Life cycle assessment of particleboard industry in Pakistan

This work is submitted as a dissertation in partial fulfillment for the award of the degree of

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BY

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Dedicated to
my family, teachers and all those who are
busy in serving humanity
with faith, without fear

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Majid Hussain

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List of Abbreviations

Abbreviations	Full name
AD	Abiotic depletion
AP	Acidification potential
CExD	Cumulative exergy demand
CORRIM	Consortium for research on renewable industrial materials
EP	Eutrophication potential
FAE	Freshwater aquatic eco-toxicity
FSMP	Forestry sector master plan
GDP	Gross domestic product
GHG	Greenhouse gas
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 eco-toxicity
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 eco-toxicity
UF resin	Urea formaldehyde resin
VOCs	Volatile organic hydrocarbons
PB	Particleboard
m^3	Cubic meter

ABSTRACT

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. This study quantified the environmental impacts of particleboard production in Pakistan using a cradle-to-gate (distribution center) life cycle assessment approach. The system boundary comprised raw materials acquisition, transport, particleboard manufacture and finished product distribution. Primary data were collected through surveys and meetings with particleboard manufacturers, whereas secondary data were taken from the literature. The reference unit for this study was one cubic meter (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 version 8.3 software.

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 eco-toxicity impacts. The rotary dryer and hot press was the most important sectors in terms of emissions from the manufacturing process. Furthermore, greenhouse gas emissions (GHG) from off-site industrial operations of the particleboard industry represented 52% of the total emissions from the production of 1.0 m^3 of particleboard in Pakistan. The on-site industrial operations cause direct GHG emissions and accounted for about 48% of the total emissions. These operations included energy consumption in stationary sources, the company-owned vehicle fleet, and the distribution and marketing of the finished product. The use of natural gas combustion in the stationary and mobile sources, raw material transport and urea-formaldehyde resin production chain accounted for the highest emissions from the particleboard production in Pakistan.

The total cumulative exergy demand required for manufacturing of 1.0 m^3 particleboard was 15,632 mega joule-equivalents, with most of the energy usage associated with non-renewable, fossil fuel sources. Among the seven impact categories, non-renewable fossil sources had the highest contribution i.e. 12,504 MJ-eq to the total exergy removed from the nature to manufacture 1.0 m^3 particleboard. Similarly, renewable biomass was the second largest source with contribution of 1,455 MJ-eq exergies, whereas non-renewable minerals were responsible for only 25.40 MJ-eq in the total exergy required for 1.0 m^3 particleboard manufacture. The embodied energy for the manufacture of 1.0 m^3 of particleboard comprises of fossil fuels and purchased electricity consumed in stationary sources of the mill. The energy consumption in stationary sources of the particleboard mill was 5.457 GJ per m^3 of particleboard production, whereas the total energy consumption in cradle-to-gate life cycle of the 1.0 m^3 particleboard production was 8.187 GJ during 2015-16.

The wood materials used in the manufacture of particleboard can store and embodied carbon, which can be utilized to offset the carbon dioxide emissions from production chain of the particleboard mill as well as from product use and disposal, if forest management practices are on sustainable basis (scenario-II in the present study). Therefore, to manufacture 1.0 m^3 of particleboard, the carbon storage was equal to -1441 kg CO_2e, which can offset the cradle-to-gate carbon footprint (975.282 kg CO_2e) of per m^3 particleboard produced in Pakistan during 2015-16. This also leaves a net carbon flux of -564.04 kg CO_2e per m^3 particleboard manufacture as a carbon credit, which can also be used to offset the emissions from product use and disposal, consequently diminishing its impact on climate change. A sensitivity analysis was conducted for a reduction in the quantity of urea formaldehyde resin consumed and freight transport distances. 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. The identification of the major hotspots in the particleboard production chain can assist the particleboard industry to improve their environmental profile. More efforts are needed to investigate the urea-formaldehyde resin production chain and substitution of round wood with wood and agri-residues to assess the potential improvements. In addition, renewable energy sources should be encouraged to avoid GHG emissions by substituting fossil energy. This study also provides a benchmark for future research work to formulate comprehensive emissions reduction plans, because no previous research work is available on environmental profile of the particleboard produced in Pakistan.

Keywords: Life cycle assessment, Cumulative exergy demand, SimaPro, Particleboard, Environmental impacts, Wood, Carbon footprint, Pakistan

CHAPTER # 1

INTRODUCTION
AND
REVIEW OF LITERATURE

CHAPTER # 1

INTRODUCTION AND REVIEW OF LITERATURE

1.1. Wood; a versatile material

Wood is the most important renewable material and regenerative fuel (Rivela et al., 2007; Piekarski et al., 2014; Bowyer, 1995). As a renewable material, wood is popular for its remarkable characteristics such as low specific weight, high strength, excellent insulation properties, carbon storage medium, substitute for more greenhouse-intensive building materials, easy availability and recycling etc. (England et al., 2013; Skodras et al., 2004; Milota et al., 2005). Wood is a multiuse and versatile material and is always in competition with other non-wood materials such as steel, concrete and plastics (Rivela et al., 2006, 2007; Stael et al., 2001; Petersen et al., 2005). Wood is also claimed by industry to be energy efficient, environment friendly and aesthetically pleasant material in comparison with the competing materials (Milota et al., 2005). Besides its use for manufacture of different products, its use as a biomass fuel is responsible for 14% of the global energy consumption and this demand continues to use biomass for energy purpose, partly driven by the targets to accomplish national commitments under the Kyoto Protocol (UNECE/FAO Forest Products, 2004; Koziriski and Saade, 1998; Rivela et al., 2007).

Wood panels are manufactured from processed wood using a synthetic adhesive binder resin under high heat and pressure (ANSI, 2009), whose properties can be altered (Garcia and Freire, 2014; Thoemen et al., 2010). Wood panels have been getting tremendous importance as a substitute to solid wood (FAO, 2012). The common wood panels include particleboards, high and medium density fiberboards, oriented strand boards (OSB) and veneer based products such as plywood and laminated veneer lumber (Doosthoseini, 2012). These panels are mostly used in the construction and furniture industry globally (FAO, 2012; Silva et al., 2013; Biazus et al. 2010). Recently, particleboard, the most popular wood based panels, has got maximum economic development, because it mostly consumes wood residues and used as a good alternative or substitution for non-wood materials in other sectors such as furniture, carpentry, building construction and decoration (Rivela et al., 2006). Particleboard was manufactured in the 1950s from using the industrial wood residues generated during the production of lumber and plywood products (Wilson, 2010). Before this, these wood residues were either burned or disposed of in a landfill as a waste material (Puettmann et al., 2013).

Wood based products have multiple environmental benefits as compared with non-wood products (Lippke et al., 2011; Eriksson et al., 2012; Ritter et al. 2011; Bergman et al., 2014), for example wood based products are made from renewable materials and store carbon. Wood-based panels are an alternative to lumber use in the construction sector and furniture industry (Garcia and Freire, 2014; FAO, 2012). They are manufactured using wood residues bonded with synthetic adhesive binders under high heat and pressure (Kouchaki-Penchah et al., 2016), and their properties are adjusted according to their intended usage such as structural cladding in building or non-structural use in furniture (Wilson, 2010; Puettmann et al., 2013). Pakistan is a growing manufacturer and consumer of wood-based panels, specifically plywood, fiberboard and particleboard (SEMDA, 2006). The particleboard industry uses mostly poplar, eucalyptus, farash, sumbal and mango trees as raw materials. Currently, there are more than 20 particleboard mills in Pakistan (EC-FAO Partnership Programme, 2002). Particleboard is consumed internally in Pakistan and is exported to Afghanistan, Sri Lanka, Saudi Arabia and other Gulf states in the form of furniture.

Particleboard industry is one of the growing industry in Pakistan. During 2013, particleboard industry manufactured a total of 76,000 m^3 of particleboard, contributed a world share of 0.1% and hold on 53 position in the world ranking of particleboard production (www.factfish.com). Pakistani particleboard is an engineered board product manufactured from wood particles obtained from forests and farmland plantations, mainly the popular, eucalyptus, farash and sumbal tree species. Particleboard is commonly utilized by the furniture industry for cupboard sides, tabletops, shelves, doors, dividers (96%) as well as in building wood floors (4%) (Biazus et al., 2010; Wilson, 2010; Puettmann et al., 2013). The forestry and associated wood based industries in Pakistan employed about 500,000 workers, whereas its contribution to the total gross national product (GNP) is about 0.3 percent. Particleboard industry of Pakistan contributed 6.4% to the gross domestic product (GDP) of the country during 2003-2004, which was increased to 8.4% in the year 2004-2005 (ww.boi.gov.pk). Furniture industry consumes about 60% of the particleboard produced as a raw material in Pakistan. Besides, in Pakistan, particleboard demand is expected to go up exponentially (SEMDA, 2006).

In the past, shisham, chir, oak, teak and kikar woods and bamboo were used in the Pakistani furniture industry but now particleboard is widely used. The population growth rate and a shortfall in supply of 6 million houses in the country suggest that demand for particleboard in

Pakistan will remain strong. Pakistan is forest-poor country with a total area of 4.2 million hectares under forests, which makes about 4.8% of the total land area of the country. Pakistan has also only 0.05 hectare of forest per capita as compared to the world average per capita of 1.0 hectare. The continuous increase in the population is also escalating forest depletion, because of dependence on forests for fuelwood, house construction and furniture. About 2.35 million m^3 of industrial roundwood was harvested from the state-owned forests and farmlands from 1996-2000. However, due to deficiency of roundwood in the country and more demands by the construction and forestry sector, about 532,000 m^3 of roundwood was also imported each year to fulfill the country's roundwood demands. Forests also provided fuelwood which provides 32% of the country's energy needs. About 60% of the urban and 90% of the rural households consumes fuelwood for primary energy needs such as cooking and heating (Tahir et al., 2010; PDRRFF, 2000).

1.2. Life cycle assessment: An environmental sustainability indicator

An indicator is an observed value representative of the phenomenon under study (EEA, 1999). Indicators measure information by combining different and multiple datasets; consequently, demonstrate and communicate complex phenomena in a simplified way, comprising tendencies and developments over a specified period (Roca et al., 2005). Prolific environmental policy needs the depiction of complex environmental systems in one or more simpler figures, which are comprehensive and understandable to the policymakers and public (Niemeijer, 2002). In addition, indicators provide information about the key attributes that affect the suitability of product and process from a sustainability viewpoint (Herva et al., 2011). For instance; intensity and type of energy consumed (renewable or non-renewable), materials use (resource depletion), freshwater use, wastes and pollutants production, environmental impacts of service/process/product, and overall human health and environmental risk assessment (Sikdar, 2003b).

Companies are facing increasing pressure to diminish environmental burdens of their products (Kouchaki-Penchah et al., 2016; Silva et al., 2013). To achieve this goal and assess the environmental performance of products, it is crucial to take life cycle assessment (LCA) approach (Remmen, 2007). LCA is a tool that can be applied to recognize the most significant environmental burdens posed by the products and to identify the major hotspots processes and operations that contributed more to the overall environmental burdens (Baumann and Tillmann, 2004). Similarly, before applying the substitution principle, the environmental impacts of all the products across their life cycles should be confirmed, because it will help to design products, their uses, disposal and recycle in such a manner that the environmental impacts are diminished and decreased to a level that is competitive and could even better perform as a potential substitution (Robertson et al., 1997). Therefore, a novel and new technique with uniform perceptive is required to develop accurate and effective comparisons among various products and their alternatives. Raw materials and energy consumption impacts arises from the products with their cradle to grave must be consider and assessed.

Therefore, LCA is the tool which can be applied to a product to assess their environmental impacts, recognize the hotspot process of the life cycle, which contributes more burdens, and can also predict the effects of intended improvement actions. It can be a sophisticated and prevailing technique for enhancing the resource efficiency and energy consumption and lead to substantial cost savings. In addition, life cycle inventory and assessment is indispensable when declaring a product green based on its favorable environmental performance, provide a benchmark for improvement of environmental performance, and for comparing with the various alternatives products. Because, the data provides a base for scientific assessment of a variety of environmental performance measures such as sustainability, global warming, climate change, carbon sequestration and carbon sink, biofuel use, carbon trade and caps, green product purchasing and green building. However, the demerits of this tool are that it cannot determine and limit the explicit causes of major environmental impacts in the life cycle until all the production stages have been assessed and the data quality has been completely verified. Up to date and relevant environmental data are acquired to determine the environmental burdens of wood based products to be compared with other products. Therefore, LCA in forestry and wood chain have equal role in shaping environmental policies and strategies while evaluating environmental burdens of forest management (Nikinmaa and Markku, 2000).

Furthermore, LCA consider the entire supply chains of materials and energy. Conventionally LCA approach was based on cradle to grave framework, but in recent times a cradle to cradle approach has been introduced; however, when examining a specific product or production process, a specific system boundary approach (gate to gate or cradle to gate) can also be defined and carried out (McDonough and Braungart, 2002). Indicators generally originate 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). Therefore, LCA has largely been applied in the environmental assessment of processes (Wood et al., 2006; Burgess and Brennan, 2001; Cherubini et al., 2009) and products (Roy et al., 2009; Nieminen et al., 2007). LCA can also play a very useful role in the environmental policy when assessing the environmental impacts of the production process (Kouchaki-Penchah et al., 2016). It may also be a powerful tool for increasing the efficiency of resources and energy utilisation and lead to significant cost savings (Rivela et al., 2006).

Life cycle inventory (LCI) is one of the most effective methods for calculating hazardous emissions with tracking the input and output material and energy flows related to each phase in the manufacturing process of a product (NREL, 2009). Developed countries are conducting LCI researches to support the needs of their industries and to mitigate climate change and reduce the greenhouse gas (GHG) emissions (Lee et al., 2004; Kim and Song, 2014). Similarly, exergy is an excellent 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 et al., 2011; Hovelius, 1997). Furthermore, from thermodynamic viewpoint, 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). 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 widely been explored (Banat and Jwaied, 2008; Zhu et al., 2005; Hau and Bakshi, 2004a). In addition, it can also be applied to assess the efficiency of energy resources consumption in the processes (Castro et al., 2007).

1.3. Carbon footprint based on life cycle assessment approach

Environmental sustainability has arisen as an important subject amongst the public, researchers, policymakers, and industry. Environmental impacts can be evaluated through various impact-specific indicators based on a life cycle assessment (LCA) approach (Cucek et al., 2012). LCA is a holistic, structured, and internationally standardized tool (ISO, 2006) for measuring emissions, resource use, environmental and health impacts related to processes or products over their life cycles. The life cycle stages considered may include resource extraction ("cradle") through materials production and manufacturing ("gate"), usage, recovery, recycling, reuse ("cradle") or disposal ("grave") (Guinee et al., 2002; EC, 2010). A footprint is a quantitative measurement describing the appropriation of natural resources by humans (Hoekstra, 2008). The major categories of footprints developed to date are carbon, ecological, and water footprints, forming the so called "footprint family" (Galli et al., 2011, 2012). The carbon footprint was most probably derived from the global warming potential (GWP), an indicator often reported in LCA studies, and was first defined in the scientific literature by Hogevold (2003).

In response of the global struggle to meet the international obligations of reducing the greenhouse gas (GHG) emissions, many corporations include environmental issues in their management systems, with possible effects in their full production chain (Laurent at al., 2010; Despeisse et al., 2012; Hussain et al., 2014). Carbon footprint is the sum of all the GHG emissions directly or indirectly caused by a company, organization, process, product or person, usually measured in terms of tonne or kilogram carbon dioxide equivalents (CO_2e) (Lynas, 2007; Wiedmann and Minx, 2007; Hussain et al., 2014). It comprises carbon dioxide, methane, nitrous oxide and fluorinated gas emissions expressed in terms of CO_2e based on 100 years of radiative forcing potential (IPCC, 2007). Carbon footprint is being extensively applied for many reasons, i.e. communication of carbon footprint to customers, to help develop GHG reduction strategies along the product life cycle, and to assist consumers to identify products that contribute less to climate change (Bolwig and Gibbon, 2009).

Concerns regarding GHG emissions and global warming are progressively becoming one of the most technological and important societal and political challenges. Albeit, many carbon-related indicators have been developed but carbon footprint is the most widely applied and popular indicator to raise awareness on the GHG emissions and global warming impact (Hoffmann and Busch, 2008). The carbon footprint is quantified in mass units; thus, it is equivalent to the global warming characterized category in the LCA studies. The carbon footprints can also be used to inform the internal environmental management of the industry. In addition, carbon labels are a way to communicate summarized product carbon footprints to the final consumers (Edwards-Jones et al., 2009). For instance, Carbon Trust, a not-for-profit company, was a pioneer in the development of carbon label for products in the Europe.

Carbon footprint reporting or disclosure to the third party or public can be part of compliance with the legislative requirements, carbon trading, improvement of brand image or as a part of corporate social responsibility (Pandey et al., 2011; L.E.K. Consulting LLP, 2007;

Carbon Trust, 2007b). Legislative measures have been taken to calculate and diminish the carbon footprint of organizations, corporations, cities, and products and it is playing a vital role in the policy development (Courchene and Allan, 2008; Good Company, 2008). Besides policy development, carbon footprint application has gain popularity in business and products sustainability assessment. Some corporations have recognized that a carbon constrained economy may arrive soon and therefore are moving to quantify carbon footprint, reduce emissions and to take competitive advantage (Kleiner, 2007).

Recently, numerous methodological approaches have been developed to calculate products' carbon footprints, for example the GHG Protocol Product Standard (WRI and WBCSD, 2011); the PAS 2050 (BSI, 2011); ISO/TS 14067 (ISO/TS, 2013) and the Climate Declaration (IEC, 2008a). The ISO/TS 14067 published a carbon footprint tool (ISO/TS, 2013) which provides specific requirements and guidelines for the calculation and communication of the carbon footprint of products, building on existing ISO standards on life cycle assessment (ISO, 2006 a, b) and on standards for environmental labels and declarations (ISO, 2000, 2006c). This standard provides requirements for the treatment of GHG emissions and removals e.g. fossil and biogenic carbon, carbon storage in products, land-use change and additional requirements for the communication of the carbon footprint. The concept of Climate Declaration was introduced by the international environmental product declaration (IEC, 2008a), which is a single issue environmental product declaration (EPD), and only quantified GHG emissions. It is based on the full EPD standards such as ISO 14040 and 14044 standards for life cycle assessment method and ISO 14025 standards for environmental declarations (ISO, 2006a, 2006b, 2006c).

To assess products' environmental impacts, specific guidelines called product category rules (PCR) are developed for each product category. The PCR is a specific and similar set of rules to calculate the climatic or environmental impacts of products within the same product category, for example reference unit, system boundary, allocation rules and cut-off criteria. However, there are several EPD program operators which results in duplicate PCRs and lack of harmonization between them (Ingwersen and Stevenson, 2012; Subramanian et al., 2012). Whereas, the GHG Protocol Product Standard developed by World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI) in 2011 provides requirements to calculate GHG emissions of products and provides requirements for public reporting (WRI and WBCSD, 2011). It is also based on the ISO standards for life cycle assessment (ISO, 2006 a, b). The present study is also based on this approach.

1.4. Global overview of the LCA and carbon footprint of particleboard production

In the early 70^{th} of the last century, the idea of environmental impacts assessment of wood products arose due to the consequence of two oil crises. Therefore, initial research and case studies were conducted specifically on energy audit of the manufacturing processes (Ressel, 1986), however, with the passage of time, this focus was extended toward considering the environmental impacts of wood products (Werner and Richter, 2007). Now-a-days, life cycle assessment (LCA) is widely adopted by numerous scientists for a wide range of scientific investigations in the wood panels industry globally. However, the environmental impacts assessment of the wood industry has got keen attention in the recent times, because, life cycle inventory (LCI) data are indispensable for the scientific documentation of environmental performance of wood based panels as governed by various new purchasing guidelines, building standards, energy and climate change policy issues (Wilson, 2010). Therefore, LCA is highly recommended for improvement of the environmental protection proficiencies and competition strengths of corporations (Yacout et al., 2016; Lai-Li et al., 2009).

J. B Wilson (2010) conducted a comprehensive study on the LCI of particleboard manufacture in the US, by examining different processes of the particleboard production chain from raw material extraction to manufacture of final product, fuels, electricity use and packing of the product. The author further explored the embodied energy, carbon footprint, carbon stock and net carbon flux for 1.0 m^3 of particleboard produced in the US (Table 1). The results revealed that the on-site emissions contributed only 15% (57.3 Kg CO_2e) to the overall carbon footprint (392 Kg CO_2e) of the production of 1.0 m^3 particleboard in the U.S. whereas, the carbon stock of the particleboard was equals to 898 kg CO_2e, which offset the carbon footprint of the particleboard production and leaves a net carbon flux of -898 kg CO_2, which can also be used to offset the emissions from product use and disposal in the future (Table 4). Thus, the author concluded that particleboard has promising characteristics in terms of energy consumption and carbon stock, because, wood fuel use in particleboard manufacture process is one of the important renewable fuel source which can substitute the fossil fuels which are non-renewable. In addition, the author declared that particleboard can also be considered a better than climate-neutral material, because of its more net carbon flux than carbon footprint.

Similarly, another recent study on LCA of particleboard production was conducted by Puettmann et al., 2013 in the USA. The results exhibited that forest resources contributed less emissions as compared to manufacturing processes such as drying, boiler and pressing processes of particleboard, which are a function of fossil fuels used and resin type. Wood combustion accounted to 25% of the total energy consumption, whereas fossil fuels represented 10,241 MJ cradle to gate energy (68%) required for 1.0 m^3 particleboard manufacture. Moreover, combustion of fossil fuels emitted CO_2 to the air which contribute to the global warming and climate change. Therefore, the carbon footprint of 1.0 m^3 particleboard production was equal to 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 1.0 m^3 particleboard manufacture using the default TRACI 2.0 impact assessment method present in SimaPro, version 8.2; a LCA environmental modelling software. Based on the SimaPro v.8.2 environmental modelling (PRe-Consultants, 2007), for global warming potential, about 73% of the CO_2e emissions was released by particleboard production chain, with 23% and 4% emissions from wood residues production and forest operations, respectively. Likewise, particleboard production, wood residues production, and forest operations contributed 73% and 22%, and 5% to the total acidification impact category, whereas, for eutrophication, particleboard production contributed 59%, followed by forest operations (23%) and wood residues preparation (18%), respectively. In the same way, particleboard production, wood residues preparation and forest operations produce similar impacts at 48%, 37%, and 15% to the total smog impact category, respectively (Table 5). The authors also concluded that particleboard can be considered a better than climate-neutral material, because of its more net carbon flux than carbon footprint.

Silva et al., 2013 conducted a detailed study on LCA of medium density particleboard in Brazil, considering the forest and industrial production phases separately. The authors investigated environmental burdens of seven impacts categories, including global warming potential (GWP), acidification (AC), eutrophication (EP), abiotic depletion (AD), photo-chemical oxidation (PO), eco-toxicity (EC) and human toxicity (HT), for the purpose to identify the major contributors and hotspots and to help assist the particleboard industry to improve their manufacturing process toward environmental sustainability. The authors find out that industrial production of 1.0 m^3 particleboard was corresponded to the most of impact categories, except eco-toxicity. The production process was responsible for 83% (AD), 86% (AC), 61% (EP), 92%

(GWP), 93% (PO), and 97% (HT), Whereas, glyphosate herbicide was the main contributor to the eco-toxicity (99%) from forest production phase. Heavy fuel oil (HFO) as a source of thermal energy and UF resin used as a synthetic binder was identified the main hotspots to the environmental burdens. Therefore, sensitivity analysis was also performed for HFO to substitute it with wood residues and the results revealed that wood residues are more environmentally preferable as well as viable in terms of its availability to the mill.

Rivela et al., 2006 conducted a comprehensive LCA of resin bonded wood particleboard in the Spain following the ISO standards and eco-indicator 99 methodology to measure the potential environmental impacts of this industry. The production chain was divided into three subsystems i.e. wood preparation, board shaping and board finishing. The results exhibited that damage to human health (93.8%) was mainly produced by board finishing subsystem. The main contribution to this category was related to energy consumption. Thus, board finishing had the greatest impact on this category, as it is the subsystem most dependent on the use of electricity. whereas, damage to ecosystem quality (82%) and resources (62%) was mainly contributed by the board shaping subsystem. Natural gas consumption linked to the manufacture of UF stood for the highest contribution in damage to resources, thus, the most significant was the subsystem of board shaping. The authors also concluded that forest residues use in the particleboard production is more sustainable than their use as a fuel.

Kouchaki-Penchah et al., 2016 published a recent comprehensive study on the LCA of particleboard manufacturing in Iran. The system covered energy and resource inputs consumption and environmental burdens posed by the production chain of 1.0 m^3 of particleboard was identified using the CML method and cumulative exergy demand (CExD) indicator. The results exhibited that abiotic depletion (AD) was mainly caused by UF resin (40.84%), followed by natural gas (32.64%), and electricity (18.09%), whereas, electricity, UF resin and transport had also corresponded to the highest contribution as 50.97%, 30.86% and 11.79% in the acidification (AC) impact category, respectively. UF resin and transportation was also the largest contributors to eutrophication (EP) by about 61.70% and 23.75%, respectively. Similarly, UF resin, production process and electricity contributed 35.64%, 29.3, and 20.36% to the global warming potential (GWP), respectively. In addition, transportation (70%) and UF resin (20.68%) was the main contributor to ozone layer depletion (OLD), respectively (Table 5).

Human toxicity (HT) was mostly caused by UF resin (51.10%), electricity (23.14%) and natural gas (17.13%), respectively, whereas, UF resin and electricity also contributed around 38.74% and 26.66% to the fresh water aquatic ecotoxicity (FE), followed by production process with 32% contribution to FE respectively. While, marine aquatic ecotoxicity (ME) was mostly caused by electricity with a contribution of 37.58%, UF resin with 37.57%, and natural gas with 14.21%, respectively. Moreover, terrestrial ecotoxicity (TE) had the highest contribution from UF resin (58.95%) and production process (30.79%), respectively. Likewise, photochemical oxidation (PO) had the largest contributions from production process (70.69%), and UF resin (11.48%), respectively. The authors concluded that board shaping subsystem was responsible for most of the environmental burdens categories. UF resin and electricity was the main hotspots in ozone layer depletion (OLD) and acidification (AC) impact category, whereas, manufacturing processes and transportation was the major contributor in photochemical oxidation (PO), and marine aquatic ecotoxicity (ME) impact categories, respectively. The authors also recommended that replacing natural gas from wood residues as a source for thermal energy could diminish the emissions from the production process and ultimately the various environmental impacts caused by the particleboard manufacture could also be minimized up to great extent.

Santos et al., 2014 conducted a comparative LCA of environmental burdens of particleboard manufactured from two different types of waste i.e. bagasse from sugarcane (Saccharum spp) and pine wood shavings (Pinus elliottii). The results showed that pine wood particleboard manufacture was responsible for highest environmental burdens as compared to bagasse particleboard. Transportation of raw materials to the production site, and formaldehyde emissions were mainly contributed and aggravated to the environmental burdens such as global warming potential, photochemical oxidation, acidification potential, eutrophication potential, ecotoxicity and human health toxicity potential. Transportation of raw materials was associated to the fossil fuels combustion and accounted for about 2185.94 g/m^2 from pine wood particleboard production, whereas, bagasse particleboard achieved the value of 893.53 g/m^2 from non-renewable fuels combustion during the transport of raw materials. Similarly, formaldehyde emission was related to the use of a synthetic binder i.e. urea-formaldehyde resin in the manufacture of particleboard, and accounted for the contamination of about 7,800,000 m^3 of air per m^2 of particleboard manufactured. Therefore, formaldehyde emission (99.6%) was the single largest contributor to the human toxicity potential impact category. This is in accordance with the findings presented by (Silva, 2013), where the formaldehyde emission was responsible for 96.2% of the human toxicity category during the production of medium density particleboard. The authors further investigated the fact that formaldehyde emissions from the production of particleboard into the air can contaminate the air and water in a chronic way and to dilute and neutralize its effects, about 14 m^3 of water and 120 m^3 of soil is required. In addition, the usage and disposal phase of particleboard revealed lowest or no significant contribution to the environmental burdens.

Tucker et al., 2009 conducted a comprehensive life cycle inventory (LCI) for forest and wood products in Australia. For particleboard, four mills were surveyed to collect the relevant data, covering 64% of the particleboard production capacity of Australia. The main material resource inputs considered in the life cycle inventory were wood residues, adhesives, wax, preservatives, strapping and plastic materials for packaging. Wood residues were obtained from a variety of sources such as forest shaving, chips, mill sawdust and round wood logs from softwood tree species of pine radiata and pine hoop. The results indicated that the average material inputs into 1.0 m^3 particleboard were wood chips (387 kg), softwood pulp logs (72 kg), wood shavings (151 kg), and sawdust (112 kg), whereas, the average adhesive and wax material was 65 kg and 9.9 kg into 1.0 m^3 of particleboard production, respectively. Similarly, sources of energy consumed to manufacture 1.0 m^3 particleboard includes electricity (145.6 kWh), wood wastes (1549 MJ), diesel (16 MJ), natural gas (722 MJ), fuel oil (87 MJ), and LPG (63.6MJ), respectively (Table 4). The authors concluded that this LCI of particleboard production can be used in developing a LCI databases for wood products of Australia. It can also play a headship role among manufactured products and provides guidance and benchmark to customers who are looking for environmental impacts of composite wood products.

Vertima and Ellio, 2016 conducted LCA of NU green soya particleboard produced by the "Uniboard" situated in the Quebec, Canada, a popular north American leader in the composite wood industry. The aim of the study was to developed the Environmental Product Declaration (EPD) for NU green soya particleboard based on the LCA approach, to secure a leading position in the market by providing outstanding service and state-of-the-art product innovation. The results showed that the board manufacturing process received wood materials from two sources, i.e. wood logs from thinning and wood wastes from sawmills such as sawdust, shavings and wood chips. The other secondary materials were included the production and transport of soybean made resin, wax and catalyst. The board manufacturing process included energy consumption and related emissions into the environment.

The authors calculated environmental impacts indicators using the north American impact assessment method TRACI v2.1 developed by the US EPA. Whereas, the total primary energy use was measured using the cumulative energy demand methodology v 1.09. The results revealed that raw materials acquisition had the largest contribution to both, the environmental impacts (80%) and energy consumption (60%) by the production chain of NU green soya particleboard manufacture. In addition, the raw material acquisition was also responsible for 67% of the whole life cycle water intake. The results further exhibited that NU green soya particleboard manufacturing chain contributed about 440 kg CO_2e to global warming potential, 1.54 kg SO_2e to acidification potential, 0.96 kg N_{-equi} to eutrophication potential, 25.70 kg O_{3-equi} to smog creation potential, and 3.2E-05 kg $CFC_{11-equi}$ to ozone layer depletion potential, respectively. The authors concluded that NU green soya particleboard is better than climate neutral material, because of its more net carbon flux (631.7 kg CO_2e) than the carbon footprint (407.6 kg CO_2e) (Table 4).

Silva et al., 2014 conducted a study on LCA of particleboard manufactured with sugarcane bagasse residues in Brazil. Sugarcane bagasse is one of the important Agro-industrial residues which can be utilized to manufacture composite wood products. The study was based on cradle-to-gate life cycle assessment of 1.0 m^3 particleboard manufactured from sugarcane baggase. The manufacturing process was divided into three main subsystems, bagasse generation, bagasse distribution and particleboard manufacture. The potential environmental burdens were investigated by applying the USEtox and CML methods in GaBi professional software version 6.0. The results indicated that all the hotspots emissions sources were mainly associated with the particleboard manufacture subsystem and had responsible for 24-100% environmental burdens due to heavy fuel oil, UF resin, and purchased electricity. The baggase particleboard production subsystem accounted for 99% of abiotic depletion impact category. Forest production was responsible for about 52% of the abiotic depletion potential due to the extraction of crude oil, mineral oil and other non-renewable resources required for diesel production, which is utilized during the transportation and field activities by the tractors and trucks.

Whereas, the major contributor to industrial production subsystem was production of heavy fuel oil (42%) and UF resin (36%). Heavy fuel oil is also one of the vital source of thermal energy in Brazilian traditional particleboard manufacture (Silva et al. 2013a), whose impacts are also associated to the crude oil and mineral coal extraction. Likewise, UF resin is manufacture from urea and methanol, which consumed natural gas and mineral coal in their manufacturing processes. Baggase particleboard manufacture subsystem had contributed about 97% to the acidification impact category. Industrial production processes were responsible for 91% of the acidification potential as compared to the forest production operations. This was primarily due to the heavy fuel oil combustion (69%), which emitted sulfur derivatives to the air. Baggase generation contributed about 75%, followed by baggase particleboard production with 24% contribution to the eutrophication impact category, because of nitrogen oxides emissions to the environment.

In baggase generation subsystem, about 85% of the impacts were caused by chemicals application and fields operations, because of the nitrogenous fertilizers application and diesel fuel use in the field operations. Whereas, for the baggase particleboard manufacture subsystem, about 94% of the burdens are related to the heavy fuel oil and UF resin production. Bagasse particleboard manufacture subsystem had contributed 100% to the ozone layer depletion (ODP) impacts, where 55% impacts refer to the forest production activities and 45% to bagasse particleboard industrial production. Diesel use was the major contributor (90%) to ODP impacts from forest production whereas, electricity generation was responsible for 93% of the ODP impacts from industrial production.

The results showed that 98% of the photochemical oxidation potential (POCP) impacts was caused by the bagasse particleboard production subsystem. Baggase particleboard manufacture phase contributed about 96% to the POCP impacts due to the emissions of CO_2, CH_4, N_2O, and VOCs. Similarly, drying and hot pressing operations are mainly related to 71% impacts where UF resin production accounted for 18% the POCP impacts. Baggase generation and distribution subsystems had corresponded to 2% of the POCP impacts. About 99% ecotoxicity potential (ECP) impacts were related to baggase particleboard production subsystem, in which 96% was contributed by forest production phase only. This was primarily linked with the glyphosate herbicide use and forest management operations.

The results are also in accordance with the Silva et al., 2013a for LCA of traditional particleboard production in Brazil. Therefore, glyphosate emissions are the hotspots. The bagasse particleboard manufacture subsystem was responsible for 100% of the impacts of human toxicity potential-cancer effects (HITPC). Application of UF resin was the major hotspot, amounted to 91%, which was greater than the other studies reported so far. Therefore, Silva et al., 2014b suggested that UF resin should be replaced by melamine urea formaldehyde (MUF) resin, because of its minor contributions to human toxicity and POCP. Similarly, baggase particleboard manufacture was also accounted for about 98% of the impacts for human toxicity potential-non-cancer effects (HTPNC). The impacts were mainly associated with the electricity generation (75%) due to the consumption of non-renewable resources, e.g. oil and coal in electricity production.

Furthermore, the sugarcane baggase distribution subsystem was the least contributor (less than 1%) to all the impact categories. The authors also reported that particleboard made from sugarcane baggase contributed less to the abiotic depletion and ecotoxicity impact category and therefore, can substitute the conventional particleboard. Similarly, baggase particleboard also indicated lower contributions to all the impact categories (38-40%) from land use impacts, and the primary reason for this was the less demand for land occupation by the baggase particleboard. Baggase particleboard manufacture subsystem was responsible for most of the impacts (96%) on global warming potential (GWP), to which 75% of the impacts were contributed by industrial production phase whereas, 25% was due to the forest production phase. The electricity generation contributed about 37% to the GWP impact category, followed by HFO combustion in the industrial processes with 29% contribution, whereas, UF resin production was attributed about 27% to the GWP (Table 5).

According to Silva et al., (2013), traditional particleboard manufacture has a net GWP impact of -939 kg CO_2e per m^3, however, in the present study the authors calculated a net GWP impact of -364 kg CO_2e per m^3 of bagasse particleboard manufacture (Table 4). Therefore, the authors concluded that higher the agro-industrial residues use in the manufacture of particleboard, the lower will be the carbon footprint of the particleboard manufacture. The authors also concluded that baggase particleboard are better than conventional particleboard in terms of environmental performance and sugarcane baggase be mixed up to 75% during particleboard production to get good quality particleboard product with better environmental performance.

1.5. Problem Statement

The production lines of particleboard consumed huge quantity of materials and energy resources and lead to higher levels of emissions (Kouchaki-Penchah et al., 2016). During the production and end-use of particleboard, carbon dioxide (CO_2), formaldehyde, volatile organic compounds (VOCs), total hydrocarbon (THC), particulate matter (PM) and other hazardous emissions are of great concern for the manufacturers as well as consumers (EPA, 2002; Doosthoseini et al., 2013). Thus, particleboard industry is recognized as one of the important sources of natural resources depletion and environmental pollution, because both causing ecological degradation; however, its contribution to economy and development is fully acknowledged. Therefore, the identification of sustainable options in this domain is crucial (Azapagic and Perdan, 2000), because sustainable manufacture conserve energy and natural resources as well as diminish the pollution. However, environmental management is a complex strategy which deals with multiple issues for which there is no specific and single approach to dealt with; such as an approach which is economically feasible, socially beneficial, safe and healthful (Veleva and Ellenbecker, 2001). Thus, businesses have been adopted different attitudes over the years (Sikdar, 2003a), for instance corrective actions were employed in response to the growing environmental laws and regulations, however, businesses quickly understood that adoption of pollution prevention and cleaner production strategies leads not only to environmental improvements but also increase the profits (Azapagic and Perdan, 2000).

The manufacture and use of wood based products are one of the causes for environmental degradation and dependency on finite resources, and it is an international commitment to promote the development of environment preferable products to overcome these challenges (Sandin et al., 2016; United Nations, 2012). Wood based products are not necessarily environment preferable as compared to non-forest alternatives. For instance, transformations of non-managed forests to managed forests can cause biodiversity loss and other environmental degradation, which ultimately weaken ecosystem services that are indispensable for human livelihood (MA, 2005; Sandin et al., 2016). Due to increasing global warming in the world, more attention is being paid to manufacture products with less impact to the environment and human health (Kouchaki-Penchah et al., 2016).

Many studies have been conducted on the LCA technique to assess and evaluate the environmental burdens of wood based products (Aldentun, 2002; Berg, 1997), however, no life cycle assessment for particleboard industry of Pakistan is conducted so far. Similarly, up till now, there is no published LCA of particleboard manufactured in Pakistan, however several studies have been conducted for other countries such as USA (Puettmann et al., 2013; Wilson, 2010), Spain (Rivela et al., 2006), Brazil (Silva et al., 2013), Portugal (Garcia and Freire, 2012), and Iran (Kouchaki-Penchah et al., 2016). The main differences with respect to particleboard production in Pakistan and other countries identified are associated to the sources of wood materials and energy and fossil fuels consumption in the stationary sources of the mill. Because, wood wastes and wood based industrial residues from forest operations and sawmills are the main source of raw materials to manufacture particleboard in USA, Europe and Portugal. But in Pakistan, mostly the wood materials are obtained from the forests and farmlands plantations of the farmers. With respect to fossil fuels consumption as a source of thermal energy in particleboard production process, most of the countries reported the consumption of natural gas and wood residues, whereas particleboard mills in Pakistan also used heavy fuel oil along with the other types of fuels sources. Therefore, it is indispensable to develop a comprehensive LCA of the particleboard produced in Pakistan and suggests improvement opportunities by measuring and comparing alternative production scenarios.

