INBAR Working Paper

INTERNATIONAL BAMBOO AND RATTAN ORGANISATION

Technical Paper

Life Cycle Assessment for Key Bamboo Products in Viet Nam

Vu Tan Phuong, Nguyen Viet Xuan

2020

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the German Bundestag

RECOFTC

NGHE AN FPDF

About the International Bamboo and Rattan Organisation

The International Bamboo and Rattan Organisation, INBAR, is an intergovernmental organisation dedicated to the promotion of bamboo and rattan for sustainable development. For more information, please visit www.inbar.int.

About this Working Paper

This research was carried out by the International Bamboo and Rattan Organisation (INBAR) as part of the project of Production-driven Forest Landscape Restoration under REDD+ through Private Sector-Community Partnerships as an Asian Regional Learning Exchange (FLOURISH).

FLOURISH is a four-year project which aims to develop partnerships between local communities and the private sector to achieve forest restoration, increase food productivity, and improve local livelihoods in Lao PDR, Thailand and Viet Nam. The project has financial support from the Federal Ministry for the Environment, Nature Conservation, and Nuclear Energy of Germany, via the International Climate Initiative, and is led by The Center for People and Forests in partnership with INBAR, the Technische Universität Dresden (Germany), and Nan Community College (Thailand).

International Bamboo and Rattan Organisation

P.O. Box 100102-86, Beijing 100102, China Tel: +86 10 64706161; Fax: +86 10 6470 2166
Email: info@inbar.int

Acknowledgements

The authors would like to express sincere thanks to Mr. Trinh Thang Long, Coordinator of INBAR Global Assessment of Bamboo and Rattan Programme (GABAR), Ms. Li Yanxia, Senior Programme Officer of INBAR Global Programme and FLOURISH Team Lead, Dr. Chandra Silori, Deputy Executive Director of RECOFTC, Ms. Trang Thu Hoang, FLOURISH Project Coordinator of RECOFTC, and Mr. Manh Loc Khoa, INBAR FLOURISH Filed Coordinator in Nghe An for their valuable comments and contributions to the report.

This report could not have been completed without the effective collaboration and support of Nghe An FLOURISH Project Management Unit and Bamboo processing companies in Nghe An, Ha Noi and Hoa Binh provinces. We would like to take this opportunity to thank the following people for their support and collaboration during the study's implementation: Mr. Nguyen Khac Lam, Director of Nghe An Provincial Forest Protection and Development Fund, FLOURISH Project Director; Mr. Thai Dai Phong, Director of Duc Phong Company; Mr. Nguyen Van Khai, Director General of BWG Bamboo Viet Nam and Mr. Nguyen Khac Luong, technical staff of Khanh Tam Company. We also thank the bamboo farmers and harvesting team in Chau Thang commune, Quy Chau district, for their time and participation in discussions on bamboos related issues.

List of Abbreviations

CF	Carbon fraction
EF	Emission factor
EU	European Union
FLOURISH	Production-driven Forest Landscape Restoration under REDD+ through Private Sector-Community Partnerships as an Asian Regional Learning Exchange project
FLR	Forest Landscape Restoration
GABAR	Global Assessment of Bamboo and Rattan
GMS	Great Mekong Subregion
IKI	International Climate Initiative
INBAR	The International Bamboo and Rattan Organisation
IPCC	Intergovernmental panel on climate change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory analysis
LPG	Liquified petroleum gas
MARD	Ministry of Agriculture and Rural Development
NTFPs	Non Timber Forest Products
RECOFTC	The Center for People and Forests
REDD+	Reduce emissions from deforestation and forest degradation, and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks

Table of Contents

List of Figures

List of Tables

Executive summary

Bamboo forests in Viet Nam currently cover an area of 1.4 million ha, accounting for 10% of the country's total forest area, and 83% of this area consists of bamboo and woody mixed forests. Bamboo forests are mainly distributed in the Northeast (30%), the North Central Coast (28%), the Central Highlands (17%) and the Northwest (15%). Nghe An and Thanh Hoa provinces have the largest bamboo forests in the North Central Coast Region, accounting for 95% of the region's bamboo forest area. The bamboo forests in Nghe An and Thanh Hoa provinces account for 51% and 44% of the region's total bamboo forest area, respectively. Bamboo in Viet Nam is used mainly for handicraft products, poles, panels for home-use and construction and, to an extent, for charcoal.

The handicraft products of the Duc Phong Company in Nghe An province and three panel types of the BWG Mai Chau Joint Stock Company in Hoa Binh Province were assessed. *Bambusa longissima* (Lung)—the main bamboo species used in handicraft making—is collected from natural forests in Nghe An province, and *Dendrocalamus barbatus* (Luong) in Thanh Hoa province is a key resource in the production of bamboo-based panels. The assessment indicated that the average carbon footprint value for handicraft products is 3.6641 kg CO_2e/kg product (1.0011 kg C/kg product). The carbon footprints of bamboo kitchen countertop panels, strand-woven bamboo flooring, and strand-woven bamboo mats are -0.5043 kg CO_2e/kg product (-378.22 kg CO_2e/m^3), -0.284 kg CO_2e/kg product (-340 kg CO_2e/m^3) and -0.371 kg CO_2e/kg product (-371 kg CO_2e/m^3), respectively.

The eco-costs of handicraft kitchen countertop panels, strand-woven bamboo flooring, and strand-woven bamboo mats are 1.068 €/kg product, 0.0125 €/kg product, 0.0695 €/kg product and -0.0511 €/kg product, respectively**.** The key sources of carbon emissions in handicraft production are the transportation of bamboo materials to the factory, accounting for 32.82% of the total emissions, followed by the use of recycled board and paper for packing (30.53%) and electricity consumption (26.71%). The major emission sources in the production of kitchen countertop panels, strand-woven flooring, and strand-woven mats are the consumption of electricity (estimated at 50.53 %–54.50%), freight shipping (13.23 %–30.15%) and glue application (2.73%–18.42%).

General recommendations include the need for formulation and implementation of incentives, policies and raising of awareness to promote private sector investment and the use of bamboo-based products. Specific recommendations for emission reduction at the production level are provided in the report. Regarding handicraft products, considerations should focus on enhancing the efficiency of transporting bamboo materials from the forest sites to factory, more effective use of materials and the use of recycled papers for packaging as well as improved efficiency with respect to electricity use. For bamboo-based panels, production emission reduction should focus on efficient electricity use when operating machinery and production efficiency.

To support the implementation of the mentioned recommendations, further assessment should be considered for the development of incentive policies to promote sustainable bamboo-based production and utilisation, as follows: (1) Assess the possibility of using bamboo waste from handicraft production for energy generation; (2) Assess the potential for production and use of bamboo-based panels for home-use and construction; and (3) Undertake policy analysis to identify barriers to and motivation for development of the bamboo sector.

1. Introduction

1.1. General information on the LCA study

The FLOURISH project for production-driven forest landscape restoration under REDD+ through private sector-community partnerships is funded by Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) through the grant mechanism International Climate Initiative (IKI) and implemented by INBAR, RECOFTC, and other project partners in three countries—Lao PDR, Thailand and Viet Nam. The project has had the following impacts: (1) climate change mitigation: private sector and local communities have replaced conventional cooking fuels (liquefied petroleum gas and fossil fuel) with forest biomass-based pellets and increased carbon storage through permanent tree cover and solid bamboo and wood product value chains in forest landscapes; (2) climate change adaptation: local communities have improved their capacity to adapt to climate change shocks through reduced forest fires and legitimately increased the efficiency of forest resources (timber and non-timber) harvesting and commercialisation; (3) sustainable use and conservation of biodiversity: local governments develop innovative FLR strategies for the contiguity of conservation areas and biodiversity enhancement in GMS; and (4) contribution to sustainable development (co-benefits): local communities' incomes increase as supply/business partners in respective forest product value chains and they gain access to financial institutions for resource-based collateral.

Viet Nam has shown strong commitment to mitigating and adapting to climate change. Its economy is currently undergoing restructuring with the aim of achieving a low-carbon economy and promoting sustainable development. In the forestry and land use sectors, several important policies have been issued to support emission reductions and carbon enhancement as well as biodiversity conservation. These policies include a national strategy on climate change, a national strategy on green growth and a national REDD+ action programme.

In the context of the FLOURISH project, bamboo and other NTFPs are identified as key forest products for increasing forest value, development and restoration of degraded land under the REDD+ mechanism and promotion of community-private sector partnerships, which generate sustainable livelihoods for local people and ensure long-term sustainability.

This study on the LCA of bamboo-based products is part of INBAR's contribution to the FLOURISH project under the climate change mitigation impact area led by INBAR. The study's objective is to implement LCA for selected bamboo-based products from cradle to gate in Viet Nam to unlock bamboo's potential as a key resource against climate change. It analyses material flows, carbon emissions and storage in bamboo-based production. The results will contribute to policy development by providing policy options for emission reduction and climate change resilience in Viet Nam.

1.2. Bamboo distribution and processing in Viet Nam

Woody bamboos have traditionally been recognised in grass systematics as a monophyletic group (Davidse et al., 1986) belonging to the Bambuseae sub-family in the family Poaceae. It is reported that over 100 genera and 1,642 species (Vorontsova et al., 2016) occur worldwide. Viet Nam is one of the top five countries in South East Asia in terms of bamboo diversity, with around 200 species belonging to more than 20 genera (INBAR, 2019)

In Viet Nam, bamboo is diversified and distributed throughout different ecological regions. According to MARD (2020), the total bamboo forest area in Viet Nam is 1.4 million ha, estimated at 10% of Viet Nam's total forest area. The bamboo forests include three types: natural bamboo forest, mixed tree-bamboo forest and bamboo plantations, with mixed tree-bamboo forest covering most of the area at approximately 1.1 million ha, accounting for more than 83% (Hanh, 2018). The natural bamboo forest area covers 245,073 ha while the bamboo plantation area covers 122,583 ha (Dung et al., 2019)

Viet Nam's bamboo forests are mainly distributed in the Northeast region (accounting for 30% of the country's total bamboo forests), the North Central Coast (28%), the Central Highlands (17%) and the Northwest (15%) (MARD, 2020). The top five provinces with respect to bamboo forest area, accounting for more than 52% of Viet Nam's total bamboo forest, are Nghe An (219,994 ha), Thanh Hoa (189,359 ha), Son La (161,148 ha), Lam Dong (131,891 ha) and Bac Kan (98,984 ha) (Dung et al., 2019)

Ten bamboo species potentially have commercial value for production in response to high demand from domestic and international markets: *Dendrocalamus barbatus, Bambusa longissima, Phyllostachys pubescens, Dendrocalamus spp., Bambusa spp, Schizostachyum spp, Arundinaria spp. and Indosasa spp, Bambusa procera, Thyrsostachys siamensis,* and *Maclurochloa sp*. Of these, Lung (*Bambusa longissima sp.nov*) and Luong (*Dendrocalamus barbatus*) are the most commonly distributed bamboo species in Thanh Hoa and Nghe An provinces. They are the main source of raw material supplies for bamboo processing factories in Nghe An Hoa Binh and other traditional bamboo processing areas, such as Hanoi and Thai Binh, for the production of handicraft, furniture and construction materials.

