation and finished product trimming stages are combusted in the dryers to recover energy. Stationary wastes, including paper and cardboard, hazardous wastes produced from the maintenance of the company-owned vehicles, and other manufacture operations were also reported during the survey of the mills. "Other wastes" consisted of toners, oil and air filters, batteries, solvents, and lamps. Although these wastes were in very small quantities, all these wastes were considered known outputs to the technosphere during the environmental impacts modeling by the SimaPro v.8.3 software.

3.5 Life cycle impact assessment and modeling

The environmental impact analysis was performed using two life cycle impact assessment (LCIA) methods: CML 2000 V2.05 (Guinee 2001; Silva et al., 2014a) and cumulative exergy demand (CExD) (Kouchaki-Penchah et al. 2016) in SimaPro v.8.3 software. These two methods were chosen because they were applied in other LCA studies of composite wood products (e.g., Silva et al. 2013a; González-García et al. 2011). SimaPro v.8.3 was also used to access secondary data from sources such as the Ecoinvent database v.3.0 (Ecoinvent 2004) (Table 8), as there is no country-specific database developed for Pakistan. Ten environmental impact categories are analyzed by CML 2000 v2.05 methodology, whereas seven subcategories of exergy are evaluated through the CExD indicator. The environmental impact categories include abiotic depletion, acidification potential, eutrophication potential, global warming potential, photochemical oxidation, human toxicity, ozone layer depletion, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity. The exergy subcategories are non-renewable fossil, non-renewable nuclear, non-renewable metals, non-renewable minerals, renewable water, renewable potential, and renewable biomass.

Mass-based allocation was adopted for all the resource inputs and outputs and associated impacts. Wood logs were hauled by medium trucks with a payload of 10–20 t covering 336 km on average (Table 1). It was assumed that the medium trucks consumed 10-l diesel per 100-km road travel. Seven of the surveyed mills reported that logs along with bark are used for particleboard manufacture in Pakistan; one mill removed bark from the logs. The justification of the factory managers was that the thin bark of poplar, eucalyptus, and farash is difficult to peel.

3.6 Cutoff rules and other assumptions

According to the product category rule (PCR) guidelines, if a mass or energy flow is less than 1% of the cumulative mass or energy of the total, it may be excluded from the analysis, provided its environmental relevance is minor (FPInnovations 2011). However, this analysis considered all the mass and energy flows for primary data and no cutoffs were applied in the impact assessment. The data collection, assumptions, and life cycle impact analysis followed the protocols developed by the CORRIM guidelines for performing life cycle inventories on wood products (Puettmann et al. 2014) and International Organization for Standardization (ISO 2006). Additional considerations included:

- The eight particleboard mills surveyed were assumed to be representative of "state of the art" of the Pakistani particleboard manufacture practices.
- All survey data collected from the eight particleboard mills were production-weighted in comparison to the total surveyed production for the year 2015–2016.
- The particleboard density mainly depends on the species used for its manufacture and its grades which needs certain mechanical properties according to the standards. The density of the Pakistani particleboard was assumed to be 750 kg/m^3, based on discussion with the production managers of all the surveyed particleboard mills.
- The logs utilized in the particleboard production are assumed to be manually felled using axes and then bucked manually using cross-cut saws; therefore, no fossil fuel energy was consumed on the harvest of wood logs for particleboard manufacture.
- For wood and wood waste (green), 50% moisture content (MC) on a dry basis was assumed, whereas for sawdust/sander dust and dry wood waste, 3–5% MC on a dry basis was assumed.
- Primary raw materials such as logs were assumed to be transported by trucks with a payload of 20 metric tonnes, whereas secondary raw materials were assumed to be transported by trucks with a payload of 10 metric tonnes.
- The finished particleboard product was assumed to be distributed using trucks with a payload of 30 metric tonnes.
- One hundred percent of diesel fuel consumption was assumed for raw materials and product distribution and marketing purpose. Furthermore, it was assumed that large trucks consumed 20 l of diesel per 100-km road travel, whereas medium and small trucks consumed 10-l diesel per 100-km travel.

