Do Novel Wooden Composites Provide an Environmentally Favorable Alternative for Panel-type Furniture?

Sidan Li,[a,b] Yuan Yuan,[c] Jinman Wang,[a] and Minghui Guo [a,]*

The environmental performance was assessed for a wardrobe made from hybrid modified ammonium lignosulfonate/wood fiber composites (HWC). The HWC wardrobe system involved four subsystems, namely the raw materials supply, energy consumption, wardrobe manufacturing, and transportation. A comparative life cycle assessment of a wardrobe built from conventional medium-density fiberboard with three primary damage categories was also performed. The results suggested that the HWC composites were a more sustainable material compared with conventional boards. The raw materials supply and energy consumption influenced the three primary damage categories. Climate change on human health, particulate matter formation, fossil depletion, and human toxicity had a dominant contribution to the overall environmental impact. Also, a sensitivity analysis was performed with a focus on using wood waste as a raw material and on the different conditions for the modification of lignosulfonate for manufacturing HWC. The results indicated that the use of wood waste and an appropriate amount of unmodified lignosulfonate as a binder aids in efficient HWC production for wardrobes. These results can help to improve HWC wardrobe technology and in choosing the appropriate wardrobe system.

Keywords: Wooden furniture; HMAL/WF composites (HWC); Medium-density fiberboard (MDF); Life cycle assessment (LCA); Sustainability

Contact information: a: Key Lab of Bio-based Material Science and Technology of Ministry of Education, Material Science and Engineering College, Northeast Forestry University, Harbin 150040, China;
b: Heilongjiang Bayi Agricultural University, Daqing 163319, China; c: Heilongjiang Provincial Key Laboratory of Environmental Microbiology and Recycling of Argo-Waste in Cold Region, College of Life Science and Technology, Heilongjiang Bayi Agricultural University, Daqing 163319, China;
** Corresponding author: gmh1964@126.com*

INTRODUCTION

The world is facing challenges from social, environmental, and economic areas. Furniture products are household necessities that are used in the daily lives of people. Currently, this industry accounts for a considerable portion of global trade (Azizi *et al.* 2016). In 2015, the world furniture market was worth 455 billion US dollars, while the volume of export trade reached 52.8 billion US dollars. Furniture products have become promising and one of the leading export merchandises in China (Wang *et al.* 2016). Sustainable development of this industry is a major concern in developed and developing countries (González-García *et al.* 2011), especially in China, which has resulted in strict rules concerning the impact of products. The development of new urban markets in China has enhanced the domestic demands in furniture industries. The furniture market is increasing the awareness of their environmental pollution and energy consumption. Hence, environmental and economic concerns are stimulating research into green techniques, such as selecting green materials, using renewable materials, and adopting cleaner processes and the eco-design approach (Luz *et al.* 2010). Composite boards for furniture in China are main panels, which are made from petroleum-based adhesives and have caused several negative environmental impacts, especially because of the emission of volatile organic compounds and formaldehyde during the production phase (Li *et al.* 2009).

As a by-product of the paper industry, industrial lignin has been used in a wide variety of fields in the past few years (Li *et al.* 2015; Ten and Vermerris 2015). Industrial lignin is used as a low-value fuel in paper-pulp manufacturing. In view of the recent focus of the community on sustainable development and carbon-neutral products, there have been several discussions and research on using lignin-based binders. Various kinds of lignin-based binders, such as industrial lignin alone or mixed with cross-linking agents, have been investigated in the last decade (Li and Geng 2004; Geng and Li 2006; Liu and Li 2006; Mancera *et al.* 2011; Duval *et al.* 2013; Privas and Navard 2013; Aracri *et al.* 2014; Zhang *et al.* 2017). However, industrial lignin has been found to be unsatisfactory as a binder in boards because of the relatively low reactivity of its chemical structure. Therefore, the development of sustainable materials requires a more effective use of modified lignin (Ikeda *et al.* 2017). For instance, a major amount of research has investigated the manufacturing of nonconventional fiberboards by using a natural binder made with modified ammonium lignosulfonate (Yuan *et al.* 2014; Hu and Guo 2015).

Currently, the furniture manufacturing industry seems to be important from economic and social standpoints and from the perspective of environmentally compatible industries (Azizi *et al.* 2016). As an effective and valuable tool, the life cycle assessment (LCA) methodology is used to assess the environmental impact of materials, products, and service systems, with the intent of assessing the environmental damage caused over the whole life of a product (ISO 14040 2006). These trends reinforce the importance of using LCA for sustainable design procedures and for evaluating the novel material technologies and production processes that impact the environment in remarkable ways (Linkosalmi *et al.* 2016; Kirchain Jr. *et al.* 2017). Several studies have evaluated wood-based products and furniture from an LCA perspective. These studies have focused on conventional wooden material selection and assessment, such as standard particle boards, fiberboards, and hardboards (Iritani *et al.* 2015; Nakano *et al.* 2018). In contrast, only a few studies have applied LCA to furniture manufactured with nonconventional green boards. In China, no LCA studies have been performed to investigate the till date on furniture made with green wooden panels based on lignin-based binders.