In recent years, Viet Nam has consumed around 1 billion bamboo poles annually for different purposes (MARD, 2018), of which handicraft production is a particularly important sector. In 2018, the estimated handicraft export value was USD$250 million (MARD, 2018). Bamboo-based products include lanterns, lamps, trays and baskets, brooms, place mats and coasters, chopsticks, hats, furniture including tables and chairs, pellets, panels and activated carbon. Through intensive investment in high-technology facilities, companies have focused on producing bamboo-based products such as tables and chairs, pellets, panels, and activated carbon, while the other commodities are normally produced by villagers who work in handicrafts. They are then transported to the companies for further treatment.

Supported by considerable resources of material and cheap labour costs, many handicraft companies are focusing on rattan- and bamboo-based production in Viet Nam. At the national level, Viet Nam has approximately 290 companies and exporters specialising in bamboo-based products (Viet Nam Yellow Pages, 2019). Ha Tay (now Ha Noi), Thai Binh, Nghe An and Thanh Hoa provinces are main locations for bamboo processing and have more than 50 companies and enterprises processing and producing rattan and bamboo products (mainly Lung). Some well-known companies are listed below.

No.	Company name	Address
1	Ha Linh Rattan and Bamboo Company	Phu Nghia Industry Park, Chuong My district, Hanoi, Viet Nam
2	Hoa Binh Rattan Bamboo Co., Ltd	Dong Phuong Yen, Chuong My, Hanoi, Viet Nam
3	Viet Nam Handicraft Company	1/194 Nguyen Trai, Thanh Xuan, Hanoi, Viet Nam
4	Vitranexco Co., Ltd	No.8 Hamlet, An Hai Bac ward, Son Tra district, Da Nang, Viet Nam
5	Huong Trang Co., Ltd	Cat Dang village, Y Yen district. Nam Dinh, Viet Nam
6	Thai An Production Import and Export Co., Ltd	No103 Lot H, Cat Bi Apartment Building, Group E6, Cat Bi Ward, Hai An District, Hai Phong City, Viet Nam
7	Bamboo Village Co., Ltd	54 Phung Van Cung Street, ward 7, Phu Nhuan District, Ho Chi Minh city, Viet Nam
8	Tk Viet Nam JSC	Le Van Luong street, Hanoi, Viet Nam
9	Keico	182 Gia Binh, Bac Ninh, Viet Nam
10	Duc Phong Co., Ltd	Lot 15 - Nghi Phu industry zone, Vinh City, Nghe An province, Viet Nam

Nghe An has the largest area of bamboo compared to other provinces in Viet Nam, with 220,000 ha accounting for 15% of the total bamboo forest area. Lung (*Bambusa longissima*) is one of the many bamboo species distributed in Nghe An province and one of the most commonly traded bamboo species in Quy Chau and Que Phong. In Nghe An, 95% of Lung forest—approximately 29,000 ha—is naturally grown in protection and production forests that cover a limited area of Lung plantation under some piloted projects. According to officials of the Nghe An Forest Protection and Development Fund, around 40–50% of harvested Lung is processed in Nghe An, while the remaining volume is traded outside the province. Raw materials are mainly collected from four districts: Quy Chau, Que Phong, Con Cuong and Tuong Duong. Tian Lin et al. (2019) summarised the area and total volume of Lung species in the following table.

Table 1. Allocation and volume of Lung species in Nghe An province.

Districts	Lung area (ha)	Volume (ton)
Quy Chau	9,731	716,896
Que Phong	17,178	1,016,670
Con Cuong	1,705	Na
Tuong Duong	1,151	Na

Owing to the high demand on the market for Lung materials to produce bamboo-based products, the People's Committee of Nghe An issued Decision No. 654/QD-UBND, dated 13 February 2018, on the sustainable development of rattan and bamboo materials towards 2025. Specific objectives with respect to the Lung species are (1) to sustainably protect and exploit the naturally pure bamboo forests (5,815 ha); (2) to sustainably protect and exploit the woody and Lung mixed forests (21,111 ha); (3) to sustainably protect and exploit approximately 68 ha of Lung plantations; (4) to enhance forest enrichment using Lung species in the natural forests in Que Phong and Quy Chau district; and (5) to establish 130 ha of new Lung plantations.

Nghe An province has two large, influential companies in the industry of bamboo-based products—Khanh Tam and Duc Phong. Khanh Tam located in the Que Phong district, specialises in toothpicks, activated charcoal and carbon and bamboo blinds. The Duc Phong processing factory, located in Vinh city, focuses on bamboo handicrafts, including table lamps, hanging lamps, and bamboo baskets (see Figure 1). The two companies consume bamboos produced by different types of the Lung rotation cycle; thus, it is likely that they may have to compete with one another for raw materials (Tian, 2019). Poor rotation management skills are also serious concerns with respect to the degradation of Lung forests in these districts. The underlying cause is the delay in forest land's devolution to households and local communities (Tian Lin et al, 2019).

Figure 1. Handcrafters and their bamboo-based products in Duc Phong Company

2. Materials and methods

2.1. Location and selection of bamboo-based products

A consultative and participatory approach to selecting key bamboo-based products for the LCA study was applied with the INBAR FLOURISH management team and Nghe An project management unit under the Nghe An Department of Agriculture and Rural Development. The selection followed several criteria, including (1) major bamboo-based products produced in the project area; (2) bamboo materials in the project area must be sources for bamboo processing in the vicinity; (3) it must have potential for climate change mitigation; and (4) reliable data must be available. The table below shows the bamboo-based products and location selected for this study. Bamboo charcoal and activated charcoal are produced by the Khanh Tam company in Nghe An. However, they were not selected for this study because the company has only recently been established and is operating in its pilot phase. As such, the available data were insufficient and too unreliable for assessment.

Table 2. Selected bamboo-based products and locations for LCA

ID	Bamboo-based products	Location and bamboo source
1	Handicraft (light decoration, traditional products etc.)	Duc Phong Company Ltd., located in Vinh City, Nghe An province. The company is a relatively large-scale business in this sector. The bamboo material is from the Quy Chau and Que Phong districts. Additional locations include the traditional handicraft villages of Phu Nghia commune in the Chuong My district of Hanoi. These villages use bamboo materials sourced from Nghe An province.
2	Panels (flooring and ply board)	BWG Mai Chau Bamboo Factory in Hoa Binh province. This is Viet Nam's largest industrial bamboo manufacturing factory. The factory produces a wide range of bamboo products, focusing on panels and furniture.
3	Indoor furniture (tables, chairs)	

The geographical locations of the bamboo materials and factories producing bamboo-based products are shown in Figure 2. The three study locations are Nghe An province (apricot colour) with two factories (Duc Phong and Khan Tam); Ha Noi (yellow colour) with traditional handicraft villages; and Hoa Binh province (green colour) where the BWG factory is located.

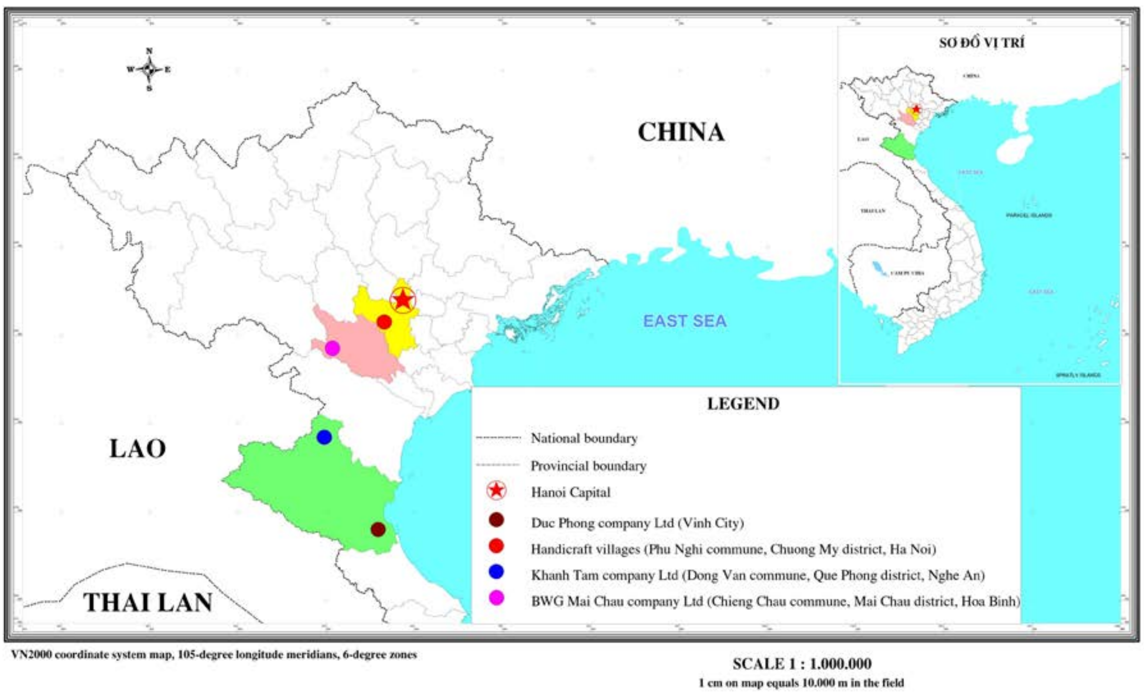

Figure 2. Location map of study sites for the life cycle assessment of bamboo-based products

2.2. Methods

A comprehensive LCA includes four components: (1) a goal and scope definition that describe the specific product under study, its function, aspects of the life cycle to be studied and the purpose of the study; (2) the generation of a life cycle inventory that includes a detailed account of all the inputs and outputs involved in the defined environmental impact categories; (3) inventory analyses that are organised to enable the evaluation of impacts in commonly used categories (for instance, energy consumption, greenhouse gas emissions, waste products); and (4) interpretation of results that are reported as informatively as possible wherein the need and opportunities to reduce the impact on the environment are evaluated (Vogtländer and Van der Lugt, 2014). The following sections will describe the steps involved in LCA analyses in detail.