According to a recent report of Intergovernmental Panel on Climate Change (IPCC), the global industrial sector contributed about 30% of the total GHG emissions (IPCC, 2014; Kucukvar et al., 2015). Thus, sustainable and environment friendly manufacturing facilities are crucial for realizing low-carbon economy (Wang et al., 2013; Hoffmann and Busch, 2008). A variety of forest based products have been investigated in carbon footprint studies, ranging from biofuels (e.g., see Cherubini et al., 2009) to materials consumed in home construction (e.g., see Salazar & Sowlati, 2008; Perez-Garcia, et al., 2005; Gustavsson & Sathre, 2006). Similarly, some forest products corporations have also been calculating their own carbon footprints (e.g., see Miner, 2010 and Heath et al., 2010); however, few of these studies are published in peer reviewed journals (Parigiani et al., 2011). Often, wood is assumed to be a carbon-neutral material as it embodies biogenic carbon that was recently sequestered by the living trees. However, wood processing operations (such as primary and secondary raw materials acquisition and manufacturing processes of particleboard) can contribute to the carbon footprint (Werner and

Richter, 2007). Therefore, it is a dire need to conduct a study on the carbon footprint based on LCA of the particleboard manufactured in Pakistan which illustrates the total GHG emissions from raw material extraction and transport, manufacturing of particleboard product, fossil fuels and purchased electricity consumption and the transportation of finished particleboard product to markets. Furthermore, this study will also provide a benchmark for future research work to formulate comprehensive GHG emissions reduction plans, because no previous research work is available on carbon footprint of the particleboard production chain in Pakistan. Therefore, a total of 8.187 GJ of energy was consumed by particleboard industry for production of 1.0 m^3 of product, which emitted 975.282 kg CO_2e emissions per m^3 during 2015-16 (Table 9).

1.6. Objectives of the thesis

- To study environmental profile analysis of particleboard produced in Pakistan during the year 2015-2016 using life cycle assessment approach.
- To quantify and investigate GHG emissions hotspots across the particleboard manufacturing process in Pakistan.
- To assess improvement opportunities by measuring and comparing alternative production scenarios for particleboard manufacture in Pakistan.

CHAPTER # 2

MATERIALS AND METHODS

CHAPTER # 2

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PART-I

2.1. Environmental profile analysis of particleboard production; a study in a Pakistani technological condition

2.1.1. Design of the study

The study was designed in three components. First, to collect data from Pakistan on particleboard production and determine the materials flow, energy use and emissions to soil, air and water from the manufacturing process. Second, to investigate various environmental impacts in terms of abiotic resources depletion, global warming potential, ozone layer depletion, acidification potential, photochemical oxidation, eutrophication potential, eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, terrestrial eco-toxicity, and human toxicity. Third, to suggest improvement opportunities by evaluating alternative production scenarios.

2.1.2. Reference unit

Reference unit provides a reference to which the inputs and outputs are referred (ISO, 2006). In the present study, the declared functional unit for particleboard production was one cubic meter (1.0 m^3) finished particleboard. All inputs and outputs data were assigned to the declared unit of product based on the mass of products and co-products in accordance with ISO protocol (ISO, 2006) and Pakistan standard industrial classification (PSIC, 2010). Moreover, the density of particleboard manufactured was usually 750 kg/m^3 with a moisture content of 2-5% in Pakistan. The bending strength of the Pakistani particleboard is ranged from 14-16 newton/square millimeter (N/sq.mm), internal bond strength ranged from 0.3-0.4 N/sq.mm whereas the delamination strength is 1 N/sq.mm. Similarly, the board thickness tolerance and length and width tolerance is equal to ±0.2 and ±0.25 mm, respectively. The bowing of the particleboard is equal to, or more than 15 mm/m. In addition, the content of free formaldehyde is 6.5 mg HCHO/100g board, based on the perforator coefficient method regulated by DIN EN 120 as moving half-year average (www.sunlightwood.net.pk).

2.1.3. The particleboard production process

Particleboard is a composite wood panel product manufactured from wood residues such as forest slashes, planer shavings, sawdust, sawmill residues, plywood trim, and logs, fines and chips bonded by water-resistant resin adhesives mostly for indoor uses (Puettmann et al., 2013; Silva et al.,2013; Wilson, 2010; Rivela et al., 2006). The particleboard production chain was analyzed, because it is one of the important wood based materials in Pakistan. For this purpose, eight (08) particleboard industries assumed representative of the 'state of the art' were identified to analyze the production process in detail, as can be seen in Figure 1. According to the demands of the customers, a vast variety of particle size and board thickness is manufactured. For instance, the typical particle sizes are 4880*2440 mm or 2440*1220 mm whereas the board thickness can range from 4-25 mm in Pakistan (Sunwood Pakistan, 2015). Globally, forest logs/thinning's and sawmill residues makes the two exclusive sources of wood raw materials for particleboard production. The sawmill residues comprise of sawdust, slab wood, planer shaving, hacked or pulp chip and docking. However, in Pakistan mostly the roundwood logs were used as primary raw materials for particleboard production. Each particleboard industry has its specific process settings; however, the general process flow sheet is common in all of them. In addition, the manufacturing process of particleboard is properly linear, process controlled and highly automated.

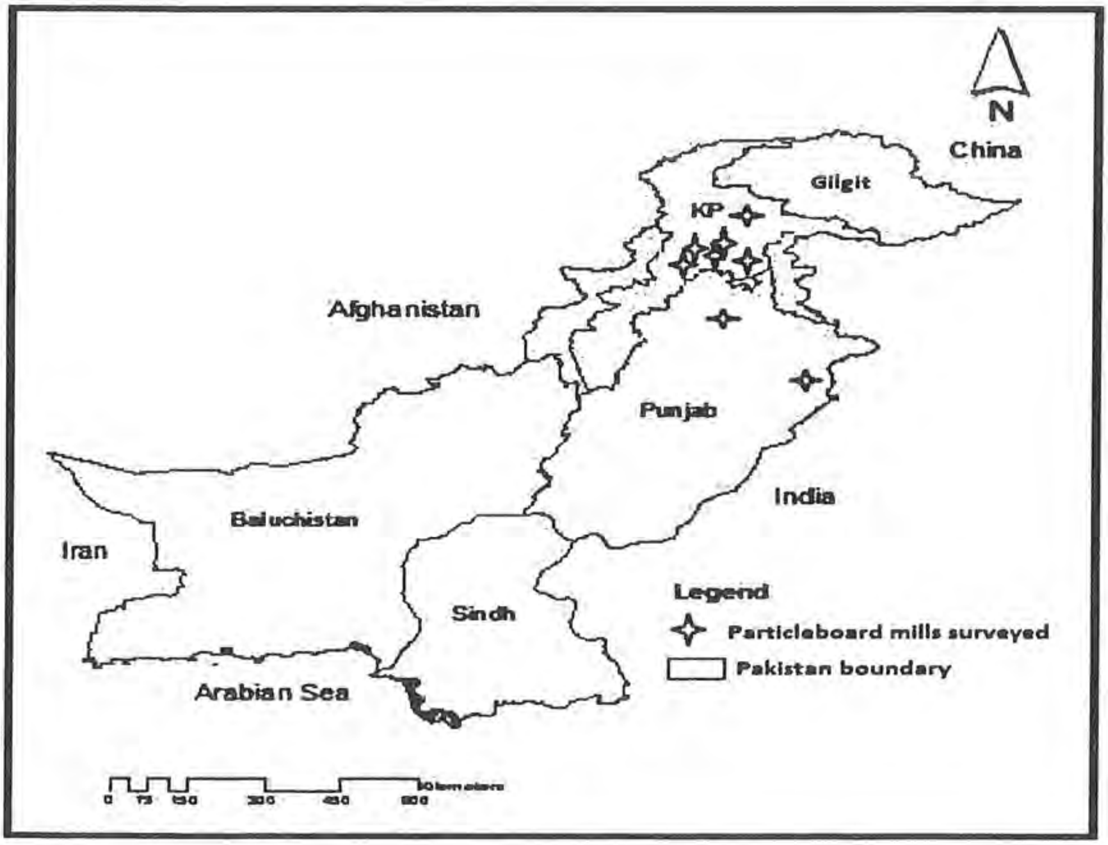

Fig. 1: Location map of the surveyed particleboard mills

The general manufacturing process of the particleboard comprises of the following steps (Fig. 2).

a. Sort and storage of wood materials

Wood logs/thinning's and residues of diverse origin are brought to the factory normally by large and medium trucks. Initially, the logs and residues are sorted by geometry and moisture content and stored outdoor in the factory, awaiting use in the manufacturing process. The moisture content can vary from 10-100% on an oven dry weight basis. On average basis, about 40% of the wood material consumed is poplar (mainly mixture of *Populus alba* and *Populus nigra)*, followed by farash (*Tamarix appyla*) (33%) and Eucalyptus (*Eucalyptus camaldulensis*) (23%) in the particleboard industry of Pakistan. In addition, the least consumption of Sumbal (*Salmalia malabarica*) was also reported from a single mill, which was equal to 4% of the overall consumption of wood materials by the particleboard industry in Pakistan.

However, use of sawmill residues such as sawdust were not reported from any of the factory surveyed. It was due to the heavy dependence of poultry industry on the sawdust for using sawdust in the poultry farms/sheds spreading on the ground inside the sheds, which is also used as a fertilizer in the agriculture farms by the farmers after discarding from the poultry farms. The poultry farms buy the sawdust at higher price than the particleboard mills and become one of the competing industry for particleboard industry in Pakistan. Similarly, in old times, the particleboard industry used bagasse, a raw material produced after the sugarcane is processed and crushed in sugar mill, but now that is used for paper making and its availability is also very rare for particleboard industry in Pakistan.

b. Debarking

Bark of logs is considered an impurity in the final particleboard, therefore it must be removed before particle production. Mostly, the removed bark is sent to the dryers or boiler for energy recovery. However, most of the particleboard mill convert and crush the logs into wood particles along with the bark, which degrade the quality of the final particleboard product and that is the main reason that particleboard produced in Pakistan is of inferior quality as compared to the global standards of particleboard manufacture and quality.

c. Particle production and storage

The quality of final particleboard product entirely depends on the moisture content and shape of wood particles. The debarked logs are cut by chippers, hammermills and shaving machines into flakes of desired particle sizes, the oversized particles are send back for further breakdown.

The oversized particles geometry is then reduced to desired dimensions using refiners, flakers and hammermills. The particles of varying sizes and moisture content are placed in different silos, which adjust the mass inflowing to the units of manufacturing process. The fine particles are placed on both the surfaces (outside layers) for smoothness, whereas the coarser particles in the core (inside layer) for strength, thus making a three-layer structure of particleboard. The process comprises of two parallel lines, which attain different level of dryness, mostly higher level of dryness at the interior layer. The silo of interior layer is fed by chips and shaving, whereas the silos of the exterior layer's uses sawdust and shavings.

d. Screening

A set of screens are installed from which the wood residues are passed to sort the particles by size. The screens allowed the desired size particles for use in the process of face and core layers whereas the undersized particles, called fines, either use in the board, or occasionally utilized as wood fuel for dryers.

e. Drying

The particles are passed from dryers of either single-pass or triple-pass configuration, where particles from silos are dried by hot gas from burners. When enter to the dryers, the moisture content of the particles is 10-100% on oven dry weight basis and are dried up to the MC of 3-5% depending on the intended use of particles for face or core layers. Normally the dryers use direct-fired natural gas, while some also use sander dust acquired from the later process step. In addition, gas produced at the cogeneration unit is also used in the dryers and sometimes, the exhausted gas from the boiler is driven to the one on the exterior layer. The particles drying at higher temperature in the dryers often produced particulates and volatile organic compounds. These emissions from the dryers go to cyclones and controlling devices like regenerative catalytic oxidizers (RCOs), regenerative thermal oxidizers (RTOs), and biofilters.

f. Blending

In this process, resin, catalyst, wax, and scavengers are added in the form of distant droplets onto the dried particles. This process of adding glue onto the particles is usually called blending. The resin acts as a binder and its dosage play a vital role in the stability of the final product. The most common resin used is urea-formaldehyde (UF), phenol-formaldehyde (PF) and melamine-formaldehyde (MF). However, UF resin is the most cheaper and easily available adhesive to use, because it results in a clear film. Therefore, it is the utmost dominant adhesive used for boards which are not exposed to moisture (GDC, 2004; AWPAI, 2004). Whereas, the particleboards in which more moisture resistance is desired are glued with either polymeric isocyanate or melamine urea formaldehyde resins. The colloidal aqueous solution of urea formaldehyde (UF) is usually modified by addition of different additives to get the final mixture with better properties. For instance, paraffin wax is added to improve the water resistance quality and control swelling produced by temporary wetting of the boards. Both catalyst and hardeners control the rate of resin-curing during the pressing process. The aqueous solution of resin and other additives are sprayed through nozzles onto the particles. Regular inspection of adhesive flow rates and particle MC ensure consistent blending.

g. Mat forming

After blending process, the blended particles are spread on a tray or conveyor to form a mat. The mat is generally multiple layers (3 or 5) comprising of face and core layers. A separate long mat of each layer is get through the movement of tray/conveyor or forming station. The size of particles and their resin and moisture contents are controlled for each layer to acquire desire board characteristics.

h. Hot pressing

Formed mats of glued particles are moved into big multi-opening hot presses for pressing and curing. The multiple-opening are close instantaneously. Usually, the mat is pre-press before the hot press to decrease their thickness. During the process of pre-pressing, the parallel lines are combined in such a way that the face layer is initially placed, then the core layer with coarse particles is laid down on it, which forms the inner layer, followed by a second face layer. The presses work at adequate temperature (140-220 °C) and pressure (2-5 MPa) to cure the resin and obtain the desire thickness of the board. The physical properties of the panel are controlled during the press process, that is why, pressing is called the nucleus of particleboard production. However, due to the high temperature and resin curing, hazardous air pollutants (HAPs), particulates and VOCs are emitted to the air. If there are emissions control devices i.e. RCOs, TROs, and biofilters, then these devices treat these emissions in the particleboard factory.

i. Cooling

The hot boards are then transferred to a cooling wheel to decrease the elevated temperature of the boards and to equilibrate the MC and fully stabilize the resin curing and release formaldehyde gas. However, to produce intensification of resistance in the board, the temperature of the board must be controlled at 30 °C. Small quantity of air emissions emits at this point.

j. Sanding

The cooled panels are moved to the sander for achieving desired smoothness and thickness. In addition, smooth and flat surfaces of the panel are acquired and the sander dust is removed. After the surface smoothness, the panels are cut into desired board length and width according to the consumer demands. Sander dust produced during this process are send back to the production line before the forming step to recycle it or it is utilized as a fuel in the dryers. Particulates emissions are go to cyclones and baghouses, if installed.

k. Sawing

Comparatively large boards are swan into specific dimensions of length and width according to the consumer requirements. The board trims are then hammermilled into particles and sent back along the saw dust to the production process to recycle it. The boards are now ready to be shipped or staked and stored. However, the boards should be store under suitable conditions of humidity and temperature otherwise, their quality can be significantly affected. Other important processes consist of oil and boiler heater and their fuel combustion to produce heat and energy for running the processes of board manufacture. Moreover, emissions control devices like cyclones, RCOs, baghouses and RTOs are installed in the factory. The boilers are usually fired with natural gas, wood residues or oil fuels, however, because of boiler combustion, carbon monoxide (CO), carbon dioxide (CO_2) and other notorious gases are released into the air.

Therefore, the emissions control devices are installed to regulate and diminish the chemical and particulate emissions. Huge quantity of electricity and natural gas is consumed to operate the RCOs, biofilters, and RTOs systems. However, it should be noted that no industry out of the eight industries surveyed installed any emissions control devices in Pakistan, and all the particulates and air emissions generated are released directly into the environment. The wood logs and other raw materials are transported by trucks from various places to the particleboard mills. The finished boards are distributed through the large trucks (ten wheelers) and trailers within the entire country.

l. 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), carbon dioxide (CO_2) and other gases into the air. Electricity and natural gas are consumed to operate the RCOs, biofilters, and RTOs systems. The logs and other raw materials are transported by trucks from various places to the particleboard mills.

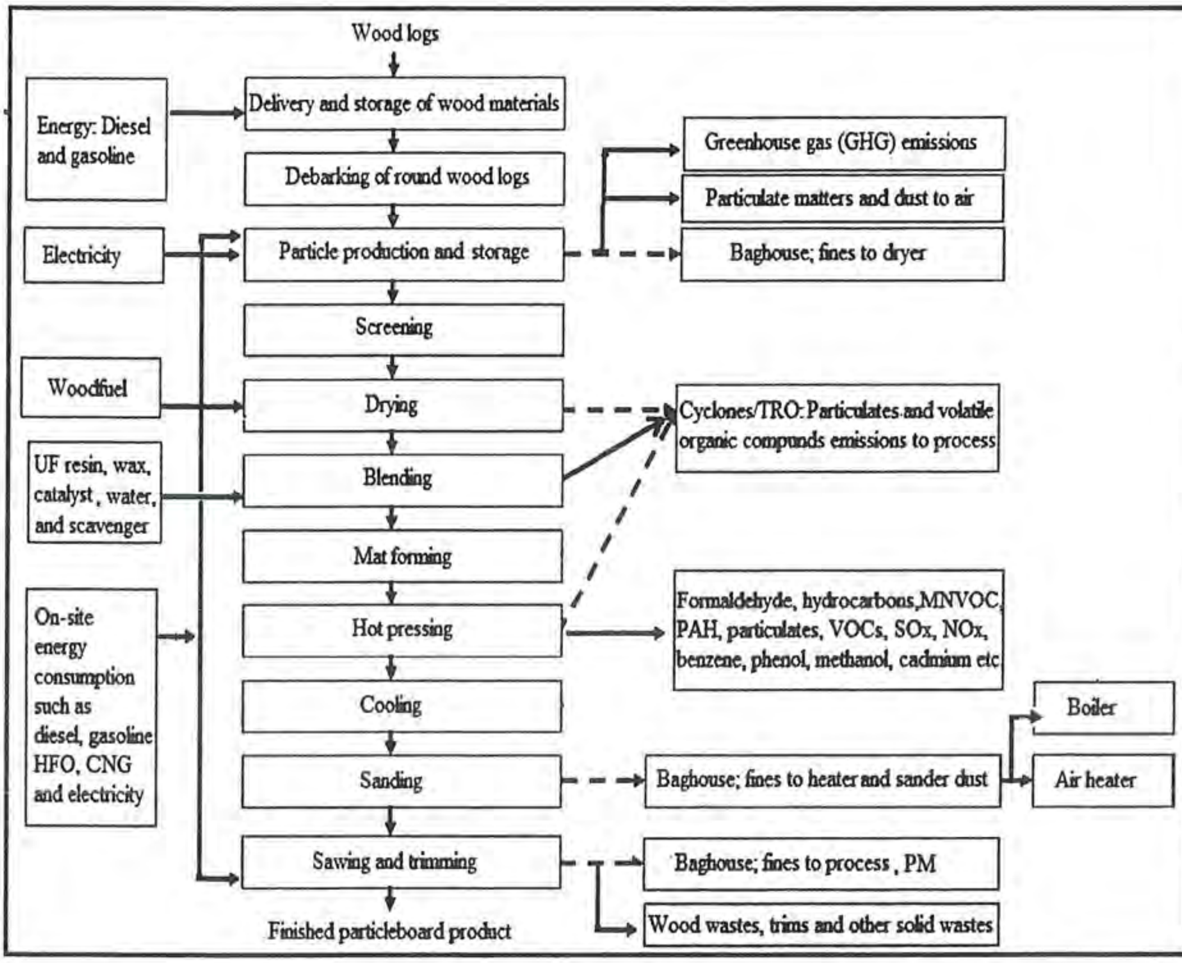

Fig. 2: Flow sheet diagram of a typical particleboard manufacturing process

2.1.4. Life cycle inventory (LCI) and data quality assessment

High quality data is a pre-requisite to get a scientifically reliable assessment. Therefore, in the present study, life cycle inventory data of particleboard manufacture comprised of production weighted average data acquired from eight particleboard manufacturing factories in Pakistan. This study was conducted in accordance with the ISO 14040-14044 protocol (ISO 2006a, ISO 2006b), and covered the production period 2015-2016. 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. 1). Therefore, large freight distance is covered to distribute the product. Thus, finished product distribution is one of the important components of the particleboard production chain in Pakistan and therefore, our study is a cradle-to-gate (distribution center) approach as shown in Fig. 3.

Particleboard mills were visited to collect the required data through surveys and interviews with mill managers and workers (Appendix A in supplemental materials). Data regarding production capacity, manufacturing process, fossil fuels and electricity use in the mill, total distance travelled 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. 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 form of the weighted co-efficient 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 co-efficient 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 (Equation 1), the weighted standard deviation was calculated (Equation 2). Furthermore, the weighted co-efficient of variation (CV_w) was calculated and documented for individual values by using Equation 3 (Puettmann et al., 2014; Toshkov, 2012; NIST, 1996).

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

$$Sd_w = \sqrt{\sum_{i=1}^{N} w_i \, (x_i - \bar{x}_w)^2 \, x \, \frac{N'}{(N'-1)\sum_{i=1}^{N} w_i}} \quad (2)$$

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

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 'state of the art' of the Pakistani particleboard manufacture practices; they collectively produced 45,832 m^3 of particleboard in 2015-16, 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 footprint from fossil fuels combustion and electricity generation were estimated using the Intergovernmental Panel on Climate Change (IPCC) emissions 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 of 336 km distance by road. Other raw materials such as urea formaldehyde (UF) resin, and paraffin wax, urea scavenger, ammonium sulphate catalyst were transported by small trucks with a payload up to 7-10 metric tonnes, travelling an average of 113, and 103 km distance by road, respectively. Likewise, the finished particleboard is distributed by large trucks with a payload up to 30 metric tonnes covering an average of 847 km distance by road.

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 particles formation and finished product trimming stage are combusted in the dryers to recover energy for heating purpose. However, the stationary wastes produced from the 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. Then the total wastes were categorized into 4 groups, i.e. 1). paper and cardboard wastes, 2). Rubber wastes, 3). Textiles (wiping clothes) wastes, and 4). Other wastes. The other wastes category consists of toners, oil and air filters, batteries, solvents and lamps. Although, these wastes were in very small quantities and were not properly landfilled and managed by the particleboard factories, however in the present study, all these wastes were considered known outputs to technosphere during the environmental impacts modeling by the SimaPro v.8.3 software.

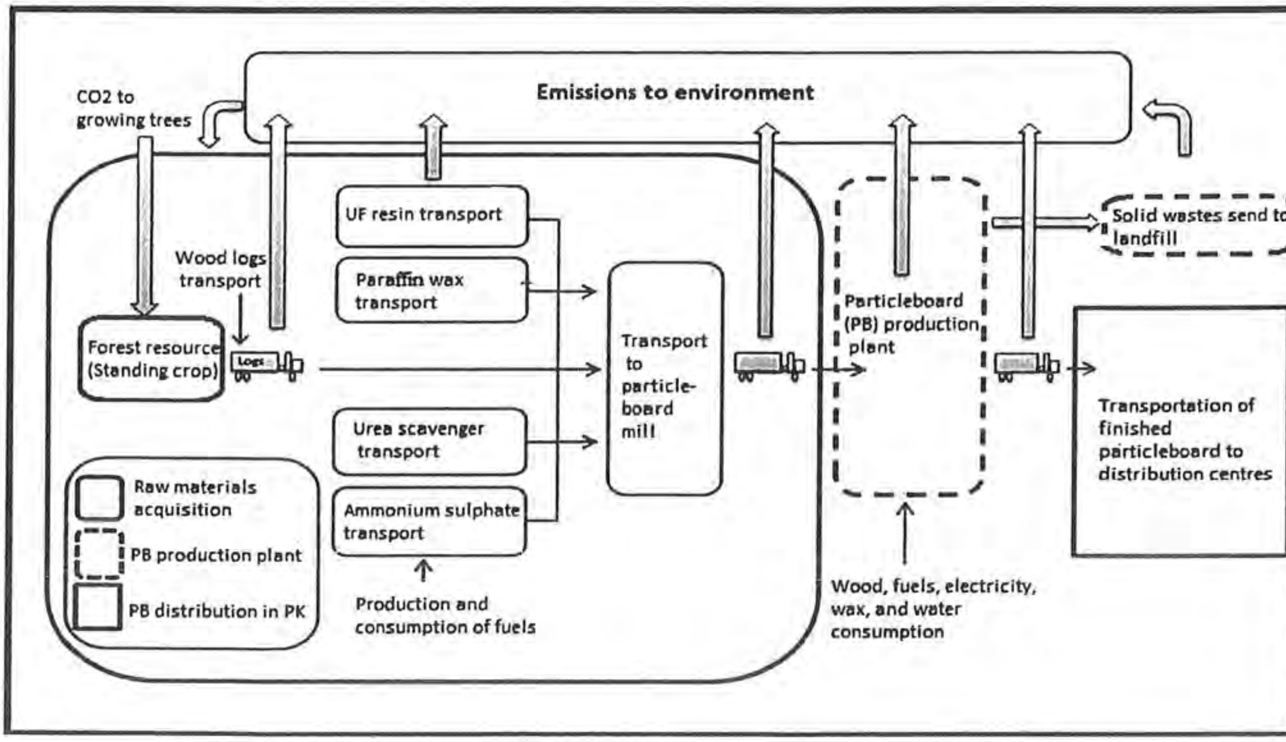

Fig 3: System boundary of the present study based on cradle to gate life cycle assessment.

2.1.5. Life cycle impact assessment and environmental modeling

The environmental impacts analysis was performed using two LCIA methods; **CML, 2000 V2.05** (Guinee 2001; Silva et al., 2014), **and cumulative exergy demand (CExD)** (Kouchaki-Penchah et al., 2016) present in SimaPro v.8.3 software. SimaPro v.8.3 also comprised of Franklin Associates (FAL) database, which give impacts of electricity and fuels for the US (PRe-Consultants, 2007). However, for all those materials, which are not included in the FAL database, another detailed database for Europe called the Ecoinvent v3.0 was used to show the environmental impacts (Ecoinvent, 2004). As, there is no country specific database developed for Pakistan yet, therefore, we used this software along with the Ecoinvent v.3.0 databases for environmental impacts modelling.

Ten environmental impact categories were analyzed and assessed by CML, 2000 method, whereas seven categories of exergy were evaluated through cumulative exergy demand (CExD) indicator. The environmental impact categories include abiotic depletion (AD), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), photochemical oxidation (PO), human toxicity (HT), ozone layer depletion (OLD), fresh water aquatic ecotoxicity (FAE), marine aquatic ecotoxicity (MAE), and terrestrial ecotoxicity (TE). Likewise, the exergy categories comprise non-renewable fossil, non-renewable nuclear, non-renewable metals, and non-renewable minerals, renewable potential, renewable water and renewable biomass. The choice of selecting these two methods is primarily because CML, 2000 and CExD methods were applied by many scientists for LCA studies of composite wood products (Silva et al. 2013a, 2014b; Gonzalez-Garcia et al. 2009, 2011; Kouchaki-Penchah et al., 2016).

Mass-based allocation was adopted for all the resources inputs and outputs and associated impacts. To conduct this study, it was assumed that the logs utilized in the particleboard production are 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. Wood logs were hauled by medium trucks with a payload of 10-20 metric tonnes covering 336 km distance on average basis (Table 1). It was assumed that the medium trucks consumed 10-liter 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.

PART-II

2.2. Carbon footprint as an environmental sustainability indicator for the particleboard produced in Pakistan

2.2.1. System boundary and reference unit

A "cradle to gate" life cycle model was established for particleboard manufactured during the year 2015-2016 using a reference unit of 1.0 m^3 of uncoated particleboard produced. The model was used to quantify GHG emissions during raw materials acquisition, product manufacturing and final distribution. The model also included the consumption of electricity, fossil fuels, urea-formaldehyde resin and other chemicals, and the transport of secondary materials. The study follows the "World Business Council for Sustainable Development (WBSCD) / World Resource Institute (WRI) Product Life Cycle Accounting and Reporting Standard and CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products" (WBCSD/WRI, 2001; Puettmann et al., 2014). 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 4-25 mm in Pakistan (SMEDA, 2006). The density of particleboard manufactured is usually 750 kg/m^3 with a moisture content of 2-5%. Each particleboard industry has its specific process settings; however, the general process flow is common to all of them as described in Fig. 2.

Wood-based manufacturing processes are commonly multi-functional, i.e. more than one co-product is produced (Malca and Freire, 2006, 2011; Jungmeier et al., 2002a). This requires a decision about how to divide ("allocate') the environmental impacts among the co-products. The particleboard production chain usually consists of two multiple output processes i.e. the sawmill process and the incineration of residues for energy recovery (Santos et al., 2014). However, in Pakistan, more than 88% of particleboard mills consume roundwood (logs) and no wood residues are collected from the sawmills. The capital goods production (building site, infrastructure, equipments, their maintenance, repairs & decommissioning), and consumers commuting to and from the point of particleboard purchase were excluded from this study.

2.2.2. Data collection sources and inventory

The primary data for this study were collected as a component of Ph.D research at the Department of Environmental Sciences, Quaid-i-Azam University, Islamabad, Pakistan. Particleboard mills were visited to collect the required information through surveys and interviews with mill managers and workers (Fig. 4). Data regarding production capacity, manufacturing process, fossil fuels and electricity use in stationary and mobile sources, total distance travelled by the industry fleet, and the amount of waste generated were provided. 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. Primary raw materials such as logs were assumed to be transported by trucks with a payload of 20 metric tonnes. 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. Secondary data were obtained from industry annual reports and peer-reviewed published literature.

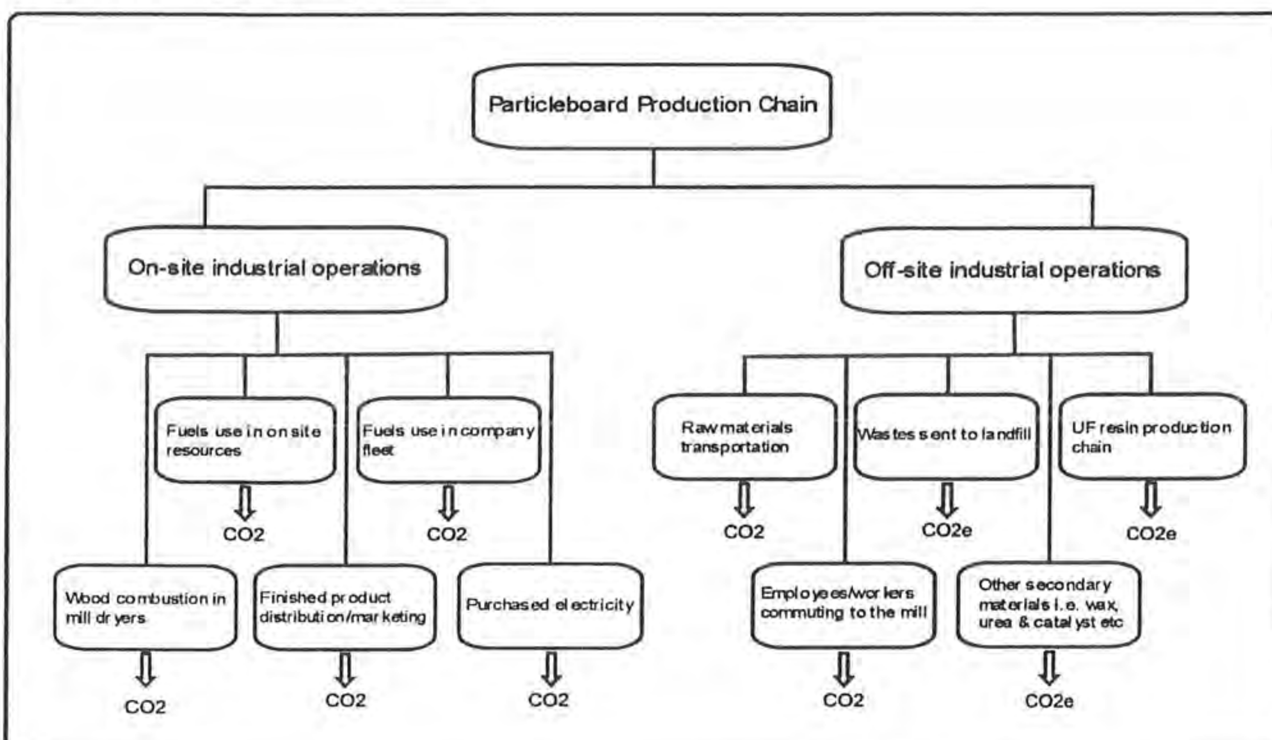

Fig 4. GHG emissions sources in particleboard production chain in Pakistan

The average particleboard production of the eight surveyed mills was 45,832 m^3 during the year 2015-16. The expected production capacity of the particleboard industry was estimated as 90,000 m^3 during the year 2015-16, because most of the factories were running at about 50% of production capacity mainly due to raw material and energy deficiencies in the country. Only roundwood (logs) were reported for production of particleboard. Mills reported production weighted average input values per m^3 of production was 775 kg for wood raw materials, 93 kg for resin, 5.0 kg of urea scavenger, 6.45 kg of wax and 1.67 kg of ammonium sulphate. Particleboard manufacturing is a dry process and most of the moisture content up to 95% is evaporated from the green wood particles before mixing with the adhesives to manufacture the product. However, small amounts of water are used for cleaning, glue preparation and mixing, cooking, washing and sanitary and other manufacturing processes. The water is obtained from two sources, i.e. ground water and municipal water. About 13 liters of water is pumped from ground water source whereas only 5.0 liters of water is utilized from the municipality provided water to produce 1.0 m^3 particleboard.

2.2.3. GHG emissions estimation from fossil fuels combustion in stationary sources

Stationary sources comprise all the fixed sources emitting GHG to the atmosphere such as installations at manufacturing operations that burn fossil fuels for heat, power or energy generation (e.g. furnaces, kilns, dryers, boilers, and ovens. GHG emissions from fossil fuels combustion in the stationary sources were estimated following the equation (1) outlined by World Business Council for Sustainable Development and World Resource Institute (WBCSD/WRI, 2001). For detail of the calculation procedure, see supplemental material. The equation (1) is given below.

$$E_{f,\,GHG} = FC_f * EF_{f,\,GHG} \qquad (1)$$

where;

$E_{f,\,GHG}$ is GHG emissions for fuel type f (tCO_2e), FC_f is use of fuel type f (GJ), and $EF_{f,\,GHG}$ is emission factor for the fuel type f per GHG type ($tCO_2e\ GJ^{-1}$).

2.2.4. GHG emissions estimation from purchased electricity consumed in particleboard mill

Particleboard industry of Pakistan is mainly depended on purchased electricity from the national grid to run heavy machinery of their production line. The GHG emissions from purchased electricity were quantified by multiplying the quantity of electricity (kWh) consumed per m^3 particleboard manufactured with their respective emission factor developed by World Business Council for Sustainable Development and World Resource Institute (WBCSD/WRI, 2001). The following equation (2) was applied for the estimation of GHG emissions from purchased electricity in the particleboard industry. The emission factor can be seen in Table A of supplemental materials.

$$E_e = C_e * EF_e\ GHG \qquad (2)$$

Where,

E_e is CO_2e emissions from purchased electricity consumption in the particleboard industry; C_e represents quantity of electricity consumed per m^3 particleboard produced and *EFe GHG* is emission factor for the purchased electricity.

2.2.5. GHG emissions estimation from mobile sources

GHG emissions from mobile sources include emissions from the primary and secondary raw materials transportation, the company owned vehicle fleet, finished particleboard product distribution and marketing and employees commuting to work. For the company owned vehicles fleet, consumption data for fossil fuels were obtained from the particleboard mill. GHG emissions from fossil fuels consumption in the mobile sources are estimated from equation (3) developed by World Business Council for Sustainable Development and World Resource Institute (WBCSD/WRI, 2001) (see, Supplemental Material Table A).

$$\boldsymbol{E} = \frac{\Sigma a\,[\boldsymbol{Fuela} * \boldsymbol{EFa}]}{\mathbf{1000}} \qquad (3)$$

where;

E is GHG emissions (tCO_2e), $Fuel_a$ is total fuel used of type a (GJ) Efa is GHG emissions from one GJ of energy from fuel type a ($tCO_2e\ GJ^{-1}$), a is type of fuel e.g. petrol, diesel, CNG, HFO etc.

2.2.6. GHG emissions estimations from transportation and commuting

Transportation and travel emissions were estimated from the multiplication of a model GHG emission factors (tonne CO_2e/tonne.km and tonne CO_2e/km travelled or passenger kilometer) with the average transport and commute data per m^3 of particleboard. Emission factors and transport data sources vary per kind and mode of transport or commute.

2.2.6.1. GHG emissions estimation from raw materials and finished product distribution/marketing

Bottom-up data were collected from the particleboard mills during the surveys about the total distance travelled by the trucks used for raw materials and finished product distribution. We also noted type and mode of transport for each activity. For raw materials delivery, the mode of transport and average distance of one-way haul was reported from the mill manager and from the drivers of the trucks. Often, the primary raw material i.e. wood logs were transported by a medium truck with a payload of 10 metric tonnes. Secondary raw materials i.e. resin, wax, urea scavenger etc. were transported by small truck with a pay load of 0.5 metric tonne. The finished product was distributed across the entire country by a large truck with a payload of 30 metric tonnes. It was assumed that the large trucks consumed 20 liters of diesel per 100 km travel, whereas the medium and small trucks consumed 10-liter diesel per 100 km travel. Based on this assumption, specific emission factors per tonne·kilometer (t·km) were calculated (see supplemental material Table L).

2.2.6.2. GHG emissions estimation from mill employee's/worker's commuting

The number of employees in each particleboard factory was noted during the survey. About 88% of the surveyed particleboard industries were situated in industrial zones, which are isolated from the urban and residential areas. A 50-km distance from the mills was assumed to be traveled by each worker each work day. The number of trips per week was estimated based on the assumption that the mill operational time is 25 days a month. It was assumed that all the workers commute to the mill through the local bus service. Finally, the total passenger·km distance travelled was multiplied by its model emission factor, to estimate the overall emissions from employee's commuting per m^3 particleboard production. The model emission factor for local bus commuting was taken from DEFRA/DECC, 2010, UK (Supplemental material Table L).

2.2.7. GHG emissions from Urea-formaldehyde (UF) resin and secondary materials production chain

The GHG emissions from UF resin production chain was derived from Wilson, 2009 CORRIM (Consortium for Research on Renewable Industrial Materials) report-phase II, Module H, based on SimaPro database for U.S, because there is no specific UF resin data available for Pakistan. GHG emissions from other secondary materials such as paraffin wax, urea scavenger and ammonium sulphate were calculated using SimaPro software version 8.3 using the IPCC, 2013 methodology for 100-year time horizon global warming potential (GWP) based on ecoinvent 3.0 database.