3.7 Limitations of the study

The present study is based on cradle-to-gate life cycle assessment, which did not include some of the potentially important sources of emissions from the particleboard production chain, due to unavailability of the relevant and accurate data. For instance, the forest operations can include growing of the seedlings, site preparation, planting, thinning, fertilizer use, and final harvesting (Johnson et al. 2005). However, numerous studies (Wilson 2008, Wilson, 2010a; 2010b, Puettmann et al., 2013a; Puettmann et al., 2012; Puettmann et al. 2013b; Puettmann et al. 2013c; Puettmann et al. 2013d) have found that the impacts of forest operations are very small in comparison with product manufacturing. The use and disposal of the particleboard were also not included in this study, because the final use of particleboard and end of life is uncertain, as some of the particleboard is consumed within the country while some are exported to Afghanistan, Sri Lanka, Saudi Arabia, and other Gulf states in the form of furniture.

Similarly, LCA provides a holistic view of environmental impacts and this has been considered as one of the strength of this approach; however, it does not completely address localized impacts of the systems or phenomena and does not consider temporal variations as well. Therefore, environmental impacts are not time or space specific and results from LCA studies are defined as potential impacts. Moreover, the accuracy and reliability of the study greatly depend on the quality and availability of consistent, accurate, and complete data. But unfortunately, there is no country-specific database for industrial inputs and outputs of any product including particleboard. We had collected data about inputs and outputs of particleboard production through questionnaire surveys from the particleboard mill officials. We have noted their reply regarding the input or output. Therefore, the data uncertainty is a big issue in LCA studies from developing countries such as Pakistan.

Mostly, the geographical coverage of databases used for LCA environmental impacts modeling is limited to Europe and the USA, which can affect the comparability between studies conducted in other part of the world such as developing countries as the case in our study. Therefore, country-specific databases should be developed just like Ecoinvent in Europe and Franklin Associates and CORRIM in the USA, which provides relevant, accurate, consistent, and complete data in regional context of these countries. In addition, the current LCA study focuses only on the environmental aspects of particleboard production and does not incorporate social or economic impacts of the particleboard product due to unavailability of relevant, accurate, and consistent data; however, it should be investigated in future studies using Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) of particleboard production in Pakistan.

4 Results and discussion

The LCI data for 1.0 m^3 particleboard manufacture are presented in Table 1. The results of life cycle impact assessment for 1.0 m^3 particleboard manufacture and the relative contribution per process to the environmental impact categories are presented in Fig. 3. The UF resin production, transport of primary and secondary materials and finished particleboard distribution and marketing, HFO and natural gas consumption, and urea scavenger had the highest contributions to most of the impact categories. Our results are in accordance with previous research, in that environmental burdens are mostly associated with adhesive production, transport of resource materials, fossil fuel combustion and electricity consumption, specifically in the wood particle preparation and board finishing steps (Puettmann et al., 2013a; Santos et al. 2014; Kouchaki-Penchah et al. 2016; Silva et al. 2013a; Garcia and Freire 2012; Rivela et al. 2006).

The on-site industrial processes of the particleboard manufacture were accountable for most of the impacts in AD, mainly UF resin production (42%), from transport of primary and secondary resource materials (20%), natural gas consumption (13%), finished product distribution and marketing (9.54%), HFO use (7.51%), and other secondary materials such as paraffin wax, etc. (5%). Our results are in accordance with Kouchaki-Penchah et al. (2016) who reported that AD was mainly caused by UF resin (40%), followed by natural gas (32%) and electricity (18%) in the Iranian particleboard manufacturing process. However, the contribution of these processes in the Iranian particleboard production process was higher because most of the particleboard manufacturers there use second hand production lines with old technologies, which leads to high energy consumption and ultimately to higher levels of emissions (Kouchaki-Penchah et al. 2016). On the other hand, the UF resin (30%) and HFO (35%) were responsible for most of the impacts in the AD impact category in the Brazilian and Portuguese particleboard manufacturing process (Silva et al. 2013a, 2015). The AD impacts of HFO production are mainly associated with the extraction of minerals, coal, crude oils, and other non-renewable resources required for its production. Likewise, UF resin contributes higher impacts in the AD category due to the production of methanol and urea consumed to manufacture the resin, because natural gas and mineral coal are utilized in their production processes (Garcia and Freire 2012; Silva et al. 2013b).