The case study presented in this article focused on a complete wardrobe with new materials for the wardrobe components. A previous study used LCA to investigate a preliminary case on the comparative environmental performance of conventional medium-density fiberboard (MDF) and a nonconventional green board called hybrid modified ammonium lignosulfonate (HMAL)/wood fiber (WF) composite (HWC) (Yuan and Guo 2017). For HMAL, ammonium lignosulfonate was oxidized using H_2O_2 at 60 °C for 30 min, then mixed with PEI solutions according to the MAL/PEI weight ratio of 7:1.

To enhance the utilization of novel wood composites, sustainable strategies were analyzed by assessing the environmental impact of a wardrobe composed of HWC. This study evaluated the environmental impacts of using an HWC wardrobe. In the process, this study compared those impacts with the environmental impacts caused by current wood products made of conventional MDF over the entire life cycle of the wardrobe. The study intended to assess the effects of replacing the raw materials and current binder material with a modified lignosulfonate on the overall sustainable design of the HWC wardrobe and the important wood products sector in China.

EXPERIMENTAL

Goal and Scope Definition

The goal was to assess the environmental impacts (on human health, ecosystem quality, and resources) of a wardrobe made of HWC, and then compare them with the impacts caused by an MDF wardrobe made with conventional composite board with urea-formaldehyde adhesives. Other issues addressed were investigated and discussed in the discussion sections. This project was developed in partnership with a national company (the Greater Khingan Range Hengyou Furniture) located in Greater Khingan area, China. This company that produces furniture was selected as a representative to provide related production inventory data required for this study. This company is one of the favorite Chinese producers of wooden furniture with an annual turnover of 3.82 million dollars in 2017.

Functional Unit

The functional unit provides support for inputs and outputs based on ISO 14044 (2006). Wooden wardrobes are panel products commonly used indoors with a strong market demand. This study paid attention to wooden wardrobes with double doors used for primary needs because this is the most produced wardrobe in this specific factory. The functional unit that was selected corresponded to one wooden wardrobe (100 kg) with the main dimensions 2000 mm × 1000 mm × 500 mm (Fig. 1). The HWC for the main structure and material of the wardrobe was produced by the Chinese company mentioned above. Metal, such as steel, was used in the screws, and plastics were used in the accessory members, packaging, *etc*.

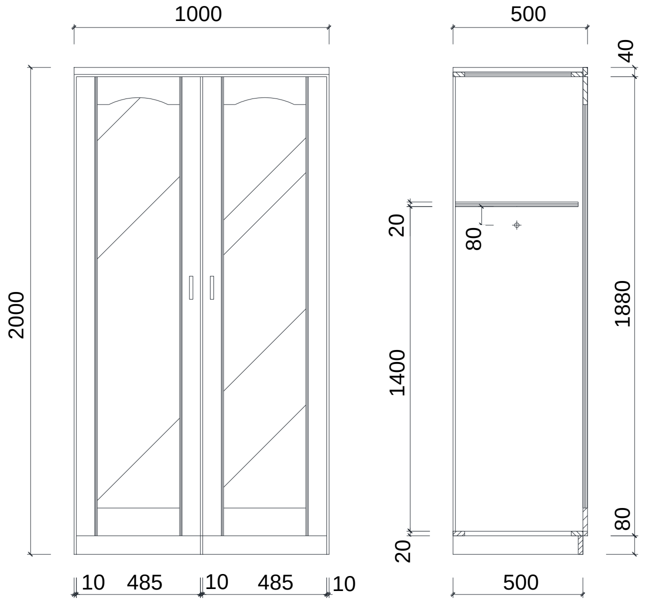

Fig. 1. Schematic of wardrobe in function unit

Description of the System

The complete life cycle of manufacturing an HWC wardrobe from raw materials to production to delivery to the final user is illustrated in Fig. 2. The HWC wardrobe process chain was divided into the four following subsystems: raw materials supply, energy consumption, HWC wardrobe manufacturing, and transportation. The HWC wardrobe manufacturing stage was comprised of assembling, surface treatment, and packaging. During assembling, the HWCs were cut, shaped into a given size, and connected with each other, and then surface treatments, such as painting, were performed. Packaging was the last production step before the wardrobe was delivered. Energy consumption, such as heating, electricity, and water consumption, was also considered in the assessment process. All of the associated transportation processes in the life cycle, including waste disposal, were within the system boundaries. The use phase of furniture needed little energy input, and the maintenance data was out of reach; therefore, the use phase was excluded from the system boundary. Different scenarios of the end of life were considered during the sensitivity analysis.