2.2.8. GHG emissions estimations from wood combustion in particleboard mill

In Pakistan, the particleboard industry uses wood for fueling the dryers. The total quantity of wood fuel consumed in metric tonnes was reported in the surveys. The average value of each type of wood in tonnes was then multiplied by the emission factor to estimate the CO_2

emissions from wood combustion in the manufacturing process of 1.0 m^3 particleboard. The calculation was done by the following equation (4).

$$E = C \times EF \qquad (4)$$

where;

E_{GHG} is CO_2 emissions from wood combustion (tCO_2e), C is wood consumption (tonne), Energy content is equals to 20.90 MJ/kg (Wilson, 2010), and EF is emissions factor for CO_2 /TJ provided by revised 1996 IPCC guidelines for national greenhouse gas inventories.

2.2.9. GHG emissions estimation from wastes sent to landfill

Wood wastes produced during the wood particles formation and finished product trimming stages are combusted to recover energy for heating. Paper and cardboard wastes, hazardous wastes produced from the maintenance of the company owned vehicles and other manufacture operations were also reported during the survey of the mills. Wastes were categorized into 4 groups, i.e. 1). paper and cardboard wastes., 2). Rubber wastes, 3). Textiles (wiping clothes) wastes, and 4). Other wastes (e.g. toners, oil and air filters, batteries, solvents). In the present study, the GHG emissions estimation from four sub-processes of wastes generation in the particleboard industry considers degradable organic carbon (DOC) content of the respective wastes, and does not include changes in the conversion of carbon to methane emissions with time (IPCC, 1996). Methane (CH_4) emissions from different types of wastes sent to landfill were estimated by applying the method outlined by IPCC (see, supplemental material Table L). The global warming potential (GWP) of methane adopted in the present study are also taken from IPCC (2001) for a time horizon of 100 years, which is equal to 23 times greater than that of carbon dioxide. The equation (5) is used for estimation of methane emission, which is given below:

$$\textit{Methane emission} = (L_w \times L_o) \times (1-R) \times (1-Ox) \qquad (5)$$

where;

L_w is quantity of landfilled wastes (kg) by particleboard industry, L_o is methane generation potential (tonne) and was calculated by equation (6) below, R represent recovered methane from landfill equals to 0 (IPCC, 1996) and Ox is waste oxidation factor, also equals to 0 (IPCC, 2000).

$$L_o = MCF \times DOC \times DOC_F \times F \times 16/12 \ (kg\ C/kg\ waste) \qquad (6)$$

where;

MCF is methane correction factor, which is equals to 0.6 (IPCC, 2000), *DOC* is the waste degradable organic content i.e. 40% for paper and cardboard (IPCC, 1996), *DOC* for rubber wastes is 39% (IPCC, 2006), *DOC* for textiles and wiping clothes is 24% (IPCC, 2006), *DOC* for other type of wastes is 1% (IPCC, 2006), and *DOC* for general solid wastes is equal to 20% (IPCC, 1996), DOC_F is dissimilated fraction of degradable organic carbon, equals to 60% (IPCC, 2000), and *F* is fraction of methane in landfill gas by volume, which is equals to 50% (IPCC, 2000).

2.3. Background information on industrial resource inputs of the particleboard industry

Background information about different resource inputs were collected from particleboard industries of Pakistan. The average production value of particleboard was calculated as 45,832 m^3 during the studied year 2015-16. Whereas the expected production capacity of the particleboard industry was estimated as 90,000 m^3 during the year 2015-16, because it was reported that most of the factories are running on 50% of their production capacity, mainly due to raw material deficiency and energy crises in the country. The consumption of primary (wood logs) and secondary (UF resin, paraffin wax, urea scavenger etc.) raw materials and energy was quite varied for production of 1.0 m^3 of particleboard. The average value of consumption of primary and secondary raw materials was 775 kg and resin was 93 kg, urea scavenger was equal to 5 kg, paraffin wax equals to 6.48, and ammonium sulphate catalyst was 1.67 kg per m^3 particleboard manufacture during the year 2015-16, respectively as can be seen in Table 1.

Particleboard industry is conventionally depending on fossil fuels and purchased electricity to fulfill their need of energy. This is because; particleboard manufacturing process is a mechanical operation, required large amount of fossil fuels and electricity to run the machines. Particleboard manufacturing is a dry process and most of the moisture content up to 95% is evaporated from the green wood particles before mixing with the adhesives to manufacture the product. However, some quantities of water are still used throughout the industrials operations of the mill such as cleaning, glue preparation and mixing, cooking, washing and sanitary and other manufacturing processes. The water is obtained from two sources, i.e. ground water and municipal water. About 13 liters of water is pumped from ground water source whereas only 5 liters of water is utilized from the municipality provided water to produce 1.0 m^3 particleboard during the year 2015-16. Wastes are also generated from the manufacturing and business operations of the particleboard industry in Pakistan.

The wastes (in the form of discarded parts, such as oil and air filters, etc.) generated by the company owned vehicles were also estimated based on total number of vehicles and their maintenance and exchange of spare-parts information's obtained from the company manager working estimation. These wastes contain the rubber tires discarded by the company fleet each year, whereas, the expert estimate about the air and oil filters, lamps, toners, batteries and lubricants and solvents were also taken from the mill officials. The wood waste and sander dust were amounted to 7 and 29 kg per m^3 of particleboard product, respectively, which was burned in the dryers for getting heat energy for drying process of the green chips. No hazardous wastes were recycled and all were sent to landfill during 2015-16.

2.4. Cut off 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 cut-offs 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). 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 is 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 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.
- The UF resin were converted to solid content based one percentages reported by the surveyed particleboard mills.
- The allocation of the fossil energy source is also based on the information given by all the particleboard mills.
- 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.
- 100% of diesel fuel consumption was assumed for raw materials and product distribution and marketing purpose. Furthermore, it was assumed that large trucks consumed 20 liters of diesel per 100 km road travel, whereas medium and small trucks consumed 10-liter diesel per 100 km travel.
- A 50-km distance from the mills was assumed to be traveled by each worker each work day. The number of trips per week was estimated based on the assumption that the mill operational time is 25 days a month.
- It was further assumed that all the workers commute to the mill through the local bus service.

2.5. Scope of the study

The scope of this work was environmental profile analysis of a wood based panel called particleboard using a life cycle assessment approach. The focus of the study was to provide a comprehensive LCI data in the production process of particleboard in Pakistan, to identify the major environmental burdens and, eventually, propose some environmental improvement potentials by a gate-to-gate analysis of the production process. The system boundaries of this work were defined in section 2.1.3, 2.2.1 and Fig. 3, respectively. The scope specifies reference unit, reference flow and the product system (ISO, 2006 a,b). The reference unit provides a reference to which the inputs and outputs are referred. It is the quantitative measure of the functions of the goods or services provide (Soheili-Fard and Kouchaki-Penchah, 2015). Therefore, it is compulsory to ensure that the reference unit is complete, consistent and can work for product comparison (Chang et al., 2014). Thus, for an easier comparison with other studies, the reference unit applied in the present study was 1 m^3 uncoated finished particleboard panel production during the year 2015-2016.

Primary data were collected through questionnaire surveys and personal meeting with the particleboard mill officials, whereas secondary data were taken from the Ecoinvent database, literature and CORRIM reports. Data regarding the GHG emissions and particulate matter from the particleboard mills were provided by the Environmental Protection Agency, (EPA-KP) Khyber Pakhtunkhwa, Peshawar Office. Environmental Protection Agency, Pakistan is an executive agency of the Government of Pakistan and working as an attached department of the Ministry of Climate Change and is responsible to implement the Pakistan Environmental Protection Act, 1997 in the country. An act to provide for the protection, conservation, rehabilitation and improvement of environment, for the prevention and control of pollution and promotion of sustainable development in Pakistan. EPA-Pakistan is also providing all kind of technical assistance to the Ministry of Climate Change. It has four regional offices in the four provincial capitals in Pakistan; moreover it has regional Laboratories for samples analysis and testing using internationally recognized methods and protocols under the supervision of technical experts. Therefore, data regarding the GHG emissions from different particleboard mills provided by EPA-KP Peshawar office were reliable and accurate to be used in the LCIA of particleboard production in Pakistan.

2.6. Limitations of the study

Carbon footprint is a widely-used indicator for climate change impacts assessment. Nevertheless, environmental sustainability is a broader concept and includes other environmental impacts such as the depletion of natural resources, eutrophication, acidification and eco-toxicity. Exclusive attention on carbon footprint potentially risks trade-off carbon footprint improvements at the expense of other environmental impacts (Laurent et al., 2012). The present study is based on the 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 which can include growing of the seedlings, site preparation, planting, thinning, fertilizer use and final harvesting (Johnson et al. 2005). However, numerous studies (Wilson, 2005b, 2008, 2010; 2010b, Puettmann et al., 2013; Puettmann et al., 2012; 2012b; Puettmann et al., 2013a; 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. Furthermore, the production of UF resin and other secondary materials i.e. paraffin wax, urea scavenger, and ammonium sulphate was derived from Wilson, 2009 based on SimaPro Ecoinvent database for the USA, which may not be representative of conditions in Pakistan. Therefore, primary data about the production chain of UF resin and secondary materials should be collected from the chemical industries in Pakistan to get a more realistic picture of GHG emissions.

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 considered 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 depends on the quality and availability of consistent, accurate and complete data. Mostly, the geographical coverage of databases used for LCA environmental impacts modeling are limited to Europe and 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, LCA focuses on the environmental aspects of processes and products 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.

CHAPTER # 3

RESULTS
AND
DISCUSSION

CHAPTER # 3

RESULTS AND DISCUSSION

PART-I

3.1. Environmental profile analysis of particleboard production; a study in a Pakistani technological condition

The results of life cycle impact assessment for 1.0 m^3 particleboard manufacture and the relative contribution per process to the environmental impacts categories are presented in Table 2 and Fig. 5, respectively. A mandatory step in the LCA is characterization (Silva et al., 2014), which was performed in this study, to analyse the relative contribution of different processes to the impact categories to detect the hotspots processes in the manufacture of 1.0 m^3 particleboard. Therefore, characterization results expressed that UF resin production, transport of raw materials and finished particleboard distribution, heavy fuel oil (HFO) and natural gas consumption and urea scavenger had the highest contributions on majority of the impact categories (Table 3). Our results are in accordance with previous research, in that environmental burdens are mostly associated with adhesives production, transport of resource materials, fossil fuels combustion and electricity consumption, specifically in the wood particles preparation and board finishing steps (Puettmann et al. 2013; Santos et al. 2014; Kouchaki-Penchah et al. 2016; Silva et al. 2013a; Garcia and Freire 2012; Rivela et al. 2006). The LCI data for 1.0 m^3 particleboard manufacture are presented in Table 1. A comprehensive discussion of the impacts in each category is explained in the section below.

3.1.1. Abiotic depletion (AD)

The on-site industrial processes of the particleboard manufacture were accountable for majority of the impacts in AD, mainly from UF resin production (42%) and fossil fuels use (21%), whereas transport of raw materials and finished product distribution and marketing contributed about 30% to the impacts in AD category (Table 3). Among fossil fuel use, HFO had contributed about 7.51% while natural gas consumption was responsible for 13% of the impacts in AD category (Fig. 5). Furthermore, the AD impacts of HFO production was attributed to the extraction of mineral oil, crude oil, and other non-renewable resources utilized in its production. Similarly, transport of primary raw material (wood logs) was accounted for 6.73% whereas transport of secondary raw materials corresponded to 13% of the impacts as shown in Fig. 5.

Finished particleboard distribution and marketing accounted for 9.54% of the impacts in the AD category.

Concerning UF resin, AD impacts are attributed to the production of urea and methanol used to manufacture the UF resin, because, mineral coal and natural gas are used in their manufacturing processes. The other manufacturing processes contributed less to the overall impacts in the AD category. Our results are in accordance with the Ganne-Chedeville and Diederichs, 2015, that environmental burdens caused by traditional particleboard manufacture are mostly associated with adhesives production, fossil fuels combustion and consumption, specifically in the wood particles preparation and board finishing steps (Santos et al., 2014; Fruhwald et al., 2000). Specification per substance for AD impact category in particleboard production process is summarized in Appendix B (supplemental materials).

3.1.2. Acidification Potential (AP)

In the acidification potential category, again industrial processes had the highest contribution and about 54% of the impacts are related to the UF resin production, followed by transport of raw material and finished particleboard (26%), whereas, natural gas consumption contributed about 8% to the impacts in the acidification category. The impacts to acidification from the UF resin production was due to the production of urea and methanol in its production chain whereas, transport consumed fossil fuels which emitted carbon and sulfur to the air. The other production processes were attributed to less contribution and presented in Fig. 5. Whereas, specification per substance for AP impact category are tabulated in Appendix C as can be seen in supplemental materials.

3.1.3. Eutrophication Potential (EP)

In the eutrophication potential impact category, UF resin production had the highest contribution (52%), due to the urea and methanol production emissions in the form of NO_x to air and hydrocarbons to water. Whereas, transport of raw materials and finished product distribution was the second largest contributor with 33%, followed by wood combustion in the dryers for energy/heat generation with 7% to the impacts in EP category. Among transportation activities, wood logs transport was responsible for 6.67%, and transport of UF resin and other materials were responsible for 17% and 9.50% of the impacts in EP category, respectively. In addition, the NOx emissions from HFO combustion was amounted to 2.12% of the impacts, whereas, urea scavenger also contributed 3.21% to the impacts in the EP category. Other processes were responsible for minor contributions as presented in Fig. 5. Moreover, contribution of each substance to EP impact category is presented in Appendix D of the supplemental materials.

3.1.4. Global Warming Potential (GWP)

The UF resin production reveals the highest contribution (45%) to GWP impact category, due to the urea and methanol production. Transportation activities across the country contributed about 44% to the impacts, followed by electricity generation with 16% contribution. Among the various transportation activities, transport of raw materials to the mill contributed about 10.24% to the impacts in the GWP category. Whereas, about 20% impacts were attributed to transport of UF resin and other secondary materials such as paraffin wax, urea scavenger and ammonium sulphate in the GWP impact category. In addition, finished product distribution accounted for 14% of the emissions in the GWP impact category. Furthermore, in the GWP impact category, the contribution of HFO, urea scavenger, and natural gas consumption was 1.62%, 3%, and 1.62%, respectively (Fig. 5). Specification per substance responsible for GWP impact category is summarized in Appendix E of the supplemental materials.

3.1.5. Photochemical Oxidation (PO)

The UF resin production had the largest contribution (52%) to the photochemical oxidation impact category. Wood combustion in the dryer was accounted for 20% of the impacts in the PO category, followed by transport of raw materials and finished product distribution and marketing with 17% contribution to the impacts in the PO category. Among all the transportation sessions, transport of wood logs to the mill was responsible for 3.81%, whereas transport of UF resin and other secondary materials were contributed to 7.91% emissions to the total impacts in PO impact category, respectively. Among the fossil fuels, HFO and natural gas consumption was the highest contributor with 5% and 2.44% to the total impacts in the PO impact category, respectively. The contributions from other processes to the impacts of PO category is presented in Fig. 5. Furthermore, the specification per substance to PO impact category is presented in Appendix K of the supplemental materials.

3.1.6. Human Toxicity (HT)

The UF resin production was the single major contributor to human toxicity impacts (56%), followed by transport of secondary raw materials with 12% contribution as can be seen in Fig. 5. The highest contribution from UF resin production was due to the result of free formaldehyde emissions from the particleboard production process. Wood combustion in the dryer was responsible for about 6% of the impacts in the HT category. Moreover, transport of wood logs and finished product distribution and marketing contributed about 8.41%, and 9% to the total impacts in the HT impact category, respectively. Urea scavenger was corresponded to 3.47% to the impacts in HT, whereas HFO and natural gas consumption attributed to 1.42% and 1.96% to the overall impacts in HT impact category, respectively (Fig. 5).

Manufacturing processes and transportation was the major contributor in the HT impact categories in Iranian particleboard production (Kouchaki-Penchah et al. 2016). Our results are also in accordance with the Silva et al., 2015 that large impacts on HT are also due to the heat production through cogeneration of wood in the Brazilian particleboard production. In addition, substances contributed to the HT impact category is presented in Appendix G of the supplemental materials.

3.1.7. Ozone Layer Depletion (OLD)

The UF resin production was the main contributor to OLD by 35% of the overall contributing emissions. Similarly, transport of raw materials and finished product distribution and marketing was responsible for 29% and 15% of the impacts in the OLD category, whereas, HFO combustion was the third highest contributor with 12% of the emissions to OLD impact category. Natural gas consumption was attributed to 3.3% of the total impacts in the OLD as shown in Fig. 5 and Table 3, respectively. Overall transportation activities were accounted for 44% of the contributing emissions to ozone layer depletion, followed by UF resin production and HFO, which is in line with the results reported by Kouchaki-Penchah et al., 2016. Specification per substance to OLD impact category is shown in Appendix F of the supplemental materials.

3.1.8. Freshwater Aquatic Ecotoxicity (FAE)

The UF resin use and transportation had the largest contribution 57% and 26% to the impacts in the FAE impact category, respectively. Transport of raw materials and finished particleboard distribution and marketing was responsible for about 17%, and 9.36% of the impacts, whereas HFO and natural gas consumption contributed 1% and 3% to the total emissions in the FAE impact category, respectively. The wood combustion in the dryer was accounted for 7% of the impacts in the FAE impact category. The contribution from other processes are illustrated in Fig. 5 and Table 2. The specification per substance to FAE impact category is documented in Appendix H of the supplemental materials.

3.1.9. Marine Aquatic Ecotoxicity (MAE)

The UF resin use and transportation had the largest contribution 63% and 26% to the impacts in the MAE impact category, respectively. Transport of raw materials and finished particleboard distribution and marketing was responsible for about 15%, and 6.28% of the impacts, whereas HFO and natural gas consumption contributed 1.6% and 3.8% to the total emissions in the MAE impact category, respectively. The urea scavenger and wood combustion in the dryer was accounted for 2.2% and 3.74% of the impacts in the MAE impact category. The contribution from other processes are illustrated in Fig. 5 and Table 2. The contribution of various substance to the MAE impact category is summarized in Appendix I of the supplemental materials.

3.1.10. Terrestrial Ecotoxicity (TE)

The UF resin production had the single largest contributor (74%) to the emissions in the TE impact category. Similarly, transport of raw materials and finished particleboard distribution and marketing contributed to 10% and 4% to the total impacts in the TE impact category, followed by urea scavenger with 5.92% contribution to the TE impact category as indicated by Fig. 5, respectively. Likewise, the specification per substance to TE impact category is tabulated in Appendix J of the supplemental materials.

3.1.11. Discussion

The LCI data of the 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 impacts categories are presented in Fig. 5. The UF resin production, transport of raw materials and finished particleboard distribution, heavy fuel oil (HFO), 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 adhesives production, fossil fuels combustion and electricity consumption, specifically in the wood particles preparation and board finishing steps (Puettmann et al., 2013; Santos et al., 2014; Kouchaki-Penchah et al., 2016; Silva et al., 2013; Rivela et al., 2006).

The on-site industrial processes of the particleboard manufacture were accountable for most the impacts in abiotic depletion (AD), mainly from UF resin production (42%), and fossil fuels use (21%), whereas transport of raw materials and finished product distribution contributed about 30% to the impacts in AD category. Among fossil fuel use, HFO had contributed about 7.51% while natural gas consumption was responsible for 13% of the impacts in AD category (Fig. 5). Our results were in line with the 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 were 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 heavy fuel oil (HFO) (35%) was 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 is utilized in their production processes (Garcia and Freire 2012; Silva et al. 2013b).

The UF resin production and use was responsible for half (54%) of the impacts in the acidification potential (AP) impact category, followed by transportation and fossil fuels use in the Pakistani particleboard production chain. The impacts to AP from the UF resin production was due to the production of urea and methanol in its production chain whereas, transport consumed fossil fuels which emitted carbon and sulfur to the air. Similarly, in the Iranian particleboard industrial processes, UF resin, transport, and electricity was 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 is in important hotspot in the AP impact category due to the production of sulphur, methanol and urea (Silva et al. 2013a, 2015).

In the eutrophication potential (EP) impact category, UF resin production had the highest contribution (52%), due to the urea and methanol production emissions in the form of NOx to air and hydrocarbons to water. Whereas, transport of raw materials and finished product distribution was the second largest contributor with 33%, followed by wood combustion in the dryers for energy/heat generation with 7% to the impacts in EP category. Likewise, UF resin production, the use of diesel in the harvest, processing and transport of wood materials, and NO_x emissions from the combustion of HFO and wood residues were also the largest contributors to EP impact category in the Iranian and Brazilian particleboard manufacturing process (Kouchaki-Penchah et al. 2016; Silva et al. 2013a).

The UF resin production reveals the highest contribution (45%) to GWP impact category, followed by transportation (44%), and purchased electricity (16%) as can be seen in Fig. 5. Among different transportation sessions, about 20% impacts were attributed to transport of UF resin and other secondary materials such as paraffin wax, urea scavenger and ammonium sulphate in the GWP impact category. Whereas, finished particleboard distribution amounted to 14% of the impacts in the GWP category. Transport of raw materials and finished particleboard are important due to fossil fuels combustion and the long distances from the source of primary and secondary materials to the manufacturing site (Fig. 1), 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 is 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 forests/farmlands 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 is 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 had the largest contribution (52%) to the photochemical oxidation impact category. The primary reason for this high contribution was the emissions of carbon monoxides, methane, nitrous oxides and volatile organic hydrocarbons (VOCs) from the production of urea and methanol used in the UF resin manufacturing process. Therefore, UF resin should be replaced by other type of resin such as melamine urea formaldehyde (MUF) resin primarily because of its minor contributions to PO and human toxicity (Silva et al., 2014b). Among all the transportation sessions, transport of wood logs to the mill was responsible for 3.81%, whereas transport of UF resin and other secondary materials were contributed to 7.91% emissions to the total impacts in PO impact category, respectively. The primary reason for this contribution was consumption of fossil fuels in the vehicles, which emitted CO, NO_x and SO_x to the air. Among the fossil fuels, HFO and natural gas consumption was the highest contributor to the total impacts in the PO impact category, respectively. The combustion of these fossil fuels caused VOCs emissions during the wood particles drying and hot pressing process of the particleboard manufacture (Silva et al. 2013a).

The UF resin production represents the most important hotspot for all the impact categories, which agrees with the former 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). However, huge environmental concerns are raised about its impacts mainly due to free formaldehyde emissions from healing process of the wood composite panels production (Kinga, 1996; European Panel Federation, 2004). Since, free formaldehyde emissions might cause cancer in humans and by exceeding concentration above 0.1 ppm can cause bad effects on human health such as nausea, nose, eyes and throat irritation, which comes under the HT impact category (Silva et al., 2013b; Athanassiadou, E, 2000).

Therefore, Silva et al., 2014b suggested that UF resin should be replaced by melamine urea formaldehyde (MUF) resin, because of its minor contributions to environmental impacts but would be more expensive, however technical characteristics of the board should not be changed (Jungmeier et al., 2002a; 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). Woodfuel use in the particleboard manufacturing process is one of the important renewable fuel source which can substitute the fossil fuels which are non-renewable (Wilson, 2010). However, wood residues use in the particleboard production is more sustainable than their use as a fuel (Rivela et al., 2006). This was in accordance with the findings of Santos et al., 2014 that wood based particleboard manufacture was responsible for the highest environmental burdens as compared to bagasse (agri-residue based) particleboard (Silva et al., 2014). Therefore, higher the agri-industrial residues use in the manufacture of particleboard, the lower will be the environmental impacts (Silva et al., 2013a).

Wood particle dryers, primary recovery cyclones and direct-fired units of the plant emit solid particulate matter (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 emissions control devices. Therefore, it is evident that the particleboard mill can reduce their emissions from manufacturing process by installing emissions 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 VOCs 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).

3.1.12. Sensitivity analysis for the improvement opportunities in the particleboard manufacturing process

The major hotspots in each environmental impact category in the LCA of particleboard manufacture in Pakistan are summarized in Table 2 and Fig. 5, respectively. It is evident from the results, that most of the hotspots occurred in the board manufacturing activities in the industrial unit such as UF resin use, electricity consumption, wood combustion in the dryer, HFO and natural gas consumption. However, transportation of raw materials and finished product distribution and marketing contributed to almost all the ten impact categories. Therefore, three scenarios, baseline-scenario I, scenario-II and scenario-III were considered for transport activities of the particleboard plant. Baseline-scenario I demonstrated the present situation of the study, whereas scenario-II showed 25% reduction in the mileage of the particleboard mill transportation activities and scenario-III represented the 50% reduction in the mileage of the transport activity.

In addition, the effect of the assumed scenario-II and scenario-III on environmental impacts were assessed as shown in Table 7. As can be seen, the scenario-II has decreased all the environmental impacts such as global warming (11%), ozone layer depletion (10%), eutrophication potential (8%), and acidification potential (7%), human toxicity (7%), freshwater aquatic ecotoxicity (7%), and abiotic depletion (7.5%) Whereas, scenario-III further decreased the environmental impacts as compared to the baseline scenario I values in the present study (Table 3). In scenario-III, the environmental impacts of global warming, ozone layer depletion, eutrophication, acidification were decreased up to 22%, 30%, 16%, and 14%, respectively.

The proposed reduction in mileage of the transport of the particleboard mills could be achieved by acquiring the raw and secondary materials from nearby areas of the mills, whereas, diverting all the mill freight into high mobility freight highways such as motorways in Pakistan to reduce the mileage, fuels consumption and time to reach the destination point. Most of the GT roads of Pakistan are passing from urban areas and marketing places, where due to huge traffic jam, the mill freight consumes more fuels and needs to covered more mileage to reach the target point by alternative small roads. Drivers often choose slow, circuitous local routes because they are toll free, without any load limits and have fewer police check posts.

Most of the environmental impacts in particleboard are associated with the UF resin use. Based on our survey results, 93 kg of UF resin is required for manufacture of 1.0 m^3 particleboard in Pakistan, whereas, only 68, 72 and 68 kg of UF resin per m^3 was used by USA, Brazilian, and Spanish manufacturers, respectively (Puettmann et al. 2013; 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 per m^3 particleboard manufacture in 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.

Similarly, substituting the inputs with alternative ones having least environmental impacts could bring a significant improvement in the environmental profile of particleboard manufacture. Substituting UF resin with other types of resin such as phenol–formaldehyde, tannin–urea–formaldehyde, melamine–urea–formaldehyde, and isocyanate could alter the technical characteristics and properties of the particleboard and therefore, is out of the scope of this study (Silva et al., 2013; Kouchaki-Penchah et al., 2016), because for substitution of alternative materials, the technical properties of the panel should not be altered (Jungmeier et al., 2002; Gonzalez-Garcia et al., 2009; Silva et al., 2013; Kouchaki-Penchah et al., 2016). Although, a comprehensive LCA of UF resin was developed for USA (Wilson, 2009), and Brazil (Silva et al., 2013). However, up till now, no study has been conducted for UF resin production in Pakistan. However, the substitution of HFO by diesel or wood residues in the production line of particleboard manufacture do not changes the technical properties of the board and was conducted for particleboard manufacture in Brazil (Silva et al., 2013) and Iran (Kouchaki-Penchah et al., 2016). Silva et al., 2013 investigated that 100% substitution of HFO with wood residues caused lowest impacts in all the impact categories, whereas in case of unavailability of wood residues, diesel substitution was the second good alternative. About 75.5 kg/m^3 of wood residues were needed to fulfill the thermal energy demand in the Brazilian particleboard mill, whereas the wood residues generated were equal to 97.2 kg/m^3 of particleboard manufactured, thus wood residues can easily displaced HFO in the particleboard manufacturing process (Silva et al., 2013). Kouchaki-Penchah et al. 2016 applied sensitivity analysis for diesel fuel in the Iranian particleboard production line, which is the main thermal energy source with all the wood wastes and residues generated during the production process of particleboard. The results showed an improvement in the economic efficiency and also decrease for some of the impacts such as EP, HT and TE. Although, in a comparison between biomass fuels and natural gas, it seems that the use of natural gas is more favorable from the ecological sustainability perspective than that of biomass fuels (Rivela et al., 2006a). Similarly, Silva et al., 2015 also performed sensitivity analysis for UF resin and considered the addition of 10% of melamine urea formaldehyde (MUF) to the UF resin for the particleboard produced in Brazil. The authors concluded MUF can substitute UF resin because of its lower contribution to PO and HT impact category.

Likewise, Kouchaki-Penchah et al., 2016 reported the use of sander dust in the Iranian particleboard manufacturing plant, as an alternative biomass fuel, showed significant reduction in the environmental impact categories. Therefore, alternative renewable energies should be encouraged to avoid the damage to resources and greenhouse gas emissions by substituting fossil energy (Jungmeier et al., 2002; Rivela et al., 2006b). Similarly, for recommending an alternative energy option, the most important aspects are its supply ways and environmental burdens caused by its consumption. Therefore, all the wood wastes and sander dust generated during the manufacture of 1.0 m^3 particleboard in Pakistan were burnt in the dryers for getting thermal energy for wood chips and board drying and could not fulfill the demand of thermal energy of the mill alone. Therefore, due to deficiency of woody biomass in the country, more research should be conducted on this issue, while formulating and devising improvements opportunities by adopting alternative options in the particleboard manufacturing process in Pakistan.

3.1.13. Cumulative Exergy Demand (CExD) of 1.0 m^3 particleboard production process

Exergy is defined as the work potential of a material or a form of energy in relation to its environment and provides a natural basis for assessing the efficiency of resource use and identifying possible trade-offs and cost effective opportunities for conservation (Rivela et al., 2006). Cumulative exergy demand (CExD) is referred to the sum of exergy of all the resources needed to provide a service or product (Kouchaki-Penchah et al., 2016: Bosch et al., 2007). CExD indicator is varied from the common cumulative energy demand (CED) by a single exemption that it is considers the quality of energetic and non-energetic resources, which make it one of the valuable indicator (Iribarren et al., 2014). Therefore, CExD indicator is identified as a promising technique to show the total exergy removed from nature to provide a product (Bosch et al., 2007).

Regarding our work, CExD is the sum of all the exergy removed from nature to manufacture 1.0 m^3 of particleboard during the year 2015-16 in Pakistan. Previously, CML 2000, and CExD v1.03 methods have been applied by other scientists (Silva et al., 2013; Saravia-

Cortez et al., 2013; Kouchaki-Penchah et al., 2015), Therefore in the present study, the life cycle impact assessment (LCIA) of 1.0 m^3 particleboard was modeled in SimaPro v.8.3 software applying these methodologies; because SimaPro is one of the leading and common LCA software for measuring the environmental impacts of a product based on life cycle assessment approach (Mousazadeh et al., 2009).

The CExD indicator results and related hotspots with 1.0 m^3 particleboard production process is summarized in Table 7 and Fig. 6, respectively. The total cumulative exergy demand required for manufacturing of 1.0 m^3 particleboard was equal to 15,632 mega joule-equivalent (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. However, among the seven impact categories, non-renewable fossil sources had the highest contribution i.e. 12,504 MJ-eq to the total exergy removed from the nature to manufacture 1.0 m^3 particleboard. Similarly, renewable biomass was the second largest source with contribution of 1,455 MJ-eq exergies, whereas non-renewable minerals were responsible for only 25.40 MJ-eq in the total exergy required for 1.0 m^3 particleboard manufacture (Fig. 7).

As can be seen in Table 7, among the various manufacturing processes, UF resin production, fossil fuels consumption, transportation activities and purchased electricity 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). Transport of finished product distribution and marketing was identified as the second largest contributor to the exergy removed from nature to manufacture 1.0 m^3 of particleboard. Similarly, HFO, purchased electricity, and natural gas consumption were also the main hotspots in all impact categories of cumulative exergy demand, and was responsible for removal of exergies from the nature to product 1.0 m^3 particleboard (Fig. 6).

Kouchaki-Penchah et al., 2016 reported that particle generation, dryers, boilers, hot press vents, wood chips piles, bins, chips and resin storage and handling systems, panel blending, panel forming, panel cooling, panel sanding and trimming operations are the most important sources of emissions in the particleboard production plant (EPA, 2002). The emissions from these operations to different environmental compartments are summarized in Table 2. HFO and natural gas consumption in the machineries and diesel fuel use in the internal transport of materials etc. had the largest contribution to the nitrous oxides (NO_x), dinitrogen monoxide

(N_2O), sulfur dioxide (SO_2), cadmium (Cd), chromium (Cr) carbon dioxide (CO_2), and carbon monoxides (CO) emissions (Kouchaki-Penchah et al., 2016). Therefore, energy efficiency and minimization in the drying process of wood particles is extremely important, because this is one of the most energy consuming operations in the particleboard manufacture process (Zarea-Hosseinabadi et al., 2012).

PART-II

3.2. Carbon footprint as an environmental sustainability indicator for the particleboard produced in Pakistan.

3.2.1. GHG emissions from fossil fuels consumed by stationary sources

The consolidated GHG emissions from fossil fuels consumption in the point sources of particleboard industry were132.08 kg CO_2e per m^3 particleboard produced during the year 2015-2016 (Table 9). According to the surveyed mill information's, on average basis, a total of 45,832 m^3 particleboard were manufactured and distributed by the particleboard industries at the cost of huge fossil fuels consumption during the year 2015-2016. Based on our analysis, the highest GHG emissions was caused by natural gas, contributed 59% emissions to the total emissions from fossil fuels energy consumption in stationary sources of the particleboard industry in 2015-16 (Table 9). Whereas, 37% of emissions was derived from heavy fuel oil, followed by diesel with 1% emissions during the studied period. The least emission was corresponded to petrol/gasoline, which was less than 1% of the aggregate emissions from the fossil fuels consumed by point sources during the studied period (2015-16).

Similarly, in terms of energy consumption and subsequent emissions from stationary sources, it was found that about 0.0436 GJ of diesel energy was consumed, which released 3.268 kg CO_2e per m^3 particleboard manufacture during 2015-16 (Table 9). Whereas, 1.659 kg CO_2e emissions per m^3 was caused at the cost of 0.0241 GJ of petrol/gasoline energy consumed by fixed sources during 2015-16. Likewise, about 1.560 GJ of natural gas was consumed by point sources, contributing 78.02 kg CO_2e per m^3 particleboard produced. Moreover, 0.6551 GJ of heavy fuel oil was burnt in the on-site resources of the particleboard mills, which accounted to 49.13 kg CO_2e per m^3 particleboard manufacture during the studied period as shown in Table 9.

3.2.2. GHG emissions from fossil fuels burned by company owned vehicles fleet

Diesel and petrol/gasoline fuel consumption in the company owned fleet of particleboard industry for managerial and business activities were 0.0409 GJ and 0.0091 GJ per m^3, which resulted in 3.06 kg CO_2e and 0.633 kg CO_2e emissions per m^3 in 2015-16, respectively. However, large quantity of natural gas i.e. 1.5877 GJ per m^3 particleboard was consumed by the company owned fleet for various managerial and business activities, emitted 79.86 kg CO_2e emissions per m^3 particleboard produced during the study period (Table 9). Natural gas consumption was the largest emitter, contributed 95% emissions from company owned fleet in

2015-16. Whereas, diesel represented about 4% of emissions. However, about 1% emissions were caused by petrol/gasoline consumption in the company owned vehicles fleet of the particleboard industry during 2015-16 in Pakistan. Moreover, the total quantity of energy consumed by the company owned vehicles fleet was 0.0348 GJ per m^3 particleboard produced, which accounted for 2.532 kg CO_2e emissions per m^3 particleboard produced in 2015-16 as presented in Table 9.

3.2.3. GHG emissions from particleboard product distribution/marketing

Particleboard industry distributed finished particleboard product through large truck/trailer with a payload of 30 metric tonnes/trip. The one-way transport distance of the product distribution was noted from each mill during the survey, considering the mill as a reference point. Most of the particleboard industries distributed their product across the entire country. Therefore, we calculated the production weighted average value for the transportation distance of all the mill to get the representative average value of distance in tonne.kilometer (t.km) for product distribution and marketing. Therefore, a total of 847 tonne.km per m^3 distance was travelled by a large truck for distribution of the particleboard product, which caused the emissions of 69.454 kg CO_2e per m^3 during the year 2015-16 (Table 9).

3.2.4. GHG emissions from wood combustion in the dryer of the particleboard mill

The aggregated GHG emissions from wood combustion for energy/heat recovery in the dryers of the particleboard mills were 98.313 kg CO_2 emissions per m^3 of particleboard manufactured during 2015-16 as exhibited in Table 9. While, the total wood energy consumption was 0.8778 GJ per m^3 particleboard produced. The wood fuel generated 0.1254 GJ of energy for 1 m^3 of particleboard production, and corresponded to 14.044 kg CO_2 emissions per m^3. Whereas, combustion of sander dust produced 0.6061 GJ of energy, which emitted 67.883 kg CO_2 per m^3 particleboard produced. In addition, wood waste combustion added 0.1463 GJ of energy to the dryers of the mill, while released 16.385 kg CO_2 emissions per m^3 particleboard during the year 2015-16 (Table 9).

Our analysis further revealed that the sander dust was the highest emitter, contributed about 69% of CO_2 emissions to the total emissions from wood combustion in the dryers. Whereas, 17% of the emissions was attributed to the wood waste combustion, followed by wood fuel combustion with 14% of emissions to the overall emissions from wood combustion in the particleboard mills during 2015-16 (Table 9). However, it should be noted that per IPCC recommendation and GHG protocol, CO_2 emissions from wood combustion was not added to the particleboard industry emissions, because the biomass absorbs carbon dioxide during its growth phase, which compensate emissions from its combustion, However, the biomass carbon neutrality assumption is applied on sustainably managed forest, which is not the case in our study and we have considered the biogenic carbon as accounted carbon. In addition, we have proposed scenario-II by assuming biogenic carbon neutrality of the biomass combusted in the dryer of the particleboard production line in Pakistan, excluding the biogenic emissions from the total carbon footprint of the particleboard produced in Pakistan. Similarly, the methane and nitrous oxide emissions should always be accounted in the company emissions, since plants do not reabsorb these gases during its growth period. However, methane, nitrous oxide and other gases are produced in lesser amount (Wilson, 2010), which are not included in the present study.

3.2.5. GHG emissions from purchased electricity in the particleboard mill

All the surveyed particleboard mills purchased electricity from the national grid of Pakistan. It was not possible to obtained the electricity consumption data for each unit process of the mill, because of data unavailability. Therefore, the total quantity of purchased electricity was recorded, which was normalized to the average value of electricity consumption per m^3 particleboard produced during the year 2015-16. A total of 183 kWh of purchased electricity was consumed by the mill to produce 1.0 m^3 of particleboard product during 2015-16 (Table 9). The purchased electricity corresponded to 0.6588 GJ of energy per m^3, which emitted 88.40 kg CO_2e per m^3 particleboard manufactured.