In AP impact category, UF resin is responsible for 54% of the impacts, followed by transport of resource materials and finished particleboard (26%) and natural gas consumption (8%) (Fig. 3). Similarly, in the Iranian particleboard industrial processes, transport, UF resin, and electricity also corresponded to the highest contribution to the AP impact category (Kouchaki-Penchah et al. 2016). However, for the Brazilian particleboard production, HFO and UF resin are an important hotspot in the AP impact category due to the production of sulfur, methanol, and urea (Silva et al. 2013a, 2015). In the EP impact category, again UF resin had the highest contribution (52%), followed by transport of resource materials and finished product distribution (33%), and wood combustion in the dryer (7%), due to the CO, CO_2, urea, and methanol production emissions in the form of NO_x to air and hydrocarbons to water. Likewise, the use of diesel in the harvest, processing, and transport of wood materials, NO_x emissions from the combustion of HFO and wood residues, and UF resin production were also the largest contributors to EP impact category in the Iranian and Brazilian particleboard manufacturing scenarios (Kouchaki-Penchah et al. 2016; Silva et al. 2013a).

The UF resin production (45%) and transport of primary and secondary materials and finished particleboard product distribution (44%) are responsible for highest contribution to the GWP impact category, due to the CO, CO_2, NO_x, urea, and

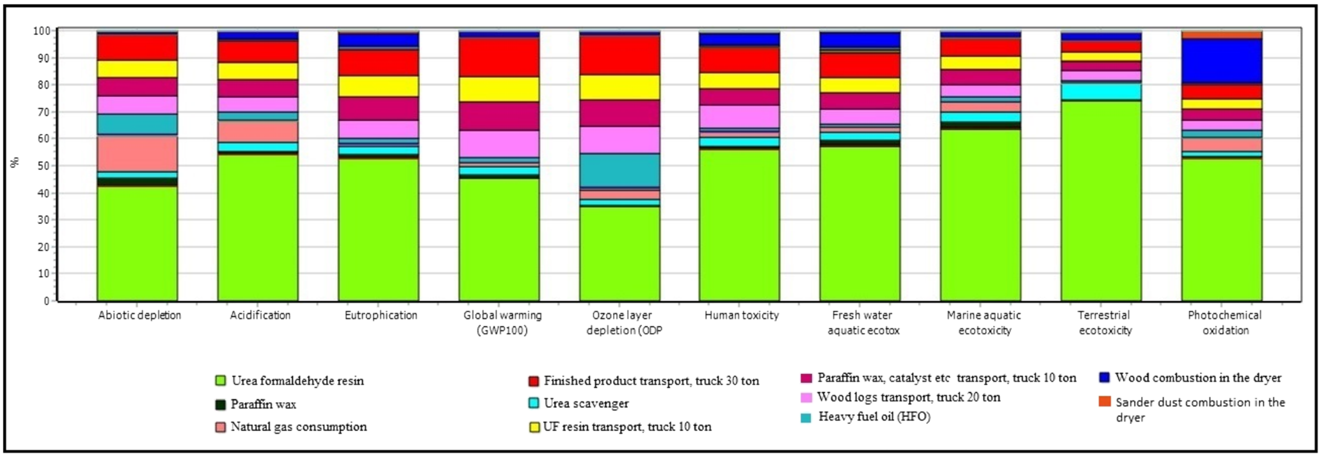

Fig. 3 Relative contribution per process (in %) to various environmental impacts

methanol production. Transport of raw materials accounted for about 30% to the impacts, followed by finished particleboard across the country which contributed about 14% to the impacts in the GWP impact category. Transport of raw materials and finished particleboard is important due to fossil fuel combustion and the long distances from the source of primary and secondary materials to the manufacturing site and the large quantity of wood consumed in the particleboard manufacture (Saravia-Cortez et al. 2013; Kouchaki-Penchah et al. 2016). Thus, the results indicated that the location of the raw materials relative to the manufacturing site could be considered to reduce the environmental impacts (Santos et al. 2014). In addition, electricity and HFO combustion are also an important hotspot in the GWP impact category in Iranian and Brazilian particleboard manufacturing process (Silva et al. 2013a, 2015; Kouchaki-Penchah et al. 2016).