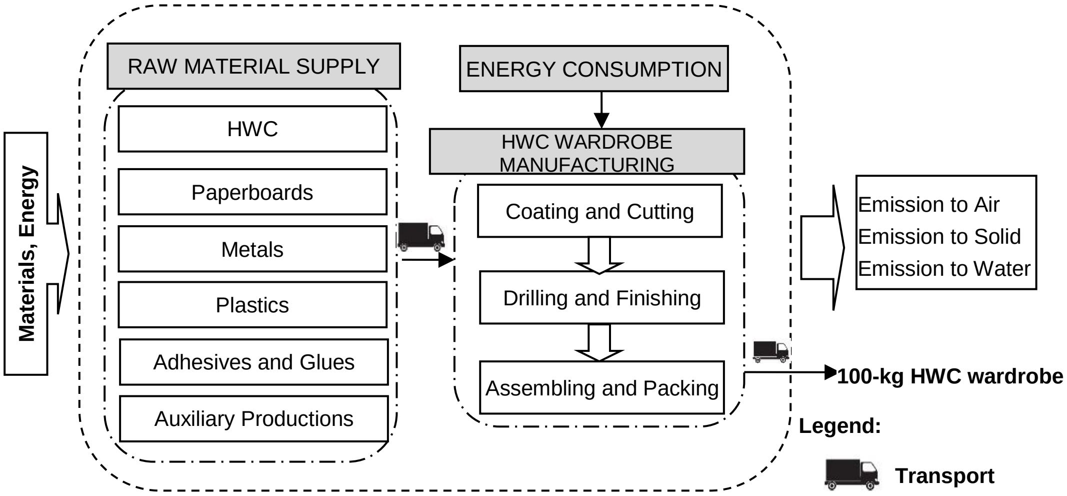

Fig. 2. System boundary and main processes for production of HWC wardrobes

The raw materials supply stage included key materials (green chips and ammonium lignosulfonate) for the HWC, solid pine timber for paperboards, metals, plastics, and adhesives. Compared with conventional wardrobe, the main difference is the wooden composites. The green chips and ammonium lignosulfonate, as the primary materials of the HWC, were evaluated according to previous reports (Yuan and Guo 2017). The physical mechanical properties of HWC were superior to the furniture grade MDF of the Chinese standard GB/T 11718 (2009). The HWC was the primary integrating component of the wardrobe. The wardrobe was transported by truck from Hengyou Furniture Co. Ltd (Greater Khingan area, China) for an approximate distance of 200 km. The paperboards were used as a packaging material for one-layer corrugated boxes, which decreased the environmental impact and energy consumption by a large amount (Yi *et al.* 2017). Other components included metals, plastics, and adhesives, which were obtained from different suppliers in China. These components accounted for approximately 5.0% of the entire mass of the HWC wardrobe system.

Data Quality and Simplification

The LCA was built by GaBi 8.7 software (Thinkstep, Leinfelden-Echterdingen, Germany) for the HWC wardrobe system to investigate the inventory data and perform the impact assessment. The data quality was high and reliable; it came from different evaluation sources with reliability and consistency based on ISO standards. Additionally, data from secondary literature was used when the key process emission data was not available. To avoid irregular conditions, the representative process data consisted of the average data taken from the specific field methods.

The life cycle inventory for the HWC wardrobe is shown in Table 1. This study dealt with the lack of regional or local inventory databases. In these cases, valid assumptions and simplifications were made to integrate the available databases into the HWC wardrobe LCA. Therefore, it was important to consolidate the database inventories for reliable assessment and to introduce life cycle consciousness in the Chinese furniture industry (Teixeira *et al.* 2010).

Table 1. Life Cycle Inventory of 100-kg HWC Wardrobe

Input	Amount	Output	Amount
Raw Materials	kg	Product	kg
Green Chips (50% water content)	202.55	HWC Wardrobe	100
Solid Pine Timber	11.34		
Ammonium Lignosulfonate	23.73	Emission to Air	kg
Hydrogen Peroxide (Aqueous 50 wt. %)	14.92	Carbon Dioxide	16.19
Metals	19.71	Carbon Monoxide	0.07
Plastic	5.94	Nitrogen Oxides	0.49
polyvinyl Acetate Adhesive	0.63	Sulfur Dioxide	0.02
Polyurethane Coating	10.32	Emission to Soil	kg
Paraffin Emulsion	0.81	Dust Waste	41.05
Energy	MJ	Paints Waste	0.47
Electricity from Grid	392.5	Filterable Matter	0.47
Energy from Biomass	57.2	Emission to Water	kg
Transportation	ton·km	COD	0.11
Truck (4 ton to 5 ton)	16.93		
Truck (12 ton to 14 ton)	25.47		

All of the inventory data for the foreground of the wooden composites were from primary sources. Annual data for China were collected from furniture companies that used the modern furniture techniques. The environmental emission sources for HWC wardrobe manufacturing were coating, cutting, drilling, and finishing. The field emission data were estimated based on the Chinese standard HJ/T 315-2006 (2006) in the HWC wardrobe manufacturing subsystem. For material transportation, the transportation methods and distances were identified for each raw material according to procurement by the furniture manufacturers. The average distance between the sites of the country for product export and the main raw materials was taken from Chinese references (Chen *et al.* 2015). Subsidiary processes included thermal energy consumption, electricity consumption, diesel consumption, and adhesive production, and were mainly obtained from GaBi Thinkstep databases (Thinkstep, 2018) and other databases to cover some missing datasets such as Ecoinvent 3.5 (Swiss Centre for Life Cycle Inventories, 2018). Lignosulfonate product specific LCA reports were also available, and the data sources are summarized in Table 2.