3.2.6. GHG emissions from wastes sent to landfill

Particleboard industry produced 0.1103 kg of wastes per m^3 particleboard, which amounted to 0.1893 kg CO_2e emission per m^3 during 2015-16. Based on 1.0 m^3 particleboard production, a total of 0.0151 kg of paper and cardboard waste was disposed of in landfill, which released about 0.0362 kg CO_2e emissions during 2015-16. Whereas, the rubber waste emitted 0.1209 kg CO_2e emissions per m^3 from the generation of 0.0151 kg of rubber waste per m^3 particleboard produced in the studied period. Each mill gives uniform/clothes to their workers twice in a year, after every six months. The wiping and worker's clothes are discarded each year to the landfill as a general waste. About 0.0072 kg of textile waste was generated by 1.0 m^3 of particleboard production, emitting 0.0103 kg CO_2e emissions to the atmosphere from landfill. Whereas, toners, batteries, oil and air filters, lamps and solvents etc. are grouped in one category of waste called "Other waste", which caused emissions of 0.0217 kg CO_2e per m^3, while producing a waste mass of 0.0363 kg per m^3 particleboard manufactured during 2015-16 as shown in Table 9. Based on our calculation and results, the highest emission (64%) was caused by rubber wastes whereas paper and cardboard waste contributed about 19% of emissions to the total emissions from waste sent to landfill during 2015-16. Similarly, the other waste accounted for about 12% of the emissions, followed by the textile waste emission with a contribution of 5% to the total waste emissions per m^3 particleboard product during the studied period (Fig. 8).

3.2.7. GHG emissions from primary and secondary raw materials transportation

On production weighted average basis, a total of 336 t.km of distance per m^3 particleboard was travelled by the medium truck to ship the primary raw material i.e. wood logs to the particleboard mills, emitting 112.89 kg CO_2e emissions per m^3 in 2015-16. Whereas, the secondary raw materials such as UF resin, and paraffin wax, ammonium sulphate, and urea scavenger. contributed about 66.78 kg CO_2e and 60.87 kg CO_2e emissions from travelling 113 t.km and 103 t.km per m^3 particleboard manufacture in the year 2015-16. The aggregation of distance (in tonne kilometer per m^3) travelled by both the transportation mode of primary and secondary raw materials to the particleboard mill was equal to 552 t.km per m^3 particleboard produced. Similarly, the consolidated emissions from the transportation of both the materials were 240.55 kg CO_2e per m^3 particleboard manufacture in 2015-16 (Table 9).

3.2.8. GHG emissions from UF resin and other secondary materials production chain

About 93 kg of urea-formaldehyde (UF) resin was consumed per 1.0 m^3 of particleboard production, which results in 230.08 kg CO_2e emissions. In addition, other additives such as paraffin wax, urea scavenger and ammonium sulphate had contributed 24.35 kg CO_2e emissions to the total emissions from 1.0 m^3 particleboard manufacture as can be seen in Table 9.

3.2.9. GHG emissions from employee's/worker's commuting to the particleboard mill

The method of GHG emissions estimation from workers commuting was adopted from Ozawa-meida et al. (2011) with a minor modification in assumptions. According to our surveys results, the total number of employee's/workers were 135 on average basis in the particleboard industry of Pakistan. We have assumed a specific distance of 50 km radius from the particleboard mill, and each worker commutes this distance (50 km) each day to go for work to the mill. The distance travelled in term of passenger kilometer (pass.km) was estimated for all the workers of the surveyed industries on average basis and then the pass.km distance was divided by the average particleboard production of the particleboard industry of Pakistan to get pass.km distance travelled per m^3 particleboard produced during 2015-16. Based on our analysis and results, about 44 pass.km distance was travelled by the workers for production of 1.0 m^3 of particleboard, which caused an emissions of 8.316 kg CO_2e per m^3 in the studied period as presented in Table 9. In addition, it was also assumed that all the workers are commuting through the local bus service to the mill. The emission factor for workers commuting through local bus was 0.189 kg CO_2e/pass.km, taken from Defra/DECC, 2010.

3.2.10. Discussion

Particleboard industry in the USA, Portugal, Brazil, and Spain is the leading manufacturer of particleboard product, conducted their carbon footprint based on life cycle assessment approach for last few years in the ever history of particleboard industry globally (Puettmann et al., 2013; Wilson, 2010; Silva et al., 2013; Garcia and Freire, 2014). Therefore, the results of their studies act as a benchmark in terms of life cycle assessments and carbon footprint of particleboard industry, because, these countries calculated life cycle impacts and carbon emissions for every step of the production chain of particleboard manufacture. Similarly, particleboard industry in Pakistan is also a leading manufacturer of wood based panel product with a huge production capacity in the country. Therefore, particleboard industry in Pakistan also needs to be examined scientifically, in terms of emissions and pollutants associated with activities undertaken by the industry and measure future emissions due to new investments and growth of the company. Therefore, our study is the first to calculate life cycle carbon footprint of particleboard produced in Pakistan. We estimated carbon footprint for particleboard production chain in Pakistan, comprising of major industrial activities. However, mostly data pertaining the GHG emissions from particleboard industry has been infrequently reported throughout the world. So, we compared our study findings mostly with the results of carbon footprints of USA (Puettmann et al., 2013; Wilson, 2010), Brazil (Silva et al., 2013) and Portugal (Garcia and Freire, 2014), because of unavailability of the relevant literature on the carbon footprint of particleboard industry in Pakistan.

Summing up all the GHG emissions from the particleboard production chain in terms of carbon dioxide equivalents (CO_2e), carbon footprint of particleboard production was 975.282 kg CO_2e in the year 2015-16 (Table 9). Our results reveal large variations, both in terms of total carbon footprint and in its structure. Carbon footprint of 1.0 m^3 of particleboard production in

Pakistan is relatively higher (975.282 kg CO_2e) than reported by Wilson, 2010, (392 kg CO_2e) and Puettmann et al, 2013 (376 kg CO_2e) for 1.0 m^3 of particleboard production in the USA. Whereas, Garcia and Freire, 2014 reported 188 kg CO_2e emissions per m^3 particleboard produced in Portugal following the ISO/TS 14067 standards. Our carbon footprint value was higher because varied system boundaries were used by Wilson, 2010; Puettmann et al., 2013 and Garcia and Freire, 2014 in their studies. The system boundary of our study also includes transportation of product distribution/marketing, company owned fleet and workers commuting to the industry which was not considered in the US and Portugal carbon footprint studies. Even, we have also calculated the GWP impact category using the SimaPro v.8.3 software in the Part-I of this thesis, where the GWP value equals to 552 kg CO_2e, which is again higher than the reported GWP values for the USA, Brazil and Portugal. The difference in the carbon footprint value in Part-I and Part-II of the present study is also attributed to varying system boundary in both the cases, including the workers commuting and adhesives production in the later case (Part-II).

Our results are in accordance with the US particleboard industry, where 73% (274.78 kg CO_2e/m^3) of the CO_2e emissions come from on-site industrial operations of particleboard, with 23% (86.18 kg CO_2e/m^3) and 04% (14.71 kg CO_2e/m^3) corresponded to wood residue production and forestry operations (Puettmann et al., 2013). Whereas in another study, only 15% (57.3 kgCO_2e) of the emissions is attributed to the on-site carbon footprint of the US particleboard industry (Wilson, 2010). Similarly, in Portugal particleboard industry, the industrial process stage contributed 36% to the total emissions on per m^3 particleboard manufacture basis (Garcia and Freire, 2014). This difference of GHG emissions from on-site industrial operations was primarily due to varied system boundaries of both the studies.

Particleboard industry direct emissions were mainly related to fossil fuels consumption in on-site machinery, company owned vehicles fleet and finished product distribution and marketing. Whereas, emissions from wood combustion was also estimated and accounted in the carbon footprint of particleboard manufacture in the baseline scenario-I without carbon neutrality assumption (the result of the present study), however, as per IPCC and other organizations recommendation, the biogenic carbon is not accounted in the total GHG emission, because the trees had absorbed the same quantity of CO_2 during their growth phase, so the release of trapped CO_2 due to biomass combustion will have a net zero result on the overall GHG emissions, because of biogenic carbon-neutral emissions concept about wood combustion according to many organizations having environmental concerns (IPCC, 2007; USEPA, 2003; BSI, 2008; Wilson, 2010, Hussain et al., 2014). However, this assumption is true where the forest management and biomass harvest operations are on sustainable basis, which is not the case in our study. Moreover, there was no use of renewable energy for running manufacturing machinery and office based activities in any of the particleboard mill in Pakistan.

GHG emissions from purchased electricity was resulted from power generation acquired by the particleboard mill, which is occurred at a place where it was generated, not in the mill. As, particleboard industry is totally depended on national grid for purchased electricity. Thus, 9% of the GHG emissions were attributed to purchased electricity in 2015-16 (Fig. 8). It should also be noted that the emission factor adopted in our study is based on the values of WBCSD, 2001; GHG protocol, which is relatively generic and covered a wide range of situations. Therefore, the results of a study conducted on local emission factor could reproduce real emissions more accurately and could be considerably vary from those calculated based on the adopted IPCC and WBCSD factors. Similarly, the other indirect emissions are due to the consequence of particleboard industry activities, but arise from the sources that are owned or controlled by others. Particleboard industry indirect emissions were mainly related to raw material transport, wastes generated and employee's commuting to the mill.

The carbon footprint of 1.0 m^3 particleboard manufacture by detailed sources exhibited that transport of raw materials accounted for the highest emissions about 25% of the total emissions from the particleboard industry, followed by UF resin production which made up 24% emissions during the year 2015-16 (Fig.8). Similarly, fossil fuels consumed in stationary sources accounted for 13% of the total emissions from per m^3 particleboard production chain in Pakistan. Whereas, fossil fuels consumption in company owned vehicles fleet contributed about 9% emissions to the total emissions of particleboard industry during 2015-16. GHG emissions from fossil fuels consumption in stationary sources was larger than that from mobile sources. The potential reason for this difference can be attributed to the strong reliance of particleboard industry on fossil fuels combustion and electricity for their on-sites manufacturing machinery, whereas required less by the mobile facilities. Finished particleboard product distribution and marketing was responsible for about 7% of the emissions during 2015-2016 as can be seen in Fig. 8.

According to the data provided by the particleboard industries, natural gas consumption was the major source for energy in stationary sources, followed by heavy fuel oil, diesel, and petrol/gasoline in 2015-16 (Fig. 8). This was in line with the results of Garcia and Freire, 2014, who reported that in the industrial process of particleboard manufacture in Portugal, the major GHG emissions contributor was the combustion of natural gas for wood drying. In addition, heavy fuel oil (HFO) was the second largest emitter in fossil fuels consumed in particleboard industry of Pakistan, because it is readily available and cheaper as compared to petrol, that is why the mill consumed it in large quantities for on-site operations. Similarly, electricity and wood combustion for energy corresponded to 10% and 9% emissions, however, emissions from wood combustion in the dryer was considered accounted emissions in the consolidated carbon footprint of 1.0 m^3 particleboard production during 2015-16. Worker's commuting to the mill constituted about 1% emissions while the least emissions i.e. less than 1% was corresponded to wastes sent to landfill by the particleboard industry during 2015-16 in Pakistan (Fig. 8).

3.2.11. Carbon footprint, carbon stock, and net carbon flux of 1.0 m^3 particleboard

Now-a-days, climate change is a big issue and topic of debate for corporations, government organizations and individuals, to find ways to diminish those GHG emissions, which are escalating it significantly. Carbon dioxide is the major contributor to GHG emissions with a minor addition from methane and nitrous oxide. However, fluorinated gases are also contributed to GHG emissions but those gases are not included in our study. There are two possible ways to reduce GHG emissions, i.e. through carbon sequestration and sink so that it is not present in the atmosphere in the form of carbon dioxide, and by decreasing the fossil fuels consumption. Therefore, the concept of carbon flux has been introduced through the product's life cycle to measure the overall impacts of carbon dioxide on climate change as assessed by the sum of its carbon storage and carbon footprint (Wilson, 2010). Carbon is stored in trees, wood based products and fuel. During the growth phase of trees, they sequester carbon dioxide from the atmosphere to produce wood substance, which contained about half of carbon by weight, releasing oxygen back to the atmosphere (Garcia and Freire, 2014). This stored carbon is remains in the wood until it is burned or decomposed due to bacterial or chemical action. Therefore, carbon sequestration by wood make them one of the potential mean to fight against the global warming and climate change.

Therefore, the wood stored carbon was traced for the manufacture of particleboard in and out of the production process to find the balance for its carbon flow. Thus, this analysis tracked carbon from raw materials inputs through manufacture of final product, waste, co-products and generation of GHG emissions. The percent average value of carbon in wood was taken from the earlier CORRIM (Consortium for Research on Renewable Industrial Materials) life cycle inventory studies of particleboard, plywood, OSB and softwood lumber as 52.4% (Wilson, 2010; Wilson, 2008; Kline 2005; Milota et al., 2005; Wilson and Sakimoto, 2005; Puettmann et al., 2013; Kutnar and Hill, 2014), which provided life cycle inventory data for wood input supply. The wood inputs comprise of wood residues such as sawdust, plywood trim, chips, wood particles, shavings, sawdust and outputs of particleboard, wood fuel as well as emissions from wood (Wilson, 2008).

The carbon content in the wood of 1.0 m^3 of particleboard is 393 kg in Pakistan and, if carbon neutrality for wood is assumed, then 1.0 m^3 of particleboard stores 1441 kg of CO_2. In the estimation of carbon flux, the carbon stored in a wood based product is considered as negative carbon, which is deducted from the total carbon footprint of the product (Scenario II in Table 9). The CO_2e is calculated by the molar mass ratio of carbon dioxide to carbon of 44/12 for 3.67 times the wood carbon content (Wilson, 2010; Puettmann et al., 2013). Moreover, the secondary raw materials such as UF resin, urea scavenger and paraffin wax also store carbon but that are not accounted in the carbon flux, because they are acquired from fossil feedstock of natural gas or crude oil (Wilson, 2010, 2009). The reason for this exclusion was that it takes millions of years to renew the fossil feedstock carbon cycle. On the other hand, wood can renew its carbon cycle continuously and that is why only carbon flux values of wood are considered in this study. The service life of the particleboard can be 10-80 years, during which it holds store the carbon content present in it. Although, this storage of carbon in the particleboard can be further extended to additional 100 years if placed in modern landfill (Skog, 2008). Similarly, after the release of carbon dioxide to the atmosphere, it is again absorbed by the growing trees to produce more wood, thus renewing its carbon cycle constantly.

Carbon footprint is the sum of all the GHG emissions in terms of CO_2e from direct and indirect activities of a company, organization, product, process or even individual (Hussain et al., 2014). It comprises of carbon dioxide, methane, nitrous oxide and fluorinated gases emissions expressed in terms of CO_2e based on 100 years of radiative forcing potential of IPCC (IPCC, 2007). Figure 10 demonstrates the carbon footprint, carbon store and net carbon flux for 1.0 m^3 particleboard manufacture during 2015-16 in Pakistan. The total carbon footprint based on cradle to gate approach was equal to 975.282 kg CO_2e per m^3 of particleboard produced in 2015-16. Whereas, the carbon footprint of energy consumption (fossil fuels and purchased electricity) in stationary sources of the mill was 220 kg CO_2e per m^3 of particleboard produced. Therefore, it makes about 23% of the total cradle to gate emissions from particleboard industry in the studied period. On the other hand, wood combustion for energy recovery for dryer/boiler also emitted carbon dioxide to the atmosphere, however, its carbon footprint was not considered in the total carbon footprint of the particleboard production in the scenario-II of the present study as can be seen in Table 1, and it was considered neutral carbon because the CO_2 emitted during wood combustion are reabsorbed by the trees after its release back to atmosphere, assuming sustainable forest management in Pakistan. Thus, the carbon store (1441 kg CO_2e) in 1.0 m^3 of particleboard can be used to offset the carbon footprint (975.282 kg CO_2e), to estimate the net carbon flux, which was -564.04 kg CO_2e per m^3 of particleboard produced during 2015-16 (Fig. 10 and Table 9).

Therefore, this extra carbon store can be considered for offsetting the GHG emissions from the stages beyond the particleboard product cradle-to-gate such as product use, disposal, or recycling and even against the carbon dioxide present in the atmosphere. Thus, due to large carbon storage in particleboard product than its carbon footprint from its production chain and beyond, it is proved that particleboard is better than climate neutral material (in case of scenario-II in Table 9). Because, a climate neutral material is the one, which would have store carbon equal to its carbon footprint (Wilson, 2010; Puettmann et al., 2013). For atmospheric carbon dioxide reduction through wood, two out of the three strategies related with wood described by IPCC included the use of wood based products (IPCC,1996; Wilson, 2010).

Similarly, IPCC further stated that replacing the high-fuel-intensive products with the wood based products provide long term and permanent avoidance of fossil carbon emissions, whereas carbon storage in the woody biomass provide short term and temporary emissions avoidance. Thus, it is more effective and environmentally sustainable to use wood for products manufacture and to replace the fossil fuels-intensive products with the wood based products rather than storing the carbon in the woody biomass (Sharma and Wang 2010; IPCC 2001a, 2001b). So, these strategies of IPCC can be adopted and implemented from the particleboard production and use, because its manufacture consumed wood as a fuel, thus replacing significant quantity of fossil fuels consumption for energy requirements and displace fossil-intensive products as well. Because, the wood based products such as particleboard results in less GHG emissions to the environment as compared to the other competing products such as steel and metals based products and therefore, the wood based products as well as fuels have lower environmental impacts (Kutnar and Hill, 2014; Bergman et al., 2014).

The forest resources of Pakistan provide its people with wood to builds houses, materials for furniture and wood panels manufacturing and other domestic needs, and fuelwood. About 46% of energy needs are provided by biomass sources such as agricultural residues and fuelwood. 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 over exploitation (GOP, 2004). The annual raw material requirement for particleboard and fibreboard was estimated by the forestry sector master plan (FSMP) at 22,000 m^3 per year (EC-FAO Partnership Programme, 2002). To satisfy the wood requirement of Pakistan, about 532,000 m^3 of roundwood is imported each year. Inadequate measures have been taken by the forest departments to curtail illegal cutting and the scarcity of local woods species poses a serious threat to the furniture and wood panels industry in Pakistan (EC-TRTAP, 2007). However, forest management practices in Pakistan are under-developed 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 for both the furniture and particleboard industries in Pakistan. 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.

3.2.12. Wood and its better use; particleboard manufacture or biomass fuel

Particleboard is commonly manufactured from forest residues, small wood particles and sawdust, which have originated either from natural forests or dedicated irrigated and farmlands plantations, a renewable energy resource important for both environment and energy sector (Rivela et al., 2006). Biomass fuels are fulfilling about 14% of the global energy demand, from 1-3% in developed countries and about 43% in the developing and under developing countries (Koziski and Saade, 1998; Akinbami et al., 2003). Therefore, it is a dare need to maintain equilibrium between the natural resource consumption and their regeneration through effective, efficient and optimized process technology, products with long service life and an aptitude for recycling, refurbishing, repairing and ultimately incineration with energy recovery (Rivela et al., 2006; Lafleur and Fraanje, 1997). However, wood products reuse and recycling is good but the reprocessed wood has limited potential for further applications in manufacturing new products. In addition, to restore the physico-chemical properties of the reprocessed wood, more non-renewable energy and materials are required (Fraanje, 1997).

That is why; there is a growing concern about establishing a suitable multi-criteria approach while dealing with environmental planning and natural resource management, because both the areas have many contradictory interests. Therefore, environmental economic assessment and decision making issues are contradictory in nature and satisfaction of all the criteria's is very difficult. Thus, planning process become very complicated matter in terms of physical, technical, social and economic viewpoint (Gómez-Sal, 2003). To select the most suitable and appropriate use of wood materials, many basic steps must be considered such as description of availability of the wood materials and their properties, selection of suitable and optimized technology, assessment of potential market for the product manufactured, and evaluation of relative economics. Thus, the mosaic approach breakdown the sustainable development concept into three main parts; economic, ecological, and social sustainability (Smith and McDonald, 1998).

3.2.12.1. Economic sustainability

In Pakistan, most of the particleboard mills consumed virgin green wood harvested either from natural forests or farmlands plantations of the farmers. Therefore, to satisfy the wood requirement of the country, about 532,000 m^3 of round wood is also imported each year to fulfill the country's round wood demands. Whereas, all the wood wastes generated from the manufacture of particleboard such as sander dust, wood wastes produced during the final product sanding and trimming process are combusted in the dryers for energy purpose in the mill. Therefore, wood resources are consumed thoroughly in the particleboard manufacturing process and using and recycling of it for particleboard production is advantageous as compared to the biomass combustion for energy recovery (Rivela et al., 2006).

Similarly, one of the IPCC strategy is replacing high-fuel-intensive products with the wood based products provide long term and permanent avoidance of fossil carbon emissions (IPCC, 2001a). Thus, it is more effective, economical and environmentally sustainable to use wood for products manufacture and to replace the fossil fuels-intensive products with the wood based products rather than storing carbon in the standing woody biomass (Sharma and Wang 2010; IPCC 2001a, 2001b). So, this strategy of IPCC can be adopted and implemented in the particleboard production and use, because its manufacture consumed wood as a raw material as well as fuel, thus replacing significant quantity of fossil fuels consumption for energy requirements and displace costly and fossil fuels-intensive products. Furthermore, wood based products such as particleboard results in less GHG emissions to the environment as compared to the other competing products such as steel and metal based products and consequently, the wood based products and biofuels have lower environmental impacts (Kutnar and Hill, 2014; Bergman et al., 2015).

3.2.12.2. Ecological sustainability

Ecological sustainability of the particleboard manufacture can be evaluated and assessed from comparing the particleboard with other competing materials and from biomass fuels with other energy sources. Petersen and Solberg, 2005 reported that wood based products had less contribution to the impacts in global warming, if they were not disposed of after usage. In addition, energy consumption, wastes generation, toxic emissions of SO_2, CO, VOCs, and use of non-renewable resources showed least contribution to environmental burdens from particleboard manufacture as compared to other products (Rivela et al., 2006). However, previous studies also showed highly variable emissions from wood combustion, which was depended on many factors such as combustion conditions, fuels and machineries (McDonald et al., 2000). Because, complete combustion of wood is difficult to attain, thus, incomplete combustion generated several by-products comprising particulate matter (PM) and polycyclic aromatic hydrocarbon (PAHs) (Kralovec et al., 2000). In addition, some fraction of extremely hazardous substances i.e. polychlorinated dibenzofurans (PCDFs), coplanar polychlorinated biphenyl (PCBs), and polychlorinated dibenzodioxins (PCDDs) were also released into the air (Yasuhara et al., 2003).

Environmental impacts of 1.0 TJ heat produced by wood combustion and 1.0 TJ heat produced by natural gas was characterized using eco-indicator 99 methodology (Rivela et al., 2006). The results indicated that the energy acquired from natural gas seems to be favorable for some of the environmental impacts such as eco-toxicity, acidification, respiratory inorganics, and eutrophication. Whereas, the damage to ecosystem quality and human health was highly significant using wood as a fuel, however, natural gas caused more damage to resources depletion. The authors also confirmed that production of particleboard triggered less depletion of natural resources as compared with combustion of wood wastes in a coal power plant (Cornelissen and Hirs, 2002; Rivela et al., 2006).

3.2.12.3. Social sustainability

It is an urgent need to evaluate and assess the forest and agriculture dependent communities that how they are utilizing their natural resources and what is their natural resources long-run sustainability. Because, it is essential to enhance the understanding of mechanism of people's dependence, interaction with and utilization of their local environment for existence. Similarly, sustainable livelihood is also associated with capabilities, material and social resources and accomplishments needed for survival (Petersen and Sandhovel, 2001). The forestry and associated wood based industries in Pakistan employed about five million workers and its contribution to the total GDP of the country was 8.4% in the year 2004-2005 (ww.boi.gov.pk). Therefore, composite wood products such as particleboard manufacture are playing a vital role in the rural development, employment and livelihood of the forest dependent community of Pakistan.

3.2.13. Emissions-cutting measures

The major emissions sources ("hotspots") in the carbon footprint of particleboard manufactured in Pakistan are the UF resin 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 particleboard in Pakistan, whereas, only 68, 72 and 68 kg of UF resin per m^3 was used by USA, Brazilian, and Spanish manufacturers, respectively (Puettmann et al., 2013; Silva et al., 2013; Rivela et al., 2006). The large quantity of urea-formaldehyde 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, removal of bark from the furnish could decrease the quantity of UF resin required and could provide a potentially carbon neutral fuel for mill processes. These could combine to greatly reduce the carbon footprint of the particleboard product. Similarly, the reduction in freight mileage of the transport of the particleboard mills could be achieved by producing the raw and secondary materials in areas close to the mills, and by diverting mill freight onto highways. Currently drivers use inefficient local roads because tolls are imposed on high mobility freight highways.

The main differences with respect to particleboard production in Pakistan and other countries are the sources of wood materials and fossil fuels consumed. With respect to fossil fuels, studies in other countries reported consumption of natural gas, whereas particleboard mills in Pakistan also used heavy fuel oil, which has a greater carbon footprint. Wood fuel use in the particleboard manufacturing process can be an important renewable fuel source that substitutes for fossil fuels and thus improves the environmental profile of the final product (Wilson, 2010). For example, Kouchaki-Penchah et al. (2016) reported the use of sander dust in the Iranian particleboard manufacturing plant and showed significant reduction in the environmental impacts. Therefore, alternative renewable energies should be encouraged to avoid GHG emissions by substituting fossil energy (Jungmeier et al., 2002b; Rivela et al., 2006). However, all the wood wastes and sander dust generated during the manufacture of particleboard in Pakistan are already being used internally and are thus not available to fulfill the demand for additional bio-energy.

Wood residues from forest operations and sawmills and agri-industrial residues (bagasse from sugarcane industry) are the main source of raw materials to manufacture particleboard in the USA, Europe and Brazil (Wilson, 2010; Puettmann et al., 2013; Rivela et al., 2006; Silva et al., 2013, 2014; Santos et al., 2014). But in Pakistan the wood materials (in the form of roundwood) are obtained mostly directly from the forests and farmlands plantations of the farmers. The use of sawmill and agri-industrial residues such as sawdust and baggase were not reported from any of the factories surveyed. Therefore, wood residues from the forest operations and sawmills and baggase residues from the agri-industry are potential materials for the particleboard production in Pakistan. Since, wood residues are more sustainable than other raw materials (Rivela et al., 2006; Silva et al., 2015), higher the residues use in the manufacture of particleboard could reduce the carbon footprint. Therefore, due to the general deficiency of woody biomass for fuel and raw materials in Pakistan, more work is needed to identify opportunities for improving the particleboard manufacturing process.

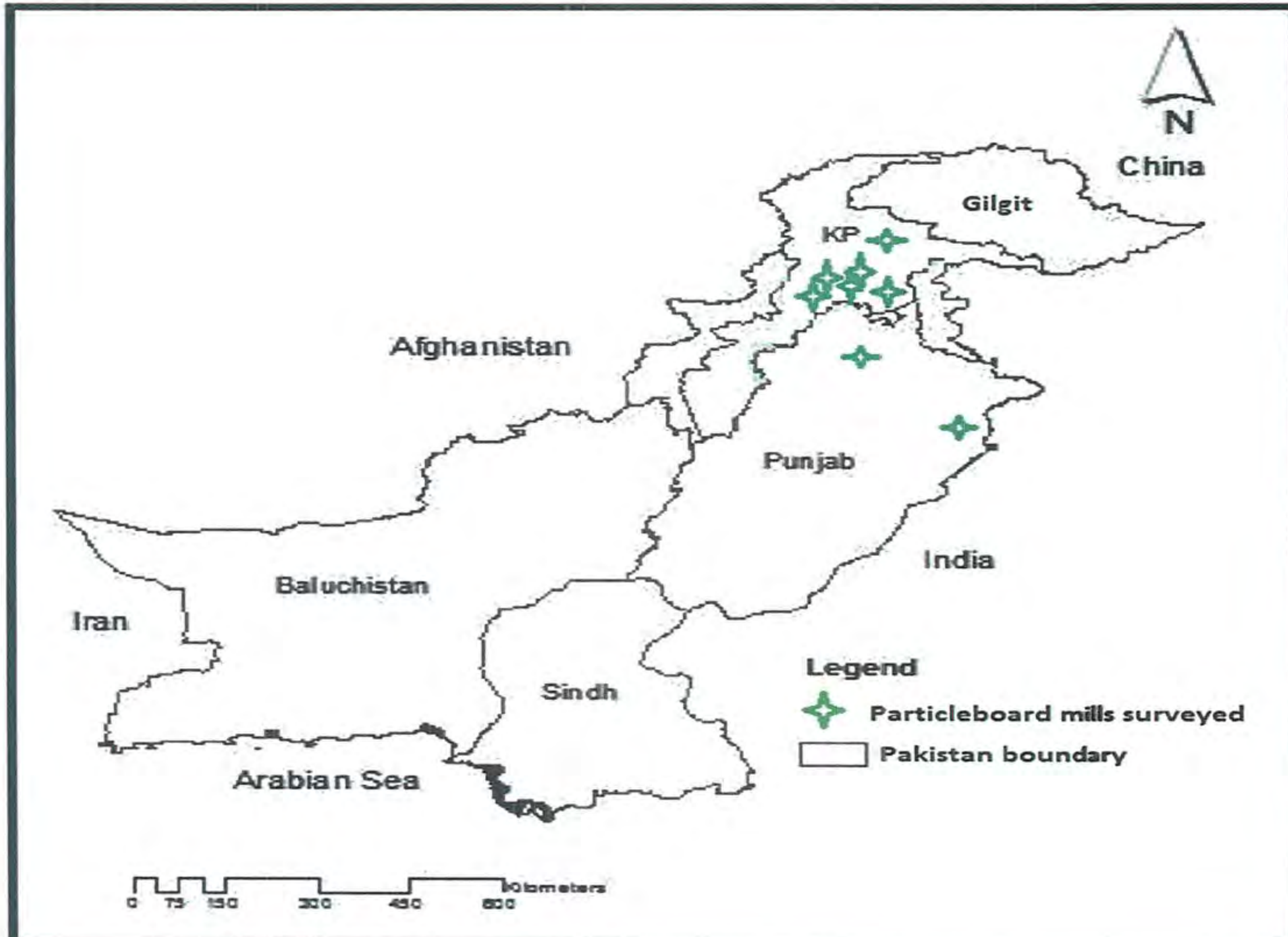

Fig. 1: Location map of the surveyed particleboard mills.

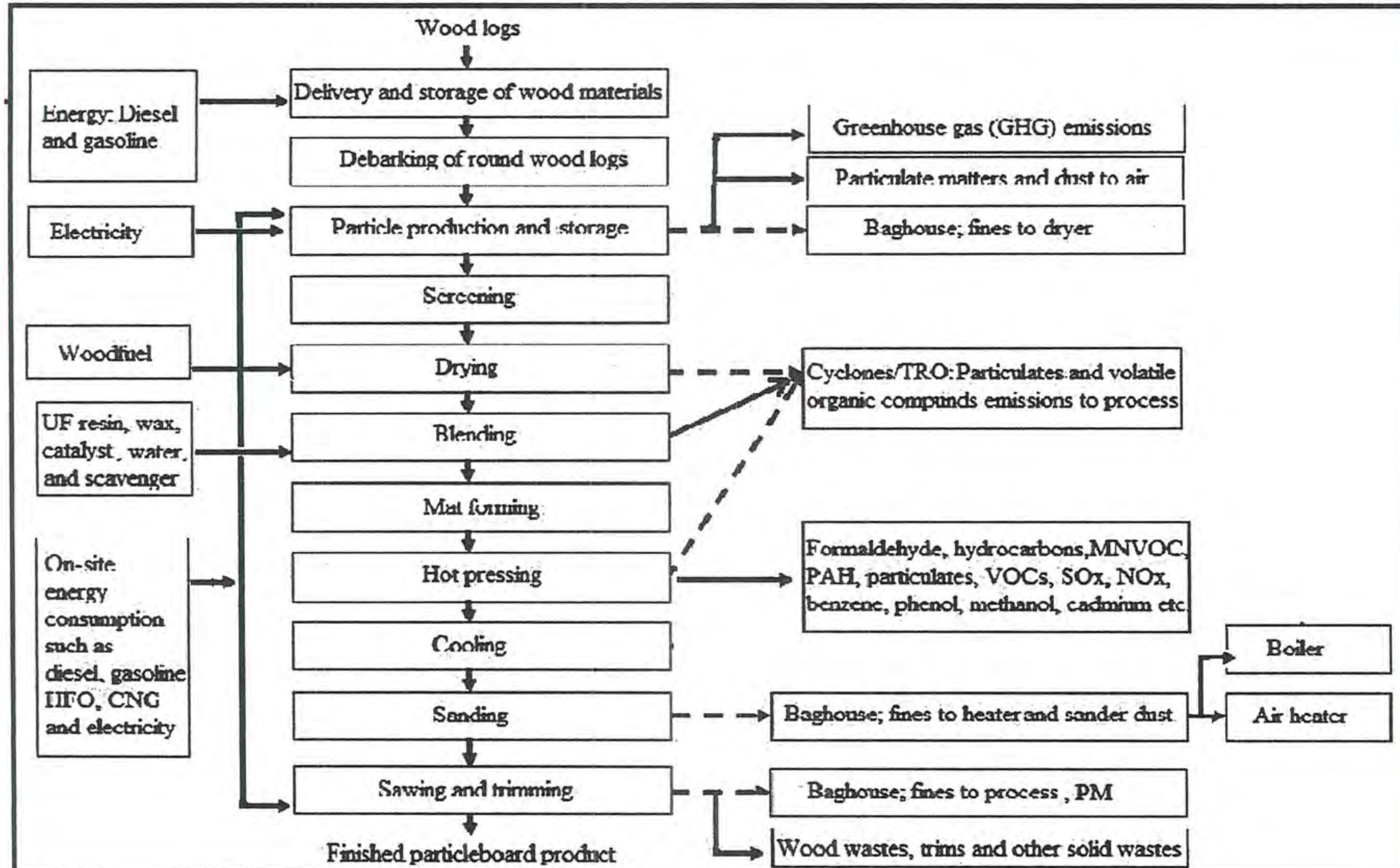

Fig. 2: Flow sheet diagram of a typical particleboard manufacturing process.

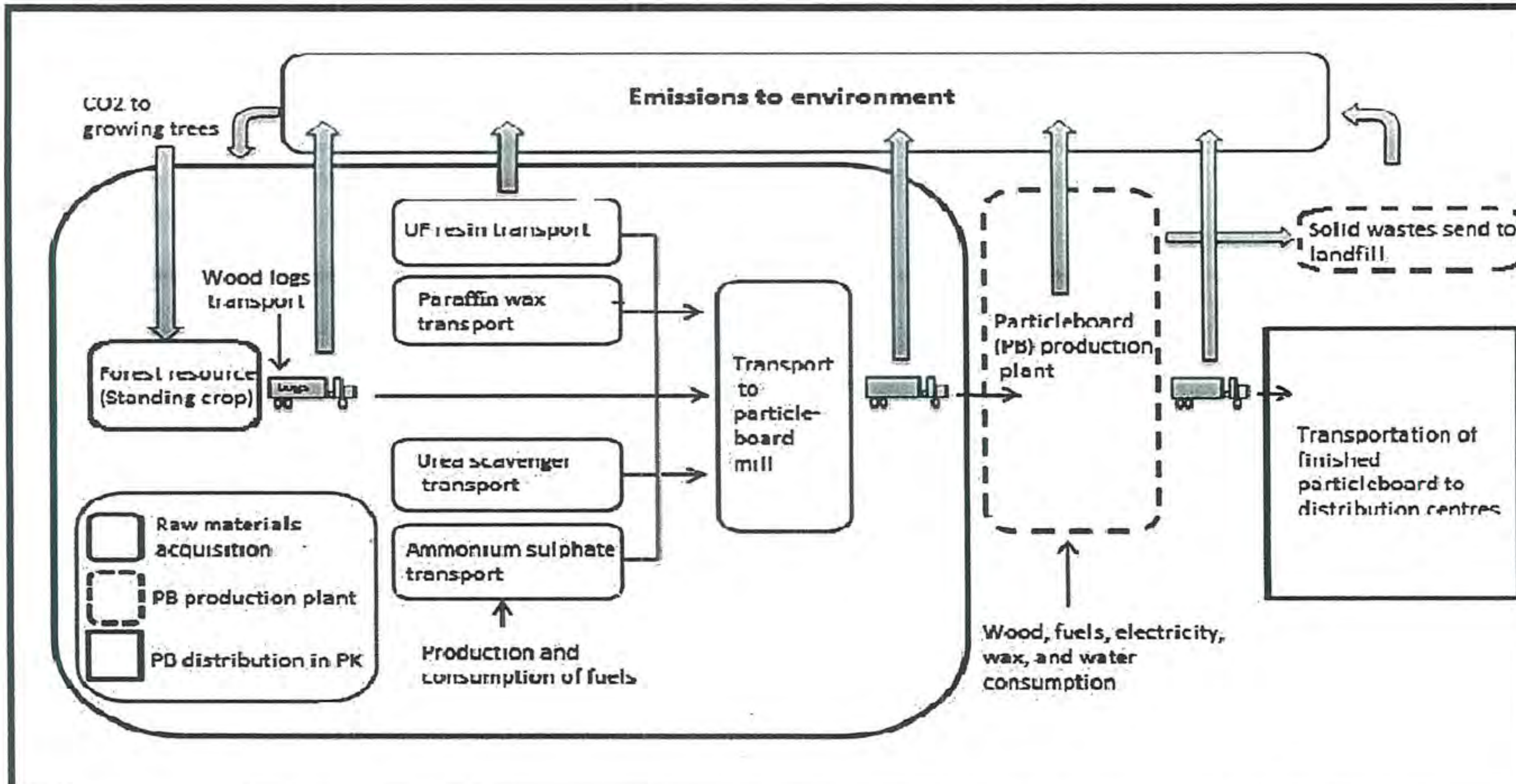

Fig. 3: System boundary of the particleboard (PB) manufacturing life cycle model, cradle-to-gate (distribution center) perspective.