The amount of biogenic carbon stored in the product, specifically in the cradle-to-gate assessments, is often reported because the embodied carbon may be emitted back to environment during the use or end of life phases, such as through incineration (Garcia and Freire 2014; Silva et al. 2015). Wood-based products are often considered to be carbon-neutral materials because they sequester carbon (dioxide gas) during the trees' growth that is equal to that released during their eventual combustion or decomposition (Sharma et al. 2011; England et al. 2013). This "biogenic carbon" neutrality does not necessarily indicate GHG neutrality, as carbon emissions can occur as methane (a more powerful greenhouse gas than carbon dioxide) or be derived from non-sustainable forestry (Kutnar and Hill 2014; Jungmeier et al. 2002a). Forest management practices in Pakistan appear to be unsustainable, given the expectation that forests in Pakistan will be depleted within the coming 15 years if the current annual rate of deforestation (2.1%) continues (GAIN Report 2014). This suggests that the biomass used in particleboard production in Pakistan is not carbon neutral because it does not come from forest/farmland plantation with stable stocks of carbon. The assumption is further complicated by the fact that about 532,000 m^3 of roundwood is imported to Pakistan each year (EC-TRTAP 2007); the sustainability and carbon neutrality of this material are unknown. However, biogenic carbon storage and substitution for fossil fuels can be considered to offset GHG emissions from the particleboard production under a sustainable forest management scenario.

The UF resin production, wood combustion, and transport activities had the largest contribution (52, 20, and 17%, respectively) to the PO impact category. The primary reason for this high contribution was the emissions of CO, CO_2, CH_4, N_2O, and VOCs from the wood and fossil fuel combustion and production of urea and methanol used in the UF resin manufacturing process. Among the fossil fuels, natural gas and HFO were the highest contributors with 5 and 2.44% to the total impacts in the PO impact category, respectively. The combustion of these fossil fuels caused VOC emissions during the wood particle drying and hot pressing process of the particleboard manufacture (Silva et al. 2013a). The UF resin, transport of raw materials, wood combustion in the dryers, and urea scavenger production were the major contributors to HT impacts (Fig. 3). The highest contribution from transport of raw materials and finished product distribution, wood combustion in the dryers, and adhesive production were due to the CO, CO_2, NO_x, VOCs, and free formaldehyde emissions from the particleboard production process. Therefore, manufacturing processes and transportation were the major contributor in the PO and HT impact categories (Kouchaki-Penchah et al. 2016). Our results are in accordance with Silva et al. (2015) that large impacts on HT are mostly due to the heat production through cogeneration of wood in the Brazilian particleboard production. Transportation was accounted for 44% of the contributing emissions to ozone layer depletion, followed by UF resin production (35%) and HFO (12%), which is in line with the results reported by Kouchaki-Penchah et al. (2016).

The UF resin production represents the most important hotspot for all the impact categories, which agrees with previous studies (Werner and Richter 2007; Silva et al. 2013a, 2015; Rivela et al. 2006; Santos et al. 2014, Garcia and Freire 2012; Kouchaki-Penchah et al. 2016), except TE in Brazil and HT in Portugal (Silva et al. 2015). UF resin is also of concern because of free formaldehyde emissions from the finished product (Kinga et al., 1996; European Panel Federation 2004). These free formaldehyde emissions might cause cancer in humans and can cause nose, eye, and throat irritation, which comes under the HT impact category (Silva et al. 2013b; Athanassiadou 2000). Therefore, Silva et al. (2014b) suggested that UF resin should be replaced by melamine urea formaldehyde (MUF) resin, which lessens the free formaldehyde risk but is more expensive (Jungmeier et al., 2002; Gonzalez-Garcia et al. 2009). Similarly, substituting HFO with in-mill wood residues can diminish environmental burdens of the particleboard produced (Silva et al. 2013a). Wood is an important renewable fuel source which can substitute for fossil fuels in energy-intensive processes such as wood (particles) drying (Wilson, 2010a).