2.2.1. Literature review and secondary data collection

Information on LCA and carbon footprint assessment of relevant final products was collected through a literature review focused on assessment procedures, the methods applied for LCA and the LCA results of other bamboo-based products. In addition, the literature review focuses on secondary data concerning the environmental burdens of specific materials and processes that will be collected from the Ecoinvent v3.6 LCA database. The environmental burdens will ultimately be identified through field survey. The secondary data, including material flows and consumption, the effectiveness of material use for the production of individual products, the volume of production etc., will be collected from the surveyed factories to facilitate the LCA.

Secondary data from the surveyed factories will be collected to assess material consumption associated with the production of bamboo-based products. These data include (i) bamboo biomass; (ii) additives; (iii) electricity; (iv) Fossil fuels (i.e. Diesels, Petro); (v) Others (water, gases etc.); (vii) Volume of produced products; etc. The data is collected for three recent years from 2017-2019 from factory's records and interviews.

2.2.2. Boundary and scope definition

System boundary is a critical step in the application of LCAs, which uses to identify the boundaries of process flow and data collection. A simple product may involve numerous life cycle processes (Li, Zhang, Liu, Ke and Alting, 2014). It is not an easy task to identify the boundaries for an LCA (Finnveden et al., 2009; Li et al., 2014) because the specific data and data types prepared for the LCA are vast and difficult to assemble comprehensively (Finnveden et al., 2009). This report uses system boundary identification procedures (ISO, 2006) that are widely used in other LCA studies (Pablo Van der Lugt, Vogtländer, Van Der Vegte and Brezet, 2012).

The system boundaries were identified across three levels by individuals working in selected companies, including 1) director, 2) technical staff, and 3) farmers. This strategy was useful in compiling an inventory of the system boundary; however, it was impossible to trace the energy consumption of each stage in the production process. Additionally, bamboo-based products of the selected companies have been delivered to many destinations, and thus some key final destinations were selected to draw the system boundaries. Finally, we accepted that the emissions at any stage that are less than 1% of the entire process should be excluded from our calculations, which may be a source of uncertainty in the LCA analysis.

The following steps were taken to identify the system boundary and the scope definition of the products.

- Step 1: Identify key final products produced from the Lung species.
- Step 2: Explore all stages of the Lung LCA to summarise the system of the chain of production and consumption of each product, which includes inputs, outputs, final products and by-products. Energy, transportation types and other materials used in the production process (i.e., the functional unit (FU)) are summarised based on interviews and company records to determine the energy consumption at each stage of the production process. Emissions in any phases/steps that were less than 1% (in comparison to the first and the last steps) were excluded from the analyses.
- Step 3: Determine the system boundaries of the LCAs, which include “cradle-to-gate” plus “end-of-life”. A carbon footprint boundary was defined as the emissions captured in association with the organisation, event, person or product.
- Step 4: Define the scope or explore the types of emissions sources captured within a carbon footprint (energy and transport) for each key product.
- Step 5: Define the FUs of the key products’ life cycles. The FUs should be measurable and in line with the study objective.

2.2.3. The life cycle inventory (LCI)

Instructions described in ISO 14044 were used to collect data for the LCI (ISO, 2006). The qualitative and quantitative data for inclusion in the inventory were collected for each unit process that is included within the system boundary. The procedures are as follows:

- Draw non-specific process flow diagrams that outline all the unit processes to be modelled, including their interrelationships.
- Describe each unit process in detail with respect to factors influencing the inputs and outputs.
- List flows and the relevant data for operating conditions associated with each unit process.
- Develop a list that specifies the units used.

- Describe the data collection and calculation techniques needed for all data.
- Provide instructions to clearly document any special cases, irregularities or other items associated with the data provided.

2.2.4. Life cycle inventory analyses (LCIA)

2.2.4.1. Cradle-to-gate calculations on key products

The LCIA is a system used to express the result of an LCI in one score, the so-called "single indicator". Two single indicators—the CO_2e "carbon footprint" and the "eco-costs"—were used in the cradle-to-gate calculations. The CO_2e carbon footprint does not include other polluting emissions, such as SOx, NOx and fine dust (Pablo Van der Lugt et al., 2012). The eco-costs system covers 3,000 polluting substances as well as materials depletion (Vogtländer and Baetens, 2010). To identify suitable tools for the LCAs, we contacted Dr J.G Vogtländer at Delft University of Technology in the Netherlands, an expert in LCAs and related software, for advice. He encouraged us to use IdematLightLCA for this report, since 1) people struggle and often make mistakes using software such as OpenLCA and Sigmapro and 2) databases such as Ecoinvent are normally not available free of charge and 3) the Ecoinvent database is often outdated.

IdematLightLCA is an app that may be used on both iOS and Android. The calculation results are no less accurate than full LCA calculations that can easily include mistakes. More importantly, tables of emission factors, eco-costs factors and LCA data of other materials and processes have been calculated and updated using Sigmapro and the Idematapp LCA database of the Delft University of Technology. Thus, owing to the considerable convenience offered by the app, IdematLightLCA was used to run LCIA for this report. To comply with the app's requirements, some materials were converted to other units, as follows:

- Electricity: 1 kWh ~ 3.6 MJ
- Petrol: 1 litre ~ 0.775 kg

2.2.4.2. End-of-life calculations on final products

A credit can be earned for the avoidance of fossil fuels if the final products are burned for electricity or heat. In this report, we used the Idemat database called Idemat 2015 Hardwood 12% MC, bamboo, cork, combustion in small electric power plant, to calculate the credits in a scenario wherein one kg of bamboo waste is eventually burned in a small electric power plant. This was because a large percentage of the selected bamboo-based products are exported to developed countries, such as Canada, Germany, the Netherlands and other European countries.

2.2.4.3. Calculations of carbon sequestration in forests and building industry

To calculate the final result, the effects of carbon sequestration at the global level must be taken into account. The following steps will be taken to estimate carbon sequestration of the key selected species:

- Review studies in relation to the biomass and carbon sequestration of different species, conducted under the ongoing national REDD+ programme.
- Calculate the ratio of carbon stored in forests to that stored in end products. This step complies with the baseline LCA. National information, such as economic growth, export records and growth, was summarised to calculate a land-use change correction factor to reflect the fact that another type of biomass existed in the area before it was changed to forests/plantations. This step complies with the IPCC standards. In this case, the Tier 2 Gain-Loss Method (Verchot et al., 2006) of the IPCC is used to compare the situation of land conversion during a given period of time.
- Calculate the additional stored carbon in forests and plantations due to the growth of the key species and its allocation to the end products.
- Calculate the additional stored carbon in the building industry.
- Calculate the total result of carbon sequestration.

Since almost all Lung forest is naturally grown in protection and production forests, no significant land conversion from other land uses to Lung forest has occurred in recent decades. This scenario means that Lung materials used to process bamboo-based products in Nghe An province are collected from natural forests. Thus, no additional calculations and estimations were conducted for the LCA of the handicraft products.

2.3. Scope of the study

This study focuses on life cycle assessments for selected bamboo-based products produced by factories in Nghe An, Hoa Binh and Ha Noi to assess emissions associated with production and carbon storage in the products throughout its life cycle. This assessment starts from the extraction of raw materials through to processing, transport, use and disposal. The emissions generated from harvesting residuals through decay are omitted, as they are not significant sources.

3. Results

3.1. LCA of handicraft products

Duc Phong Company, Nghe An province

In Duc Phong Company, we had two meetings with the company's director and technical staff. During the first visit to Nghe An, which took place 14–15 January 2020, with support from the director and his staff, we explored the system boundary of Lung's life cycle. The director, Mr Thai Dai Phong, explained to the team members the production system of the Lung species "from cradle to warehouse gate". He also provided information regarding the core markets to which final bamboo-based products are exported, including Europe, Japan and other developed countries. Mr Phong encouraged us to go further with the European market since approximately 85% of handicraft products are sold to customers in Europe. Before these products are distributed to warehouses and final customers, they are shifted to Rotterdam harbour. Details of the system boundary are illustrated in Figure 3 below.

The Duc Phong Company's annual bamboo material consumption is around 1,000 tons (fresh weight) or 400 tons dry weight. Local farmers harvest Lung for selling from April to September. According to the director, ideal bamboo culms for handicraft processing are in the range of 1.5 to 2 years old, 4 to 6 cm in diameter and 60 to 70 cm in length. Around 80% or 320 tons of dry weight is considered waste, of which approximately 256 tons is sold to local people for cooking purposes, while the rest is burned to dry bamboo materials.