Table 2. Summary of Data Sources

Category	Material/Component	Data	LCI Source
Raw Materials	Green Chips (50% water content)	GLO: Used wood, wood chips (50% H_2O content)	Thinkstep
	Solid Pine Timber	CN: Timber pine (10.7% H_2O content)	
	Ammonium Lignosulfonate	Lignin based phenolic material.	González-García (2011)
	Hydrogen Peroxide (Aqueous 50 wt%)	RER: Hydrogen peroxide (50% H_2O_2)	Ecoinvent 3.5
	Metals	GLO: Steel welded pipe worldsteel	World Steel association (2017)
	Plastic	CN: Plastic foil (Polyethylene, PE)	Thinkstep
	Polyvinyl acetate adhesive	RER: Polyvinyl acetate (PVAC)	Ecoinvent 3.5
	Polyurethane coating	RER: PUR dispersion adhesive	
	Paraffin Emulsion	CN: Wax / Paraffins at refinery from crude oil	Thinkstep
Energy	Electricity from Grid	CN: Electricity from hard coal	
	Energy from Biomass	CN: Thermal energy from biomass (solid)	
Transportation	Truck (4 ton to 5 ton)	CN: Transport, small truck (up to 14 t total cap., 9.3t payload)	
	Truck (12 ton to 14 ton)		
	Fuel for transportation	CN: Diesel mix at filling station	

CN=China, GLO=Global, RER=Europe.

Life Cycle Impact Assessment

In this study, the ReCiPe 1.08 Endpoint method and its impact categories were selected for evaluating the different types of damages over the entire life of the product (La Rosa *et al.* 2013). The three main damage categories were damage to human health (HH), damage to the ecosystem quality (EQ), and damage to resources (R). Damage to HH was shown as the number of years lived as disabled and the number of years of life lost; its unit was disability adjusted life years (DALYs). Damage to the EQ was shown as the loss of species within a given period, and its unit was species years (species·yr). Damage to R was shown as the surplus of energy for future resource integration (Rivela *et al.* 2007).

This was helpful for highlighting the drawbacks of specific categories and the possible environmental benefits. When conventional MDF was replaced with HWC in the wardrobe products, it was essential to detect the hot spots and further demonstrate the observed impacts. The characterization step analyzed the contributions of different subsystems to the damage categories and sub-categories. The results of the characterization and damage assessment are shown in Tables 3 and 4.

Table 3. Characterization and Damage Assessment of 100-kg HWC Wardrobe

Characterization Step						
Category	Unit	Raw Material Supply	Energy Consumption	Wardrobe Manufacturing	Transportation	Total
Damage to Human Health						
Climate Change Human Health	DALY × E^{+3}	72.12	51.8	3.71	33.7	161.33
Human Toxicity	DALY × E^{+3}	52.89	7.75	6.25	58.10	124.99
Ionizing Radiation	DALY × E^{+7}	47.91	34.42	2.47	22.40	107.20
Ozone Depletion	DALY × E^{+11}	38.80	36.22	7.29	16.25	98.56
Particulate Matter Formation	DALY × E^{+3}	17.23	15.10	5.00	2.99	40.32
Photochemical Oxidant Formation	DALY × E^{+7}	135.0	13.69	7.89	75.23	231.81
Damage to Ecosystem Quality						
Climate Change Ecosystems	Species·yr × E^{+4}	40.11	66.32	5.15	4.94	116.52
Freshwater Ecotoxicity	Species·yr × E^{+8}	8.98	21.23	2.16	37.23	69.60
Freshwater Eutrophication	Species·yr × E^{+8}	11.59	1.72	1.48	12.04	26.83
Marine Ecotoxicity	Species·yr × E^{+8}	11.79	12.67	2.16	13.35	39.97
Terrestrial Acidification	Species·yr × E^{+6}	23.59	52.36	2.65	30.12	108.72
Terrestrial Ecotoxicity	Species·yr × E^{+7}	70.77	50.82	2.61	1.22	125.42
Damage to Resources						
Fossil Depletion	\$ × E^{+3}	64.53	53.70	1.83	32.49	152.55
Metal Depletion	\$ × E^{+5}	24.54	17.62	1.26	11.48	54.90
Damage Assessment						
HH	DALY × E^{+2}	14.23	7.47	1.49	9.49	32.68
EQ	Species·yr × E^{+4}	40.40	66.44	5.18	49.74	161.76
R	\$ × E^{+3}	64.78	53.88	1.843	32.61	153.11

Table 4. Life Cycle Impact Assessment of the Two Wardrobe Samples Under Study

Category	Unit	Conventional Wardrobe	HWC Wardrobe
HH	DALY × E^{+2}	66.52	32.68
EQ	Species·yr × E^{+4}	385.36	161.76
R	\$ × E^{+3}	527.44	153.11

RESULTS AND DISCUSSION

Main Findings

Figure 3 shows the relative contributions of the four stages to each subsystem and the impact category. The contributions of the raw materials supply ranged from 25.0% for the EQ to 43.6% for HH, while the contribution of the energy consumption stage ranged from 21.3% for HH to 41.1% for the EQ. The transportation stage contributed 21.3% for R and 31.3% for the EQ, and the HWC wardrobe manufacturing stage contributed 1.2% for R to 3.8% for HH. It was found that the subsystems for the raw materials supply and energy consumption were responsible for all of the damage categories, and HWC wardrobe manufacturing had the lowest contribution to the environmental impact. This was consistent with the results of Yuan and Guo (2017).