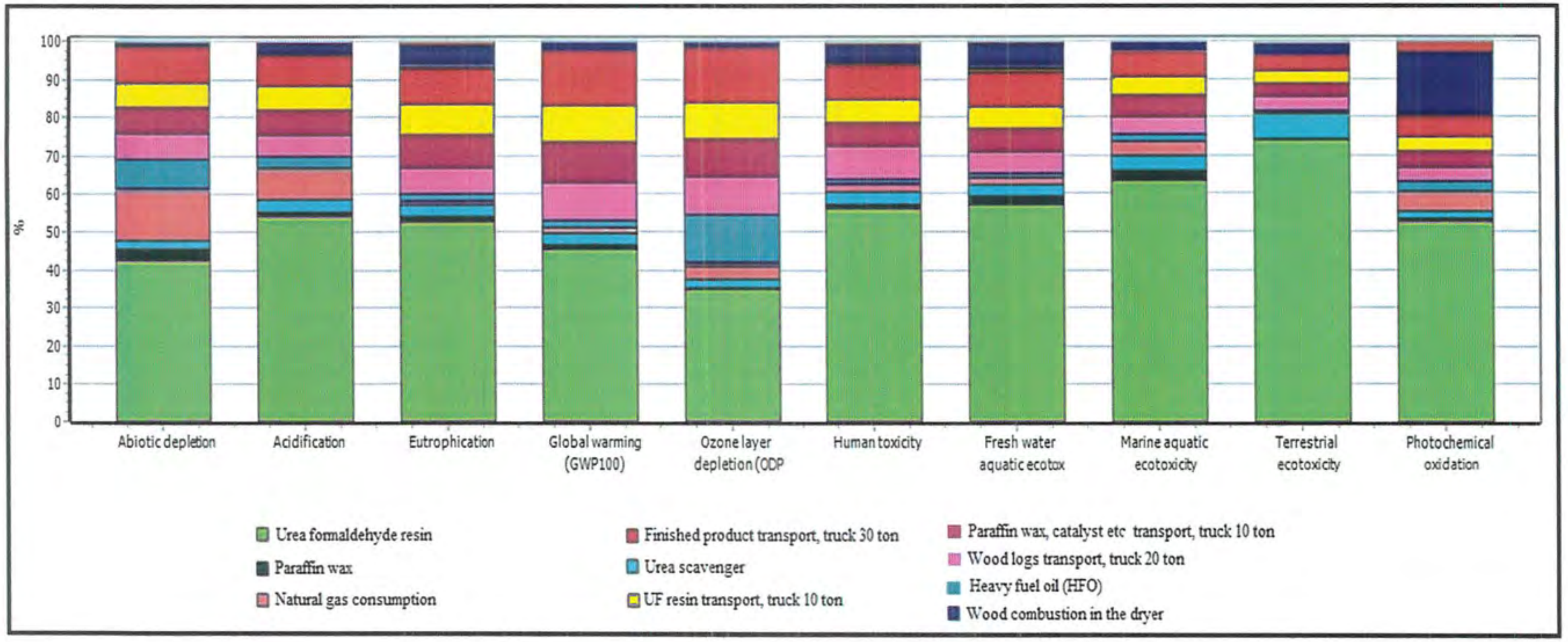

Figure 5: Relative contribution per process (in %) to various environmental impacts.

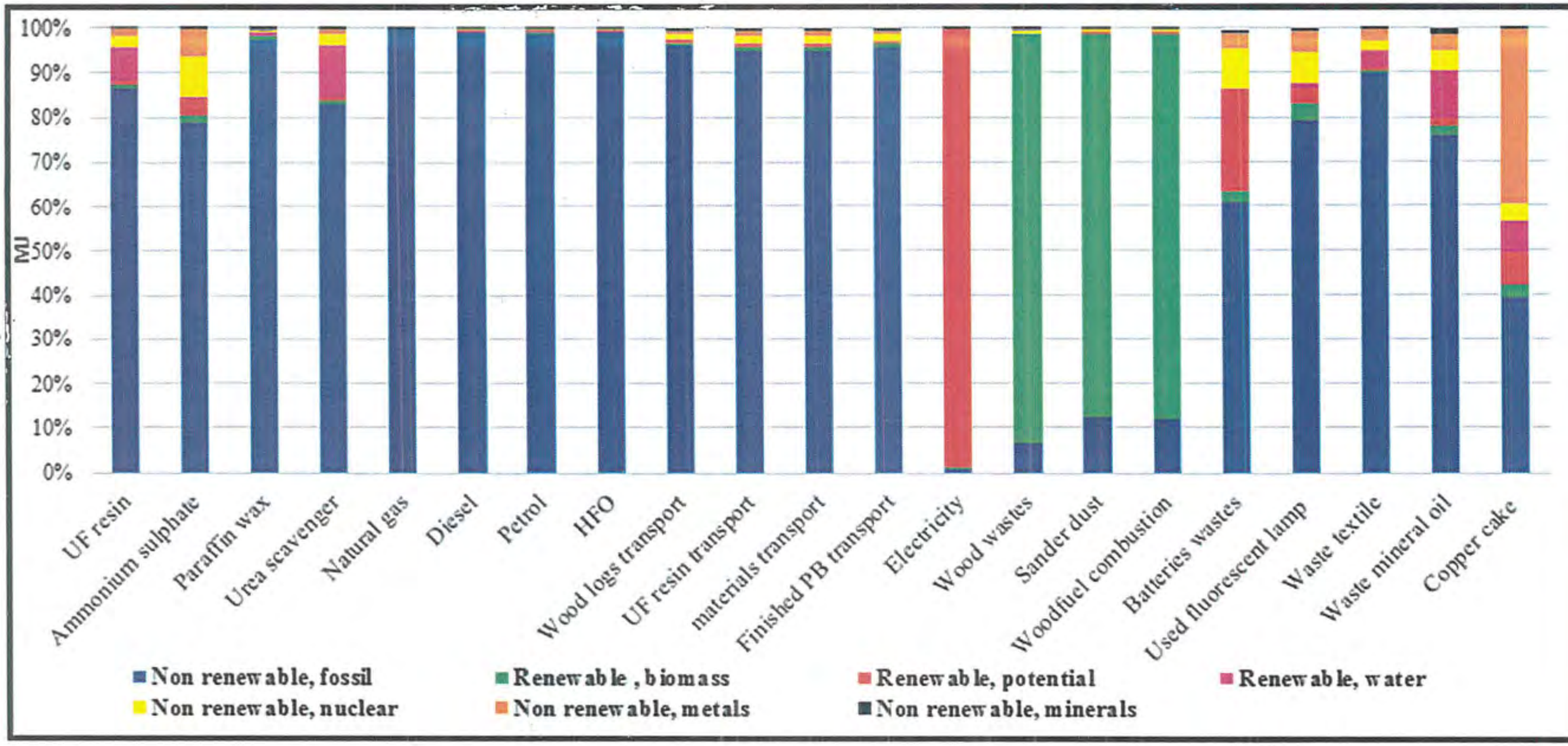

Fig. 6: Energy consumption by single score calculated through cumulative exergy demand (CExD) indicator.

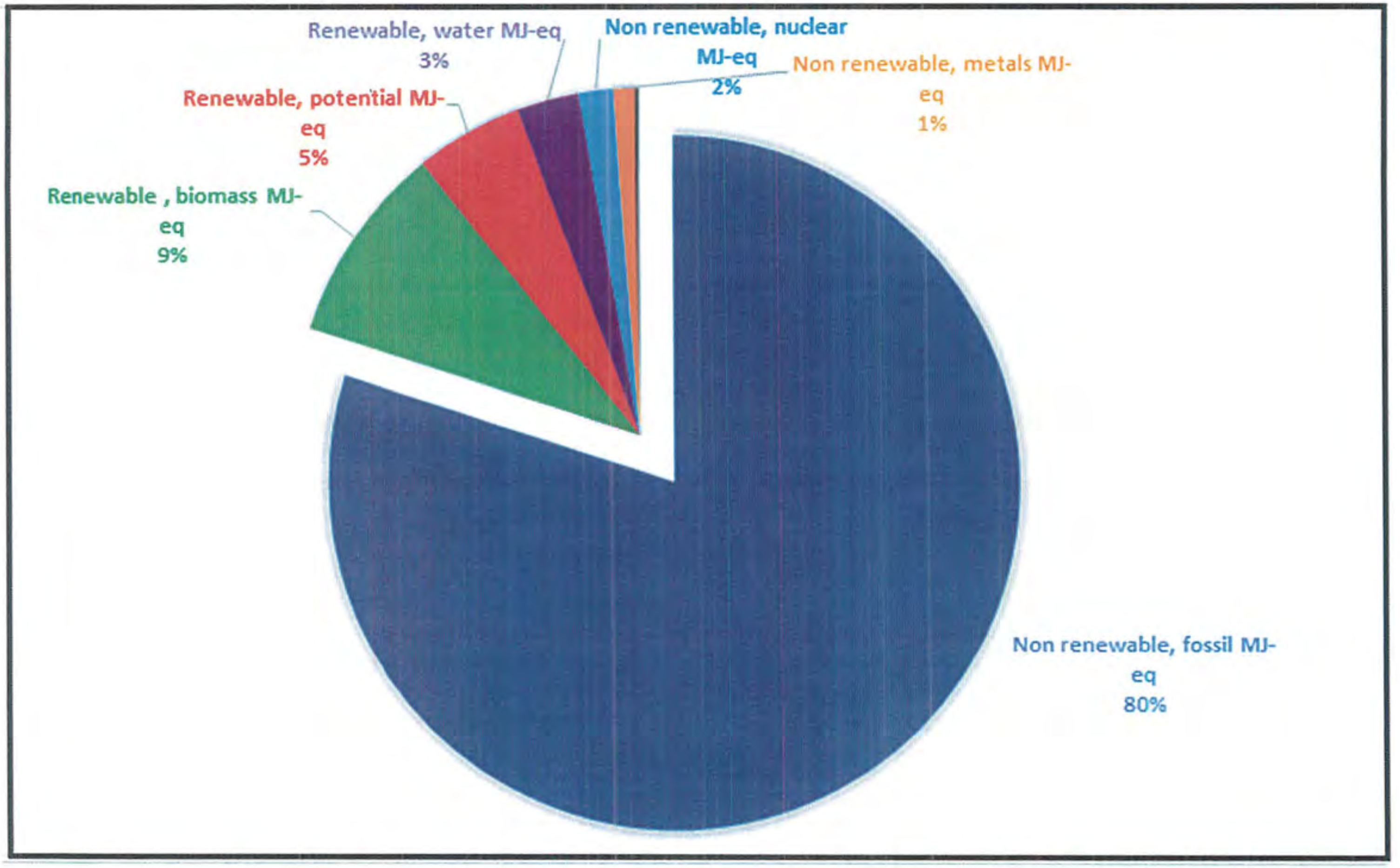

Fig. 7: Relative percent contribution of each subcategory to total cumulative exergy demand.

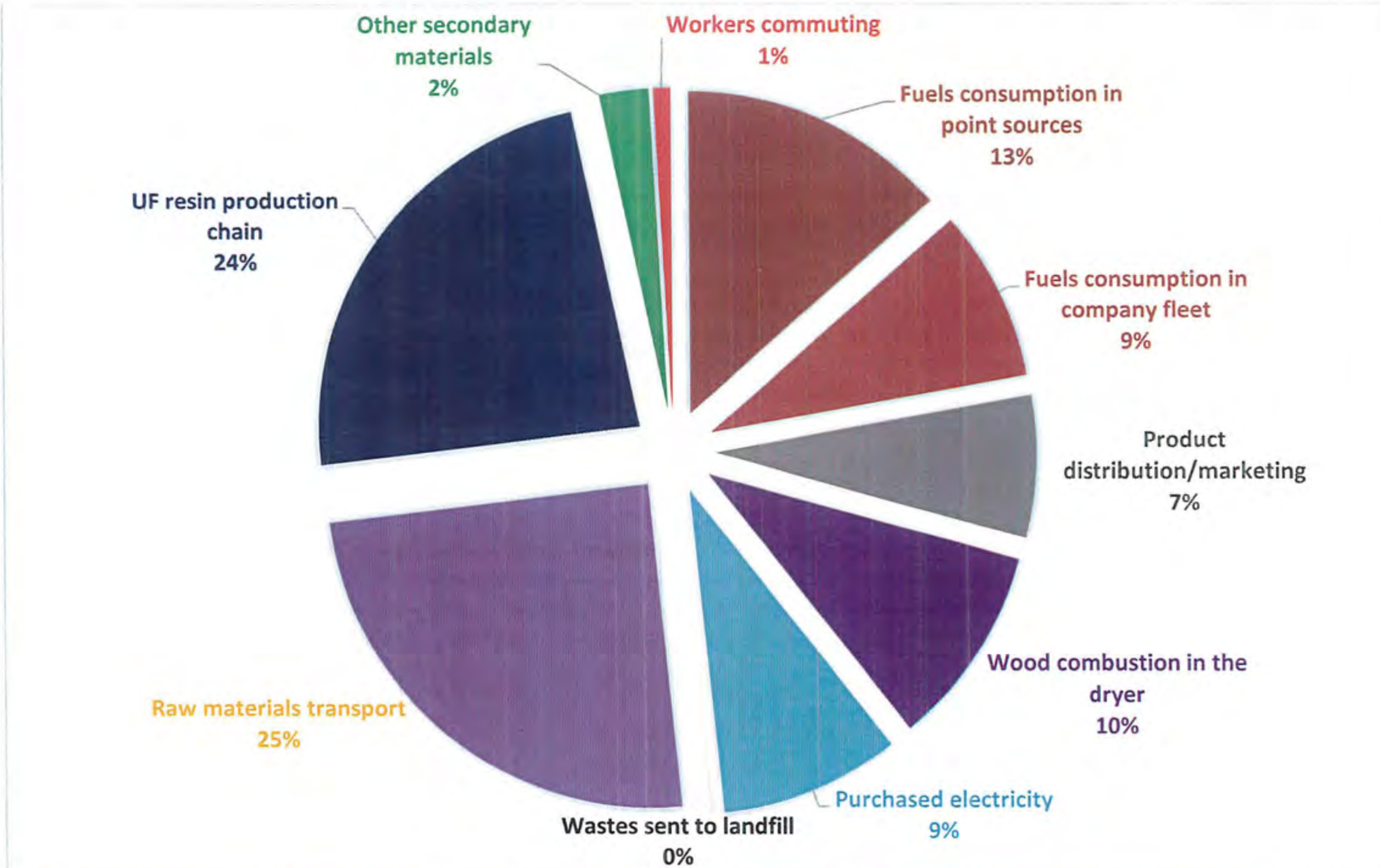

Fig. 8: GHG emissions by detailed sources from per 1.0 m^3 particleboard produced in 2015-16.

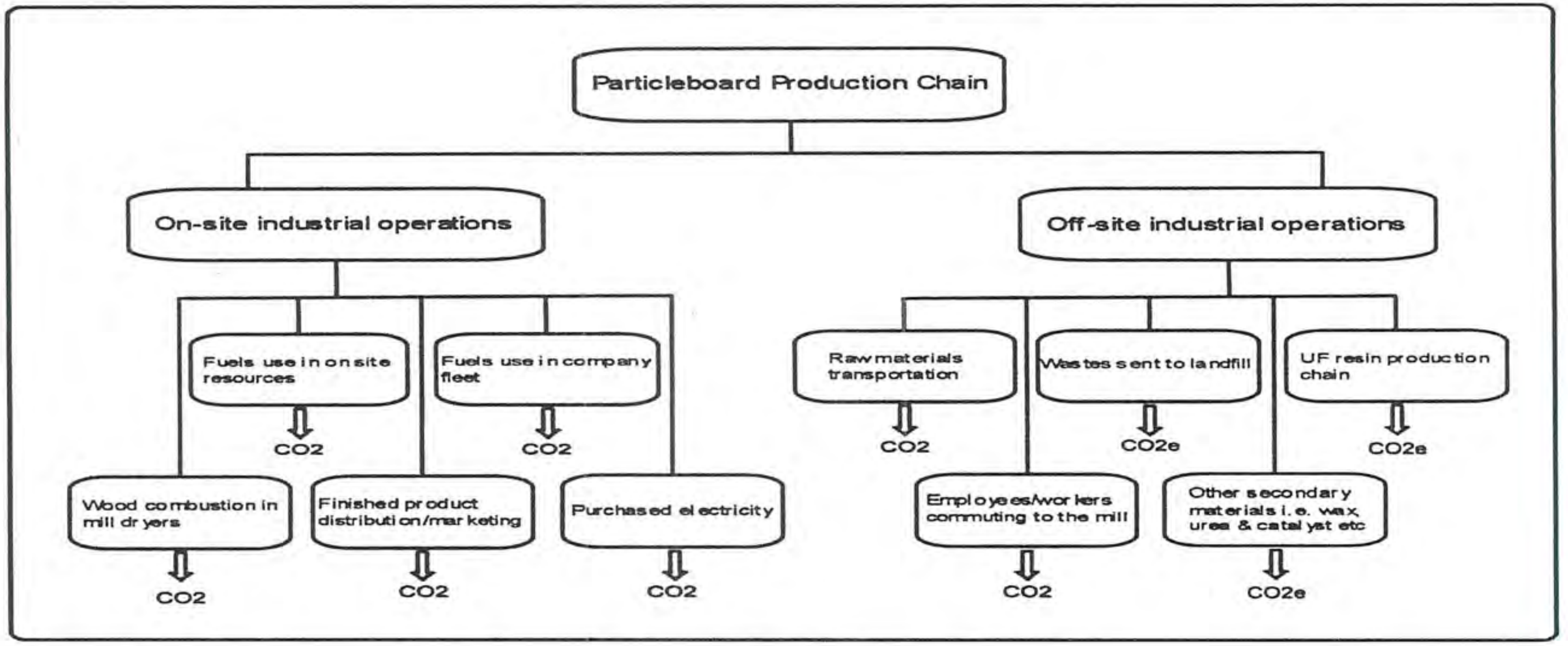

Fig 9. GHG emissions sources in particleboard production chain in Pakistan.

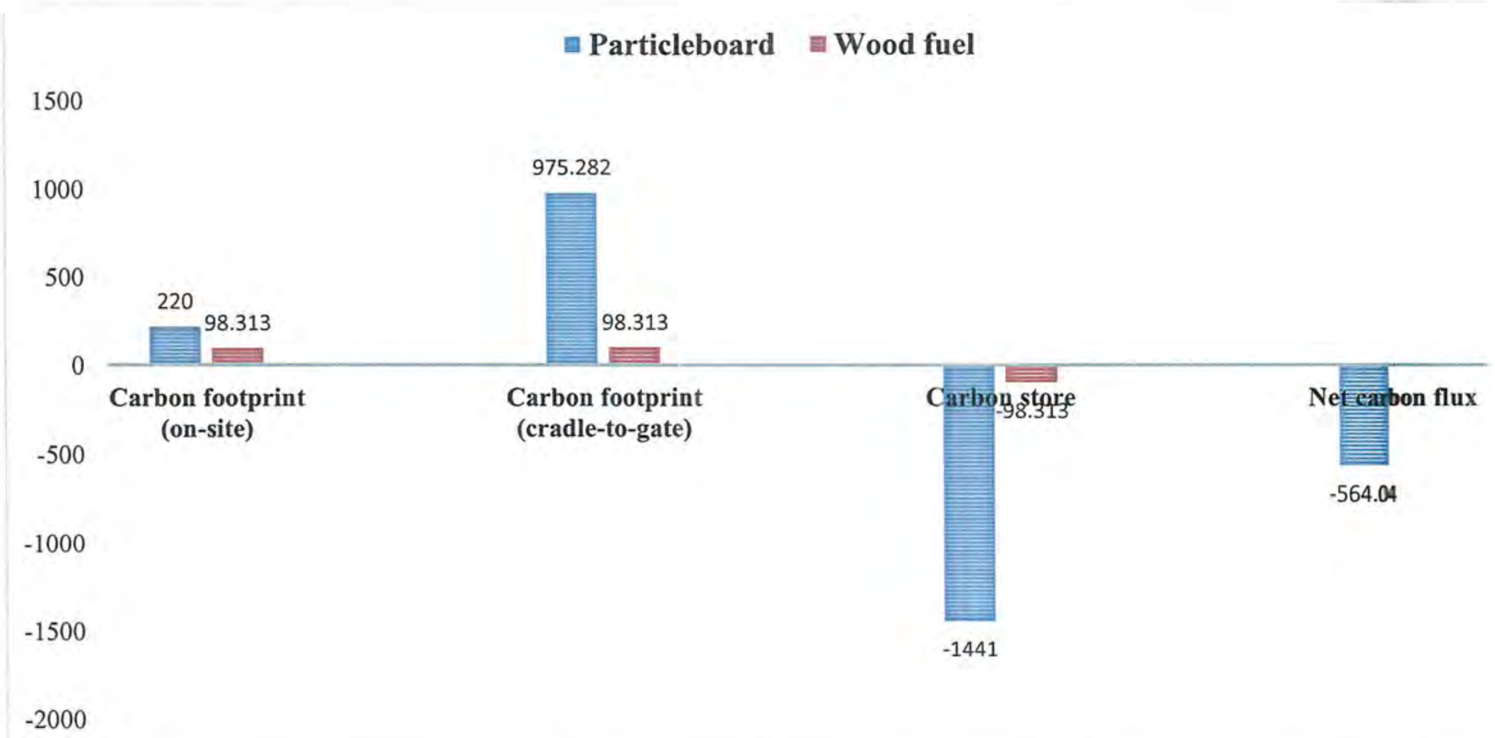

Fig.10: The carbon footprint, carbon stock, and net carbon flux in $kgCO_2e$ of 1.0 m^3 particleboard produced (Scenario-II).

Table 1: Life cycle inventory of inputs/outputs to produce 1.0 m^3 of particleboard in Pakistan during 2015-16.

Products	Value	Unit/m^3	Weighted Co-efficient of Variation (CVw)
Particleboard	1	m^3	
Material resources and fuels			
Ground water	1.30E+01	L	60.69%
Municipal water	5.00E+00	L	38.65%
Wood logs, average Pak. 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 sulphate, 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/logs 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 sulphate 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%
NO_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 and cardboards etc.	1.51E-02	kg	46.62%
Toner	1.33E-03	kg	84.47%

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 um	Air	g	370.74	Flakers, hammer mill, rotary dryers, sander dust
Particulates, > 10 um	Air	g	547.85	Flakers, hammer mill, rotary dryers, sander dust

Particulates, > 2.5 um, and < 10um	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

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

Impact category	Measurement unit	Baseline Scenario-I impacts	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 SO2 eq	3.343	3.124	7	2.907	14
Eutrophication potential (EP)	kg PO4- eq	0.610	0.560	8	0.511	16
Global warming potential (GWP100)	kg CO2 eq	552.000	490.624	11	430.033	22
Ozone layer depletion (OLD)	kg CFC-11 eq	0.0001	0.00009	10	0.00007	30
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	256717.37	242982.00	5	229388.81	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

*Baseline scenario-I represent the results of the present study.

Table 4: Comparative analysis of resource inputs and carbon emissions, storage and net carbon flux for 1.0 m^3 particleboard manufacturing in Pakistan and world.

Name of country	Wood residues (kg)	UF resin (kg)	Paraffin Wax (kg)	Ammonium sulphate as a catalyst (kg)	Urea-scavenger (kg)	Sander dust (kg)	Wood fuel (kg)	Electricity (kWh)	Natural gas (m^3)	Diesel (L)	Petrol (L)	HFO (L)	LPG (L)	Water (L)	Carbon Footprint (kg CO_2e)	Carbon store (kgCO_2)	Net carbon flux (kgCO_2)	References
LCA of PB manufacture in USA	672	68	2.5	0.72	2.9	25	2.1	157	30	0.26	0.021	NA	0.33	304	392	-1290	-898	Wilson, 2010
LCA of PB manufacture in USA	703	68	2.5	0.72	2.9	25	2	158	30	0.32	0.021	NA	0.33	304	376	-1289	-913	Puettmann et al., 2013
LCA of MDP in Brazil	725	72	5.47	1.38	NA	NA	NA	141	NA	1.7	NA	13.7	NA	175	NA	NA	NA	Silva et al., 2013
LCA of PB manufacture in Spain	666	67.94	2.13	0.74	NA	NA	NA	105	NA	NA	NA	NA	NA	19.69	NA	NA	NA	Rivela et al., 2006
LCA of PB manufacture in Iran	1360	80	2.5	0.5	0.2	41	48	159	83	61 (MJ)	NA	NA	NA	180	NA	NA	NA	Kouchaki-Penchah et al., 2016
*LCA of PB manufacture from bagasse in Brazil (m^2)	27	1.5	0.15	0.023	NA	NA	NA	93.11	NA	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)	35.41	1.5	0.15	0.023	NA	NA	NA	68.65	NA	157	NA	NA	NA	0.0745	NA	NA	NA	Santos et al., 2014
LCI of PB production in Australia	721	65	9.85	NA	NA	NA	1549 (MJ)	145.61	722 (MJ)	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	601	27	1	2.4	24	NA	6507MJ	481 (MJ)	NA	NA	NA	NA	NA	7311	407.6	-1039	-631.7	Vertima and Ellio, 2016
LCA of particleboard industry in Pakistan	**775**	**93**	**6.48**	**1.67**	**05**	**29**	**06**	**183**	**41**	**1.15**	**0.71**	**18.3**	NA	**18**	**975.28**	**1441**	**(-564.04)**	**Present study**

*NA = Data not available in the literature
**Santos et al., 2014, applied m^2 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 (kgCO2e)	AP (kg SO2 eq)	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 USA	375.67	215.47	0.1299	37.44	0.97	*NA	NA	NA	NA	NA	Puettmann et al., 2013
LCA of particleboard production in Brazil	333.28	2.4	0.132	0.28	0.98	82.8	NA	6.71E-07	NA	NA	Silva et al., 2013
LCA of particleboard production in Spain	0.33	6	6	NA	225.1	115.1	NA	32	NA	NA	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	81951.11	32.19	Kouchaki-Penchah et al., 2016
LCA of particleboard manufacture from bagasse (1.0 m^2)**	74.42	42.22	81.42	24.76	2692	NA	NA	7800000	NA	NA	Santos et al., 2014
LCA of particleboard manufacture from pine wood shavings (1.0 m^2)**	168.06	95.24	183.68	25.71	3984.7	NA	NA	7847000	NA	NA	Santos et al., 2014
LCA of NU green soya particleboard in Canada	440	1.54	0.96	25.7 (kg O3eq)	NA	NA	3.2E-05	NA	NA	NA	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	NA	Silva et al., 2014

*NA = Data not available in the literature
**Santos et al., 2014, applied m^2 functional unit for their LCA study of PB only

Note: 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

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)	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 SO2 eq	3.343	2.897	13
Eutrophication potential (EP)	kg PO4- eq	0.610	0.530	13
Global warming potential (GWP100)	kg CO2 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	256717.37	216322.738	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

*Baseline scenario-I represent the results of the present study.

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	1,455.38	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 sulphate
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 modelling 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 100kW | 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 30kW | 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

Table 9: Energy use and GHG emissions from production chain of 1.0 m^3 particleboard manufactured during 2015-16 with and without carbon neutrality assumption.

GHG emissions sources	Unit/m^3	Amount or distance travelled/m^3	Energy in GJ/m^3	Baseline scenario-I without carbon neutrality assumption (GHG emissions (kg CO_2e/m^3)	Scenario-II-Assuming biogenic carbon neutrality (GHG emissions (kg CO_2e/m^3)
Total of on-site energy consumption and GHG emissions			**5.4575**	**471.802**	**373.48**
1.GHG emissions from fossil fuels used in stationary sources			**2.2831**	**132.08**	**132.08**
a. Diesel fuel	tonne	0.000983	0.0436	3.268	3.268
b. Petrol/gasoline fuel	tonne	0.000537	0.0241	1.659	1.659
c. Natural gas	1000m^3	0.04	1.5604	78.02	78.02
d. Heavy fuel oil	tonne	0.0163	0.6551	49.132	49.132
2. GHG emissions from fossil fuels burned by company owned vehicles fleet			**1.6378**	**83.555**	**83.555**
a. Diesel fuel	tonne	0.000923	0.0409	3.06	3.06
b. Petrol/gasoline fuel	tonne	0.000204	0.0091	0.633	0.633
c. Natural gas	1000m^3	0.0407	1.5877	79.861	79.861
3. GHG emissions from particleboard product distribution/marketing					
a. Transportation of finished product by large truck/trailer (one-way haul)	tonne·km	**847**	**0**	**69.454**	**69.454**
4. GHG emissions from wood combustion in the dryers			**0.8778**	**98.313**	0
a. Wood fuel	kg	6	0.1254	14.044	0
b. Sander dust	kg	29	0.6061	67.883	0
c. Wood waste	kg	7	0.1463	16.385	0
5. GHG emissions from purchased electricity obtained from national grid	**kWh**	**183**	**0.6588**	**88.4**	**88.4**
Total of off-site energy consumption and GHG emissions			**2.73**	**503.48**	**503.48**
1. GHG emissions from wastes sent to landfill (unspecified)	**kg**	**0.1103**	0	**0.1893**	**0.1893**
a. Paper and cardboard waste	kg	0.0151	0	0.0362	0.0362
b. Rubber wastes	kg	0.0517	0	0.1209	0.1209
c. Textiles (wiping clothes) waste	kg	0.0072	0	0.0103	0.0103
d. Others wastes (toners, batteries, filters and solvents etc.)	kg	0.0363	0	0.0217	0.0217

2. GHG emissions from raw material transport	**tonne·km**	**552**	0	**240.552**	**240.552**
a. Transportation of wood logs by medium truck		336	0	112.896	112.896
b. Transportation of UF resin by small truck	tonne·km	113	0	66.783	66.783
c. Transportation of wax, ammonium sulphate etc. by small truck	tonne·km	103	0	60.873	60.873
3. GHG emissions from UF resin production chain*	**kg**	**93**	**2.73**	**230.08**	**230.08**
4. GHG emissions from other secondary materials**				**24.35**	**24.35**
a. Urea scavenger	kg	5	0	16.27	16.27
b. Paraffin wax	kg	6.48	0	4.83	4.83
c. Ammonium sulphate	kg	1.67	0	3.25	3.25
5. GHG emissions from employee's commuting	passenger·km	44	0	**8.316**	**8.316**
Grand total of energy consumption and associated GHG emissions from 1.0 m^3 particleboard production			**8.187**	**975.282**	**876.96**
Carbon dioxide equivalents (CO2e) store by 1.0 m3 particleboard produced					**-1441**
Net carbon flux for 1.0 m3 particleboard production in Pakistan assuming biogenic carbon neutrality					**-564.04**

Source: Estimates are based on data obtained from field surveys conducted in the particleboard mills of Pakistan and peer-reviewed published literature.
* GHG emissions from UF resin production chain was derived from Wilson, 2009 CORRIM report-phase II, Module H, based on SimaPro database for U.S
** GHG emissions from other secondary materials such as urea scavenger, paraffin wax and ammonium sulphate was calculated by IPCC 2013 GWP 100-year V.1.00 method in SimaPro 8.2 software based on Ecoinvent 3.0 database.

CHAPTER # 4

CONCLUSIONS
AND
RECOMMENDATIONS

CHAPTER # 4

THESIS CONCLUSIONS AND RECOMMENDATIONS

4.1. Thesis conclusions

Sustainability and green thinking has got enormous importance in the wood industry over the past decade. Manufacture of wood based materials and their associated environmental burdens contribute to the overall environmental performance of the final product. The life cycle assessment concept provides the framework for the compilation of relevant and representative data for products or services within a defined system boundary. The LCA values are the fundamental information for the development of environmental product declarations (EPDs). EPDs offer concise and relevant information for the comparison of competing products. Therefore, Chapter 1 introduces the characteristics of wood as a renewable and biological material, particleboard industry in Pakistan, life cycle assessment and global overview of the life cycle assessment of particleboard produced in the world. Because, the present study deals with the cradle-to-gate (distribution center) life cycle assessment of 1.0 m^3 particleboard manufactured in Pakistan. The carbon footprint based on cradle-to-gate LCA approach was also conducted for the manufacture of 1.0 m^3 of particleboard produced during 2015-16 in Pakistan. High quality data is a pre-requisite to get a scientifically reliable assessment. Therefore, in the present study, life cycle inventory data of particleboard manufacture comprised of production weighted average data acquired from eight particleboard manufacturing mills in Pakistan. The study covers environmental impacts from the resource inputs and outputs such as wood logs, fuels, catalyst, resin, paraffin wax, wastes, and electricity through raw inputs transport, particleboard manufacture and final distribution and marketing. Therefore, the present study objectives were to develop a comprehensive LCA of particleboard produced in Pakistan during 2015-2016, to assess the environmental burdens posed by particleboard production and to assess improvement opportunities by measuring and comparing alternative production scenarios for particleboard manufactured in Pakistan.

Chapter 2 presents the life cycle inventory of eight particleboard mills in Pakistan. The system boundary comprised of raw materials acquisition, transport, particleboard manufacture and finished product distribution. The reference unit applied in this study was 1 m^3 uncoated finished particleboard produced during 2015-2016. The primary data was collected through questionnaire surveys, personal meetings with the particleboard manufacturers. Whereas, some of the secondary data was also taken from published literature and CORRIM studies. This study follows the ISO, CORRIM, and WBSCD GHG protocol and guidelines for national greenhouse gas inventory. To identify the main hotspots and characterize the production process, ten environmental impact categories and cumulative exergy demand (CExD) indicator with different subcategories were assessed. Similarly, chapter 3 presents the life cycle impacts assessment of the 1 m^3 particleboard produced in Pakistan during the year 2015-2016. The environmental impacts assessment was performed by SimaPro version 8.3 environmental modeling software. The results showed that UF resin production and transport of raw materials and finished particleboard 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 eco-toxicity impacts. The total cumulative exergy demand required for manufacturing of 1.0 m^3 particleboard was equal to 15,632 megajoule-equivalent (MJ-eq) from the seven impact categories i.e. non-renewable fossil, non-renewable nuclear, non-renewable metals, non-renewable minerals, renewable water, renewable potential, and renewable biomass. Among the seven impact categories, non-renewable fossil sources had the highest contribution i.e. 12,504 MJ-eq to the total exergy removed from the nature to manufacture 1.0 m^3 particleboard. Similarly, renewable biomass was the second largest source with contribution of 1,455 MJ-eq exergies, whereas non-renewable minerals were responsible for only 25.40 MJ-eq in the total exergy required for 1.0 m^3 particleboard manufacture.

GHG emissions from off-site sources of the particleboard industry represented the highest emissions of 52% to the total emissions from production chain of 0.1 m^3 of particleboard industry in Pakistan. This was due to the energy consumption in mobile sources, transport of primary and secondary raw materials and finished product distribution and marketing and workers commuting. Thus, the off-site sources caused indirect emissions which are due to the consequence of particleboard industry activities, but arise from the sources that are owned or controlled by others. Whereas, the on-site sources resulted in 48% emissions to the total emissions from 1.0 m^3 particleboard production chain during the year 2015-16. However in this category, emissions from wood combustion in the dryer do not contribute to global warming and was excluded from the total carbon footprint in the scenario-II assuming biogenic carbon neutral at particleboard production in Pakistan. The embodied energy for the manufacture of 1.0 m^3 of particleboard comprises of fossil fuels and purchased electricity consumed in stationary sources of the mill. The energy consumption in stationary sources of the particleboard mill was 5.457 GJ per m^3 of particleboard production, whereas the total energy consumption in cradle-to-gate life cycle of the 1.0 m^3 particleboard production was 8.187 GJ during 2015-16. Wood combustion provided 0.8778 GJ energy per m^3 of particleboard manufactured. The wood fuel use was highly recommended because it is a renewable and sustainable climate change neutral fuel, which displaces the fossil fuel, a non-renewable fuel. The wood materials used in the manufacture of particleboard can store and embodied carbon, which can be utilized to offset the carbon dioxide emissions from production chain of the particleboard mill as well as from product use and disposal, if assuming forest management practices on sustainable basis.

Therefore, to manufacture 1.0 m^3 of particleboard, the carbon storage was equal to -1441 kg CO_2e, which can offset the cradle-to-gate carbon footprint (975.282 kg CO_2e) of per m^3 particleboard produced during 2015-16 in Pakistan. This also leaves a net carbon flux of -564.04 kg CO_2e per m^3 particleboard manufacture as a carbon credit, which can also be used to offset the emissions from product use and disposal, consequently diminishing its impact on climate change. The carbon stored by the finished particleboard product remains in it for its entire service life and even present in it for longer period if it is recycled or placed in a modern landfill, where it can be stored up to 100 years. This is in accordance with the IPCC recommendation that use wood biomass as a fuel and in products, because it can displace the fossil fuels and emissions intensive products, which is environmentally more effective than only storing the carbon in trees.

Hazardous emissions from the manufacturing process of particleboard caused by fossil fuels based machinery, hot press, hammer mill, rotary dryers, and vacuum pump, these were recognized as the most effective sources of emissions to the air. Most of the surveyed mills did not install the emissions control systems, therefore, emissions control systems are highly recommended to reduce the hazardous emissions from particleboard mills in Pakistan. The air emissions data was provided by Environmental Protection Agency, Khyber Pakhtunkhwa, Pakistan, and most of the mills were exceeded the permissible limits set by the National Environmental Quality Standards (NEQS) of Pakistan. Finally, improvements might possibly be attained by enhancing energy efficiency, reducing transportation freight distances, and getting the full benefit of wood residues. In addition, the results of this study can also be used in other subsequent LCA studies such as building elements, plywood, fiberboard, and furniture industry. The present study will also provide a benchmark for other wood based and non-wood based industries in Pakistan.

Transportation of raw materials and specifically finished particleboard distribution and marketing was the substantial contributor in all the impact categories. Sensitivity analysis was conducted for reduction in the transport distances to assist the particleboard industry to improve their environmental sustainability. Three scenarios for transportation step were assessed and the results indicated that reducing the freight distances can clearly decrease all the ten environmental impacts categories, thus it is an environmentally preferable and viable option to manage and decrease the mileage distance covered by the particleboard mill freight vehicles. Furthermore, a detail research should also be conducted on the UF resin production in Pakistan, to identify the improvements opportunities and possibilities of using other alternate resins. Moreover, other wood sources such as wood residues from sawmill, furniture and plywood industries, and other agro-industrial residues such as sugarcane bagasse should also be investigated to assess the potential improvements. The consumption of purchased electricity should be optimized by many ways such as improving the efficiency of electrical equipment's and motors and minimize the work stoppage hours.

4.2. Recommendations and future perspectives

The present study provides a benchmark for the carbon footprint assessment of particleboard industry in Pakistan. The research findings of our study provided a base for the detailed and scientific assessment of environmental performance of particleboard manufacture in Pakistan. The data can also be used in numerous ways to demonstrate favorable performance of particleboard regarding environmental sustainability, global warming, climate change, wood fuel use, carbon storage, green purchasing and building. In addition, we can also determine the environmental impacts of a production process alteration and substitution with other alternative materials such as pine wood and wood residues to assess potential improvements. However, to compare the results of this study with others, it is essential that their system boundary is similar to us, whereas for energy comparison used the gross calorific values (higher heating values) of the fuels. Furthermore, particleboard industry needs to make addition of emissions from forestry operations, which is not included in the present study. There is also a dire need to confirm reliable and accurate database formation for particleboard industry in Pakistan to enhance the overall accuracy of the data collection and subsequent GHG estimates.