Wood particle dryers, primary recovery cyclones, and direct-fired units of the plant emit solid PM, wood dust, condensable PM, VOCs, and combustion products such as CO_2, CO, NO_x, and N_2O into the air (EPA 2002). The hot press process is the major contributor to formaldehyde, total hydrocarbons (THC), condensable PM, PM-10, acrolein, methanol, isobutyl ketone, benzene, and acetaldehyde (Table 2). However, none of the surveyed particleboard mills had installed emission control devices. Therefore, it is evident that the particleboard mill can reduce their emissions from manufacturing process by installing emission control devices and systems, i.e., absorption systems, multi-cyclones, wet electrostatic precipitators, sand filter scrubbers, fabric filters, and oxidation systems for PM emissions. In addition, regenerative thermal oxidation systems could be installed to control the VOC emissions from dryers as well as press exhaust gases, whereas bio-filtration systems should also be installed for monitoring and controlling of different pollutants comprising organic compounds, CO, NO_x, and PM emissions from press exhaust streams (Kouchaki-Penchah et al. 2016; EPA 2002).

4.1 Cumulative exergy demand

The total cumulative exergy demand required for manufacturing of 1.0 m^3 particleboard was 15,632 MJ-eq from the seven impact categories, i.e., non-renewable fossil, non-renewable nuclear, non-renewable metals, non-renewable minerals, renewable potential, renewable water, and renewable biomass (Fig. 4). Among the seven impact categories, non-renewable fossil sources had the highest contribution (80%), whereas renewable biomass combustion in the dryers was identified as the second largest contributor (9%) (Figs. 5 and 6). As can be seen in Table 7, among the various manufacturing processes, UF resin production, fossil fuel consumption, transportation activities, and electricity production and consumption were the most energy-intensive processes, which is in accordance with other studies (Werner and Richter 2007; Santos et al. 2014b; Kouchaki-Penchah et al. 2016).

5 Sensitivity analysis for improvement opportunities in particleboard production process

Most of the environmental impacts in particleboard are associated with the UF resin use and the transportation of raw materials and finished products. Based on our survey results, 93 kg of UF resin is required for manufacture of 1.0 m^3