During the second visit to Duc Phong Company from 9 to 13 March 2019, we actively worked with the technical staff to assess the average energy consumption of each step towards the production of a final handicraft product. The company has recently produced a hundred product types, and thus it is likely impossible to determine the energy consumption of each product. We based our assessment on the total number of products produced in 2019, that year's electric and energy consumption bills, transportation costs in 2019 and other expenses in 2019, such as glue bills, diesel and gasoline bills to assess the average consumption in each stage of handicraft production (equivalent to a 0.3-kg table lamp). Below are listed the key characteristics of a handicraft product:

- Material: Organic bamboo named "Lung" in Viet Namese, bamboos over three years old
- Colour: Natural/Black
- Size: 47x47x15 mm.
- Net weight: 0.3 kg
- Gross weight: 1.2 kg

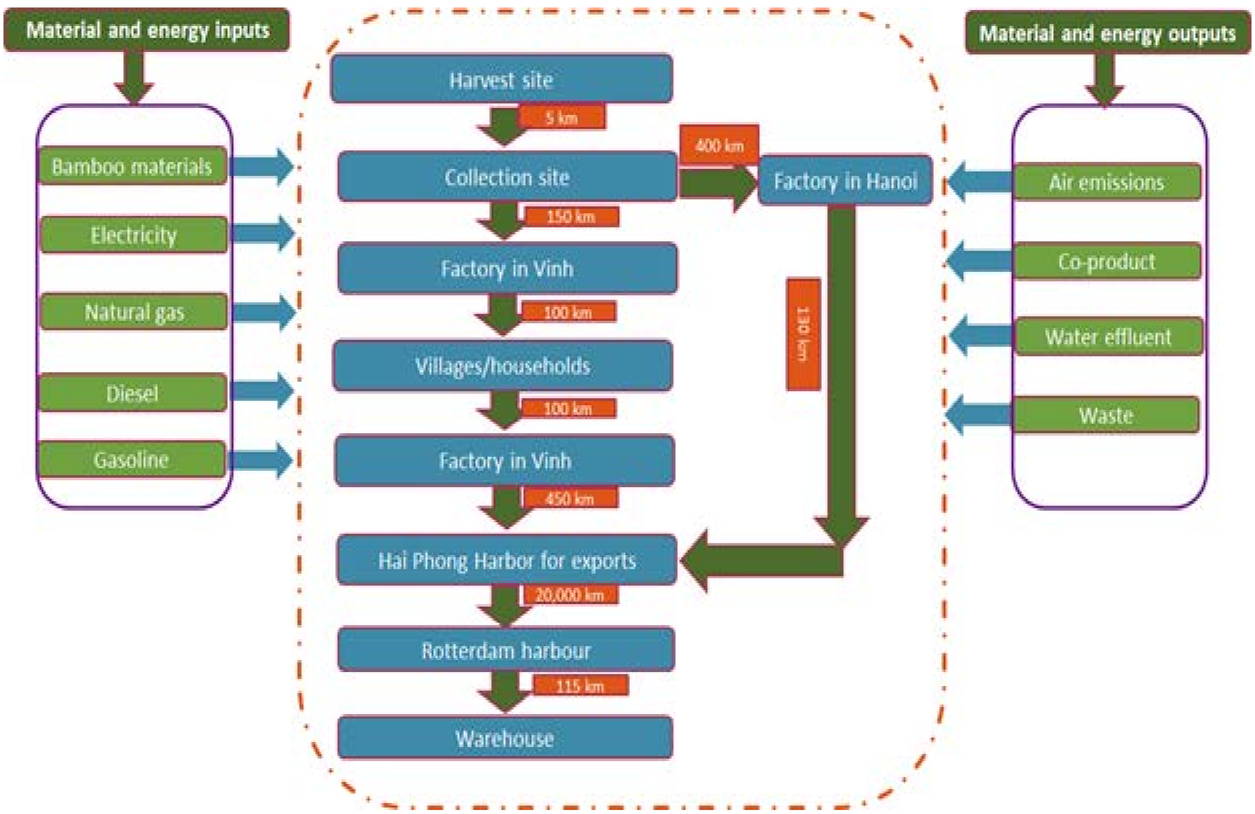

Figure 3. The production system of handicraft products from Lung (cradle to warehouse gate)

The key components in the processing of bamboo-based products by the Duc Phong Company include bamboo harvesting, domestic and overseas transportation, fuel and electric consumption, product delivery, and other additional material supporting production processing. The cycle of handicraft production from raw material to customer includes (1) cutting bamboo; (2) separation of bamboo parts; (3) skin removal; (4) collection and relocation to transportation sites; (5) transportation of bamboo materials to Vinh City; (6) splitting of bamboo; (7) polishing; (8) drying; (9) delivery of bamboo materials to households and collection of products; (10) drying products; (11) polishing and finishing; (12) transportation of products to Hai Phong harbour; (13) transport by freight ship to Rotterdam harbour and 14) transport from Rotterdam harbour to warehouse. The LCA results of carbon footprint and eco-costs are presented in Table 3.

Table 3. Average input data and carbon footprint (CO_2e, cradle to gate) of a handicraft product

Description of procedures	Amount	Unit	CO_2e/FU	CO_2e/kg	Percentage (%)
1. Transportation to transportation site, motorbikes used					
Gasoline consumption	0.004	litter/FU	0.002	0.008	0.181
2. Transportation from the site to Duc Phong Company					
Eco-costs (5 tons truck EURO3, 150 km, transport of 2500 FUs)	0.006	litter/FU	0.004	0.012	0.271
3. Splitting into small strips	0.0011	kWh/FU	0.0005	0.002	0.035
4. Removal of notch and skin	0.002	kWh/FU	0.001	0.003	0.063
5. Removal of internal parts	0.0015	kWh/FU	0.001	0.002	0.047
6. Strip polishing	0.025	kWh/FU	0.010	0.035	0.791
7. Drying using steam	0.268	kWh/FU	0.111	0.370	8.478
8. Transportation of processed materials to households					
Eco-costs (5 tons truck EURO3, 100 km, transport of 16666 FUs)	0.0006	litter/FU	0.0004	0.001	0.027
9. Transportation of final products to Duc Phong Company					
Eco-costs (5 tons truck EURO3, 100 km, 1586,53 FUs)	0.0063	litter/FU	0.004	0.013	0.305
10. Drying final products using steam	0.267	kWh/FU	0.111	0.369	8.446
11. Polishing final products	0.025	kWh/FU	0.010	0.035	0.791
12. Improving and finishing products	0.255	kWh/FU	0.106	0.352	8.067
13. Packaging (carton boxes)	0.8	kg/FU	0.400	1.333	30.534
14. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (24 tons truck EURO3, 450 km)	4.058	ton.km/FU	0.342	1.140	26.107
15. Transportation from Hai Phong harbour to Rotterdam harbour					
Eco-costs (20 feet container in a freight ship, 20,000 km)	24	ton.10km/FU	0.120	0.400	9.160
16. Transportation from Rotterdam harbour to warehouse					
Eco-costs (24 tons truck EURO3, 115 km)	1.0369	ton.km/FU	0.088	0.293	6.718
Total			**1.310**	**4.368**	**100**

Table 4. Input data and eco-costs results (€, cradle to gate) of a handicraft product in average.

Description of procedures	Amount	Unit	Eco-costs /FU	Eco-cost /kg	Percentage (%)
1. Transportation to transportation site, motorbikes used					
Gasoline consumption	0.004	litter/FU	0.002	0.008	0.657
2. Transportation from the site to Duc Phong Company				0.000	0.000
Eco-costs (5 tons truck EURO3, 150 km, transport of 2500 FUs)	0.006	litter/FU	0.004	0.012	0.986
3. Splitting into small strips	0.0011	kWh/FU	0.000	0.000	0.025
4. Removal of notch and skin	0.002	kWh/FU	0.000	0.001	0.046
5. Removal of internal parts	0.0015	kWh/FU	0.000	0.000	0.035
6. Strip polishing	0.025	kWh/FU	0.002	0.007	0.576
7. Drying using steam	0.268	kWh/FU	0.022	0.074	6.170
8. Transportation of processed materials to households				0.000	0.000
Eco-costs (5 tons truck EURO3, 100 km, transport of 16666 FUs)	0.0006	litter/FU	0.000	0.001	0.099
9. Transportation of final products to Duc Phong Company			0.000	0.000	0.000
Eco-costs (5 tons truck EURO3, 100 km, 1586,53 FUs)	0.0063	litter/FU	0.004	0.012	1.036
10. Drying final products using steam	0.267	kWh/FU	0.022	0.074	6.147
11. Polishing final products	0.025	kWh/FU	0.002	0.007	0.576
12. Improving and finishing products	0.255	kWh/FU	0.021	0.070	5.871
13. Packaging (carton boxes)	0.8	kg/FU	0.060	0.200	16.667
14. Transportation from factory to local harbour (Hai Phong)				0.000	0.000
Eco-costs (24 tons truck EURO3, 450 km)	4.058	ton.km/FU	0.127	0.425	35.405
15. Transportation from Hai Phong harbour to Rotterdam harbour				0.000	0.000
Eco-costs (20 feet container in a freight ship, 20,000 km)	24	ton.10km/FU	0.060	0.200	16.667
16. Transportation from Rotterdam harbour to warehouse				0.000	0.000
Eco-costs (24 tons truck EURO3, 115 km)	1.0369	ton.km/FU	0.033	0.109	9.047
Total			**0.360**	**1.200**	**100**

End of life calculations on handicraft products:

Wood products can be treated in different ways at the end of their life spans. In recent decades, multiple solid waste has been used to generate energy products, such as electricity, using various waste-to-energy conversion technologies (Lee, Han and Wang, 2017). In recent years, in developed countries in Europe and North America, a large percentage of wood and bamboo products’ waste ends up in electrical power plants (Vogtländer and Van der Lugt, 2014) to generate electricity and reduce GHG emissions and to decrease methane emissions from landfills (Lee et al., 2017). Under this scenario, only 10% of wood and bamboo products perish in landfills (Vogtländer and Van der Lugt, 2014). This scenario was also used in this report to calculate carbon footprint credits and eco-cost. Van der Lugt et al. (2012) used data from the Idemat database, which is called Idemat2015 Hardwood 12% MC, bamboo, cork, combustion in small electric power plant, to calculate the credits in a scenario wherein one kg of bamboo waste is eventually burned in a small electric power plant. The results are as follows:

- Carbon footprint: 0.779 x 0.9 = 0.704 kg CO_2e per kg of bamboo product (MC 12%).
- Eco-costs: 0.145 x 0.9 = 0.132 € eco-costs per kg of bamboo product (MC 12%).