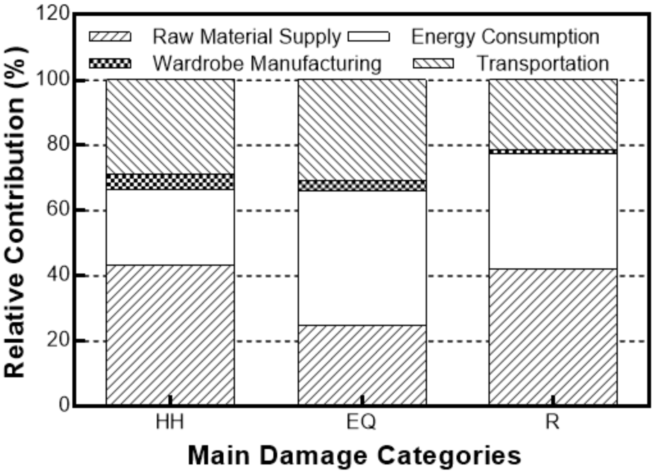

Fig. 3. Relative contributions to the three main damage categories for the four stages of each subsystem

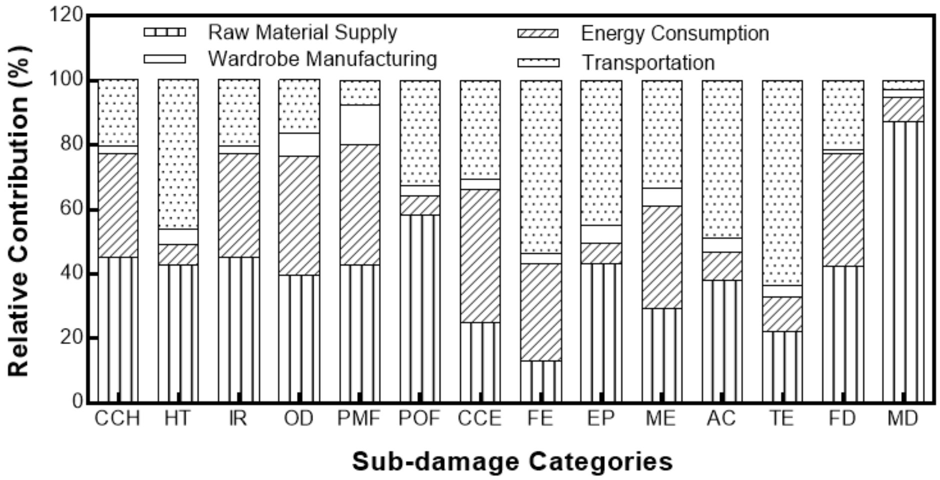

Fig. 4. Relative contributions to the sub-damage categories for the four stages of each subsystem

Damage to Human Health

Table 3 shows the relative contributions to the sub-damage categories for the four stages of each subsystem. Damage to HH was further divided into six sub-damage categories, which were climate change on HH (CCH), human toxicity (HT), particulate matter formation (PMF), ozone depletion (OD), ionizing radiation (IR), and photochemical oxidant formation (POF).

Considering the existing six categories (Fig. 4), 44.7% of the CCH damage occurred in the raw materials supply stage because of CO_2 emissions from the production of HMAL/WF, and 32.1% of the CCH damage was because of energy consumption. For the HT category, 46.5% of the impact was caused during the energy consumption stage, and 42.3% of the environmental impact occurred during the raw materials supply stage. For the PMF category, the impactful stages were the raw materials supply (42.7%) and energy consumption (37.5%). For the IR, OD, and POF categories, 44.7%, 32.1%, and 20.9% of the environmental impacts were caused during the raw materials supply stage, energy consumption stage, and transportation, respectively. For the OD category, 39.4% of the impact occurred in the raw materials supply stage and 36.7% of the impact happened during the energy consumption stage. The damage to HH was the main impact because the CCH, HT, and PMF categories had a total of 0.653 (Fig. 5). The sum of IR, OD, and POF was deemed the least important in the damage to HH.

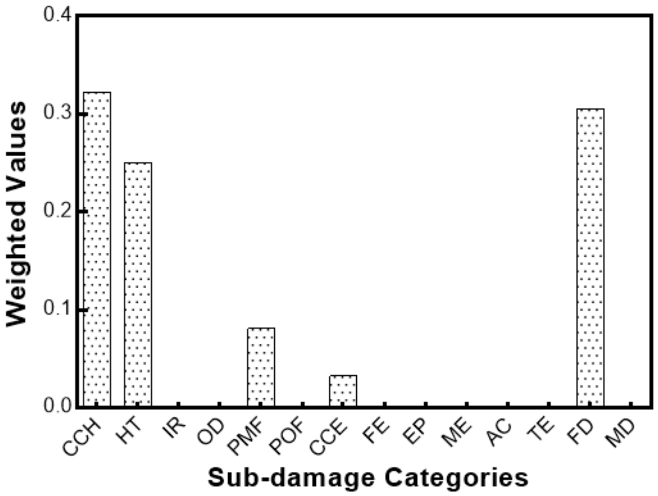

Fig. 5. Differently weighted sub-damage categories

Damage to the Ecosystem Quality

In Table 3, the damage to the EQ was further divided into six sub-damage categories, which were climate change ecosystems (CCE), freshwater ecotoxicity (FE), freshwater eutrophication (EP), marine ecotoxicity (ME), terrestrial acidification (AC), and terrestrial ecotoxicity (TE). The distribution stage was the main contributor, causing impacts of more than 44% for FE (53.5%), EP (44.9%), AC (48.9%), and TE (63.4%) for 2000-km distances (Fig. 4). This was because of diesel consumption in the transportation stage, which was due to fossil fuel consumption, as well as CO_2 and CH_4 emissions from fossil fuels. The CCE showed the highest impact with 0.0322, while the other sub-damage categories were less important with a sum of 0.000151 (Fig. 5).