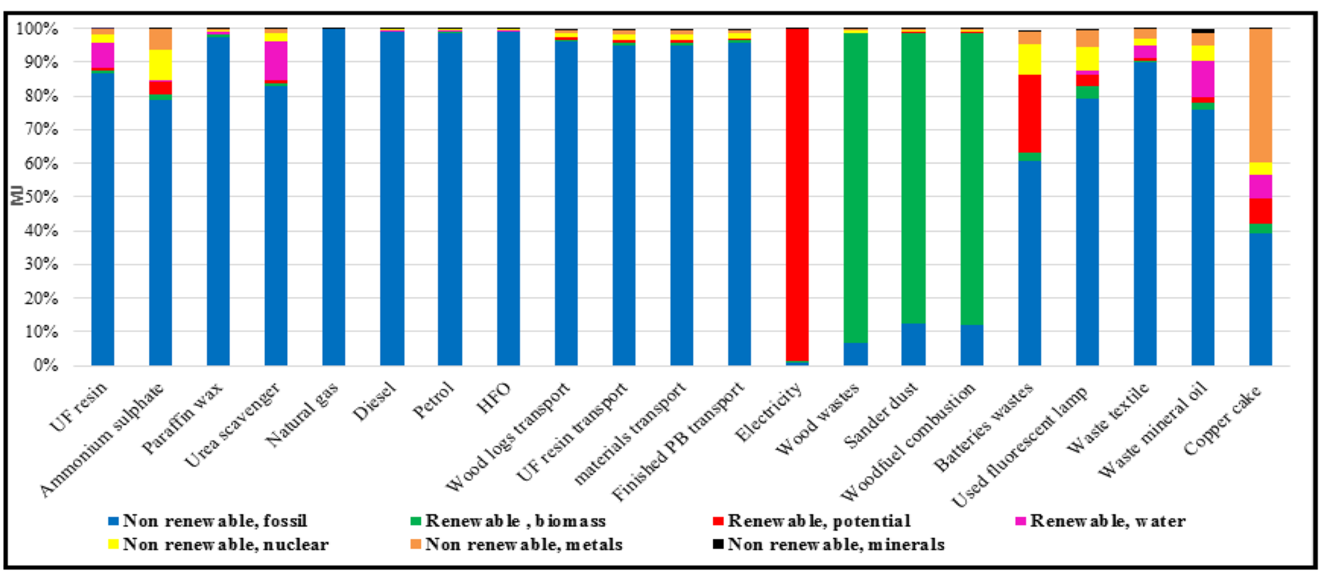

Fig. 4 Energy consumption by single score calculated through cumulative exergy demand (CExD) indicator

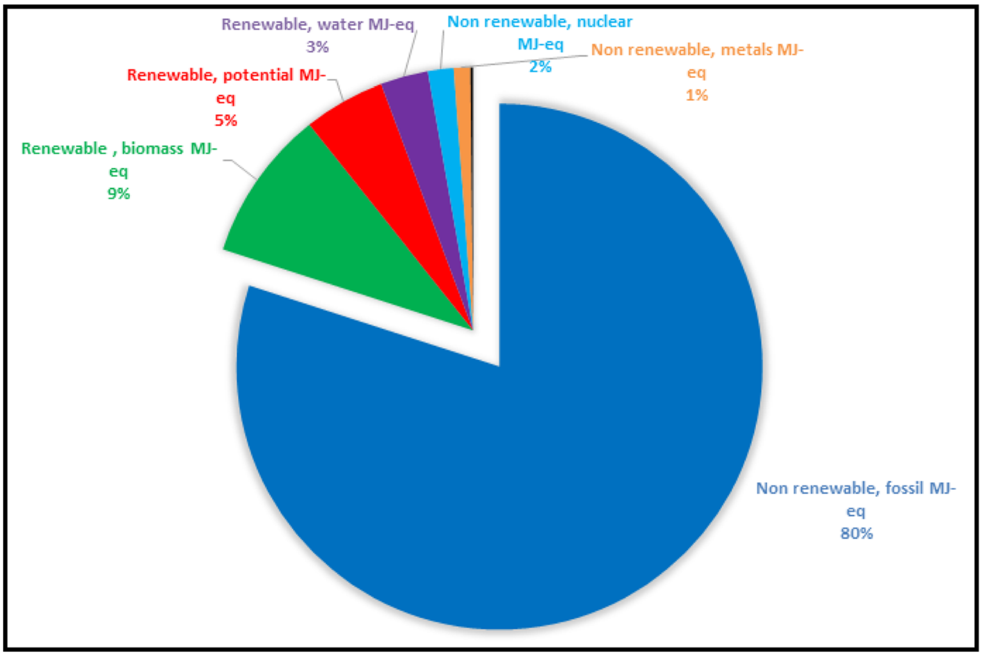

Fig. 5 Relative percent contribution of each subcategory to total cumulative exergy demand

particleboard in Pakistan, whereas only 68, 72, and 68 kg of UF resin per m^3 was used by the USA, Brazilian, and Spanish manufacturers, respectively (Puettmann et al., 2013a; Silva et al. 2013a, b; Rivela et al. 2006). The large quantity of UF resin application by the Pakistani particleboard industry is primarily due to the bark present along with the wood in the particleboard furnish; additional resin inputs are required to achieve suitable mechanical properties in the finished product. Therefore, we assumed that the removal of bark from the furnish could decrease the quantity of UF resin required. We performed a sensitivity analysis for UF resin by reducing the quantity of UF resin to 70 kg/m^3 particleboard manufacture in

Fig. 6 Location map of the surveyed particleboard mills

Pakistan (25% reduction). The results indicated a decrease in most of the environmental impacts such as AP (13%), HT (14%), GWP (11%), MAE (16%), AD (10.54%), TE (18%), and PO (13%) as illustrated in Table 6.