LCA focuses on the environmental aspects of processes and products 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. A lot of research work is needed to be conducted on the identification of environmental impacts of wood panels of Pakistan. In this sense, future work can be focused on the comparison of different wood panel materials such particleboard, plywood, fiberboard and oriented strand board for specific applications. Because, this analysis will verify the real discrepancies about the potential differences between material resources inputs and processes, thus would find out the best practices by the industry and will serve as a support to legal requirements in this sector. In addition, there is a dire need to conduct more research on consistent and recognized methodology of environmental modeling in LCA, e.g. in relations to the modeling of end of life processes of long lived products. Therefore, it is very crucial to build develop a consensus within the LCA community to agree on specific methods of modeling of wood based products to make conscious choices of modeling approaches which are not typical today. More research work is needed for case studies of wood panels applying latest LCIA methods for biodiversity loss, climate change, and water cycle disturbances caused by wood based products in Pakistan.

The particleboard industry of Pakistan should use melamine formaldehyde resin, iso-cyanate formaldehyde resin instead of urea formaldehyde resin, because UF resin is class A carcinogen according to US EPA, whereas the other types of resin have least environmental and health concerns, thus, it is recommended that particleboard industry in Pakistan should substitute UF resin with other types of resins having less environmental and health impacts. Furthermore, the production of UF resin and other secondary materials i.e. paraffin wax, urea scavenger, and ammonium sulphate was derived from Wilson, 2009 based on SimaPro Ecoinvent database for the USA, which may not be representative of conditions in Pakistan. Therefore, primary data about the production chain of UF resin and secondary materials should be collected from the chemical industries in Pakistan to get a more realistic picture of GHG emissions. Similarly, transportation was one of the major contributors to environmental burdens from particleboard manufacture in Pakistan, due to the primary reason of use of circuitous and local routes by the divers of the particleboard mill fright. Therefore, it is recommended that high mobility highways and motorways should be used for raw material acquisition and finished product distribution.

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SUPPLEMTENTAL MATERIALS

Table A: Production weighted average, standard deviation and co-efficient of variation for the inputs/outputs of manufacture of 1.0 m^3 particleboard (PB) produced during 2015-2016.

Groundwater consumption in PB industries	Ground water (liter)	PB production(m^3)
	xi	wi
Premier PB mill	1135624	45000
Mumtaz PB mill	1179360	37440
Woodworld PB mill	144000	30000
Fronitor PB mill	450000	60000
ZRK PB mill	450000	75000
Ravi PB mill	300000	30000
Haidery PB mill	624000	56160
Taj PB mill	300000	33000
N	8	
Mill average (unweighted)	572873 m^3	
Production-weighted average ($\dot{X}$w)	584484.8838 m^3	
Sdw	354741.8835	
CVw	0.606930809	
CVw	60.69%	

Municipal water consumption in PB industries	Municipal water (liter)	PB production (m^3)
	xi	wi
Premier PB mill	150000	45000
Mumtaz PB mill	156000	37440
Woodworld PB mill	150000	30000
Fronitor PB mill	150000	60000
ZRK PB mill	312000	75000
Ravi PB mill	150000	30000
Haidery PB mill	300000	56160
Taj PB mill	150000	33000
N	8	
Mill average (unweighted)	189750 m^3	
Production-weighted average ($\dot{X}$w)	206733.8789 m^3	
Sdw	80005.85119	
CVw	0.386999226	
CVw	38.69%	

Wood logs consumption in PB industries	Wood logs (tonne)	Wood logs (Kg)	PB production (m^3)
	xi		wi
Premier PB mill	31500	31500000	45000
Mumtaz PB mill	21600	21600000	37440
Woodworld PB mill	19500	19500000	30000
Fronitor PB mill	42000	42000000	60000
ZRK PB mill	56250	56250000	75000
Ravi PB mill	18000	18000000	30000
Haidery PB mill	37800	37800000	56160
Taj PB mill	24750	24750000	33000
N	8		
Mill average (unweighted)	31425 m^3		
Production-weighted average ($\dot{X}$w)	35541.6039 m^3		
Sdw	14098.36452		
CVw	0.396672152		
CVw	39.66%		

U-F Resin consumption in PB industries	UF Resin (kg)	PB production (m^3)
	xi	wi
Premier PB mill	3600000	45000
Mumtaz PB mill	2620800	37440
Woodworld PB mill	2100000	30000
Fronitor PB mill	4800000	60000
ZRK PB mill	6750000	75000
Ravi PB mill	2400000	30000
Haidery PB mill	5054400	56160
Taj PB mill	2640000	33000
N	8	
Mill average (unweighted)	3745650 m^3	
Production-weighted average ($\dot{X}$w)	4256268.02 m^3	
Sdw	1737601.653	
CVw	0.408245356	
CVw	40.82%	

Urea Scavenger consumption in PB industries	Urea scavenger (kg)	PB production (m^3)
	xi	wi
Premier PB mill	180000	45000
Mumtaz PB mill	156000	37440
Woodworld PB mill	135000	30000
Fronitor PB mill	240000	60000
ZRK PB mill	300000	75000
Ravi PB mill	150000	30000
Haidery PB mill	280800	56160
Taj PB mill	180000	33000
N	8	
Mill average (unweighted)	202725 m^3	
Production-weighted average (Ẋw)	221223.0442 m^3	
Sdw	64944.45673	
CVw	0.293570035	
CVw	29.35%	

Wax consumption in PB industries	Wax (kg)	PB production (m^3)
	xi	wi
Premier PB mill	135000	45000
Mumtaz PB mill	124800	37440
Woodworld PB mill	900000	30000
Fronitor PB mill	300000	60000
ZRK PB mill	450000	75000
Ravi PB mill	120000	30000
Haidery PB mill	202800	56160
Taj PB mill	135000	33000
N	8	
Mill average (unweighted)	295950 m^3	
Production-weighted average (Ẋw)	297167.9214 m^3	
Sdw	231963.2395	
CVw	0.780579675	
CVw	78.00%	

Ammonium sulphate consumption in PB industries	Ammonium sulphate (kg)	PB production (m^3)
	xi	wi
Premier PB mill	45000	45000
Mumtaz PB mill	46800	37440
Woodworld PB mill	36000	30000
Fronitor PB mill	90000	60000
ZRK PB mill	150000	75000
Ravi PB mill	36000	30000
Haidery PB mill	78000	56160
Taj PB mill	36000	33000
N	8	
Mill average (unweighted)	64725 m^3	
Production-weighted average (Ẋw)	76802.1603 m^3	
Sdw	44890.6599	
CVw	0.584497359	
CVw	58.44%	

Purchased Electricity consumption in PB industries	Electricity (kWh)	PB production (m^3)
	xi	wi
Premier PB mill	7650000	45000
Mumtaz PB mill	6552000	37440
Woodworld PB mill	4200000	30000
Fronitor PB mill	9600000	60000
ZRK PB mill	12000000	75000
Ravi PB mill	4500000	30000
Haidery PB mill	10108800	56160
Taj PB mill	5280000	33000
N	8	
Mill average (unweighted)	7486350 m^3	
Production-weighted average (Ẋw)	8370177.545 m^3	
Sdw	2891523.442	
CVw	0.345455449	
CVw	34.50%	

Diesel consumption in PB industries	Diesel (liter)	PB production (m^3)
	xi	wi
Premier PB mill	36000	45000
Mumtaz PB mill	31200	37440
Woodworld PB mill	30000	30000
Fronitor PB mill	45000	60000
ZRK PB mill	90000	75000
Ravi PB mill	24960	30000
Haidery PB mill	78000	56160
Taj PB mill	36000	33000
N	8	
Mill average (unweighted)	46395 m^3	
Production-weighted average (Ẋw)	53069.852m^3	
Sdw	26272.04574	
CVw	0.495046517	
CVw	49.50%	

Petrol consumption in PB industries	Petrol (liter)	PB production (m^3)
	xi	wi
Premier PB mill	15000	45000
Mumtaz PB mill	12480	37440
Woodworld PB mill	15000	30000
Fronitor PB mill	30000	60000
ZRK PB mill	60000	75000
Ravi PB mill	21000	30000
Haidery PB mill	46800	56160
Taj PB mill	27000	33000
N	8	
Mill average (unweighted)	28410 m^3	
Production-weighted average (Ẋw)	32846.53 m^3	
Sdw	18641.77327	
CVw	0.567541571	
CVw	56.70%	

Natural gas consumption in PB industries	Natural gas (m3)	PB production (m^3)
	xi	wi
Premier PB mill	1350000	45000
Mumtaz PB mill	1310400	37440
Woodworld PB mill	900000	30000
Fronitor PB mill	2400000	60000
ZRK PB mill	3000000	75000
Ravi PB mill	900000	30000
Haidery PB mill	2134080	56160
Taj PB mill	990000	33000
N	8	
Mill average (unweighted)	1623060 m^3	
Production-weighted average ($\dot{X}w$)	1869425.283 m^3	
Sdw	832732.844	
CVw	0.445448583	
CVw	44.54%	

Heavy fuel oil (HFO) consumption in PB industries	HFO (liter)	PB production (m^3)
	xi	wi
Premier PB mill	675000	45000
Mumtaz PB mill	486720	37440
Woodworld PB mill	360000	30000
Fronitor PB mill	1080000	60000
ZRK PB mill	1500000	75000
Ravi PB mill	360000	30000
Haidery PB mill	842400	56160
Taj PB mill	429000	33000
N	8	
Mill average (unweighted)	716640 m^3	
Production-weighted average ($\dot{X}w$)	842782.27 m^3	
Sdw	437576.3399	
CVw	0.51920449	
CVw	51.90%	

Wood wastes consumption in PB industries	Wood waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	180000	45000
Mumtaz PB mill	224640	37440
Woodworld PB mill	200000	30000
Fronitor PB mill	420000	60000
ZRK PB mill	600000	75000
Ravi PB mill	150000	30000
Haidery PB mill	280800	56160
Taj PB mill	198000	33000
N	8	
Mill average (unweighted)	281680 m^3	
Production-weighted average ($\dot{X}w$)	326007.2 m^3	
Sdw	172686.4126	
CVw	0.529701179	
CVw	52.90%	

Sander dust consumption in PB industries	Sander dust (kg)	PB production (m^3)
	xi	wi
Premier PB mill	900000	45000
Mumtaz PB mill	780000	37440
Woodworld PB mill	600000	30000
Fronitor PB mill	1500000	60000
ZRK PB mill	2100000	75000
Ravi PB mill	750000	30000
Haidery PB mill	1872000	56160
Taj PB mill	900000	33000
N	8	
Mill average (unweighted)	1175250 m^3	
Production-weighted average ($\dot{X}w$)	1343520.786 m^3	
Sdw	597344.4663	
CVw	0.444611258	
CVw	44.40%	

Wood fuel (kg) in PB industries	Wood fuel	PB production (m^3)
	x_i	w_i
Premier PB mill	300000	45000
Mumtaz PB mill	149760	37440
Woodworld PB mill	120000	30000
Fronitor PB mill	360000	60000
ZRK PB mill	360000	75000
Ravi PB mill	45000	30000
Haidery PB mill	449280	56160
Taj PB mill	132000	33000
N	8	
Mill average (unweighted)	239505 m^3	
Production-weighted average ($\dot{X}_w$)	278899.5 m^3	
Sdw	139847.6923	
CVw	50.1%	

Transport of Wood logs by the PB industries	Wood logs transport (t.km)	PB production (m^3)
	xi	wi
Premier PB mill	400	45000
Mumtaz PB mill	100	37440
Woodworld PB mill	100	30000
Fronitor PB mill	400	60000
ZRK PB mill	200	75000
Ravi PB mill	500	30000
Haidery PB mill	500	56160
Taj PB mill	500	33000
N	8	
Mill average (unweighted)	337.5 m^3	
Production-weighted average ($\dot{X}w$)	336.399 m^3	
Sdw	165.4263298	
CVw	0.491755802	
CVw	49.17%	

Transport of UF resin by the PB industries	UF resin transport (t.km)	PB production (m^3)
	xi	wi
Premier PB mill	125	45000
Mumtaz PB mill	125	37440
Woodworld PB mill	90	30000
Fronitor PB mill	120	60000
ZRK PB mill	125	75000
Ravi PB mill	100	30000
Haidery PB mill	70	56160
Taj PB mill	150	33000
N	8	
Mill average (unweighted)	113.125 m^3	
Production-weighted average (Ẋw)	113.0965 m^3	
Sdw	24.69136315	
CVw	0.218321074	
CVw	21.83%	

Transport of Wax by the PB industries	Wax transport (t.km)	PB production (m^3)
	xi	wi
Premier PB mill	125	45000
Mumtaz PB mill	100	37440
Woodworld PB mill	50	30000
Fronitor PB mill	100	60000
ZRK PB mill	125	75000
Ravi PB mill	100	30000
Haidery PB mill	70	56160
Taj PB mill	150	33000
N	8	
Mill average (unweighted)	102.5 m^3	
Production-weighted average (Ẋw)	103.997 m^3	
Sdw	29.39591294	
CVw	0.282661906	
CVw	28.26%	

Product distribution distance covered by the PB industries	product distribution transport distance (t.km)	PB production (m^3)
	xi	wi
Premier PB mill	1000	45000
Mumtaz PB mill	700	37440
Woodworld PB mill	700	30000
Fronitor PB mill	1000	60000
ZRK PB mill	1000	75000
Ravi PB mill	700	30000
Haidery PB mill	700	56160
Taj PB mill	700	33000
N	8	
Mill average (unweighted)	812.5 m^3	
Production-weighted average ($\dot{X}w$)	847.299 m^3	
Sdw	160.3307558	
CVw	0.189225597	
CVw	18.92%	

Batteries wastes produced by PB industries	Batteries waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	200	45000
Mumtaz PB mill	160	37440
Woodworld PB mill	120	30000
Fronitor PB mill	280	60000
ZRK PB mill	800	75000
Ravi PB mill	100	30000
Haidery PB mill	180	56160
Taj PB mill	120	33000
N	8	
Mill average (unweighted)	245 m^3	
Production-weighted average ($\dot{X}w$)	306.762 m^3	
Sdw	273.4787424	
CVw	0.891499379	
CVw	89.14%	

Air filters wastes produced by PB industries	Air filters waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	43	45000
Mumtaz PB mill	30	37440
Woodworld PB mill	26	30000
Fronitor PB mill	54	60000
ZRK PB mill	72	75000
Ravi PB mill	18	30000
Haidery PB mill	40	56160
Taj PB mill	14	33000
N	8	
Mill average (unweighted)	37.125 m^3	
Production-weighted average ($\dot{X}w$)	42.898 m^3	
Sdw	20.31142657	
CVw	0.473476084	
CVw	47.34%	

Oil filters wastes produced by PB industries	Oil filters waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	60	45000
Mumtaz PB mill	42	37440
Woodworld PB mill	36	30000
Fronitor PB mill	75	60000
ZRK PB mill	200	75000
Ravi PB mill	30	30000
Haidery PB mill	55	56160
Taj PB mill	25	33000
N	8	
Mill average (unweighted)	65.375 m^3	
Production-weighted average ($\dot{X}w$)	80.922 m^3	
Sdw	66.56346651	
CVw	0.82255567	
CVw	82.25%	

Lubricants etc. wastes produced by PB industries	Lubricants oil etc. waste (liters)	PB production (m^3)
	xi	wi
Premier PB mill	1000	45000
Mumtaz PB mill	1000	37440
Woodworld PB mill	800	30000
Fronitor PB mill	1200	60000
ZRK PB mill	1500	75000
Ravi PB mill	1000	30000
Haidery PB mill	1200	56160
Taj PB mill	1000	33000
N	8	
Mill average (unweighted)	1087.5 m^3	
Production-weighted average ($\dot{X}w$)	1149.296 m^3	
Sdw	226.2840786	
CVw	0.196889254	
CVw	19.68%	

Fluorescent Lamp wastes produced by PB industries	Fluorescent lamp waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	30	45000
Mumtaz PB mill	24	37440
Woodworld PB mill	16	30000
Fronitor PB mill	36	60000
ZRK PB mill	45	75000
Ravi PB mill	21	30000
Haidery PB mill	21	56160
Taj PB mill	45	33000
N	8	
Mill average (unweighted)	29.75 m^3	
Production-weighted average ($\dot{X}w$)	31.522 m^3	
Sdw	11.14049908	
CVw	0.35336003	
CVw	35.33%	

Wiping clothes wastes produced by PB industries	**Wiping clothes waste (kg)**	**PB production (m^3)**
	xi	wi
Premier PB mill	240	45000
Mumtaz PB mill	200	37440
Woodworld PB mill	150	30000
Fronitor PB mill	300	60000
ZRK PB mill	500	75000
Ravi PB mill	200	30000
Haidery PB mill	500	56160
Taj PB mill	300	33000
N	8	
Mill average (unweighted)	298.75 m^3	
Production-weighted average (Ẋw)	333.5188 m^3	
Sdw	140.6523732	
CVw	0.421722446	
CVw	42.17%	

SPM emitted to air by PB industries	**SPM (mg/m^3)**	**PB production (m^3)**
	xi	wi
Premier PB mill	2520	45000
Mumtaz PB mill	505	37440
Woodworld PB mill	801	30000
Fronitor PB mill		
ZRK PB mill		
Ravi PB mill		
Haidery PB mill		
Taj PB mill		
N	3	
Mill average (unweighted)	1275.333 m^3	
Production-weighted average (Ẋw)	1390.405 m^3	
Sdw	1138.677121	
CVw	0.818953234	
CVw	82%	

CO emitted to air by PB industries	**CO (mg/m³)**	**PB production (m³)**
	xi	wi
Premier PB mill	395	45000
Mumtaz PB mill	1820	37440
Woodworld PB mill	2825	30000
Fronitor PB mill	1217	60000
ZRK PB mill		
Ravi PB mill		
Haidery PB mill		
Taj PB mill		
N	4	
Mill average (unweighted)	1564.25 m³	
Production-weighted average (Ẋw)	1413.1628 m³	
Sdw	942.7834289	
CVw	0.667144226	
CVw	67%	

NOx emitted to air by PB industries	**NOx (mg/m³)**	**PB production (m³)**
	xi	wi
Premier PB mill	304	45000
Mumtaz PB mill	190	37440
Woodworld PB mill	165	30000
Fronitor PB mill	425	60000
ZRK PB mill		
Ravi PB mill		
Haidery PB mill		
Taj PB mill		
N	4	
Mill average (unweighted)	271 m³	
Production-weighted average (Ẋw)	297.167 m³	
Sdw	122.3690324	
CVw	0.411784417	
CVw	41%	

SOx emitted to air by PB industry	SOx (mg/m^3)	PB production (m^3)
	xi	wi
Premier PB mill	75	45000
Mumtaz PB mill	51	37440
Woodworld PB mill	10	30000
Fronitor PB mill		
ZRK PB mill		
Ravi PB mill		
Haidery PB mill		
Taj PB mill		
N	3	
Mill average (unweighted)	45.33 m^3	
Production-weighted average (Ẋw)	49.665 m^3	
Sdw	31.8727738	
CVw	0.641742894	
CVw	64%	

Rubber wastes produced by PB industries	Rubber waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	2000	45000
Mumtaz PB mill	1600	37440
Woodworld PB mill	1200	30000
Fronitor PB mill	2800	60000
ZRK PB mill	4600	75000
Ravi PB mill	1000	30000
Haidery PB mill	1800	56160
Taj PB mill	1200	33000
N	8	
Mill average (unweighted)	2025 m^3	
Production-weighted average (Ẋw)	2372.045 m^3	
Sdw	1336.772968	
CVw	0.563552758	
CVw	56.35%	

Paper and cardboard wastes produced by PB industries	Paper and cardboard waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	360	45000
Mumtaz PB mill	800	37440
Woodworld PB mill	200	30000
Fronitor PB mill	1000	60000
ZRK PB mill	1000	75000
Ravi PB mill	300	30000
Haidery PB mill	800	56160
Taj PB mill	400	33000
N	8	
Mill average (unweighted)	607.50 m^3	
Production-weighted average (Ẋw)	693.617 m^3	
Sdw	323.3710282	
CVw	0.466209765	
CVw	46.62%	

Toner wastes produced by PB industries	Toner waste (kg)	PB production (m^3)
	xi	wi
Premier PB mill	24	45000
Mumtaz PB mill	50	37440
Woodworld PB mill	10	30000
Fronitor PB mill	30	60000
ZRK PB mill	100	75000
Ravi PB mill	15	30000
Haidery PB mill	150	56160
Taj PB mill	30	33000
N	8	
Mill average (unweighted)	51.125 m^3	
Production-weighted average (Ẋw)	61.145 m^3	
Sdw	51.65573774	
CVw	0.844798066	
CVw	84.47%	

Diesel consumption in mobile sources by PB industries	Diesel used (liters)	PB production (m^3)
	xi	wi
Premier PB mill	48000	45000
Mumtaz PB mill	20160	37440
Woodworld PB mill	12000	30000
Fronitor PB mill	75000	60000
ZRK PB mill	90000	75000
Ravi PB mill	24000	30000
Haidery PB mill	45000	56160
Taj PB mill	15000	33000
N	8	
Mill average (unweighted)	41145 m^3	
Production-weighted average ($\dot{X}w$)	49828.129 m^3	
Sdw	30399.3991	
CVw	0.610085157	
CVw	61%	

Petrol consumption in mobile sources by PB industries	Petrol used (liters)	PB production (m^3)
	xi	wi
Premier PB mill	6000	45000
Mumtaz PB mill	4500	37440
Woodworld PB mill	3900	30000
Fronitor PB mill	3000	60000
ZRK PB mill	45000	75000
Ravi PB mill	1500	30000
Haidery PB mill	6000	56160
Taj PB mill	3000	33000
N	8	
Mill average (unweighted)	9112.5 m^3	
Production-weighted average ($\dot{X}w$)	12524.386 m^3	
Sdw	17667.84099	
CVw	1.410675193	
CVw	141.00%	

CNG consumption in mobile sources by PB industries	CNG used (liters)	PB production (m^3)
	xi	wi
Premier PB mill	9000	45000
Mumtaz PB mill	3000	37440
Woodworld PB mill	1500	30000
Fronitor PB mill	1500	60000
ZRK PB mill	24000	75000
Ravi PB mill	3000	30000
Haidery PB mill	6000	56160
Taj PB mill	3000	33000
N	8	
Mill average (unweighted)	6375 m^3	
Production-weighted average ($\dot{X}w$)	8124.058 m^3	
Sdw	8964.377201	
CVw	1.103435769	
CVw	110%	

Table B: Specification per substance for Abiotic depletion (AD) impact category in PB production process.

Substance	Compartment	Unit	Total
Aluminium	Raw	kg Sb eq	3.195E-09
Argon	Raw	kg Sb eq	5.410E-09
Borax	Raw	kg Sb eq	3.131E-08
Bromine	Raw	kg Sb eq	4.832E-08
Cadmium	Raw	kg Sb eq	0.0006259
Calcite	Raw	kg Sb eq	1.528E-09
Chromium	Raw	kg Sb eq	4.116E-05
Cinnabar	Raw	kg Sb eq	4.023E-08
Coal, 26.4 MJ per kg	Raw	kg Sb eq	0.018137
Coal, brown	Raw	kg Sb eq	0.037524
Coal, hard	Raw	kg Sb eq	0.211173
Cobalt	Raw	kg Sb eq	9.076E-11
Fluorine	Raw	kg Sb eq	1.552E-09
Fluorspar	Raw	kg Sb eq	6.328E-09
Gas, natural/m^3	Raw	kg Sb eq	1.1337814
Gypsum	Raw	kg Sb eq	1.793E-06
Iron	Raw	kg Sb eq	4.921E-07
Lead	Raw	kg Sb eq	0.0004267
Lithium	Raw	kg Sb eq	4.996E-11
Manganese	Raw	kg Sb eq	2.999E-07
Molybdenum	Raw	kg Sb eq	9.330E-06
Nickel	Raw	kg Sb eq	2.093E-07
Oil, crude	Raw	kg Sb eq	2.2348590
Palladium	Raw	kg Sb eq	1.585E-08
Phosphorus	Raw	kg Sb eq	1.077E-07
Platinum	Raw	kg Sb eq	7.684E-08
Potassium chloride	Raw	kg Sb eq	1.103E-10
Silver, 0.007% in sulfide, Ag 0.004%	Raw	kg Sb eq	8.483E-05
Sodium chloride	Raw	kg Sb eq	5.045E-09
Sodium nitrate	Raw	kg Sb eq	8.776E-21
Sodium sulfate	Raw	kg Sb eq	2.091E-07
Sulfur	Raw	kg Sb eq	2.116E-07
Tin	Raw	kg Sb eq	8.445E-06
TiO_2, 54% in ilmenite, 2.6% in crude ore	Raw	kg Sb eq	3.128E-10
Uranium	Raw	kg Sb eq	5.234E-07
Xenon	Raw	kg Sb eq	0.001232
Zinc	Raw	kg Sb eq	5.645E-05
Zirconium	Raw	kg Sb eq	3.293E-08
Total		**kg Sb eq**	**6.059**

Table C: Specification per substance for Acidification potential (AP) impact category in PB production.

Substance	Compartment	Unit	Total
Ammonia	Air	kg SO2 eq	0.03771
Nitrogen oxides	Air	kg SO2 eq	0.58298
Sulfur dioxide	Air	kg SO2 eq	2.15399
Sulfur monoxide	Air	kg SO2 eq	0.00393
Total		**kg SO2 eq**	**3.343**

Table D: Specification per substance for Eutrophication potential (EP) impact category.

Substance	Compartment	Unit	Total
Ammonia	Air	kg PO4--- eq	0.008250724
Ammonia	Water	kg PO4--- eq	0.000126479
Ammonium carbonate	Air	kg PO4--- eq	1.89292E-09
Ammonium, ion	Water	kg PO4--- eq	0.000941949
Chemical Oxygen Demand	Water	kg PO4--- eq	0.024997902
Nitrate	Air	kg PO4--- eq	2.35605E-05
Nitrate	Water	kg PO4--- eq	0.003125384
Nitrate	Soil	kg PO4--- eq	4.8196E-05
Nitric acid	Water	kg PO4--- eq	2.48125E-09
Nitrite	Water	kg PO4--- eq	5.45606E-07
Nitrogen	Water	kg PO4--- eq	0.000458458
Nitrogen	Soil	kg PO4--- eq	1.40702E-06
Nitrogen oxides	Air	kg PO4--- eq	0.15157619
Nitrogen, total	Water	kg PO4--- eq	3.89601E-07
Phosphate	Water	kg PO4--- eq	0.09851566
Phosphoric acid	Air	kg PO4--- eq	1.9058E-10
Phosphorus	Air	kg PO4--- eq	0.001154033
Phosphorus	Water	kg PO4--- eq	0.00019202
Phosphorus	Soil	kg PO4--- eq	0.008457367
Total		**kg PO4--- eq**	**0.610**

Table E: Specification per substance for global warming potential (GWP) impact category.

Substance	Compartment	Unit	Total
Carbon dioxide	Air	kg CO2 eq	0.003019
Carbon dioxide, fossil	Air	kg CO2 eq	317.7028
Carbon dioxide, land transformation	Air	kg CO2 eq	0.151176
Carbon monoxide	Air	kg CO2 eq	7.950E-06
Carbon monoxide, fossil	Air	kg CO2 eq	1.0254043
Chloroform	Air	kg CO2 eq	2.084E-05
Dinitrogen monoxide	Air	kg CO2 eq	4.108248
Ethane, 1,1-difluoro-, HFC-152a	Air	kg CO2 eq	0.000262
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	kg CO2 eq	0.001437
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CO2 eq	0.000786
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CO2 eq	0.007357
Ethane, hexafluoro-, HFC-116	Air	kg CO2 eq	0.008812
Methane	Air	kg CO2 eq	2.942111
Methane, biogenic	Air	kg CO2 eq	0.366240
Methane, bromo-, Halon 1001	Air	kg CO2 eq	2.35E-10
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CO2 eq	0.000196
Methane, bromotrifluoro-, Halon 1301	Air	kg CO2 eq	0.036551
Methane, chlorodifluoro-, HCFC-22	Air	kg CO2 eq	0.009452
Methane, dichloro-, HCC-30	Air	kg CO2 eq	7.520E-06
Methane, dichlorodifluoro-, CFC-12	Air	kg CO2 eq	0.003457
Methane, dichlorofluoro-, HCFC-21	Air	kg CO2 eq	6.75E-08
Methane, fossil	Air	kg CO2 eq	16.22009
Methane, tetrachloro-, CFC-10	Air	kg CO2 eq	0.000377
Methane, tetrafluoro-, CFC-14	Air	kg CO2 eq	0.057185
Methane, trichlorofluoro-, CFC-11	Air	kg CO2 eq	2.36E-06
Methane, trifluoro-, HFC-23	Air	kg CO2 eq	0.00122
Sulfur hexafluoride	Air	kg CO2 eq	0.14527
Total		**kg CO2 eq**	**552.00**

Table F: Specification per substance for ozone layer depletion (OLD) impact category.

Substance	Compartment	Unit	Total
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg CFC-11 eq	3.0584E-09
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC-11 eq	1.17982E-07
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	6.38155E-07
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	kg CFC-11 eq	2.89741E-09
Methane, bromo-, Halon 1001	Air	kg CFC-11 eq	1.74004E-11
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	7.7061E-07
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	6.35676E-05
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC-11 eq	1.89059E-07
Methane, dichlorodifluoro-, CFC-12	Air	kg CFC-11 eq	2.67447E-07
Methane, monochloro-, R-40	Air	kg CFC-11 eq	1.46899E-08
Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	2.51422E-07
Methane, trichlorofluoro-, CFC-11	Air	kg CFC-11 eq	5.13492E-10
Total		**kg CFC-11 eq**	**0.0001**

Table G: Specification per substance for human toxicity (HT) impact category in the PB production.

Substance	Compartment	Unit	Total
2-Methyl-4-chlorophenoxyacetic acid	Air	kg 1,4-DB eq	4.41604E-10
2,4-D	Air	kg 1,4-DB eq	4.16665E-07
2,4-D	Soil	kg 1,4-DB eq	0.000236671
Acenaphthene	Air	kg 1,4-DB eq	0.000640146
Acenaphthene	Water	kg 1,4-DB eq	0.0087106
Acenaphthylene	Water	kg 1,4-DB eq	0.000544763
Acephate	Air	kg 1,4-DB eq	2.04102E-08
Acephate	Soil	kg 1,4-DB eq	4.735E-06
Acrolein	Air	kg 1,4-DB eq	0.006140734
Aldicarb	Soil	kg 1,4-DB eq	0.000316005
Aldrin	Soil	kg 1,4-DB eq	0.010181276
Ammonia	Air	kg 1,4-DB eq	0.00235735
Anthracene	Air	kg 1,4-DB eq	6.4701E-11
Antimony	Air	kg 1,4-DB eq	32.6493323
Antimony	Water	kg 1,4-DB eq	0.691095883
Antimony	Soil	kg 1,4-DB eq	0.001688007
Arsenic	Air	kg 1,4-DB eq	11.62456999
Arsenic	Water	kg 1,4-DB eq	0.316550574
Arsenic	Soil	kg 1,4-DB eq	0.064319407
Atrazine	Air	kg 1,4-DB eq	2.33291E-08
Atrazine	Water	kg 1,4-DB eq	3.01714E-09
Atrazine	Soil	kg 1,4-DB eq	1.97732E-05
Azinphos-methyl	Soil	kg 1,4-DB eq	3.64578E-08
Barite	Water	kg 1,4-DB eq	4.512183382
Barium	Air	kg 1,4-DB eq	1.439949567
Barium	Water	kg 1,4-DB eq	19.32788951
Barium	Soil	kg 1,4-DB eq	0.468204405
Benomyl	Soil	kg 1,4-DB eq	7.26473E-10
Bentazone	Air	kg 1,4-DB eq	6.01205E-09
Bentazone	Water	kg 1,4-DB eq	4.38651E-11
Bentazone	Soil	kg 1,4-DB eq	6.48461E-08

Benzene	Air	kg 1,4-DB eq	9.50267798
Benzene	Water	kg 1,4-DB eq	0.887675833
Benzene, 1,2-dichloro-	Air	kg 1,4-DB eq	2.96199E-08
Benzene, 1,2-dichloro-	Water	kg 1,4-DB eq	0.00014712
Benzene, chloro-	Air	kg 1,4-DB eq	5.81524E-11
Benzene, chloro-	Water	kg 1,4-DB eq	0.000224796
Benzene, ethyl-	Air	kg 1,4-DB eq	0.000386322
Benzene, ethyl-	Water	kg 1,4-DB eq	0.000104112
Benzene, hexachloro-	Air	kg 1,4-DB eq	0.105638999
Benzene, pentachloro-	Air	kg 1,4-DB eq	1.46771E-07
Benzene, pentachloronitro-	Soil	kg 1,4-DB eq	6.98602E-07
Benzyl chloride	Air	kg 1,4-DB eq	7.05641E-07
Beryllium	Air	kg 1,4-DB eq	0.04023178
Beryllium	Water	kg 1,4-DB eq	0.895196035
Bifenthrin	Soil	kg 1,4-DB eq	6.98721E-09
Butadiene	Air	kg 1,4-DB eq	6.53625E-05
Cadmium	Air	kg 1,4-DB eq	2.476372542
Cadmium	Water	kg 1,4-DB eq	0.003442393
Cadmium	Soil	kg 1,4-DB eq	0.074829118
Captan	Soil	kg 1,4-DB eq	4.78431E-08
Carbaryl	Air	kg 1,4-DB eq	2.47295E-09
Carbaryl	Water	kg 1,4-DB eq	3.63975E-13
Carbaryl	Soil	kg 1,4-DB eq	4.38921E-09
Carbendazim	Soil	kg 1,4-DB eq	1.02271E-06
Carbofuran	Soil	kg 1,4-DB eq	0.001323728
Carbon disulfide	Air	kg 1,4-DB eq	0.001197737
Carbon disulfide	Water	kg 1,4-DB eq	9.41851E-08
Chlorfenvinphos	Soil	kg 1,4-DB eq	8.76371E-06
Chloridazon	Soil	kg 1,4-DB eq	1.33733E-09
Chloroform	Air	kg 1,4-DB eq	8.82282E-06
Chloroform	Water	kg 1,4-DB eq	1.70089E-08
Chlorothalonil	Soil	kg 1,4-DB eq	1.54237E-06
Chlorpyrifos	Air	kg 1,4-DB eq	6.46765E-07
Chlorpyrifos	Soil	kg 1,4-DB eq	7.51225E-06
Chromium	Soil	kg 1,4-DB eq	0.274446968
Chromium III	Water	kg 1,4-DB eq	2.31502E-05
Chromium VI	Air	kg 1,4-DB eq	15.99758914
Chromium VI	Water	kg 1,4-DB eq	0.003374875
Chromium VI	Soil	kg 1,4-DB eq	0.003957056
Cobalt	Air	kg 1,4-DB eq	0.25677104
Cobalt	Water	kg 1,4-DB eq	0.090923948
Cobalt	Soil	kg 1,4-DB eq	0.011749456
Copper	Air	kg 1,4-DB eq	11.28439365
Copper	Water	kg 1,4-DB eq	0.024544464
Copper	Soil	kg 1,4-DB eq	0.004150767
Cypermethrin	Air	kg 1,4-DB eq	6.43139E-08
Cypermethrin	Soil	kg 1,4-DB eq	0.000837165
Deltamethrin	Soil	kg 1,4-DB eq	9.51096E-12
Diazinon	Soil	kg 1,4-DB eq	9.46455E-06
Dichlorprop	Air	kg 1,4-DB eq	2.42665E-11

Dichlorprop	Water	kg 1,4-DB eq	5.44E-10
Dichlorprop	Soil	kg 1,4-DB eq	4.06594E-09
Dichromate	Water	kg 1,4-DB eq	4.19295E-07
Dimethoate	Soil	kg 1,4-DB eq	1.56827E-05
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	kg 1,4-DB eq	0.206661271
Diuron	Soil	kg 1,4-DB eq	0.000445678
Endosulfan	Soil	kg 1,4-DB eq	1.79349E-07
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg 1,4-DB eq	4.5598E-07
Ethane, 1,1,1-trichloro-, HCFC-140	Water	kg 1,4-DB eq	1.50244E-12
Ethane, 1,2-dichloro-	Air	kg 1,4-DB eq	0.000111788
Ethane, 1,2-dichloro-	Water	kg 1,4-DB eq	5.3666E-06
Ethene	Air	kg 1,4-DB eq	0.00034977
Ethene	Water	kg 1,4-DB eq	1.12136E-05
Ethene, chloro-	Air	kg 1,4-DB eq	0.000707032
Ethene, chloro-	Water	kg 1,4-DB eq	1.08936E-05
Ethene, tetrachloro-	Air	kg 1,4-DB eq	9.17357E-07
Ethoprop	Soil	kg 1,4-DB eq	5.04133E-05
Ethylene oxide	Air	kg 1,4-DB eq	0.004000655
Ethylene oxide	Water	kg 1,4-DB eq	0.000642536
Fentin hydroxide	Soil	kg 1,4-DB eq	1.34996E-07
Folpet	Soil	kg 1,4-DB eq	4.65586E-07
Formaldehyde	Air	kg 1,4-DB eq	0.002146905
Formaldehyde	Water	kg 1,4-DB eq	0.000251679
Glyphosate	Air	kg 1,4-DB eq	6.27539E-09
Glyphosate	Water	kg 1,4-DB eq	1.70258E-10
Glyphosate	Soil	kg 1,4-DB eq	1.16323E-07
Hydrogen chloride	Air	kg 1,4-DB eq	0.004604844
Hydrogen fluoride	Air	kg 1,4-DB eq	0.169864804
Hydrogen sulfide	Air	kg 1,4-DB eq	0.000343838
Iprodione	Soil	kg 1,4-DB eq	2.75704E-07
Isoproturon	Soil	kg 1,4-DB eq	1.77528E-05
Lead	Air	kg 1,4-DB eq	0.22057171
Lead	Water	kg 1,4-DB eq	0.009552772
Lead	Soil	kg 1,4-DB eq	0.074367961
Linuron	Soil	kg 1,4-DB eq	0.000183234
m-Xylene	Air	kg 1,4-DB eq	5.62095E-06
m-Xylene	Water	kg 1,4-DB eq	6.64343E-07
Malathion	Soil	kg 1,4-DB eq	9.3682E-10
Mecoprop	Soil	kg 1,4-DB eq	4.02508E-07
Mecoprop-P	Soil	kg 1,4-DB eq	8.18353E-07
Mercury	Air	kg 1,4-DB eq	0.044530625
Mercury	Water	kg 1,4-DB eq	0.010383653
Mercury	Soil	kg 1,4-DB eq	0.000172081
Metallic ions, unspecified	Water	kg 1,4-DB eq	1.34436E-10
Metals, unspecified	Air	kg 1,4-DB eq	2.35452E-10
Metamitron	Soil	kg 1,4-DB eq	4.28915E-06
Metazachlor	Soil	kg 1,4-DB eq	4.49258E-06
Methane, bromo-, Halon 1001	Air	kg 1,4-DB eq	1.65068E-08
Methane, dichloro-, HCC-30	Air	kg 1,4-DB eq	1.48901E-06
Methane, dichloro-, HCC-30	Water	kg 1,4-DB eq	0.00013265

Methane, tetrachloro-, CFC-10	Air	kg 1,4-DB eq	4.60941E-05
Methomyl	Air	kg 1,4-DB eq	1.78886E-14
Methomyl	Water	kg 1,4-DB eq	1.48064E-16
Methomyl	Soil	kg 1,4-DB eq	3.96218E-13
Metolachlor	Air	kg 1,4-DB eq	5.47295E-08
Metolachlor	Water	kg 1,4-DB eq	5.48659E-11
Metolachlor	Soil	kg 1,4-DB eq	2.85124E-05
Molybdenum	Air	kg 1,4-DB eq	2.664673294
Molybdenum	Water	kg 1,4-DB eq	1.187648678
Molybdenum	Soil	kg 1,4-DB eq	0.008967886
Naphthalene	Air	kg 1,4-DB eq	6.92271E-07
Naphthalene	Water	kg 1,4-DB eq	2.8981E-06
Nickel	Air	kg 1,4-DB eq	6.927937982
Nickel	Water	kg 1,4-DB eq	1.395990587
Nickel	Soil	kg 1,4-DB eq	0.041447913
Nitrogen oxides	Air	kg 1,4-DB eq	1.399164834
o-Xylene	Air	kg 1,4-DB eq	2.99396E-06
o-Xylene	Water	kg 1,4-DB eq	3.62558E-07
Oxamyl	Soil	kg 1,4-DB eq	7.51197E-08
Oxydemeton methyl	Soil	kg 1,4-DB eq	8.60616E-08
p-Xylene	Water	kg 1,4-DB eq	1.74329E-08
PAH, polycyclic aromatic hydrocarbons	Air	kg 1,4-DB eq	29.29166793
PAH, polycyclic aromatic hydrocarbons	Water	kg 1,4-DB eq	7.46367895
Parathion	Soil	kg 1,4-DB eq	2.91156E-08
Parathion, methyl	Air	kg 1,4-DB eq	5.45587E-08
Parathion, methyl	Soil	kg 1,4-DB eq	1.04728E-09
Particulates, < 2.5 um	Air	kg 1,4-DB eq	0.165852241
Particulates, > 2.5 um, and < 10um	Air	kg 1,4-DB eq	0.101366212
Permethrin	Air	kg 1,4-DB eq	7.17852E-10
Permethrin	Soil	kg 1,4-DB eq	5.27171E-09
Phenol	Air	kg 1,4-DB eq	3.28641E-06
Phenol	Water	kg 1,4-DB eq	2.09283E-05
Phenol, 2,4-dichloro-	Air	kg 1,4-DB eq	2.02428E-07
Phenol, pentachloro-	Air	kg 1,4-DB eq	1.9136E-05
Phenol, pentachloro-	Soil	kg 1,4-DB eq	7.9142E-12
Phthalate, dioctyl-	Air	kg 1,4-DB eq	5.4564E-11
Pirimicarb	Soil	kg 1,4-DB eq	1.49314E-06
Propachlor	Soil	kg 1,4-DB eq	8.7565E-06
Propylene oxide	Air	kg 1,4-DB eq	0.029628406
Propylene oxide	Water	kg 1,4-DB eq	0.148135309
Selenium	Air	kg 1,4-DB eq	0.640519082
Selenium	Water	kg 1,4-DB eq	8.982411713
Selenium	Soil	kg 1,4-DB eq	0.18020139
Simazine	Soil	kg 1,4-DB eq	5.64781E-07
Sodium dichromate	Air	kg 1,4-DB eq	0.322083341
Styrene	Air	kg 1,4-DB eq	1.61835E-06
Sulfur dioxide	Air	kg 1,4-DB eq	0.092319986
Sulfur monoxide	Air	kg 1,4-DB eq	0.00031492
Thallium	Air	kg 1,4-DB eq	0.06577864
Thallium	Water	kg 1,4-DB eq	2.911775616

Thiram	Soil	kg 1,4-DB eq	1.51524E-07
Tin	Air	kg 1,4-DB eq	0.000595579
Tin	Water	kg 1,4-DB eq	1.41052E-05
Tin	Soil	kg 1,4-DB eq	1.06582E-08
Toluene	Air	kg 1,4-DB eq	0.001682483
Toluene	Water	kg 1,4-DB eq	0.00020519
Triallate	Soil	kg 1,4-DB eq	1.83896E-10
Tributyltin compounds	Water	kg 1,4-DB eq	0.000290575
Trichlorfon	Soil	kg 1,4-DB eq	2.51169E-10
Trifluralin	Air	kg 1,4-DB eq	1.61706E-07
Trifluralin	Soil	kg 1,4-DB eq	3.86839E-05
Vanadium	Air	kg 1,4-DB eq	2.304147378
Vanadium	Water	kg 1,4-DB eq	1.665120617
Vanadium	Soil	kg 1,4-DB eq	0.195841442
Xylene	Water	kg 1,4-DB eq	0.000225488
Zinc	Air	kg 1,4-DB eq	0.189184923
Zinc	Water	kg 1,4-DB eq	0.013440715
Zinc	Soil	kg 1,4-DB eq	0.029321596
Total		**kg 1,4-DB eq**	**384.032**

Table H: Specification per substance for freshwater aquatic ecotoxicity (FAE) impact category.