Especially for FE and EP, the HWC life cycle was contaminated by hydrophobic organic contaminants, *e.g.*, polycyclic aromatic hydrocarbons, during field operations. The raw materials supply stage was the second largest contributor, causing impacts of more than 30%, such as for EP (43.2%) and AC (38.3%).

Damage to Resources

The damage to R was divided into two sub-damage categories, which were fossil depletion (FD) and metal depletion (MD) (Table 3). Figure 5 shows that FD (0.305) had a higher impact than MD (0.001). The raw materials supply stage was the main contributor to MD (87.4%) and FD (42.4%). The energy consumption (35.2%) and transportation stages (21.3%) had the largest contributions to FD, as is shown in Fig. 5. Being a developing country, Chinese electric power comes from a mix of coal (77%), hydropower (18%), and other energy resources (5%) (Tong *et al.* 2013). Coal-based electricity generation plays an important role in national electricity production in China, which explained why electricity was the highest contributor in the damage to R (Hong *et al.* 2017).

Comparative Environmental Performance of the Wardrobe with the LCA

Figure 6 shows the comparative environmental performance for the HWC and conventional wardrobes. These results showed that the HWC wardrobe provided superior environmental performance compared with the conventional wardrobe of the same size. The results showed all of the inputs for the production process of the wardrobes, as well as the solid waste generation, energy consumption, and water consumption.

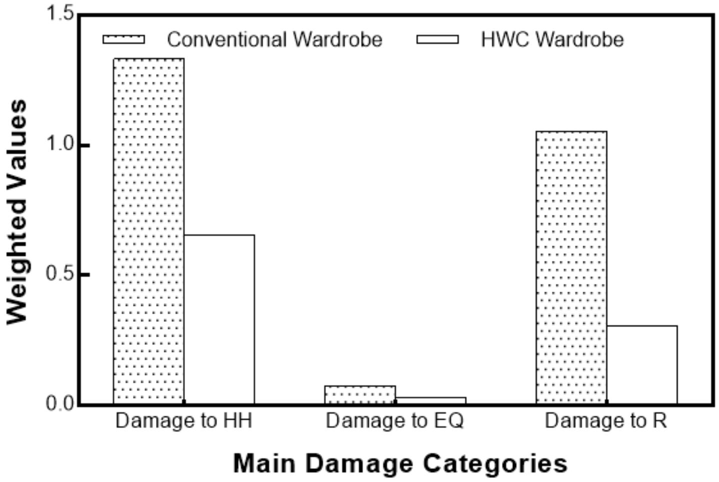

Fig. 6. Three main weighted damage categories for the conventional wardrobe and HWC wardrobe

Alternatives Focused on the Primary Component in the Wardrobe Life Cycle

The raw materials supply stage presented a great opportunity for environmental improvement, followed by the energy consumption and transportation stages. The categories CCH, FD, HT, and PMF combined had the largest contribution to the overall environmental impact for the production system (Fig. 5). Other sub-damage categories had negligible contributions to the key categories. Figure 7 presents the relative contributions of the four main sub-damage categories for each subsystem.

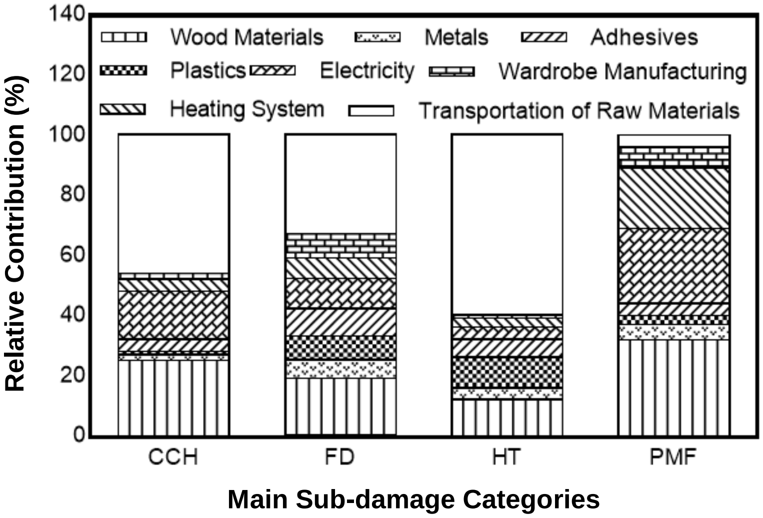

Fig. 7. Relative contributions to the four main sub-damage categories for each subsystem

Climate change on human health

The transportation stage was responsible for most of the CCH contribution (approximately 46%), as is shown in Fig. 7. The HWC and heating system contributed 25% and 7% to the impact, respectively. The combustion of fossil fuels to produce complete heat and electricity led to CO_2 and CH_4 emissions (approximately 16%).

Fossil depletion

Transportation was responsible for most of the FD contribution (33%), followed by wood materials production (19%) and electricity (10%). The cogeneration unit, including metals, plastics, and adhesives, required in the packaging stage contributed approximately 23% to this impact category.

Human toxicity

A high percentage of the total impact of the ecotoxicity potentials was linked to transportation activities (60%). The wood materials production was another hot spot with a contribution of 12% because of the wood fiber and auxiliary chemical materials required for HWC production.