Likewise, three transportation scenarios (baseline scenario I, scenario II, and scenario III) were considered for the particleboard industry. Baseline scenario I represents the present situation of particleboard industry transportation activities, whereas scenario II assumed a 25% reduction in the transportation distance of primary (wood logs) and secondary materials (UF resin, paraffin wax, urea scavenger, and ammonium sulfate) and finished particleboard distribution and marketing, whereas scenario III represented 50% reduction. The scenario II decreased all the environmental impacts, e.g., GWP (11%), OLD (10%), EP (8%), AP (7%), HT (7%), FAE (7%), and AD (7.5%) (Table 3). Scenario III further decreased the environmental impacts. Reductions in the transport to and from the particleboard mills could be achieved by acquiring the raw and secondary materials from areas nearby the mills and/or by diverting the mill freight into high mobility highways. Drivers often choose slow, circuitous local routes because they are toll free, without any load limits, and have fewer police check posts.

6 Sustainability of particleboard industry in Pakistan

The forest resources of Pakistan provide its people with wood to build houses, materials for furniture manufacturing and other domestic needs, and fuelwood. About 46% of energy needs is provided by biomass sources such as agricultural residues and fuelwood. Wood products such as particleboard manufacture are playing a vital role in rural development, employment, and livelihood of the forest-dependent community of Pakistan. On the other hand, the area covered by forest is less than 5% in Pakistan and is projected to be further depleted due to illicit cutting and commercial overexploitation (GOP 2004). The annual raw material requirement for particleboard and fiberboard was estimated by the forestry sector master plan (FSMP) at 22,000 m^3/year (EC-FAO Partnership Programme 2002). To satisfy the wood requirement of Pakistan, about 532,000 m^3 of roundwood is imported each year. All the wood wastes generated from the manufacture of particleboard are combusted in the dryers for energy purposes in the mill. Recycling these wood materials for particleboard production could be for a better use than energy recovery (Rivela et al. 2006). However, wood has a gross calorific value of about 20 MJ/kg (Wilson, 2010b), and this energy would need to be provided from some other source.

Inadequate measures have been taken by the forest departments to curtail illegal cutting, and the scarcity of local wood species poses a serious threat to the wood-using industries in Pakistan (EC-TRTAP 2007). However, forest management practices in Pakistan are underdeveloped and unsustainable; therefore, wood biomass will be totally consumed within the coming 15 years if the current rate of deforestation (2.1%) continues in Pakistan (GAIN Report 2014). Consequently, there is an urgent need to develop and implement plans to ensure a sustainable source of wood raw materials and fuelwood. Reforestation programs could provide a constant source of raw materials and could also improve the ecological conditions, increase the community incomes, and provide employment opportunities in the country.

7 Conclusions

This study presents a cradle-to-gate (distribution center) life cycle assessment of the particleboard manufactured in Pakistan. Life cycle inventory data of particleboard manufacture comprised production-weighted average data acquired from eight particleboard manufacturing mills in Pakistan. The study covers environmental impacts from the resource inputs and output such as wood logs, fuels, catalyst, resin, paraffin wax, wastes, and electricity through raw inputs, transport, particleboard production, distribution, and marketing. To identify the main hotspots and characterize the production process, ten environmental impact categories and CExD indicator with different subcategories were assessed. The total cumulative exergy demand required for manufacturing of 1.0 m^3 particleboard (15,632 MJ-eq) was almost entirely sourced from nonrenewable fossil sources (12,504 MJ-eq). The transport of raw materials and finished particleboard and UF resin production had the highest contributions to all the ten environmental impact categories, whereas HFO and natural gas consumption contributed substantially to abiotic depletion, eutrophication potential, photochemical oxidation, ozone layer depletion, and marine aquatic ecotoxicity impacts. None of the surveyed particleboard mills have installed pollution control systems; therefore, there is a great potential for reducing the environmental burdens posed by particleboard manufacture in Pakistan.

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Compliance with ethical standards

Conflict of interest The authors have declared no conflict of interest in publishing this article.

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