The emission calculations from the bamboo waste

- Bamboo waste used for cooking: The waste was used as firewood to generate heat for cooking. This is a good way for disadvantaged people to save money, electricity and gas. Usually, one ton of bamboo biomass contains 470 kg carbon, and thus one ton of bamboo biomass burned results in 1.725 tons of CO_2e. In this case, the emissions from burning were considered to be zero because 1) biomass is considered a carbon-neutral fuel in that the emissions associated with its combustion were previously fixed in the material as it grew and will once more be fixed as replacement planted forests grow and 2) the bamboo in the project site is sustainably planted and harvested. The CO_2 emitted into the atmosphere as a result of burning is then sequestered by the next generation of bamboo.
- Bamboo waste used to dry materials for handicraft production: Approximately 64 tons of bamboo waste were used as a replacement for electricity to dry handicrafts at different stages. There were approximately 80 tons of final handicraft products, which required around 64 tons of bamboo waste to dry the materials. This means that one kg of handicraft required 0.8 kg of bamboo waste. We assumed that the bamboo waste was also burned in the electrical power plant to generate electricity, which would be used to dry bamboo materials should bamboo waste be unavailable. The carbon footprint and eco-costs are considered as the reduction of emissions and eco-costs, which are allocated back to handicraft products. The results are as follows:

- Carbon footprint: 0.779 x 0.9 x 0.8 = 0.561 kg CO_2e per kg of bamboo product (MC 12%).
- Eco-costs: 0.145 x 0.9 = 0.105 € eco-costs per kg of bamboo product (MC 12%)

The total carbon footprint and eco-costs per kg of final products are calculated based on CO_{2e} calculations in three stages, including cradle-to-gate production, end of life and carbon sequestration in forests and buildings. As explained in the method section, we did not calculate carbon sequestration of Lung forests in Nghe An. Thus, the final calculations are as follows:

- Total carbon footprint per kg of the handicraft product = 4.368 – 0.704 + 0.561= **4.225 kg CO_2e/kg product**
- Total eco-costs per kg of the handicraft product = 1.20 – 0.132 + 0.105= **1.173 €/kg product**

3.2. LCA of bamboo-based construction products

Bamboo-based construction and furniture products, including bamboo kitchen countertops, strand-woven bamboo flooring, strand-woven bamboo mats, and kitchen worktop zebra bamboo panels, were used to conduct LCA in this study. The bamboo material was sourced from *Dendrocalamus barbatus*, or Luong, as it is known locally.

These bamboo-based products are made by the BWG Mai Chau Joint Stock Company. The factory is built in a 6-ha area at the Chieng Chau Industrial Zone, in the Mai Chau district in Hoa Binh province. Approximately 150 local workers currently work for the BWG, excluding managers and senior staff. Since 2015, BWG has invested and built the largest and most modern industrial bamboo manufacturing plant in Viet Nam, meeting international standards. The BWG's main products are bamboo panels, bamboo cutting boards, bamboo butcher's blocks, bamboo furniture (bamboo flooring, bamboo worktops, desk tops, table tops, countertops, kitchen bench tops), bamboo outdoor furniture (flooring, decking, cladding, horse stables, fencing) and bamboo road mats (rig mats, road access mats, crane mats, bamboo temporary road mats, bamboo composite mats).

Figure 4 below explains the production system for bamboo products used by BWG, which is considered to encompass the process from cradle to harbour gate. Raw materials are bought and delivered from Quan Son and Quan Hoa districts in Thanh Hoa province to Mai Chau district in Hoa Binh province. The figure also illustrates general procedures used to produce four key products, including kitchen countertops, floor panels, mats, and worktop panels. These include ten main steps that are applied for all products. Some additional steps may be required for each product or depending on the customers' requirements. All stages of the procedure are detailed in Figure 4.

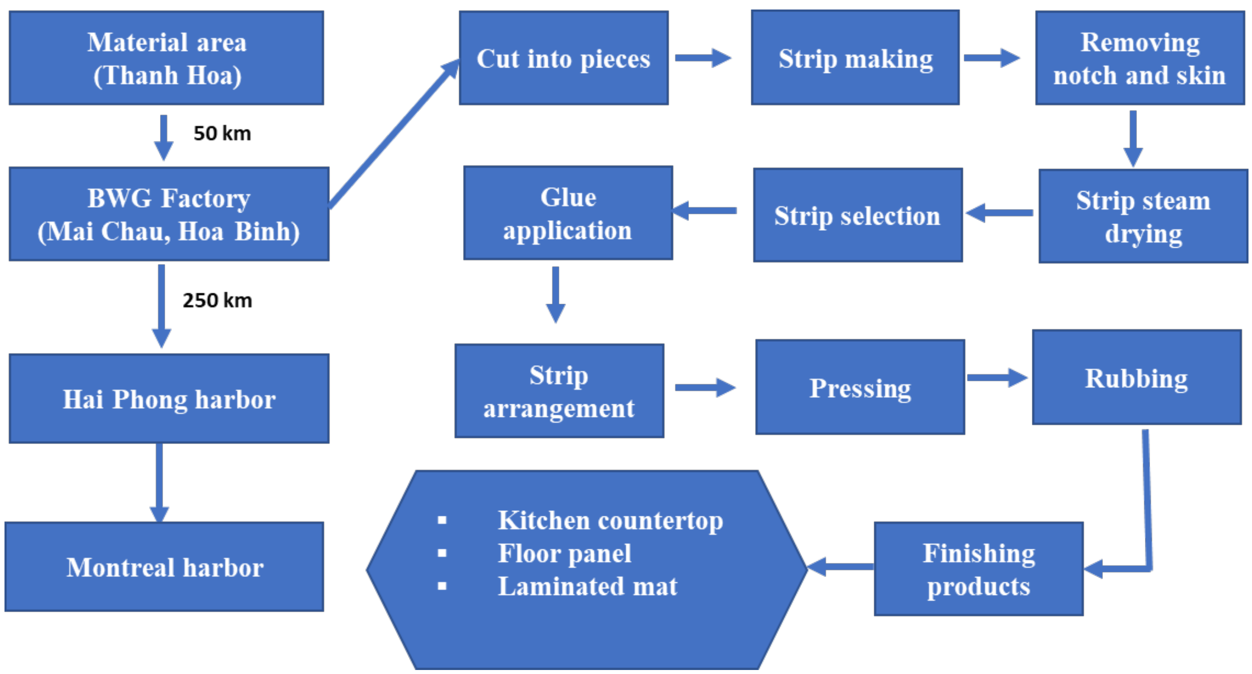

Figure 4. Production system and an overview procedure for producing bamboo-based products in BWG Company.

Kitchen countertop bamboo panels:

Kitchen countertop bamboo panel (Figure 5) is pressed from bamboo strips that have already been well treated, including carbonisation, drying and gluing. In the bamboo vertical panel, the bamboo strips are pressed together vertically. Vertical bamboo panel is harder than most wood and has a wood density of 750 kg/m^3. This product has a wide range of applications, including kitchen worktops, countertops, bamboo doors, tabletops, desktops and bamboo flooring. The bamboo countertop is especially useful for indoor home and restaurant construction, as it has a life span of approximately 15 to 20 years. A detailed description of the product is as follows:

- Material: Organic Bamboo, premium Viet Namese "Luong" bamboo culms of more than three years old.
- Structure: 03 layers vertically pressed (side-pressed) with carbonised colour.
- Colour: Natural
- Size: 1,860.55 x 1,000.125 x 38.1 mm.
- Density: 750 kg/m^3
- Weight: 53.17186 kg/FU
- Expansion rate or water absorption: 0.35%
- Moisture content: 8–12%
- Formaldehyde emission = 0.01ppm, meets all the standard of US (CARB P2), EU (SE0), Japan (F4*).
- Finish: Sanded, Mineral oil or UV.
- Certificates: FSC, BSCI, ISO9001:2015, FDA, TUV, BV.
- Packing: Shrink film, carton box/1pc
- Logo Printing Options: Laser-printing

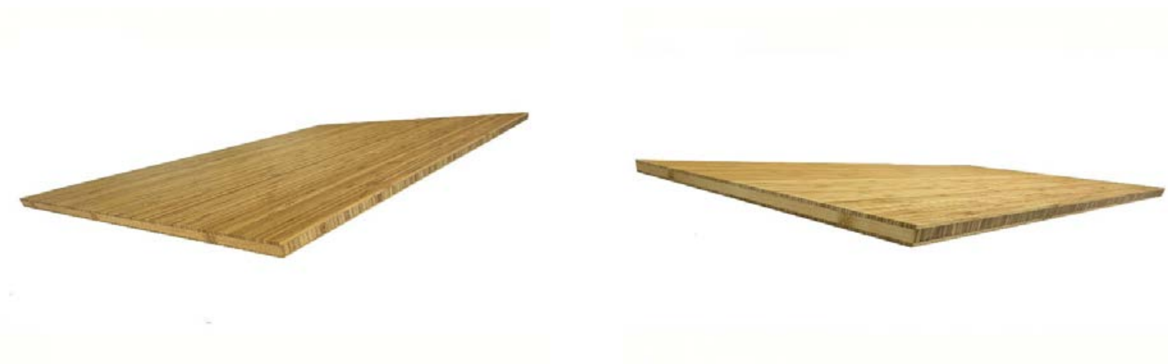

Figure 5. Bamboo kitchen countertop is made by side-pressing with carbonised colour.

The carbon footprint and eco-cost outcomes are shown in Tables 5 and 6.

Table 5. Input data and carbon footprint (CO_2e, cradle to gate) results of a kitchen countertop bamboo panel.