Substance	Compartment	Unit	Total
2-Methyl-4-chlorophenoxyacetic acid	Air	kg 1,4-DB eq	3.18436E-11
2-Methyl-4-chlorophenoxyacetic acid	Water	kg 1,4-DB eq	1.89625E-09
2-Methyl-4-chlorophenoxyacetic acid	Soil	kg 1,4-DB eq	3.38442E-09
2,4-D	Air	kg 1,4-DB eq	2.42845E-06
2,4-D	Soil	kg 1,4-DB eq	0.000148549
Acenaphthene	Air	kg 1,4-DB eq	1.92491E-07
Acenaphthene	Water	kg 1,4-DB eq	0.000850434
Acenaphthylene	Water	kg 1,4-DB eq	5.31863E-05
Acephate	Air	kg 1,4-DB eq	5.28265E-07
Acephate	Soil	kg 1,4-DB eq	1.11579E-05
Acrolein	Air	kg 1,4-DB eq	0.056011264
Aldicarb	Soil	kg 1,4-DB eq	0.059710642
Aldrin	Soil	kg 1,4-DB eq	0.000616981
Anthracene	Air	kg 1,4-DB eq	1.70462E-08
Antimony	Air	kg 1,4-DB eq	0.018100673
Antimony	Water	kg 1,4-DB eq	0.002648753
Antimony	Soil	kg 1,4-DB eq	6.40163E-06
Arsenic	Air	kg 1,4-DB eq	0.001653495
Arsenic	Water	kg 1,4-DB eq	0.068436017
Arsenic	Soil	kg 1,4-DB eq	0.000577764
Atrazine	Air	kg 1,4-DB eq	1.89254E-06
Atrazine	Water	kg 1,4-DB eq	3.2818E-06
Atrazine	Soil	kg 1,4-DB eq	0.00032027
Azinphos-methyl	Soil	kg 1,4-DB eq	1.81354E-07
Barite	Water	kg 1,4-DB eq	1.35461E-21
Barium	Air	kg 1,4-DB eq	0.081520954
Barium	Water	kg 1,4-DB eq	6.920478667

Barium	Soil	kg 1,4-DB eq	0.169317344
Benomyl	Soil	kg 1,4-DB eq	7.79091E-09
Bentazone	Air	kg 1,4-DB eq	1.58168E-08
Bentazone	Water	kg 1,4-DB eq	3.03406E-09
Bentazone	Soil	kg 1,4-DB eq	3.5558E-08
Benzene	Air	kg 1,4-DB eq	4.18618E-07
Benzene	Water	kg 1,4-DB eq	4.3805E-05
Benzene, 1,2-dichloro-	Air	kg 1,4-DB eq	9.41559E-12
Benzene, 1,2-dichloro-	Water	kg 1,4-DB eq	1.679E-05
Benzene, chloro-	Air	kg 1,4-DB eq	2.94857E-15
Benzene, chloro-	Water	kg 1,4-DB eq	8.89305E-06
Benzene, ethyl-	Air	kg 1,4-DB eq	5.20125E-08
Benzene, ethyl-	Water	kg 1,4-DB eq	6.84153E-05
Benzene, hexachloro-	Air	kg 1,4-DB eq	4.4462E-08
Benzene, pentachloro-	Air	kg 1,4-DB eq	1.33134E-10
Benzene, pentachloronitro-	Soil	kg 1,4-DB eq	1.45502E-07
Benzo(a)anthracene	Air	kg 1,4-DB eq	2.44986E-09
Benzo(a)pyrene	Air	kg 1,4-DB eq	0.000826378
Benzo(g,h,i)perylene	Air	kg 1,4-DB eq	7.32209E-10
Benzo(k)fluoranthene	Air	kg 1,4-DB eq	3.62758E-08
Benzyl chloride	Air	kg 1,4-DB eq	1.51753E-10
Beryllium	Air	kg 1,4-DB eq	0.003030676
Beryllium	Water	kg 1,4-DB eq	5.837957003
Bifenthrin	Soil	kg 1,4-DB eq	2.51637E-08
Butadiene	Air	kg 1,4-DB eq	9.56884E-15
Cadmium	Air	kg 1,4-DB eq	0.004935667
Cadmium	Water	kg 1,4-DB eq	0.224820084
Cadmium	Soil	kg 1,4-DB eq	0.004156259
Captan	Soil	kg 1,4-DB eq	1.9677E-07
Carbaryl	Air	kg 1,4-DB eq	8.55134E-08
Carbaryl	Water	kg 1,4-DB eq	3.51558E-10
Carbaryl	Soil	kg 1,4-DB eq	4.84903E-09
Carbendazim	Soil	kg 1,4-DB eq	1.45791E-05
Carbofuran	Soil	kg 1,4-DB eq	0.000545338
Carbon disulfide	Air	kg 1,4-DB eq	1.64006E-05
Carbon disulfide	Water	kg 1,4-DB eq	4.06973E-06
Chlorfenvinphos	Soil	kg 1,4-DB eq	1.15652E-07
Chloridazon	Soil	kg 1,4-DB eq	1.10422E-09
Chloroform	Air	kg 1,4-DB eq	6.61364E-11
Chloroform	Water	kg 1,4-DB eq	5.75581E-11
Chlorothalonil	Soil	kg 1,4-DB eq	1.70646E-06
Chlorpyrifos	Air	kg 1,4-DB eq	1.58335E-05
Chlorpyrifos	Soil	kg 1,4-DB eq	0.000184439
Chromium III	Water	kg 1,4-DB eq	7.80332E-05
Chromium VI	Air	kg 1,4-DB eq	3.58663E-05
Chromium VI	Water	kg 1,4-DB eq	0.027334516
Chromium VI	Soil	kg 1,4-DB eq	0.000166196
Chrysene	Air	kg 1,4-DB eq	2.36938E-09
Cobalt	Air	kg 1,4-DB eq	0.009375811
Cobalt	Water	kg 1,4-DB eq	3.206314

Cobalt	Soil	kg 1,4-DB eq	0.015359736
Copper	Air	kg 1,4-DB eq	0.582589626
Copper	Water	kg 1,4-DB eq	21.23114215
Copper	Soil	kg 1,4-DB eq	0.06222957
Cypermethrin	Air	kg 1,4-DB eq	3.23894E-05
Cypermethrin	Soil	kg 1,4-DB eq	0.032037657
Deltamethrin	Soil	kg 1,4-DB eq	1.43259E-09
Diazinon	Soil	kg 1,4-DB eq	0.000104353
Dichlorprop	Air	kg 1,4-DB eq	2.15148E-12
Dichlorprop	Water	kg 1,4-DB eq	1.2036E-10
Dichlorprop	Soil	kg 1,4-DB eq	1.16941E-11
Dichromate	Water	kg 1,4-DB eq	3.37977E-06
Dimethoate	Soil	kg 1,4-DB eq	4.4089E-07
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	kg 1,4-DB eq	0.000228077
Diuron	Soil	kg 1,4-DB eq	0.00012107
Endosulfan	Soil	kg 1,4-DB eq	1.50708E-06
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg 1,4-DB eq	3.39205E-12
Ethane, 1,1,1-trichloro-, HCFC-140	Water	kg 1,4-DB eq	1.02018E-14
Ethane, 1,2-dichloro-	Air	kg 1,4-DB eq	1.95341E-09
Ethane, 1,2-dichloro-	Water	kg 1,4-DB eq	4.40485E-09
Ethene	Air	kg 1,4-DB eq	7.85199E-15
Ethene	Water	kg 1,4-DB eq	3.85788E-07
Ethene, chloro-	Air	kg 1,4-DB eq	2.39871E-11
Ethene, chloro-	Water	kg 1,4-DB eq	2.09608E-09
Ethene, tetrachloro-	Air	kg 1,4-DB eq	6.85115E-11
Ethoprop	Soil	kg 1,4-DB eq	9.8519E-05
Ethylene oxide	Air	kg 1,4-DB eq	2.80046E-08
Ethylene oxide	Water	kg 1,4-DB eq	5.52356E-07
Fentin hydroxide	Soil	kg 1,4-DB eq	5.85136E-07
Fluoranthene	Air	kg 1,4-DB eq	9.26089E-09
Folpet	Soil	kg 1,4-DB eq	0.000164046
Formaldehyde	Air	kg 1,4-DB eq	0.021339876
Formaldehyde	Water	kg 1,4-DB eq	1.906246185
Glyphosate	Air	kg 1,4-DB eq	4.43326E-05
Glyphosate	Water	kg 1,4-DB eq	3.52347E-06
Glyphosate	Soil	kg 1,4-DB eq	1.39093E-05
Hydrogen fluoride	Air	kg 1,4-DB eq	0.006062867
Indeno (1,2,3-cd) pyrene	Air	kg 1,4-DB eq	6.3578E-09
Iprodione	Soil	kg 1,4-DB eq	3.49126E-08
Isoproturon	Soil	kg 1,4-DB eq	3.1035E-06
Lead	Air	kg 1,4-DB eq	0.001133559
Lead	Water	kg 1,4-DB eq	0.006537028
Lead	Soil	kg 1,4-DB eq	0.00049343
Linuron	Soil	kg 1,4-DB eq	0.000751367
m-Xylene	Air	kg 1,4-DB eq	9.06404E-09
m-Xylene	Water	kg 1,4-DB eq	1.17886E-06
Malathion	Soil	kg 1,4-DB eq	5.90525E-06
Mecoprop	Soil	kg 1,4-DB eq	1.62302E-08
Mecoprop-P	Soil	kg 1,4-DB eq	3.29981E-08
Mercury	Air	kg 1,4-DB eq	0.002348787

Mercury	Water	kg 1,4-DB eq	0.012220883
Mercury	Soil	kg 1,4-DB eq	2.92718E-05
Metallic ions, unspecified	Water	kg 1,4-DB eq	1.40103E-10
Metals, unspecified	Air	kg 1,4-DB eq	3.08796E-12
Metamitron	Soil	kg 1,4-DB eq	2.74213E-07
Metazachlor	Soil	kg 1,4-DB eq	3.59589E-07
Methane, bromo-, Halon 1001	Air	kg 1,4-DB eq	1.53782E-12
Methane, dichloro-, HCC-30	Air	kg 1,4-DB eq	2.50424E-11
Methane, dichloro-, HCC-30	Water	kg 1,4-DB eq	8.86733E-07
Methane, tetrachloro-, CFC-10	Air	kg 1,4-DB eq	5.27987E-11
Methomyl	Air	kg 1,4-DB eq	4.03656E-11
Methomyl	Water	kg 1,4-DB eq	6.11274E-12
Methomyl	Soil	kg 1,4-DB eq	1.29023E-10
Metolachlor	Air	kg 1,4-DB eq	3.11831E-05
Metolachlor	Water	kg 1,4-DB eq	3.80298E-06
Metolachlor	Soil	kg 1,4-DB eq	0.004727049
Molybdenum	Air	kg 1,4-DB eq	0.047748197
Molybdenum	Water	kg 1,4-DB eq	0.102334323
Molybdenum	Soil	kg 1,4-DB eq	0.000499689
Naphthalene	Air	kg 1,4-DB eq	4.23386E-08
Naphthalene	Water	kg 1,4-DB eq	0.000344117
Nickel	Air	kg 1,4-DB eq	0.124504943
Nickel	Water	kg 1,4-DB eq	13.65613774
Nickel	Soil	kg 1,4-DB eq	0.041954518
o-Xylene	Air	kg 1,4-DB eq	2.2299E-09
o-Xylene	Water	kg 1,4-DB eq	4.81988E-07
Oxamyl	Soil	kg 1,4-DB eq	2.19409E-07
Oxydemeton methyl	Soil	kg 1,4-DB eq	1.36628E-07
p-Xylene	Water	kg 1,4-DB eq	2.74159E-08
PAH, polycyclic aromatic hydrocarbons	Air	kg 1,4-DB eq	0.008807984
PAH, polycyclic aromatic hydrocarbons	Water	kg 1,4-DB eq	0.71513387
Parathion	Soil	kg 1,4-DB eq	4.96561E-06
Parathion, methyl	Air	kg 1,4-DB eq	1.02181E-06
Parathion, methyl	Soil	kg 1,4-DB eq	4.97013E-08
Permethrin	Air	kg 1,4-DB eq	1.34281E-05
Permethrin	Soil	kg 1,4-DB eq	4.27802E-07
Phenanthrene	Air	kg 1,4-DB eq	3.77051E-09
Phenanthrene	Water	kg 1,4-DB eq	3.71376E-06
Phenol	Air	kg 1,4-DB eq	9.64352E-06
Phenol	Water	kg 1,4-DB eq	0.100777327
Phenol, 2,4-dichloro-	Air	kg 1,4-DB eq	2.97376E-09
Phenol, pentachloro-	Air	kg 1,4-DB eq	3.95527E-05
Phenol, pentachloro-	Soil	kg 1,4-DB eq	2.6448E-10
Phthalate, dioctyl-	Air	kg 1,4-DB eq	7.37973E-12
Pirimicarb	Soil	kg 1,4-DB eq	9.5538E-05
Propachlor	Soil	kg 1,4-DB eq	9.90114E-06
Propylene oxide	Air	kg 1,4-DB eq	8.65338E-07
Propylene oxide	Water	kg 1,4-DB eq	0.000222203
Selenium	Air	kg 1,4-DB eq	0.007331728
Selenium	Water	kg 1,4-DB eq	0.466149979

Selenium	Soil	kg 1,4-DB eq	0.009362777
Simazine	Soil	kg 1,4-DB eq	6.38806E-06
Sodium dichromate	Air	kg 1,4-DB eq	7.22319E-07
Styrene	Air	kg 1,4-DB eq	1.73785E-09
Thallium	Air	kg 1,4-DB eq	0.000236011
Thallium	Water	kg 1,4-DB eq	0.103659212
Thiram	Soil	kg 1,4-DB eq	1.3141E-05
Tin	Air	kg 1,4-DB eq	0.000874433
Tin	Water	kg 1,4-DB eq	0.008316342
Tin	Soil	kg 1,4-DB eq	5.61384E-09
Toluene	Air	kg 1,4-DB eq	3.62223E-07
Toluene	Water	kg 1,4-DB eq	0.000195707
Triallate	Soil	kg 1,4-DB eq	1.5863E-09
Tributyltin compounds	Water	kg 1,4-DB eq	1.60189E-05
Trichlorfon	Soil	kg 1,4-DB eq	2.55021E-08
Trifluralin	Air	kg 1,4-DB eq	9.17266E-07
Trifluralin	Soil	kg 1,4-DB eq	1.2317E-05
Vanadium	Air	kg 1,4-DB eq	0.63881009
Vanadium	Water	kg 1,4-DB eq	4.702460618
Vanadium	Soil	kg 1,4-DB eq	0.050582355
Xylene	Water	kg 1,4-DB eq	0.000302225
Zinc	Air	kg 1,4-DB eq	0.032379727
Zinc	Water	kg 1,4-DB eq	1.856262659
Zinc	Soil	kg 1,4-DB eq	0.13743767
Total		**kg 1,4-DB eq**	**135.315**

Table I: Specification per substance for marine aquatic ecotoxicity (MAE) impact category.

Substance	Compartment	Unit	Total
2-Methyl-4-chlorophenoxyacetic acid	Air	kg 1,4-DB eq	8.53168E-12
2-Methyl-4-chlorophenoxyacetic acid	Water	kg 1,4-DB eq	2.53066E-12
2-Methyl-4-chlorophenoxyacetic acid	Soil	kg 1,4-DB eq	4.51013E-12
2,4-D	Air	kg 1,4-DB eq	3.31324E-07
2,4-D	Soil	kg 1,4-DB eq	8.35903E-07
Acenaphthene	Air	kg 1,4-DB eq	4.76752E-06
Acenaphthene	Water	kg 1,4-DB eq	0.000211963
Acenaphthylene	Water	kg 1,4-DB eq	1.32562E-05
Acephate	Air	kg 1,4-DB eq	1.29398E-07
Acephate	Soil	kg 1,4-DB eq	1.4753E-07
Acrolein	Air	kg 1,4-DB eq	0.061083575
Aldicarb	Soil	kg 1,4-DB eq	0.001022186
Aldrin	Soil	kg 1,4-DB eq	7.04187E-05
Anthracene	Air	kg 1,4-DB eq	2.11523E-07
Antimony	Air	kg 1,4-DB eq	161.057064
Antimony	Water	kg 1,4-DB eq	3.643715646
Antimony	Soil	kg 1,4-DB eq	0.008787815
Arsenic	Air	kg 1,4-DB eq	7.716309387
Arsenic	Water	kg 1,4-DB eq	39.64851869
Arsenic	Soil	kg 1,4-DB eq	0.332429683

Atrazine	Air	kg 1,4-DB eq	1.46265E-06
Atrazine	Water	kg 1,4-DB eq	3.2024E-07
Atrazine	Soil	kg 1,4-DB eq	3.147E-05
Azinphos-methyl	Soil	kg 1,4-DB eq	1.31809E-10
Barite	Water	kg 1,4-DB eq	6095.740341
Barium	Air	kg 1,4-DB eq	1485.662252
Barium	Water	kg 1,4-DB eq	25562.30346
Barium	Soil	kg 1,4-DB eq	618.3763875
Benomyl	Soil	kg 1,4-DB eq	9.79381E-12
Bentazone	Air	kg 1,4-DB eq	1.74181E-09
Bentazone	Water	kg 1,4-DB eq	1.31655E-11
Bentazone	Soil	kg 1,4-DB eq	1.54171E-10
Benzene	Air	kg 1,4-DB eq	1.40039E-05
Benzene	Water	kg 1,4-DB eq	2.04405E-06
Benzene, 1,2-dichloro-	Air	kg 1,4-DB eq	2.17735E-09
Benzene, 1,2-dichloro-	Water	kg 1,4-DB eq	1.09551E-05
Benzene, chloro-	Air	kg 1,4-DB eq	7.05641E-13
Benzene, chloro-	Water	kg 1,4-DB eq	2.81613E-06
Benzene, ethyl-	Air	kg 1,4-DB eq	3.16045E-07
Benzene, ethyl-	Water	kg 1,4-DB eq	5.97154E-07
Benzene, hexachloro-	Air	kg 1,4-DB eq	8.05665E-05
Benzene, pentachloro-	Air	kg 1,4-DB eq	6.24404E-08
Benzene, pentachloronitro-	Soil	kg 1,4-DB eq	2.92931E-07
Benzo(a)anthracene	Air	kg 1,4-DB eq	5.94967E-08
Benzo(a)pyrene	Air	kg 1,4-DB eq	0.012894504
Benzo(g,h,i)perylene	Air	kg 1,4-DB eq	2.78777E-08
Benzo(k)fluoranthene	Air	kg 1,4-DB eq	1.11258E-06
Benzyl chloride	Air	kg 1,4-DB eq	4.31002E-10
Beryllium	Air	kg 1,4-DB eq	83.29928073
Beryllium	Water	kg 1,4-DB eq	34465.04737
Bifenthrin	Soil	kg 1,4-DB eq	2.78511E-11
Butadiene	Air	kg 1,4-DB eq	8.06727E-14
Cadmium	Air	kg 1,4-DB eq	18.95705877
Cadmium	Water	kg 1,4-DB eq	33.52346081
Cadmium	Soil	kg 1,4-DB eq	0.599872368
Captan	Soil	kg 1,4-DB eq	3.376E-11
Carbaryl	Air	kg 1,4-DB eq	9.09061E-09
Carbaryl	Water	kg 1,4-DB eq	1.10201E-13
Carbaryl	Soil	kg 1,4-DB eq	1.5404E-12
Carbendazim	Soil	kg 1,4-DB eq	2.20499E-07
Carbofuran	Soil	kg 1,4-DB eq	1.83644E-06
Carbon disulfide	Air	kg 1,4-DB eq	0.000760389
Carbon disulfide	Water	kg 1,4-DB eq	6.93791E-08
Chlorfenvinphos	Soil	kg 1,4-DB eq	6.1346E-10
Chloridazon	Soil	kg 1,4-DB eq	4.96284E-11
Chloroform	Air	kg 1,4-DB eq	4.11268E-08
Chloroform	Water	kg 1,4-DB eq	7.91934E-11
Chlorothalonil	Soil	kg 1,4-DB eq	2.70736E-06
Chlorpyrifos	Air	kg 1,4-DB eq	1.89453E-06
Chlorpyrifos	Soil	kg 1,4-DB eq	7.46044E-08

Chromium III	Water	kg 1,4-DB eq	0.009723098
Chromium VI	Air	kg 1,4-DB eq	0.097944423
Chromium VI	Water	kg 1,4-DB eq	3.394611426
Chromium VI	Soil	kg 1,4-DB eq	0.020734974
Chrysene	Air	kg 1,4-DB eq	2.50235E-08
Cobalt	Air	kg 1,4-DB eq	79.81911194
Cobalt	Water	kg 1,4-DB eq	4118.377858
Cobalt	Soil	kg 1,4-DB eq	19.761064
Copper	Air	kg 1,4-DB eq	2343.47989
Copper	Water	kg 1,4-DB eq	4269.247778
Copper	Soil	kg 1,4-DB eq	12.5505016
Cypermethrin	Air	kg 1,4-DB eq	7.36123E-06
Cypermethrin	Soil	kg 1,4-DB eq	4.7815E-05
Deltamethrin	Soil	kg 1,4-DB eq	3.54878E-12
Diazinon	Soil	kg 1,4-DB eq	6.31779E-07
Dichlorprop	Air	kg 1,4-DB eq	1.33465E-12
Dichlorprop	Water	kg 1,4-DB eq	3.332E-13
Dichlorprop	Soil	kg 1,4-DB eq	3.22936E-14
Dichromate	Water	kg 1,4-DB eq	0.000421836
Dimethoate	Soil	kg 1,4-DB eq	1.94307E-09
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	kg 1,4-DB eq	0.0316952
Diuron	Soil	kg 1,4-DB eq	7.33439E-07
Endosulfan	Soil	kg 1,4-DB eq	9.20613E-10
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg 1,4-DB eq	8.45231E-09
Ethane, 1,1,1-trichloro-, HCFC-140	Water	kg 1,4-DB eq	2.79158E-14
Ethane, 1,2-dichloro-	Air	kg 1,4-DB eq	1.33948E-06
Ethane, 1,2-dichloro-	Water	kg 1,4-DB eq	1.56766E-08
Ethene	Air	kg 1,4-DB eq	4.35428E-14
Ethene	Water	kg 1,4-DB eq	4.76662E-10
Ethene, chloro-	Air	kg 1,4-DB eq	1.09032E-09
Ethene, chloro-	Water	kg 1,4-DB eq	2.83233E-11
Ethene, tetrachloro-	Air	kg 1,4-DB eq	5.60699E-08
Ethoprop	Soil	kg 1,4-DB eq	2.34315E-06
Ethylene oxide	Air	kg 1,4-DB eq	2.42309E-07
Ethylene oxide	Water	kg 1,4-DB eq	3.53395E-08
Fentin hydroxide	Soil	kg 1,4-DB eq	9.41439E-09
Fluoranthene	Air	kg 1,4-DB eq	1.04055E-07
Folpet	Soil	kg 1,4-DB eq	2.57527E-05
Formaldehyde	Air	kg 1,4-DB eq	0.004211138
Formaldehyde	Water	kg 1,4-DB eq	0.001288921
Glyphosate	Air	kg 1,4-DB eq	3.40085E-05
Glyphosate	Water	kg 1,4-DB eq	1.0699E-08
Glyphosate	Soil	kg 1,4-DB eq	4.2342E-08
Hydrogen fluoride	Air	kg 1,4-DB eq	679.459216
Indeno(1,2,3-cd)pyrene	Air	kg 1,4-DB eq	2.80514E-07
Iprodione	Soil	kg 1,4-DB eq	3.28148E-12
Isoproturon	Soil	kg 1,4-DB eq	3.3067E-08
Lead	Air	kg 1,4-DB eq	3.329829886
Lead	Water	kg 1,4-DB eq	0.925581851
Lead	Soil	kg 1,4-DB eq	0.056899369

Linuron	Soil	kg 1,4-DB eq	1.35528E-05
m-Xylene	Air	kg 1,4-DB eq	8.15142E-08
m-Xylene	Water	kg 1,4-DB eq	4.17925E-09
Malathion	Soil	kg 1,4-DB eq	2.40949E-08
Mecoprop	Soil	kg 1,4-DB eq	2.86192E-11
Mecoprop-P	Soil	kg 1,4-DB eq	5.81867E-11
Mercury	Air	kg 1,4-DB eq	8.891306153
Mercury	Water	kg 1,4-DB eq	1.571705585
Mercury	Soil	kg 1,4-DB eq	0.005730089
Metallic ions, unspecified	Water	kg 1,4-DB eq	1.60052E-07
Metals, unspecified	Air	kg 1,4-DB eq	2.2623E-08
Metamitron	Soil	kg 1,4-DB eq	7.50269E-10
Metazachlor	Soil	kg 1,4-DB eq	3.00115E-09
Methane, bromo-, Halon 1001	Air	kg 1,4-DB eq	1.93285E-10
Methane, dichloro-, HCC-30	Air	kg 1,4-DB eq	2.88777E-09
Methane, dichloro-, HCC-30	Water	kg 1,4-DB eq	2.55206E-07
Methane, tetrachloro-, CFC-10	Air	kg 1,4-DB eq	2.40946E-07
Methomyl	Air	kg 1,4-DB eq	1.12966E-11
Methomyl	Water	kg 1,4-DB eq	1.90627E-13
Methomyl	Soil	kg 1,4-DB eq	4.02624E-12
Metolachlor	Air	kg 1,4-DB eq	8.06093E-06
Metolachlor	Water	kg 1,4-DB eq	5.76389E-08
Metolachlor	Soil	kg 1,4-DB eq	7.45323E-05
Molybdenum	Air	kg 1,4-DB eq	956.9268734
Molybdenum	Water	kg 1,4-DB eq	450.5075049
Molybdenum	Soil	kg 1,4-DB eq	2.193290182
Naphthalene	Air	kg 1,4-DB eq	7.78484E-08
Naphthalene	Water	kg 1,4-DB eq	5.53512E-07
Nickel	Air	kg 1,4-DB eq	744.2584803
Nickel	Water	kg 1,4-DB eq	9490.170786
Nickel	Soil	kg 1,4-DB eq	29.04543521
o-Xylene	Air	kg 1,4-DB eq	2.18918E-08
o-Xylene	Water	kg 1,4-DB eq	2.14122E-09
Oxamyl	Soil	kg 1,4-DB eq	6.26245E-11
Oxydemeton methyl	Soil	kg 1,4-DB eq	2.7889E-10
p-Xylene	Water	kg 1,4-DB eq	1.0877E-10
PAH, polycyclic aromatic hydrocarbons	Air	kg 1,4-DB eq	0.218151233
PAH, polycyclic aromatic hydrocarbons	Water	kg 1,4-DB eq	0.292543537
Parathion	Soil	kg 1,4-DB eq	2.34321E-08
Parathion, methyl	Air	kg 1,4-DB eq	7.49536E-07
Parathion, methyl	Soil	kg 1,4-DB eq	2.60044E-10
Permethrin	Air	kg 1,4-DB eq	2.6096E-05
Permethrin	Soil	kg 1,4-DB eq	2.55188E-09
Phenanthrene	Air	kg 1,4-DB eq	2.17552E-08
Phenanthrene	Water	kg 1,4-DB eq	7.54245E-08
Phenol	Air	kg 1,4-DB eq	3.50846E-06
Phenol	Water	kg 1,4-DB eq	0.000456895
Phenol, 2,4-dichloro-	Air	kg 1,4-DB eq	2.84631E-09
Phenol, pentachloro-	Air	kg 1,4-DB eq	0.000150677
Phenol, pentachloro-	Soil	kg 1,4-DB eq	5.41073E-12

Phthalate, dioctyl-	Air	kg 1,4-DB eq	5.12191E-11
Pirimicarb	Soil	kg 1,4-DB eq	4.18193E-07
Propachlor	Soil	kg 1,4-DB eq	2.42091E-08
Propylene oxide	Air	kg 1,4-DB eq	2.86878E-06
Propylene oxide	Water	kg 1,4-DB eq	3.23765E-06
Selenium	Air	kg 1,4-DB eq	284.6751476
Selenium	Water	kg 1,4-DB eq	4058.316511
Selenium	Soil	kg 1,4-DB eq	81.4433327
Simazine	Soil	kg 1,4-DB eq	3.4819E-08
Sodium dichromate	Air	kg 1,4-DB eq	0.001970392
Styrene	Air	kg 1,4-DB eq	1.73785E-08
Thallium	Air	kg 1,4-DB eq	3.897993468
Thallium	Water	kg 1,4-DB eq	344.2365839
Thiram	Soil	kg 1,4-DB eq	1.24514E-08
Tin	Air	kg 1,4-DB eq	2.585430611
Tin	Water	kg 1,4-DB eq	1.002852964
Tin	Soil	kg 1,4-DB eq	6.78542E-07
Toluene	Air	kg 1,4-DB eq	3.5965E-06
Toluene	Water	kg 1,4-DB eq	6.34405E-06
Triallate	Soil	kg 1,4-DB eq	2.70247E-11
Tributyltin compounds	Water	kg 1,4-DB eq	3.028157644
Trichlorfon	Soil	kg 1,4-DB eq	5.19287E-12
Trifluralin	Air	kg 1,4-DB eq	9.66521E-06
Trifluralin	Soil	kg 1,4-DB eq	3.55892E-07
Vanadium	Air	kg 1,4-DB eq	4504.903528
Vanadium	Water	kg 1,4-DB eq	4523.010178
Vanadium	Soil	kg 1,4-DB eq	48.40677016
Xylene	Water	kg 1,4-DB eq	9.11611E-06
Zinc	Air	kg 1,4-DB eq	122.424474
Zinc	Water	kg 1,4-DB eq	336.0130019
Zinc	Soil	kg 1,4-DB eq	20.77412158
Total		**kg 1,4-DB eq**	**256717.37**

Table J: Specification per substance for terrestrial ecotoxicity (TE) impact category.