Particulate matter formation

The wood materials production had the largest contribution to this impact category (32%), and particulate matter was mainly emitted during HWC manufacturing (35%), followed by electricity production (25%) and heating (20%). The fiber preparation and board finishing of wood materials production are the main sector in the pollution of particulate matters (Kouchaki-Penchah *et al.* 2016). The fine particulate matter (PM_{10} and $PM_{2.5}$) from the PMF category is related to respiratory problems in humans. Most of the major cities in China are afflicted by principal urban pollutants, which includes SO_2 and NO_x (Yao *et al.* 2009, 2010). Specifically, $PM_{2.5}$, the pollutant with the highest amount in the region, adversely affects the Northern region of China (Song *et al.* 2016).

Sensitivity Analysis

Although the transportation stage was highlighted in the categories CCH, FD, and HT, the wood-based materials were the main contributor to the four impact categories. This was because HWC and solid wood represent 88% and 5% of the total weight, respectively. Based on prior studies, it was found that HWC as the main wood-based material has better environmental performance properties. The main contributors to the environmental profile associated with HWC were the raw materials, energy, and chemicals required for production.

Particulate alternatives focused on wood-based materials

In this study, wood-based materials were the main components of the wardrobe because HWC and solid pine timber represent 97% and 3% of the total weight, respectively. There is no published literature on strategies to replace HWC with alternative materials, especially using different kinds of recycled wood in the panel manufacturing process (Fig. 8). The four scenarios that are shown in Fig. 8 are outlined as follows:

- Scenario 0: current model, using 100% raw wood (864 kg/cm^3 HWC),
- Scenario 1: conventional model, using 100% raw wood (864 kg/cm^3 conventional MDF),
- Scenario 2: using 50% virgin wood (432 kg/cm^3 HWC) and 50% wood waste (432 kg/cm^3 HWC), and
- Scenario 3: using 0% virgin wood and 100% wood waste (864 kg/cm^3 HWC).

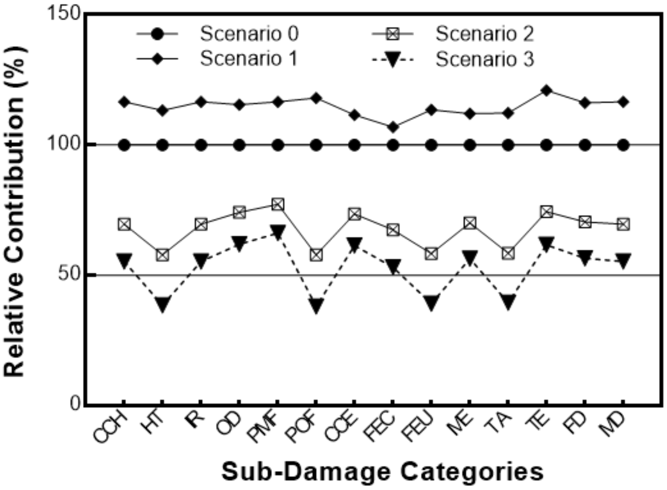

Fig. 8. Scenario analysis: environmental impact for different doses of wood waste in wardrobe production

When comparing scenarios 0 and 1, the potential impact of conventional MDF was minimized by 6.9% for the evaluated categories. The largest increase in the impact that occurred was in the TE (21.0%), followed by the POF (18.1%). From the dominant categories above, the CCH, PMF, FD, and HT increased by 16.6%, 16.6%, 16.2%, and 13.3%, respectively. When comparing scenarios 0 and 2, there was an overall minimization of the potential impacts of more than 22.7%. The largest increase in the impacts occurred for the POF (42.1%), followed by the HT (42.0%). When comparing scenarios 0 and 3, there was an overall minimization of the potential impacts of more than 38.0% because this scenario proposed the use of 100% wood waste. Again, the greatest decrease in the potential impact occurred in the POF category (62.0%), followed by the HT (61.4%). In the case of the studied wood wardrobe, it was concluded that a more efficient use of wood waste as a raw material for the HWC in the wardrobe products can present environmental advantages by proposing a potential solution to overcome resource scarcity (Sommerhuber *et al.* 2017). For furniture manufacturing companies, a potential wood waste recycling-oriented business model could be developed (Daian and Ozarska 2009).

Alternatives focused on modified conditions of lignosulfonate

The equivalence between the two HWC in terms of strength and stiffness has already been established, where two treatments were performed on lignosulfonate to improve the mechanical behaviors of the HWC for the technical project requirements.

Before HWC production, untreated lignosulfonate was purified and modified by Yuan *et al.* (2014) to increase the active groups in the lignosulfonate and improve the adhesion within the wood fibers. Various treatments have also been used by other researchers to improve the adhesion and analyze the effects of those treatments on the mechanical properties of the composites. However, these phases were not considered in the LCA. The four scenarios that are shown in Fig. 9 are outlined as follows:

- Scenario 0: current model, HWC using purified and modified lignosulfonate,
- Scenario 1: HWC using 20 wt.% unpurified lignosulfonate (based on AL consumption),
- Scenario 2: HWC using 20 wt.% unmodified lignosulfonate (based on AL consumption), and
- Scenario 3: HWC using 10 wt.% unpurified lignosulfonate and 10 wt.% unmodified lignosulfonate (based on AL consumption).