Description of procedures	Amount	Unit	Carbon footprint		
			CO_2e/FU	CO_2e/kg	Percentage (%)
1. Transportation from forest to bamboo buyers, motorbikes used					
Gasoline consumption	0.45	litter/FU	0.300	0.006	0.998
2. Transportation from the buyers' home to BWG Company					
Eco-costs (28 tons truck EURO3, 50 km, transport of 790 FUs)	1.77	ton.km/FU	1.266	0.024	4.210
3. Cut into pieces	1.15	kWh/FU	0.472	0.009	1.569
4. Strip making	1.59	kWh/FU	0.652	0.012	2.169
5. Removing notch and skin	1.67	kWh/FU	0.685	0.013	2.278
6. Carbonisation	7.30	kWh/FU	2.994	0.056	9.957
7. Drying carbonised strips	7.85	kWh/FU	3.220	0.061	10.708
8. Strip selection					
9. Glue application (first layer)					
Melamine formaldehyde used (dry condition)	0.58	kg/FU	5.540	0.104	18.424
10. Pressing strips to one-layer board	2.30	kWh/FU	0.943	0.018	3.137
11. Sanding one-layer board	2.11	kWh/FU	0.865	0.016	2.878
12. Second glue application (3-layer board)					
Melamine formaldehyde used (dry condition)	1.12	kWh/FU	0.459	0.009	1.528
13. Pressing strips to three-layer board	2.15	kWh/FU	0.882	0.017	2.933
14. Crushing board	1.92	kWh/FU	0.788	0.015	2.619
15. Cutting panels to desired form	0.45	kWh/FU	0.185	0.003	0.614
16. Dust absorption (all steps)	10.35	kWh/FU	4.245	0.080	14.118
17. Internal transportation (forklift - Diesel)	0.03	kg/FU	0.010	0.000	0.033
18. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (28 tons truck EURO3, 250 km)	8.86	ton.km/FU	0.962	0.018	3.199
19. Transportation from Hai Phong harbour to Montreal harbour					
Eco-costs (20 feet container in a freight ship, 21,201 km)	112.73	ton.10km/FU	5.410	0.102	17.991
20. Transportation from Montreal harbour to warehouse					
Eco-costs (28 tons truck EURO3, 50 km)	1.77	ton.km/FU	0.192	0.004	0.639
Total			**30.07**	**0.566**	**100**

Table 6. Input data and eco-costs results (€, cradle to gate) of a kitchen countertop bamboo panel.

Description of procedures	Amount	Unit	Eco-costs		
			Eco-costs /FU	Eco-cost /kg	Percentage (%)
1. Transportation from forest to bamboo buyers, motorbikes used					
Gasoline consumption	0.45	litter/FU	0.330	0.006	3.327
2. Transportation from the buyers' home to BWG Company					
Eco-costs (28 tons truck EURO3, 50 km, transport of 790 FUs)	1.77	ton.km/FU	0.471	0.009	4.748
3. Cut into pieces	1.15	kWh/FU	0.100	0.002	1.010
4. Strip making	1.59	kWh/FU	0.138	0.003	1.396
5. Removing notch and skin	1.67	kWh/FU	0.145	0.003	1.466
6. Carbonisation	7.30	kWh/FU	0.636	0.012	6.409
7. Drying carbonised strips	7.85	kWh/FU	0.684	0.013	6.891
8. Strip selection					
9. Glue application (first layer)					
Melamine formaldehyde used (dry condition)	0.58	kg/FU	2.320	0.044	23.387
10. Pressing strips to one-layer board	2.30	kWh/FU	0.200	0.004	2.019
11. Sanding one-layer board	2.11	kWh/FU	0.184	0.003	1.852
12. Second glue application (three-layer board)					
Melamine formaldehyde used (dry condition)	1.12	kWh/FU	0.098	0.002	0.983
13. Pressing strips to three-layer board	2.15	kWh/FU	0.187	0.004	1.887
14. Crushing board	1.92	kWh/FU	0.167	0.003	1.686
15. Cutting panels to a desired form	0.45	kWh/FU	0.039	0.001	0.395
16. Dust absorption (all steps)	10.35	kWh/FU	0.901	0.017	9.086
17. Internal transportation (forklift - Diesel)	0.03	kg/FU	0.030	0.001	0.302
18. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (28 tons truck EURO3, 250 km)	8.86	ton.km/FU	0.358	0.007	3.609
19. Transportation from Hai Phong harbour to Montreal harbour					
Eco-costs (20 feet container = 6.1x2.44x2.59m in a freight ship, 21,201 km)	112.73	ton.10km/FU	2.860	0.054	28.831
20. Transportation from Montreal harbour to warehouse					
Eco-costs (28 tons truck EURO3, 50 km, transport of 790 FUs)	1.77	ton.km/FU	0.071	0.001	0.716
Total			**9.92**	**0.187**	**100**

Strand-woven bamboo flooring:

BWG is the only factory in Viet Nam that currently produces strand-woven bamboo flooring. The company's innovative strand-woven bamboo flooring is superior to other flooring types in terms of eco-friendliness, hardness, durability and natural beauty. Strand-woven bamboo flooring (Figure 6) is a super high-strength flooring created by hot-pressing bamboo fibre strands that have already been well treated, including carbonisation, drying and gluing to form planks. Bamboo strand-woven panelling is the hardest and strongest class owing to its high density (1,200 kg/m^3). Strand-woven bamboo flooring is one of the strongest and most eco-friendly flooring solutions available and is becoming increasingly popular as an alternative to hardwood. The characteristics of the product are as follows:

- Structure: strand-woven hot-pressed
- Colour: Brown carbonised (coffee)/Dark carbonised
- Common size: 1,850 x 125 x 14 mm
- Density: 1,200 kg/m^3
- Weight: 2.428 kg/FU
- Hardness: Janka Rating 15.9, Brinell >9.5 kg/mm
- Surface Finish: Semi-gloss
- Coating: UV varnish or water-based finishes
- Edging: Square edge
- Moisture content: 8%–10%
- Joint: Tongue and Groove (T&G)
- Formaldehyde emission = 0.01 ppm meet all standards of US (CARB P2), EU (SE0), Japan (F4*).
- Installation: Floating, glue down, nail down
- Packing: Plastic film with carton box
- Boards per Pack: 06
- Expansion rate or water absorption: 0.35%
- Certificates: FSC, BCSI, ISO9001:2015.
- Domestic Warranty: 25-year durability against delamination
- Commercial Warranty: 07-year durability against delamination

 

Figure 6. Strand-woven bamboo flooring product at BWG Company during our survey

The outcomes of carbon footprints and eco-costs for different stages are detailed in the following tables.

Table 7. Input data and carbon footprint (CO_2e, cradle to gate) data of a strand-woven bamboo flooring panel.

Description of procedures	Amount	Unit	Carbon footprint		
			CO_2e/FU	CO_2e/kg	Percentage (%)
1. Transportation from forest to bamboo buyers, motorbikes used					
Gasoline consumption	0.07	litter/FU	0.040	0.016	2.116
2. Transportation from the buyers' homes to BWG Company					
Eco-costs (28 tons truck EURO3, 50 km, transport of 17300 FUs)	0.0809	ton.km/FU	0.057	0.023	3.002
3. Cut into pieces	0.052	kWh/FU	0.021	0.009	1.128
4. Strip making	0.0726	kWh/FU	0.030	0.012	1.574
5. Removing notch and skin	0.0763	kWh/FU	0.031	0.013	1.655
6. Strip selection					
7. Carbonisation	0.68	kWh/FU	0.279	0.115	14.747
8. Drying carbonised strips	0.83	kWh/FU	0.340	0.140	18.000
9. Glue application					
Melamine formaldehyde used (dry condition)	0.089	kg/FU	0.290	0.119	15.344
10. Pressing strips to board	0.22	kWh/FU	0.090	0.037	4.771
11. Sanding board (first time)	0.09	kWh/FU	0.037	0.015	1.952

14. Sanding board (second time)	0.075	kWh/FU	0.031	0.013	1.627
14. Cutting panels to desired form	0.022	kWh/FU	0.009	0.004	0.477
15. Crushing board	0.035	kWh/FU	0.014	0.006	0.759
16. Packaging (plastic films and carton boxes)					
Plastic films	0.2	kg/FU	0.150	0.062	7.937
Carton boxes	0.3	kg/FU	0.020	0.008	1.058
17. Dust absorption (all steps)	0.36	kWh/FU	0.148	0.061	7.807
18. Internal transportation (forklift - Diesel)	0.00159	kg/FU	0.000	0.000	0.000
18. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (28 tons truck EURO3, 250 km)	0.404	ton.km/FU	0.045	0.018	2.368
19. Transportation from Hai Phong harbour to Montreal harbour					
Eco-costs (20-foot container in a freight ship, 21,201 km)	51.47	ton.km/FU	0.250	0.103	13.228
20. Transportation from Montreal harbour to warehouse					
Eco-costs (28 tons truck EURO3, 50 km)	0.0809	ton.km/FU	0.009	0.004	0.450
Total			**1.89**	**0.778**	**100**

Table 8. Input data and eco-cost data (€, cradle to gate) of a strand-woven bamboo flooring panel.