Substance	Compartment	Unit	Total
2-Methyl-4-chlorophenoxyacetic acid	Air	kg 1,4-DB eq	1.28576E-12
2-Methyl-4-chlorophenoxyacetic acid	Water	kg 1,4-DB eq	9.41153E-22
2-Methyl-4-chlorophenoxyacetic acid	Soil	kg 1,4-DB eq	6.90774E-10
2,4-D	Air	kg 1,4-DB eq	3.74622E-08
2,4-D	Soil	kg 1,4-DB eq	7.95618E-06
Acenaphthene	Air	kg 1,4-DB eq	1.14152E-09
Acenaphthene	Water	kg 1,4-DB eq	6.70202E-11
Acenaphthylene	Water	kg 1,4-DB eq	4.19146E-12
Acephate	Air	kg 1,4-DB eq	4.60231E-09
Acephate	Soil	kg 1,4-DB eq	3.7047E-07
Acrolein	Air	kg 1,4-DB eq	0.001759121
Aldicarb	Soil	kg 1,4-DB eq	0.00263026
Aldrin	Soil	kg 1,4-DB eq	4.4475E-05
Anthracene	Air	kg 1,4-DB eq	3.94427E-12

Antimony	Air	kg 1,4-DB eq	0.002972987
Antimony	Water	kg 1,4-DB eq	2.23194E-24
Antimony	Soil	kg 1,4-DB eq	8.01808E-07
Arsenic	Air	kg 1,4-DB eq	0.053780338
Arsenic	Water	kg 1,4-DB eq	3.46474E-21
Arsenic	Soil	kg 1,4-DB eq	0.014400975
Atrazine	Air	kg 1,4-DB eq	1.03801E-08
Atrazine	Water	kg 1,4-DB eq	5.0418E-13
Atrazine	Soil	kg 1,4-DB eq	6.11763E-06
Azinphos-methyl	Soil	kg 1,4-DB eq	9.09575E-10
Barite	Water	kg 1,4-DB eq	3.71087E-21
Barium	Air	kg 1,4-DB eq	0.009256819
Barium	Water	kg 1,4-DB eq	1.55881E-20
Barium	Soil	kg 1,4-DB eq	0.014679078
Benomyl	Soil	kg 1,4-DB eq	5.92381E-09
Bentazone	Air	kg 1,4-DB eq	7.10771E-10
Bentazone	Water	kg 1,4-DB eq	1.09513E-17
Bentazone	Soil	kg 1,4-DB eq	2.5552E-09
Benzene	Air	kg 1,4-DB eq	7.8022E-08
Benzene	Water	kg 1,4-DB eq	6.65242E-09
Benzene, 1,2-dichloro-	Air	kg 1,4-DB eq	1.72946E-12
Benzene, 1,2-dichloro-	Water	kg 1,4-DB eq	8.57786E-09
Benzene, chloro-	Air	kg 1,4-DB eq	4.59297E-15
Benzene, chloro-	Water	kg 1,4-DB eq	1.76873E-08
Benzene, ethyl-	Air	kg 1,4-DB eq	5.6777E-10
Benzene, ethyl-	Water	kg 1,4-DB eq	1.49824E-10
Benzene, hexachloro-	Air	kg 1,4-DB eq	8.72525E-09
Benzene, pentachloro-	Air	kg 1,4-DB eq	1.4067E-11
Benzene, pentachloronitro-	Soil	kg 1,4-DB eq	2.59205E-08
Benzo(a)anthracene	Air	kg 1,4-DB eq	1.34159E-11
Benzo(a)pyrene	Air	kg 1,4-DB eq	2.2683E-06
Benzo(g,h,i)perylene	Air	kg 1,4-DB eq	3.42593E-12
Benzo(k)fluoranthene	Air	kg 1,4-DB eq	2.77678E-10
Benzyl chloride	Air	kg 1,4-DB eq	3.32774E-13
Beryllium	Air	kg 1,4-DB eq	0.000313702
Beryllium	Water	kg 1,4-DB eq	2.1101E-20
Bifenthrin	Soil	kg 1,4-DB eq	2.03509E-08
Butadiene	Air	kg 1,4-DB eq	6.83068E-16
Cadmium	Air	kg 1,4-DB eq	0.001386769
Cadmium	Water	kg 1,4-DB eq	2.16038E-24
Cadmium	Soil	kg 1,4-DB eq	0.000894453
Captan	Soil	kg 1,4-DB eq	2.01186E-08
Carbaryl	Air	kg 1,4-DB eq	4.85346E-11
Carbaryl	Water	kg 1,4-DB eq	2.01001E-20
Carbaryl	Soil	kg 1,4-DB eq	2.23641E-11
Carbendazim	Soil	kg 1,4-DB eq	3.58311E-07
Carbofuran	Soil	kg 1,4-DB eq	6.99152E-06
Carbon disulfide	Air	kg 1,4-DB eq	2.55451E-06
Carbon disulfide	Water	kg 1,4-DB eq	1.86432E-10
Chlorfenvinphos	Soil	kg 1,4-DB eq	9.41022E-09

Chloridazon	Soil	kg 1,4-DB eq	5.49655E-10
Chloroform	Air	kg 1,4-DB eq	2.79273E-11
Chloroform	Water	kg 1,4-DB eq	5.33399E-14
Chlorothalonil	Soil	kg 1,4-DB eq	1.11248E-06
Chlorpyrifos	Air	kg 1,4-DB eq	3.84398E-09
Chlorpyrifos	Soil	kg 1,4-DB eq	8.65204E-06
Chromium III	Water	kg 1,4-DB eq	2.56346E-24
Chromium VI	Air	kg 1,4-DB eq	0.014131981
Chromium VI	Water	kg 1,4-DB eq	2.24005E-22
Chromium VI	Soil	kg 1,4-DB eq	0.049858908
Chrysene	Air	kg 1,4-DB eq	1.29953E-11
Cobalt	Air	kg 1,4-DB eq	0.001599317
Cobalt	Water	kg 1,4-DB eq	2.52932E-21
Cobalt	Soil	kg 1,4-DB eq	0.002003053
Copper	Air	kg 1,4-DB eq	0.0183437
Copper	Water	kg 1,4-DB eq	7.4388E-23
Copper	Soil	kg 1,4-DB eq	0.00150606
Cypermethrin	Air	kg 1,4-DB eq	3.4559E-06
Cypermethrin	Soil	kg 1,4-DB eq	0.014441095
Deltamethrin	Soil	kg 1,4-DB eq	5.07647E-10
Diazinon	Soil	kg 1,4-DB eq	9.30276E-07
Dichlorprop	Air	kg 1,4-DB eq	1.47549E-14
Dichlorprop	Water	kg 1,4-DB eq	1.37813E-22
Dichlorprop	Soil	kg 1,4-DB eq	1.27735E-12
Dichromate	Water	kg 1,4-DB eq	2.76989E-26
Dimethoate	Soil	kg 1,4-DB eq	3.96998E-08
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	kg 1,4-DB eq	1.28494E-06
Diuron	Soil	kg 1,4-DB eq	7.96606E-06
Endosulfan	Soil	kg 1,4-DB eq	1.87532E-06
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg 1,4-DB eq	4.94905E-12
Ethane, 1,1,1-trichloro-, HCFC-140	Water	kg 1,4-DB eq	1.62301E-17
Ethane, 1,2-dichloro-	Air	kg 1,4-DB eq	4.33361E-10
Ethane, 1,2-dichloro-	Water	kg 1,4-DB eq	5.03961E-12
Ethene	Air	kg 1,4-DB eq	7.41271E-16
Ethene	Water	kg 1,4-DB eq	1.92036E-17
Ethene, chloro-	Air	kg 1,4-DB eq	2.18903E-12
Ethene, chloro-	Water	kg 1,4-DB eq	1.92328E-14
Ethene, tetrachloro-	Air	kg 1,4-DB eq	1.34535E-09
Ethoprop	Soil	kg 1,4-DB eq	2.40528E-06
Ethylene oxide	Air	kg 1,4-DB eq	7.15011E-10
Ethylene oxide	Water	kg 1,4-DB eq	9.91986E-11
Fentin hydroxide	Soil	kg 1,4-DB eq	1.76616E-08
Fluoranthene	Air	kg 1,4-DB eq	9.469E-12
Folpet	Soil	kg 1,4-DB eq	3.85563E-06
Formaldehyde	Air	kg 1,4-DB eq	0.002428509
Formaldehyde	Water	kg 1,4-DB eq	1.05827E-05
Glyphosate	Air	kg 1,4-DB eq	9.43332E-08
Glyphosate	Water	kg 1,4-DB eq	5.78671E-20
Glyphosate	Soil	kg 1,4-DB eq	9.21547E-07
Hydrogen fluoride	Air	kg 1,4-DB eq	3.85462E-06

Indeno(1,2,3-cd) pyrene	Air	kg 1,4-DB eq	3.09413E-11
Iprodione	Soil	kg 1,4-DB eq	2.17267E-08
Isoproturon	Soil	kg 1,4-DB eq	1.18967E-07
Lead	Air	kg 1,4-DB eq	0.007415366
Lead	Water	kg 1,4-DB eq	3.93415E-25
Lead	Soil	kg 1,4-DB eq	0.002455816
Linuron	Soil	kg 1,4-DB eq	2.24434E-05
m-Xylene	Air	kg 1,4-DB eq	1.35027E-10
m-Xylene	Water	kg 1,4-DB eq	1.18083E-12
Malathion	Soil	kg 1,4-DB eq	2.75943E-09
Mecoprop	Soil	kg 1,4-DB eq	2.55895E-09
Mecoprop-P	Soil	kg 1,4-DB eq	5.2027E-09
Mercury	Air	kg 1,4-DB eq	0.209686637
Mercury	Water	kg 1,4-DB eq	0.006815866
Mercury	Soil	kg 1,4-DB eq	0.001933042
Metallic ions, unspecified	Water	kg 1,4-DB eq	2.20167E-31
Metals, unspecified	Air	kg 1,4-DB eq	7.05059E-12
Metamitron	Soil	kg 1,4-DB eq	2.76205E-08
Metazachlor	Soil	kg 1,4-DB eq	1.59207E-08
Methane, bromo-, Halon 1001	Air	kg 1,4-DB eq	6.01959E-13
Methane, dichloro-, HCC-30	Air	kg 1,4-DB eq	3.21114E-12
Methane, dichloro-, HCC-30	Water	kg 1,4-DB eq	2.81159E-10
Methane, tetrachloro-, CFC-10	Air	kg 1,4-DB eq	9.86832E-11
Methomyl	Air	kg 1,4-DB eq	3.45576E-13
Methomyl	Water	kg 1,4-DB eq	9.78038E-20
Methomyl	Soil	kg 1,4-DB eq	2.79091E-12
Metolachlor	Air	kg 1,4-DB eq	2.39707E-09
Metolachlor	Water	kg 1,4-DB eq	2.10946E-14
Metolachlor	Soil	kg 1,4-DB eq	1.34558E-06
Molybdenum	Air	kg 1,4-DB eq	0.008587805
Molybdenum	Water	kg 1,4-DB eq	4.97927E-22
Molybdenum	Soil	kg 1,4-DB eq	6.88502E-05
Naphthalene	Air	kg 1,4-DB eq	6.99099E-11
Naphthalene	Water	kg 1,4-DB eq	2.56391E-10
Nickel	Air	kg 1,4-DB eq	0.022961166
Nickel	Water	kg 1,4-DB eq	4.34435E-21
Nickel	Soil	kg 1,4-DB eq	0.005933213
o-Xylene	Air	kg 1,4-DB eq	3.04186E-11
o-Xylene	Water	kg 1,4-DB eq	9.981E-13
Oxamyl	Soil	kg 1,4-DB eq	4.36587E-08
Oxydemeton methyl	Soil	kg 1,4-DB eq	1.30008E-08
p-Xylene	Water	kg 1,4-DB eq	2.44359E-14
PAH, polycyclic aromatic hydrocarbons	Air	kg 1,4-DB eq	5.22334E-05
PAH, polycyclic aromatic hydrocarbons	Water	kg 1,4-DB eq	6.02834E-08
Parathion	Soil	kg 1,4-DB eq	1.71503E-07
Parathion, methyl	Air	kg 1,4-DB eq	5.85963E-09
Parathion, methyl	Soil	kg 1,4-DB eq	3.59003E-09
Permethrin	Air	kg 1,4-DB eq	2.22956E-08
Permethrin	Soil	kg 1,4-DB eq	1.17097E-07
Phenanthrene	Air	kg 1,4-DB eq	4.03983E-13

Phenanthrene	Water	kg 1,4-DB eq	4.34589E-13
Phenol	Air	kg 1,4-DB eq	2.1E-08
Phenol	Water	kg 1,4-DB eq	1.06231E-09
Phenol, 2,4-dichloro-	Air	kg 1,4-DB eq	6.4573E-11
Phenol, pentachloro-	Air	kg 1,4-DB eq	8.47559E-06
Phenol, pentachloro-	Soil	kg 1,4-DB eq	9.67067E-10
Phthalate, dioctyl-	Air	kg 1,4-DB eq	4.53655E-15
Pirimicarb	Soil	kg 1,4-DB eq	6.865E-06
Propachlor	Soil	kg 1,4-DB eq	1.42508E-06
Propylene oxide	Air	kg 1,4-DB eq	3.55071E-08
Propylene oxide	Water	kg 1,4-DB eq	3.63044E-08
Selenium	Air	kg 1,4-DB eq	0.000718402
Selenium	Water	kg 1,4-DB eq	2.48633E-21
Selenium	Soil	kg 1,4-DB eq	0.000705415
Simazine	Soil	kg 1,4-DB eq	8.03305E-08
Sodium dichromate	Air	kg 1,4-DB eq	0.000284191
Styrene	Air	kg 1,4-DB eq	4.64336E-12
Thallium	Air	kg 1,4-DB eq	5.17702E-05
Thallium	Water	kg 1,4-DB eq	4.0506E-22
Thiram	Soil	kg 1,4-DB eq	9.73124E-07
Tin	Air	kg 1,4-DB eq	0.004957417
Tin	Water	kg 1,4-DB eq	6.40848E-25
Tin	Soil	kg 1,4-DB eq	2.42453E-08
Toluene	Air	kg 1,4-DB eq	8.18088E-08
Toluene	Water	kg 1,4-DB eq	9.62328E-09
Triallate	Soil	kg 1,4-DB eq	4.18963E-11
Tributyltin compounds	Water	kg 1,4-DB eq	3.65614E-08
Trichlorfon	Soil	kg 1,4-DB eq	1.44846E-08
Trifluralin	Air	kg 1,4-DB eq	1.55201E-09
Trifluralin	Soil	kg 1,4-DB eq	1.08934E-05
Vanadium	Air	kg 1,4-DB eq	0.245554168
Vanadium	Water	kg 1,4-DB eq	5.37679E-21
Vanadium	Soil	kg 1,4-DB eq	0.014902758
Xylene	Water	kg 1,4-DB eq	3.90214E-10
Zinc	Air	kg 1,4-DB eq	0.02182903
Zinc	Water	kg 1,4-DB eq	6.10796E-23
Zinc	Soil	kg 1,4-DB eq	0.070879805
Total		**kg 1,4-DB eq**	**3.178**

Table K: Specification per substance for photochemical oxidation (PO) impact category

Substance	Compartment	Unit	Total
1-Butanol	Air	kg C2H4 eq	5.16744E-10
1-Pentene	Air	kg C2H4 eq	8.21143E-10
1-Propanol	Air	kg C2H4 eq	1.8034E-06
2-Butene, 2-methyl-	Air	kg C2H4 eq	1.48858E-11
2-Methyl-1-propanol	Air	kg C2H4 eq	2.99251E-10
2-Propanol	Air	kg C2H4 eq	5.15269E-06
4-Methyl-2-pentanone	Air	kg C2H4 eq	1.59935E-11
Acetaldehyde	Air	kg C2H4 eq	0.000292356
Acetic acid	Air	kg C2H4 eq	1.72711E-05
Acetone	Air	kg C2H4 eq	1.02959E-05
Benzaldehyde	Air	kg C2H4 eq	-8.67195E-06
Benzene	Air	kg C2H4 eq	0.001090307
Benzene, ethyl-	Air	kg C2H4 eq	0.00028984
Butadiene	Air	kg C2H4 eq	2.50556E-08
Butane	Air	kg C2H4 eq	0.00220743
Carbon monoxide	Air	kg C2H4 eq	1.36726E-07
Carbon monoxide, biogenic	Air	kg C2H4 eq	0.043494627
Carbon monoxide, fossil	Air	kg C2H4 eq	0.017634343
Chloroform	Air	kg C2H4 eq	1.59783E-08
Cumene	Air	kg C2H4 eq	1.05144E-05
Cyclohexane	Air	kg C2H4 eq	9.30483E-10
Diethyl ether	Air	kg C2H4 eq	1.34553E-11
Dimethyl ether	Air	kg C2H4 eq	0.000383179
Ethane	Air	kg C2H4 eq	0.000979769
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg C2H4 eq	2.50233E-10
Ethanol	Air	kg C2H4 eq	2.57513E-05
Ethene	Air	kg C2H4 eq	0.00054909
Ethene, tetrachloro-	Air	kg C2H4 eq	4.81073E-09
Ethyl acetate	Air	kg C2H4 eq	2.68577E-05
Ethyne	Air	kg C2H4 eq	3.5204E-06
Formaldehyde	Air	kg C2H4 eq	0.001340847
Formic acid	Air	kg C2H4 eq	1.38841E-07
Heptane	Air	kg C2H4 eq	0.00068496
Hexane	Air	kg C2H4 eq	0.001495295
Isoprene	Air	kg C2H4 eq	0.001390909
m-Xylene	Air	kg C2H4 eq	0.000229816
Methane	Air	kg C2H4 eq	0.000767507
Methane, biogenic	Air	kg C2H4 eq	0.000109872
Methane, dichloro-, HCC-30	Air	kg C2H4 eq	5.11377E-08
Methane, fossil	Air	kg C2H4 eq	0.004231328
Methane, monochloro-, R-40	Air	kg C2H4 eq	3.67247E-09
Methanol	Air	kg C2H4 eq	0.000173991
Methyl acetate	Air	kg C2H4 eq	6.95999E-12
Methyl ethyl ketone	Air	kg C2H4 eq	4.79352E-05
Methyl formate	Air	kg C2H4 eq	1.74124E-11
o-Xylene	Air	kg C2H4 eq	2.52211E-05
Pentane	Air	kg C2H4 eq	0.003446372

Pentane, 3-methyl-	Air	kg C2H4 eq	2.35777E-08
Propanol	Air	kg C2H4 eq	2.63978E-06
Propane	Air	kg C2H4 eq	0.001422751
Propene	Air	kg C2H4 eq	0.000389833
Propionic acid	Air	kg C2H4 eq	6.69554E-07
Styrene	Air	kg C2H4 eq	4.84822E-06
Sulfur dioxide	Air	kg C2H4 eq	0.046159993
Sulfur monoxide	Air	kg C2H4 eq	0.00015746
t-Butyl methyl ether	Air	kg C2H4 eq	3.72835E-06
Toluene	Air	kg C2H4 eq	0.003277498
Total		**kg C2H4 eq**	**0.247**

Table L.
Assumptions and emission factors used to estimate GHG emissions from production chain of particleboard produced in Pakistan.

Emission source	EF/GCV	Unit	GHG Protocol source
Energy consumption in stationary sources			
When reporting energy consumption, the GRI initiative recommends using the Gross Calorific Value of fuels.			
Gross Calorific Value of diesel oil:	43.33	GJ/tonne	(GRI, 2002)
Gross Calorific Value of petroleum/gasoline:	44.8	GJ/tonne	(GRI, 2002)
Gross Calorific Value of heavy fuel oil:	40.19	GJ/tonne	(GRI, 2002)
Gross Calorific Value of natural gas:	39.01	GJ/1000m3	(GRI, 2002)
CO_2 emission factor for electricity:	0.483	$kgCO_2/kWh$	(WBCSD, 2001)
CO_2 emission factor for diesel oil:	0.074	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emission factor for petroleum/gasoline:	0.069	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emission factor for heavy fuel oil:	0.074	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emission factor for natural gas:	0.0503	tonnes CO_2/GJ	(WBCSD, 2001)
Conversion electricity kWh to GJ:	0.0036	GJ/kWh	(WBCSD, 2001)
Company freight/Transportation (energy consumption in mobile sources)			
CO_2 emissions for large trucks:	0.000082	tonnesCO_2/tonne.km (derived from data below)	
CO_2 emissions for medium trucks:	0.000336	tonnesCO_2/tonne.km (derived from data below)	
CO_2 emissions for small trucks	0.000591	tonnesCO2/tonne.km (derived from data below)	
CO_2 emissions for diesel:	2.6814	$kgCO_2$/litre	(WBCSD, 2001)
CO_2 emissions for petrol:	2.34	$kgCO_2$/litre	(WBCSD, 2001)
large trucks (high cube containers) fuel consumption:	20	liter/100km (working estimate)	
large trucks (high cube containers) average loading:	30	tonnes/movement (working estimate)	
medium trucks (vans) fuel consumption:	10	liter/100km (working estimate)	
medium trucks (vans) average loading:	10	tonnes/movement (working estimate)	
CO_2 emissions for diesel oil:	0.07477	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emissions for petrol:	0.0693	tonnes CO_2/GJ	(WBCSD, 2001)
Company business travels (energy consumption in mobile sources)			
Emissions of company vehicles are equivalent to those of average petrol and diesel driven vehicles			
CO_2 emissions for an average petrol car:	2.34321	$kgCO_2$/litre	(WBCSD, 2001)
CO_2 emissions for an average diesel car:	2.6814	$kgCO_2$/litre	(WBCSD, 2001)
CO_2 emissions for an average LPG car:	1.535007	$kgCO_2$/litre	(WBCSD, 2001)
CO_2 emissions for an average CNG car:	2.65	$kgCO_2/kg$	(DEFRA, 2001)
CO_2 emissions for diesel oil:	0.07477	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emissions for petroleum/gasoline:	0.0693	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emissions for LPG:	0.059782	tonnes CO_2/GJ	(WBCSD, 2001)
CO_2 emissions for CNG:	0.050341	tonnes CO_2/GJ	(WBCSD, 2001)
Wastes sent to landfill by PB industry			

CH_4 emissions = ((LW x L0) *(1 - R)) x (1-OX)

LW = mass of land filled waste

L0 (methane generation potential)		
L0 = MCF x DOC x DOCF x F x 16/12 (t C / t waste)		
R (recovered CH_4):	0	(IPCC, 1996)
OX (oxidation factor):	0	(IPCC, 2000)
MCF (methane correction factor):	0.6	(IPCC, 2000)
DOC (degradable organic carbon) for general waste:	0.2	(IPCC, 1996)
DOC for paper and card:	0.4	(IPCC, 1996)
DOC for non-food organic putrescibles:	0.17	(IPCC, 1996)
DOC for food:	0.15	(IPCC, 1996)
DOC for wood:	0.43	(IPCC, 1996)
DOC for rubber	0.39	(IPCC, 2006)
DOC for Textiles (Wiping clothes)	0.24	(IPCC, 2006)
DOC for others wastes	0.1	(IPCC, 2006)
DOC for inert waste:	0	(IPCC, 1996)
DOCF (fraction DOC dissimilated):	0.6	(IPCC, 2000)
F = Fraction by volume of CH_4 in landfill gas	0.5	(IPCC, 2000)
Global warming potential of CH_4:	23	(IPCC, 2001)

IPCC 'methane correction factors'

Type of site	**Methane correction value (MCF)**
Managed	1
Unmanaged - deep (>5m waste)	0.8
Unmanaged - shallow (<5m waste)	0.4
Uncategorized site - default value	0.6

Emission factor and energy content of wood burned in the dryer of PB industry and workers commutes

Net Calorific Value of wood burned in dryers of PB mill	20.90	MJ/Kg	(Wilson, 2010)
Emission factor for CO_2	112	tCO_2/TJ	(IPCC, 1996)
Emission factor for workers commuting via local bus	0.189	Kg CO_2e/pass.km	(UK DEFRA/DECC, 2010)

Questionnaire Survey Form for LCA of Particleboard Industry in Pakistan

The information(s) from this survey will be used in a Ph.D research project at the Department of Environmental Sciences, Quaid-i-Azam University, Islamabad. We will conduct life-cycle assessment that will describe environmental influences of wood product i.e. particleboard. Our objective is to acquire a database and produce life-cycle model of environmental performance for the particleboard production in Pakistan. The database will be the basis for the scientific evaluation of feasible alternatives affecting the environmental releases and energy requirements of particleboard through their life cycle. It is hoped that the output of the study will be used to competitively position wood based product i.e. particleboard in the marketplace over other types of materials.

This Ph.D research project survey is designed specifically for particleboard mills. Questions will be concentrated on annual production, electricity production and usage, fossil fuels use, material flows, and environmental emissions. We realize that you may not have all the information's requested, especially when it comes to specific equipment and processing groups. However, the data you can provide will be highly appreciated. We intend to maintain the confidentiality of the data and companies participating in this survey. Please contact us if you have any questions.

Company Name: ....

Facility Site (city, province): ....

Should we have a follow-up question about the data, please provide the name and the following information for the contact in your company.
Name: ....Title: ....

Telephone:....................................... E-mail:...

If you have any question (s) about the survey, please contact us at the following addresses.

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Questionnaire Survey Form for LCA of Particleboard Industry in Pakistan

Q.1. Company Name: ………………………………………………………………………

Q. 2. Facility Site (City and Province): ……..……………………………………………..

Q.3. Number of employees: ………………………………………

Q.4. Number of production lines: ……………………………………

Q.5. Year of installation of each line: ……………… Line 1…………….. Line 2. ……………

Annual Production (Please provide units of measurement if different than stated).

Q. 6: What is the production capacity of your particleboard industry in 2014/15 (m^3)…………

Q. 7: What is the typical size and thickness of Particleboard of your industry …………………..

Q. 8: Estimated average density of particleboard panel (kg/m^3) ………………………………....

Q. 9: What are the main sources of wood raw material in your industry?

1. Forest slash (kg) ……………………

2. Saw dust (kg) ………………………

3. Chips (kg) …………………………

4. Saw waste (kg) ………………………

5. Others (kg) …………………………...

Q. 10: Which type of resins/adhesives are used in your factory (kg) ……………………………

Q. 11: Production and transport of resin/adhesive's is from ……………………………………

Q. 12: What is the quantity of wax applied (kg) …………………………………………………..

Q.13: What is the quantity of Ammonium sulfate catalyst used (kg) …………………………....

Q. 14: What is the quantity of Urea scavenger (kg) ……………………………………………

Q.15: Other materials sold i.e. sander dust etc.

a. ……………………………………… (lb. or tons), b. ………………………… (lb or tones)

c. ……………………………………… (lb. or tons), d. ………………………… (lb or tones)

Q. 16: Amount of purchased electricity consumed from national grid in Kwh....…………………

Q. 17: Amount of electricity produced from fossil fuels (Kwh) ....

Q. 18: Amount of Natural Gas consumption in on-site operations of the unit (m^3) ....

Q.19: Quantity of sander dust used for energy production (kg) ....

Q. 20: Quantity of in-mill generated wood fuel (kg), if any ....

Q.21: Quantity of diesel consumed in the PB industry (L) ....

Q.22: Quantity of LPG consumed in the PB industry (L) ....

Q. 23: Quantity of gasoline and kerosene consumed in the PB industry (L) ....

Q. 24: Quantity of distillate fuel oil consumed in the PB industry (L) ....

Q. 25: Quantity of Water used for particleboard production (L) ....

Q. 26: Quantity of wood waste sent to landfill (kg) ....

Q. 27: Quantity of wood boiler fuel sold (kg) ....

Q. 28: Quantity of boiler ash sent to landfill (kg) ....

Q. 29: One way delivery distance by truck for input materials to particleboard mill.

1. Wood residues delivery distance (km) ....
2. Resin/adhesive delivery distance (km) ....
3. Wax delivery distance (km) ....
4. Ammonium sulfate catalyst delivery distance (km) ....
5. Urea Scavenger delivery distance (km) ....

Characteristics of Production Line(s): we are required in our protocol to describe the manufacturing process and characterize the technology, thus the questions. If the raw material input to your plant is residue, after 1. Roundwood write "none" under description.

Line 1: **Unit process center**	**Description**
1. Roundwood debarking & reduction (brand & type)	
2. Refiners (Brand and type i.e., Pallmann flaker, pressurized disc refiner, hammer mill, etc.)	
3. Screens (Brand and type)	
4. Dryers (Brand and type, i.e., flash tube, direct fired, sander dust or natural gas, recycle exhaust).	
5. Blenders (Brand and type) and where resin and wax are injected to line.	
6. Formers (Brand and type).	
7. Hot Press (Brand and type-- platen or continuous, no. openings, platen size, steam or oil heats, RF assist, etc.)	
8. Panel cooler (Brand and type).	
9. Trim saws (Brand and type)	
10. Sanders (Brand and type)	
11. Other	

** (Repeat these above steps for the Production Line 2, if there is any).

Annual Wood Use for PB industry (Please provide units of measurement if different than stated).

	Wood type (logs dry and green shavings, ply trim, sawdust, etc.).	MC of wood as delivered (% oven dry wood basis)	Annual Use Weight (tons oven dry, or volume; give units used)
1	....	....	....
2	....	....	....
3	....	....	....
4	....	....	....
5	....	....	....
6	....	....	....
7	....	....	....
8	....	....	....
9	....	....	....
10	....	....	....
	Total wood used	....	....

Species Mix of wood residue used by plant.

	Wood Species (either hardwood or softwood; or actual species if known)	**% of Total mix**
1	Softwoods	
2		
3		
4		
5	Hardwoods	
6		
7		
8		
9		
	Total	100%

Annual Energy Consumption: (Total use for boilers, oil heaters, forklifts, etc. Please provide units of measurement if different than stated).

S.No	Energy source	Unit	Amount or quantity
1	Purchased electricity	KWh	
2	Purchased stream at temp F°?	m^3 or lb	
3	If you know fuel source used to generate stream, please mention type i.e. hog fuel, natural gas etc.		
4	Coal	tons	
5	Hog fuel (self-generated or purchased please mention?	tons (oven dry)	
6	Wood waste	tons (oven dry)	
7	Sander dust	tons (oven dry)	
8	Residual fuel oil	Liters	
9	Distillate fuel oil	Liters	
10	Liquid Propane Gas (LPG)	kg or gallons	
11	Natural Gas	ft3 or m3	
12	Gasoline and kerosene	Liters or gallons	
13	Diesel	Liters or gallons	
14	Others, please specify		
Less energy sold or transferred			
1	Electricity	KWh	
2	Steam at temp F°??	lbs or m3	
3	Hog fuel	tons (oven dry)	
4	Wood waste	tons (oven dry)	

Characteristics of heat sources

1. Do you have a boiler, fuel cell, or oil heater? Tick appropriate option.

1. Boiler
2. Fuel cell
3. Oil heater
4. Others

2. If you have a boiler, what is its heat source? Tick appropriate option.

1. Hogged fuel
2. Oil
3. Natural gas
4. Others

3. If you have a fuel cell, what is its heat source? Tick appropriate option.

1. Hogged fuel
2. Oil
3. Natural gas
4. Others

4. If you have an oil heater, what is its heat source? Tick appropriate option.

1. Hogged fuel
2. Oil
3. Natural gas
4. Others

Other Related Information on an annual basis.

1. For dryer(s), tick correct option for the heat source type and state the annual fuel consumption if known:

□. Steam	lbs/m^3	....
□. Natural gas direct-fired	$ft.3/m^3$	....
□. Sander dust or other		
□. Wood fuel direct fired.	Tons (oven dry weight)	....
□. Other (please specify)	....	....

2. For dryer(s) specify the following:

☐ Type of dryer(s) (i.e. blow tube, etc.) ....

☐ How is dryer(s) heated (direct fired, heat exchanger, etc.) ....

☐ Do you recycle dryer exhaust, if so to Where ....

3. For dryer(s): check the appropriate box?

☐ Green furnish dried and approximate percentage of total.

Average moisture content into dryer % oven dry basis ....

Average moisture content out of dryer % oven dry basis ....

Percentage of total wood dried % ....

☐ Dry furnish dried and approximate percentage of total

Average moisture content into dryer % oven dry basis ....

Average moisture content out of dryer % oven dry basis ....

Percentage of total wood dried % ....

4. Formulation and usage of resin, catalyst, and other components.

Component type	**% solids by weight**	**Total annual use on a solid or wet basis-please state the basis**
Urea Formaldehyde		
Catalyst		
Wax		
Water		
Other resins (i.e. MUF, PF or PMDI, please state type		
Others, please specify		

5. Annual water use (check source(s) and give amount):

☐ . Municipal water source Gallons ....

☐. Well water source Gallons ....

☐. Recycled water Gallons ....

6. **Transportation method and average distance to deliver wood furnish (check method(s)):**

Wood furnish (logs, residue, etc.) delivery method	**Average haul one way (miles/km)**	**% of Total Shipping**
☐. Truck		
☐. Rail		
☐. Other(s)		
		Total = 100%

7. **Transportation method used to deliver resin**

Transportation means for resin delivery	**Average haul one way (miles/km)**	**% of Total Shipping**
☐. Truck		
☐. Rail		
☐. Other(s)		
		Total = 100%

8. **Transportation method used to ship particleboard panels.**

Transportation means for resin delivery	**Average haul one way (miles/km)**	**% of Total Shipping**
☐. Truck		
☐. Rail		
☐. Other(s)		
		Total = 100%

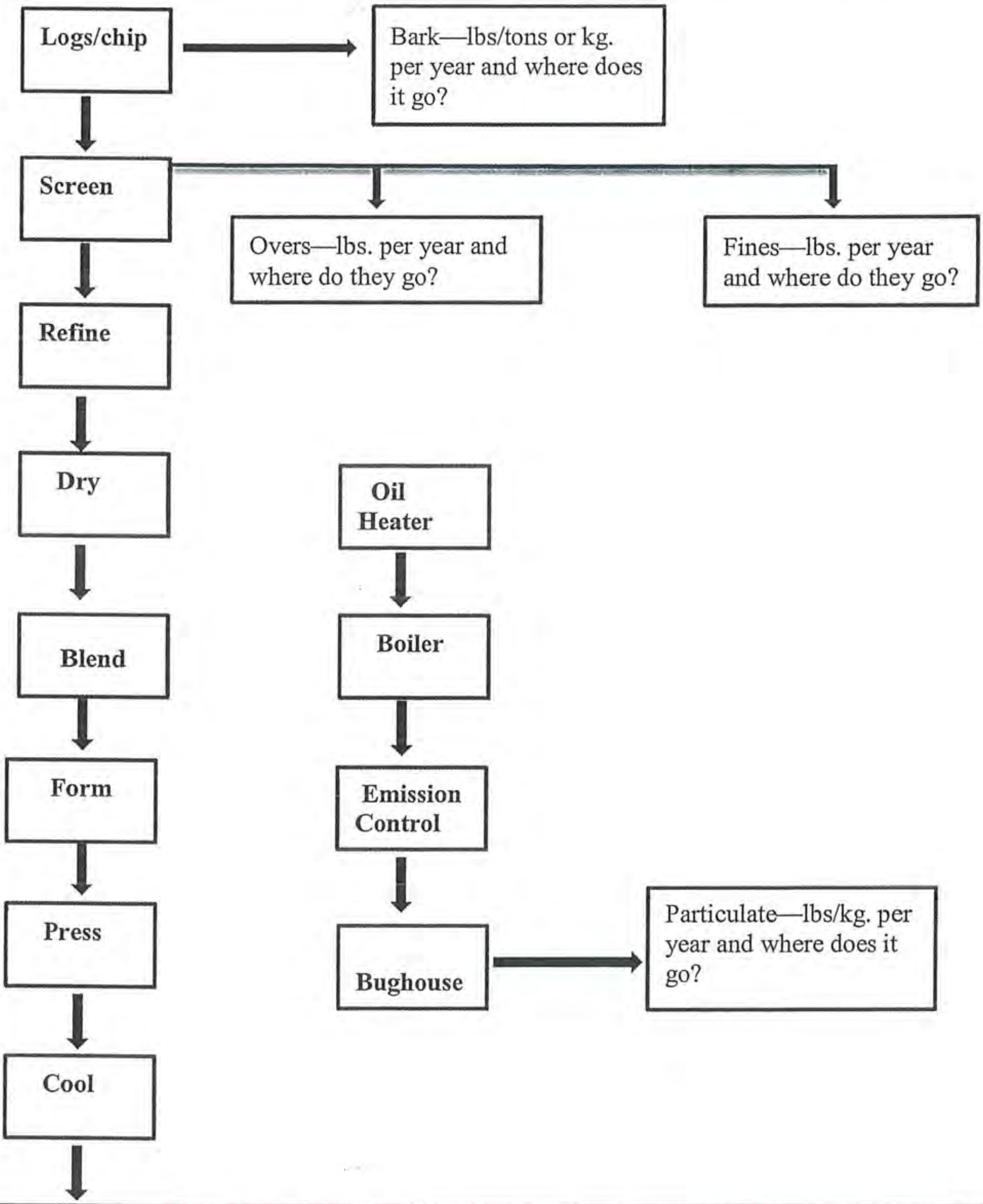
Annual Energy Use by Unit Process –Please, if you can provide the approximate use of energy in percentage of total mill use, this will be extremely helpful to us.

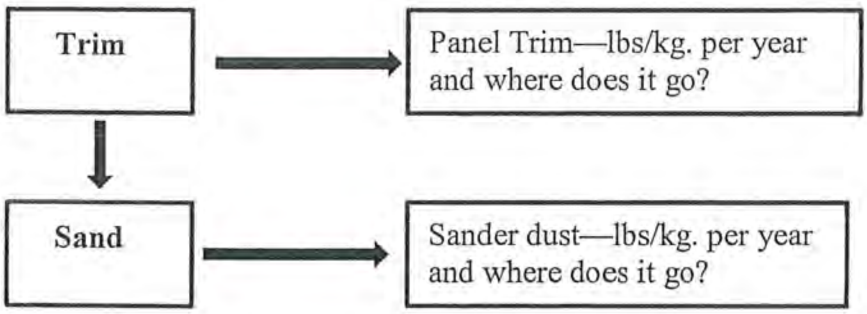
Breakdown of Natural Gas Use	Percent (%) or Annual ft3/m3 use
Dyers (if direct-fired)	
Boiler	
Oil Heater	
Emissions Control Devices	
Other	
Total	
	100% or ________ ft3/m3

Breakdown of Electricity Use	Percent (%) or Annual KWh use
Debarking and log reduction	
Refiners	
Dyers	
Blenders	
Formers	
Press(es)	
Cooler	
Trim saws	
Sander(s)	
Boiler(s)	
Oil Heater	
Emissions Control Devices	
Other	
Total	
	100% or ________ ft3/m3

Process and Material Flows

To enable us to model the flow through your operation we would like to know the process order and any by-products generated by the process and where they go. For the order, if the process flow depicted below isn't correct, i.e., your input is residue and not logs, draw a line through the box, or if the order isn't correct, i.e., the blender consists of putting the resin directly into the blow line, draw an arrow from the blender to where it is in your process. For the by-product give the lbs/tons per year and where they go, if it goes back into the process, draw a line to where it goes. If there are other by-products, please write them in and provide information. For emissions, draw a line from the process to emission control device. If a process isn't shown, please add it. Please comment on any parts of your operations that you feel we should be aware of.





Annual Material Flow

This is a general material flow survey for particleboard industry in Pakistan. This survey is designed to trace all wood coming into the plant and out. You have already provided the input material and the output panel production, what we now need to track is by-products through the operation and where they go?

Unit Process	Material type	Amount of material (lbs or tons oven dry?)	Where does it go? (Back into a specific unit process, boiler, sold, etc.?)
Debark logs	Bark		
	Screening fines		
Screen	Screening overs		
Saw & trim	Saw trim		
Sanding	Sander dust		
Bag house	Bag house dust		
Cyclone	Cyclone dust		
Other?			

PB dryers. Please provide units of measurement in terms of annual use.

Annual Dryer Throughput:(dry weight basis, lbs or tons)	Dryer No. 1	Dryer No. 2	Dryer No. 3	Dryer No. 4
Dryer fuel consumption:				
Wood waste (i.e., sander dust; lbs or tons)				
Natural gas (ft3 or m3)				

Propane (gal.)				
Other? Please state what				
Heating method; check method that applies:				
Direct-fired				
Indirect-fired(heat exchanger)				
Dryer type; check type that applies:				
Blow tube				
Other (please name)				

Emission Control Devices and Environmental Emissions

The following is a chart of emission control devices and on the following page is a listing of chemical compounds that are observed and/or permitted. Please fill in all information related to the control devices. Then list all compounds that are collected and known for the mill from all control device sources. Fill in all that apply and for which you have data. If you have more than five devices, please make a copy of this page and the next, change numbers from 1 to 6, i.e. ECD 1 to ECD 6, complete form and attach.

Emission Control Device (ECD) - Electricity, Fuel Usage and Emission Output					
	ECD1	**ECD2**	**ECD3**	**ECD4**	**ECD5**
Equipment type controlled dryer, press, oil (boiler, heater, etc.?)					
Type of device (RTO, RCO, Scrubber, WESP, cyclone, bughouse, etc.?)					
Manufacturer and year installed					
ECD exhaust temperature (F^0) and flow rate (acfm)					

Electricity use in % of total mill use or kWh, please state units					
Natural gas use in %of total mill use or ft.3 or m3, please state units					

Annual Emissions to Air (provide data for same device identified on prior page; please provide unit of measurement for each.)					
Organic Compound	**ECD1**	**ECD2**	**ECD3**	**ECD4**	**ECD5**
Equipment type controlled (boiler, dryer, press, etc.)					
Units	**Tons/year**	**Tons/year**	**Tons/year**	**Tons/year**	**Tons/year**
CO2 (you probably don't have this number but provide if you do)					
CO					
NOx					
SOx					
Total VOC					
Particulate					
PM10					
Lead					
Acrolein*					
Acetaldehyde*					
Propionaldehyde*					
Formaldehyde*					
Methanol*					
Phenol*					
Water Vapor					
* HAPS; provide total HAPS if you have data, also provide whatever individual HAPS that you record or measure					

Other (Please Specify)						

Solid Emissions to Land From All Known Sources (please provide units of measurement)

Emission	Amount (i.e., tons, lbs.—give units)	Method of disposal or end use (i.e., land fill)
Wood waste		
Boiler ash and fly ash		
Recovered particulates from pollution abatement equipment		
Other (please specify)		

Emissions to Water From All Known Sources (please provide units of measurement)		
Emission	**Amount (i.e., tons, lbs.—give units)**	**Method of disposal or end use (i.e., sewer)**
Suspended solids		
Dissolved solids		
BOD		
COD		
Chlorides		
Oil and grease		
pH of discharged water		
Other (please specify)		

Full PhD Thesis. Life cycle assessment of particleboard industry in Pakistan

by Majid Hussain

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