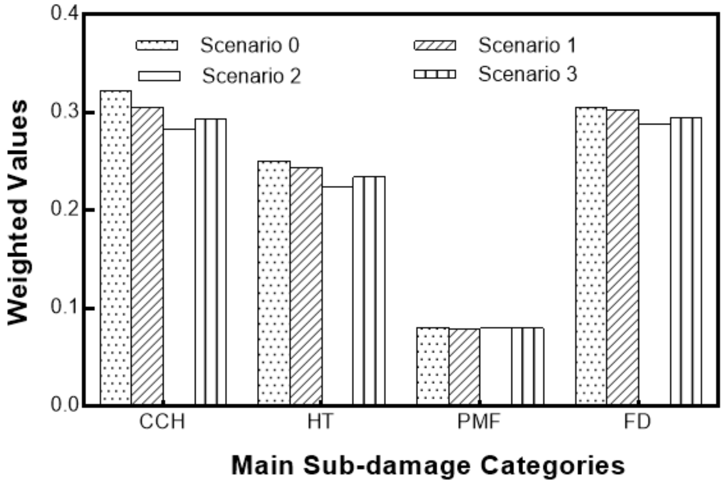

Fig. 9. Scenario analysis: weighted four main sub-damage categories

In this case study, lignosulfonate was used as a binder for the HWC. Different modified conditions of the lignosulfonate caused remarkable changes (Fig. 9). The results for scenario 2 showed that the HWC using 20 wt% unmodified lignosulfonate resulted in the largest influence on the main contributor, except for the PMF. However, when the dose of unpurified lignosulfonate was reduced, most of the impact categories became less relevant, with a difference of less than 2%, except for the CCH (5%). Overall, the results showed a minimum impact and demonstrated that the modified treatments possibly increased the impact of the HWC because of the inherent hazard of the intermediate benzene and phenol products (Eckelman 2016). This was an effort to adapt HMAL in green chemistry for industrial lignin.

Other alternative options in HWC wardrobe production

The important contribution to the environmental feature of wardrobe production was the energy requirements from fossil fuels in a cogeneration system. This process showed an important role in terms of the CCH, FD, HT, and PMF because of the use of non-renewable fuel and its associated CO_2 emissions (Vignali 2017). China is paying close attention to energy security, optimizing the energy structure, and reducing the emission factors of the grid mix (Myers 2016). For example, the application of solar, nuclear, and wind power can reduce the emission factor of electricity by 835 g CO_2eq/kWh in China, which is higher than that in the USA (609 g CO_2eq/kWh) (Qiao *et al.* 2017). Therefore, the energy efficiency and centralized transportation of HWC wardrobe production should be considered an important research target for furniture development to reduce the environmental impact of HWC wardrobe production (Peters *et al.* 2016).

Meanwhile, the transportation stage was relevant when relying on the distance optimized with consideration of improvement and management of integrated processes. The reuse of waste production and energetic valorization are alternative options that promote cleaner production strategies. For the end of life stage, a landfill scenario was set for both the wardrobe scraps and wasted elbows because thermoset composites cannot be recycled and incineration with biological heat is not a valid option in China due to its low calorific value and high cost. In another scenario, the furniture companies could expand subsidies for consumers who are trading in an older wardrobe for sustainability in extended brand benefit. The refurbished wardrobe could be reused for a prolonged life cycle.

CONCLUSIONS

1. The hybrid modified ammonium lignosulfonate/wood fiber composites (HWC) wardrobe provided superior environmental performance compared with the conventional wardrobe of the same size. Concerning the composite materials, the wardrobe case study demonstrated that HWC presented a better solution to enhance the environmental performance of the complete wardrobe.
2. The hot spots that occurred over the life cycle of HWC wardrobe manufacturing process were identified from the inventory analysis and impact assessment results. Three processes, namely the raw materials supply, energy requirements in cogeneration, and transportation activities, had a remarkable role in the environmental profile.
3. According to the four main sub-damage categories, the distribution stage was responsible for most of the climate change (CCH) contribution (approximately 46%). For the fossil depletion (FD), transportation was responsible for most of the FD impact (33%). For the human toxicity (HT), a high percentage of the total impact of ecotoxicity potentials was linked to transportation activities (60%). For the particulate matter

formation (PMF), the wood materials production was the largest contributor (32%), mainly from dust waste during HWC manufacturing (35%).

4. Alternative and potential scenarios were proposed and analyzed to compare their environmental profile with the current production process. An efficient use of wood waste as a raw material for the HWC in the wardrobe products can present environmental advantages. Different modified conditions of the lignosulfonate caused remarkable changes in environmental impact.

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APPENDIX

List of Abbreviations

AC	Terrestrial acidification
CCE	Climate change ecosystems
CCH	Climate change on human health
COD	Chemical Oxygen Demand
EP	Freshwater eutrophication
EQ	Ecosystem quality
FD	Fossil depletion
FE	Freshwater ecotoxicity
HH	Human health
HT	Human toxicity
HWC	Hybrid modified ammonium lignosulfonate/wood fiber composites
IR	Ionizing radiation
LCA	Life cycle assessment
LCI	Life cycle inventory
MD	Metal depletion
MDF	Medium-density fibreboard
ME	Marine ecotoxicity
OD	Ozone depletion
PMF	Particulate matter formation
POF	Photochemical oxidant formation
R	Resources
TE	Terrestrial ecotoxicity

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