Description of procedures	Amount	Unit	Eco-costs		
			Eco-costs/FU	Eco-cost/kg	Percentage (%)
1. Transportation from forest to bamboo buyers, motorbikes used					
Gasoline consumption	0.07	litter/FU	0.05	0.021	8.475
2. Transportation from the buyers' homes to BWG Company					
Eco-costs (28 tons truck EURO3, 50 km, transport of 17300 FUs)	0.0809	ton.km/FU	0.0206	0.008	3.492
3. Cut into pieces	0.052	kWh/FU	0.005	0.002	0.772
4. Strip making	0.0726	kWh/FU	0.006	0.003	1.077
5. Removing notch and skin	0.0763	kWh/FU	0.007	0.003	1.132
6. Strip selection					
7. Carbonisation	0.68	kWh/FU	0.060	0.025	10.090
8. Drying carbonised strips	0.83	kWh/FU	0.073	0.030	12.316
9. Glue application					
Melamine formaldehyde used (dry condition)	0.089	kg/FU	0.120	0.049	20.339
10. Pressing strips to board	0.22	kWh/FU	0.019	0.008	3.265
11. Sanding board (first time)	0.09	kWh/FU	0.008	0.003	1.335
14. Sanding board (Second time)	0.075	kWh/FU	0.007	0.003	1.113

14. Cutting panels to a desired form	0.022	kWh/FU	0.002	0.001	0.326
15. Crushing board	0.035	kWh/FU	0.003	0.001	0.519
16. Packaging (plastic films and carton boxes)					
Plastic films	0.2	kg/FU	0.01	0.004	1.695
Carton boxes	0.3	kg/FU	0.02	0.008	3.390
17. Dust absorption (all steps)	0.36	kWh/FU	0.032	0.013	5.342
18. Internal transportation (forklift - Diesel)	0.0016	kg/FU	0	0.000	0.000
18. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (28 tons truck EURO3, 250 km)	0.0809	ton.km/FU	0.016	0.007	0.670
19. Transportation from Hai Phong harbour to Montreal harbour					
Eco-costs (20 feet container in a freight ship, 21,201 km)	51.47	ton.km/FU	0.13	0.054	22.034
20. Transportation from Montreal harbour to warehouse					
Eco-costs (28 tons truck EURO3, 50 km)	0.0809	ton.km/FU	0.003	0.001	0.525
Total			**0.590**	**0.243**	**100**

Strand woven bamboo mat

In Viet Nam, bamboo road mats (access mats, bamboo rig mats, crane mats) are manufactured exclusively by the BWG Company. This product is one of the best worldwide in terms of hardness, durability and cost-effectiveness. The product has been exported in Europe and North America, particularly for the Canadian market. Bamboo composite strand-woven bamboo mat (Figure 7) is a super high-strength engineered product created by bonding together three layers of strand-woven bamboo panels. The product is also created by hot-pressing bamboo fibred strands that already have been well treated, including carbonisation, drying and gluing. The mat's wood density remains high, ranging 1,000 kg–1,100 kg/m^3.

Figure 7. Strand-woven bamboo mat made by the BWG Company with carbonised colour

Bamboo mat solution is one of the strongest and most durable eco-friendly mat solutions available (more than twice as hard as oak), making it the most cost-effective mat solution for many industries. The mat is suitable for use in various conditions, such as snow, sand, mud, gravel and wet terrain, which are proved to last more than 2 years under snow weather in Canada. Characteristics of the bamboo mat are as follows:

- Product name: Strand-woven bamboo mat
- Structure: strand-woven hot-pressed
- Colour: Brown carbonised/Dark carbonised
- Common size of FUs: 3900 x 2200 x 60 mm
- Density: 1,000 kg/m^3
- Weight: 514.8 kg/FU
- Hardness: Brinel >9.5kg/mm^2
- Impact Intensity ≥216.1 KJ/m^2
- Bending Strength ≥193.3 MPa (or N/mm^2)
- Bending Elasticity modulus ≥ 8100 MPa
- Expansion rate or water absorption: 0.35%
- Formaldehyde emission = 0.01 ppm meet all standards of US (CARB P2), EU (SE0), Japan (F4*).
- Finish: None or Outdoor oil
- Certificates: FSC, BCSI, ISO9001:2015.

- Features: super strong, stiff and stable/stronger than steel/ anti-corrosive/ eco-friendly/ termite-resistant/ water-resistant/ anti-friction/ high hardness/ high stability/ high bending strength/ high density/high durability/ extreme weather-resistant/long-lasting/more than two years' durability.

Table 9. Input data and carbon footprint data (CO_2e, cradle to gate) of a strand-woven bamboo mat.

Description of procedures	Amount	Unit	CO_2e /FU	CO_2e /kg	Percentage (%)
1. Transportation from forest to bamboo buyers, motorbikes used					
Gasoline consumption	6.864	litter/FU	4.540	0.009	2.651
2. Transportation from the buyers' homes to BWG Company					
Eco-costs (28 tons truck EURO3, 50 km, transport of 81.58 FUs)	17.16	ton.km/FU	11.810	0.023	6.895
3. Cut into pieces	8.94	kWh/FU	3.668	0.007	2.142
4. Strip making	13.52	kWh/FU	5.547	0.011	3.239
5. Removal of notch and skin	9.12	kWh/FU	3.742	0.007	2.185
6. Strip selection					
7. Carbonisation	35.62	kWh/FU	14.614	0.028	8.532
8. Drying carbonised strips	39.56	kWh/FU	16.230	0.032	9.476
9. Crushing strips	17.67	kWh/FU	7.250	0.014	4.233
10. Glue application					
Melamine formaldehyde used (dry condition)	1.456	kg/FU	4.740	0.009	2.768
11. Pressing strips to panels	37.21	kWh/FU	5.014	0.010	2.927
12. Glue activation in oven using steam	35.6	kWh/FU	15.266	0.030	8.913
14. Cutting panels to a desired product form	1.52	kWh/FU	14.606	0.028	8.528
15. Sanding forms	1.16	kWh/FU	0.624	0.001	0.364
16. Dust absorption (all steps)	15.23	kWh/FU	0.476	0.001	0.278
17. Internal transportation (forklift - Diesel)	0.317	kg/FU	0.160	0.0003	0.093
18. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (28 tons truck EURO3, 250 km)	85.8	ton.km/FU	8.857	0.017	5.171
19. Transportation from Hai Phong harbour to Montreal harbour					
Eco-costs (20 ft container = 6.1x2.44x2.59m in a freight ship, 21,201 km)	1091.427	ton.10km/FU	52.360	0.102	30.571
20. Transportation from Montreal harbour to warehouse					
Eco-costs (28 tons truck EURO3, 50 km)	17.16	ton.km/FU	1.771	0.003	1.034
Total			**171.273**	**0.333**	**100**

Table 10. Input data and eco-cost data (€, cradle to gate) of a strand-woven bamboo mat.

Description of procedures	**Amount**	**Unit**	**Eco-costs /FU**	**Eco-cost /kg**	**Percentage (%)**
1. Transportation from forest to bamboo buyers, motorbikes used					
Gasoline consumption	6.864	litter/FU	5.12	0.010	8.185
2. Transportation from the buyers' homes to BWG Company					
Eco-costs (28 tons truck EURO3, 50 km, transport of 81.58 FUs)	17.16	ton.km/FU	4.616	0.009	7.379
3. Cut into pieces	8.94	kWh/FU	0.778	0.002	1.244
4. Strip making	13.52	kWh/FU	1.176	0.002	1.881
5. Removal of notch and skin	9.12	kWh/FU	0.794	0.002	1.269
6. Strip selection					
7. Carbonisation	35.62	kWh/FU	3.099	0.006	4.955
8. Drying carbonised strips	39.56	kWh/FU	3.442	0.007	5.503
9. Crushing strips	17.67	kWh/FU	1.537	0.003	2.458
10. Glue application					
Melamine formaldehyde used (dry condition)	1.456	kg/FU	1.990	0.004	3.181
11. Pressing strips to panels	37.21	kWh/FU	3.238	0.006	5.176
12. Glue activation in oven using steam	35.6	kWh/FU	3.098	0.006	4.952
14. Cutting panels to desired product form	1.52	kWh/FU	0.132	0.000	0.211
15. Sanding forms	1.16	kWh/FU	0.101	0.000	0.161
16. Dust absorption (all steps)	15.23	kWh/FU	1.325	0.003	2.119
17. Internal transportation (forklift - Diesel)	0.317	kg/FU	0.290	0.001	0.464
18. Transportation from factory to local harbour (Hai Phong)					
Eco-costs (28 tons truck EURO3, 250 km)	85.8	ton.km/FU	3.462	0.007	5.535
19. Transportation from Hai Phong harbour to Montreal harbour					
Eco-costs (20 ft container = 6.1x2.44x2.59m in a freight ship, 21,201 km)	1091.427	ton.10km/FU	27.660	0.054	44.221
20. Transportation from Montreal harbour to warehouse					
Eco-costs (28 tons truck EURO3, 50 km)	17.16	ton.km/FU	0.692	0.001	1.107
Total			**62.550**	**0.122**	**100**

Calculations of carbon sequestration in forests and buildings:

The calculation of carbon sequestration in forests and the building industry includes five steps.

The calculation of carbon ratio:

Typically, one kg of bamboo equates to 0.42 kg of bamboo in the end product (P Van der Lugt and Vogtländer, 2015). The bamboo weight in the final product can be higher or lower than the value mentioned; it depends on the chemical materials and natural resin added to the end product that is ready to deliver to customers. We calculated the carbon ratio as follows:

- 0.42 kg d.m. of bamboo is used in 0.4263 kg d.m. of the kitchen countertop panel, since we assumed that added chemical materials account for approximately 1.5% of the handicraft product's weight. One kg d.m. of handicrafts equals 1/0.4263= **2.346 kg** d.m. above-ground bamboo-forest biomass.
- For the strand-woven bamboo flooring, 0.42 kg d.m. of bamboo is stored in 0.436 kg d.m. of the end product. The resin and other chemical materials account for approximately 3.8% of the strand-woven flooring's weight. Thus, one kg d.m. of flooring equals 1/0.436 = **2.293 kg** d.m. of above-ground biomass.
- Similarly, 0.42 kg d.m. of the bamboo is stored in 0.440 kg d.m. of the strand-woven mat. This means that one kg d.m. of flooring equals 1/0.440 = **2.274 kg** d.m. of above-ground biomass. We assumed that the finished product contained 4.7% of the resin and added chemical materials.

In this report, we used the default of 0.47 per kg dry matter as a carbon content of vegetation (IPCC, 2006; Verchot et al., 2006) and a molar weight ratio of 3,67 for CO_2 versus C to (P Van der Lugt and Vogtländer, 2015) calculate CO_2e. We used these data to calculate the CO_2 stored in the selected products as follows:

- One kg d.m. of kitchen countertop panel equals storage of 2.346x0.47x3.67 = 4.046 kg CO_2.
- One kg d.m. of strand-woven bamboo flooring equals storage of 2.293x0.47x3.67 = 3.955 kg CO_2.
- One kg d.m. of strand-oven mat equals storage of 2.274x0.47x3.67 = 3.922 kg CO_2.

The most important part of carbon storage is underground (P Van der Lugt and Vogtländer, 2015), which is stored in the root system and in the soil layer. In this report, we used a stem ratio of 3.1 (P Van der Lugt and Vogtländer, 2015) to calculate the below-ground biomass. The additional CO_2 related to the final bamboo-based products is as follows:

- One kg d.m. of the bamboo kitchen countertop panel equals 4.305 x 3.1 = **12.542 kg CO_2**.
- One kg d.m. of strand-woven flooring equals 4.207 x 3.1 = **12.260 kg CO_2**.
- One kg d.m. of the strand-woven mat equals 4.172 x 3.1 = **12.158 kg CO_2**.

The calculation of a land-use change correction factor:

The land-use change correction factor must be considered if significant growth has occurred in the bamboo-growing area in the past as well as differences in the biomass before and after land-use change. We found that a large expansion of Luong plantations had occurred during the last four decades, leading to biomass storage in the bamboo plantations.

In the early 1980s, Thanh Hoa province had approximately 38,000 ha of Luong forest. The total forest area increased significantly due to afforestation initiatives, with around 70,000 ha in 2011 (Trieu, 2010). From 2011 to 2019, the total area increased continuously by approximately 10,000 ha (Vo and Viet, 2019). Viet Nam began afforestation programmes in 1993 under programmes such as programme number 327 and 661 funded by the government and international communities. Thus, from 1993 to 2019, the area of Luong forest in Thanh Hoa increased by approximately 42,000 ha, experiencing an annual growth of 1.615%.

During the last four decades, Viet Nam in general and Thanh Hoa province in particular have experienced huge losses of forest due to both legal logging and deforestation. Only 23.6% of Viet Nam's territory was covered by forest in 1983 (Sam, 1994). The new plantations were normally initiated on bare land, and the area experienced deforestation for more than 10 years prior to 1993. As such, we assumed that the new plantations had been developed on grassland. This assumption is particularly important in terms of comparing differences in biomass before and after land conversion. The calculation of the land-use change correction factor is as follows:

- Grassland biomass: Total above-ground and below-ground biomass ranges from 6.5 to 8.5 tones d.m./ha with a carbon factor of 0.47 (Verchot et al., 2006). The average total above- and below-ground biomass is 7.5 tones d.m./ha.
- Luong biomass: Above-ground biomass of Luong plantations in Thanh Hoa province ranges from 22.23 tones d.m./ha to 37.40 tones d.m./ha (Truong, 2015) or 29.815 tones d.m./ha on average. The stem ratio of 3.1 and a carbon factor of 0.47 (Verchot et al., 2006) were also used in our calculation.
- The land-use change correction factor equals [(29.815x3.1x0.47) – (7.5x0.47)]/ (29.815x3.1x0.47) = **0.919**

The calculation of additional stored carbon in bamboo forests and its allocation:

We assumed an increase in new bamboo production to calculate the additional stored carbon in the new bamboo plantations based on national data, such as the annual growth in the bamboo-based product market, the increment of bamboo forest area, the gross domestic product (GDP) growth of the Viet Namese economy and the growth of wood resources in Viet Nam.

Annual growth in the bamboo-based product market fluctuates; however, a growing trend in the market has been evident in recent years. In 2011, the export values of these products (including rattan-based products) decreased by 2.42% compared to those recorded in 2010. However, these values increased significantly by 8.58% and 10.56%, respectively, in 2013 and 2014. In particular, although the government planned an increase of 16–18% in the export wood and non-wood forest products (NWFPs) in 2019 compared to 2018 (MARD, 2019), the export values of bamboo-based and other NWFPs experienced a significant increase of 44.4% in 2019 (Khoi, 2020). The annual expansion of new bamboo plantations has been a mere 1.615%, which may lead to the shortage of raw materials for the manufacture of bamboo-based products. However, the development of new plantations is not always directly correlated with an increase in market demand, but rather such an increase may be delayed (Van der Lugt and Vogtländer, 2015).

Between 2015 and 2018, the growth of wood supply sources in Viet Nam followed the trend in export of bamboo-based products to overseas markets. The growth rate in 2016, 2017 and 2018 was 6%, 12.5% and 8.5%, respectively (MARD, 2019). Since no data on the annual growth of bamboo supply sources are available, we assumed that the growth of wood supply sources reflected the increase in the annual growth of bamboo supply sources and that the annual growth in bamboo supply sources in Viet Nam was around 10%.

Viet Nam has experienced a high growth rate in real GDP in the last two decades. From 2014 to 2019, the growth rate ranged from 5.98% to 7.08%. A rate of 6.5% is predicted for the period 2020–2024 (STATISCA, 2020). In combination with other national data, we concluded that the annual growth in the bamboo-based product market, the GDP growth of the Viet Namese economy and the growth of wood resources in recent years are high, while the growth rate of Luong plantation area remains low. We assumed an increase of **3%** in the additional stored carbon in new bamboo plantations, which means that **0.03 kg** of each kg of bamboo is allocated to the total production of bamboo products, adding to the global carbon sequestration. This estimation is lower than that of the *Phyllostachys pubescens* bamboo species in China, where the three growth rates mentioned above are similar to those in Viet Nam. However, the area of bamboo resources increased by 2.24% annually between 2004 and 2008 (Van der Lugt and Vogtländer, 2015).

The calculation of the additional stored carbon in buildings:

This calculation is based on biomass losses in the processing stages and the ratio of chemical materials and natural resin added to the final products. The results of our interview with the director and technical staff of BWG Company showed that the processing loss is around 30%. Because the company has recently produced bamboo-based products for less than five years, they need time to increase the ratio of bamboo in the end product. We also deducted the weight of added chemical materials from 1kg of the end product, and thus the actual dry one-kg biomasses of the kitchen countertop panel, the strand-woven bamboo flooring, and the strand-oven mat are 0.985 kg (1.5% added chemical materials), 0.962 kg (3.8% added chemical materials) and 0.953 kg (4.7% added chemical materials), respectively. The additional stored carbon in buildings is calculated as follows:

- CO_2 storage in the buildings per kg d.m of the kitchen countertop panel = 0.985x0.7x0.47x3.67 or 1.189 kg. The additional carbon sequestration is related to

1.189x0.03 (the additional stored carbon in new bamboo plantations) = 0.0356 kg CO_2 per kg dry matter of the kitchen countertop panel.

- CO_2 storage in the buildings per kg d.m of the strand woven bamboo flooring = 0.962x0.7x0.47x3.67 or 1.161 kg. The additional carbon sequestration is related to 1.161x0.03 (the additional stored carbon in new bamboo plantations) = 0.0348 kg CO_2 per kg dry matter of the strand-woven bamboo flooring.
- CO_2 storage in the buildings per kg d.m of the strand-woven mat = 0.953x0.7x0.47x3.67 or 1.150 kg. The additional carbon sequestration is related to 1.150x0.03 (the additional stored carbon in new bamboo plantations) = 0.0345 kg CO_2 per kg dry matter of the strand-woven mat.

The calculation of the total result

The carbon sequestration in forests and buildings was calculated by timing the results in Steps 1, 2 and 3 and added the result in Step 4. The details are as follows:

- Carbon sequestration of the kitchen countertop panel equals = 12.542 x0.919x0.03 + 0.0356 = 0.3736 kg CO_2/kg d.m. of kitchen countertop panel. In eco-costs, 1 kg CO_2//kg d.m. final product equals 0.116 €/kg d.m. final product (Van der Lugt and Vogtländer, 2015). Thus, 0.3736 kg CO_2/kg d.m. kitchen countertop panel equals 0.0433 €/kg d.m. kitchen countertop panel. Normally, the moisture content (MC) of bamboo-based products is 10%, the final carbon sequestration and eco-costs are **0.3362 kg CO_2/kg** d.m. of kitchen countertop panel, and **0.0390 €/kg** d.m. of kitchen countertop panel.
- Carbon sequestration of the strand-woven bamboo flooring equals = 12.260x0.919x0.03 + 0.0348 = 0.3728 kg CO_2/kg d.m. of the strand-woven bamboo flooring (**0.3355 kg** CO_2 at 10% MC). This equals to 0.0432 €/kg d.m. of the strand-woven bamboo flooring (**0.0389 €** at 10% MC).
- Carbon sequestration of the strand-woven mat equals = 12.158x0.919x0.03 + 0.0345 = 0.3697 kg CO_2/kg d.m. of the strand-woven mat (**0.3327 kg** CO_2 at 10% MC). This equals to 0.0429 €/kg d.m. of strand-oven mat (**0.0386 €** at 10% MC).

The calculations of total carbon footprint and eco-costs per kg of final bamboo-based construction and furniture products are similar to those of handicraft products. The results are presented in the following table.

Table 11. Carbon footprint and eco-costs of final bamboo-based construction and furniture products

Item	**Kitchen countertop panel**	**Strand woven flooring**	**Strand woven mat**
Carbon footprint per kg			
Production process (**CO_2e/kg**)	0.566	0.778	0.333
End of life (**CO_2e/kg**)	-0.704	-0.704	-0.704
Carbon sequestration (**CO_2e/kg**)	-0.3362	-0.3355	-0.3327
Total (**CO_2e/kg**)	-0.4742	-0.2615	-0.7037
Eco-costs per kg			
Production process (**€/kg**)	0.187	0.243	0.122
End of life (**€/kg**)	-0.132	-0.132	-0.132
Carbon sequestration (**€/kg)**	-0.0390	-0.0389	-0.0386
Total (€/kg)	**0.0161**	**0.0721**	**-0.0486**

Discussion

Carbon emissions and eco-costs associated with a production system depend largely on the consumption and efficiency with which input energy, such as fossils, biomass and electricity, are used. Energy consumption and use efficiency are significantly influenced by the technology and management applied. In this report, the calculations on energy, material and transportation consumptions were grouped into various categories, including electricity, truck transportation, freight ship, board and paper recycling among others (see Appendix 1). The carbon footprints vary greatly among the products and depend largely on numerous factors, such as distance to material sites, efficiency of transportation and input materials use, technology application etc. (see Appendix 2). In the overall process of producing handicraft and bamboo-based panels, electricity consumption is claimed to contribute largest emission portion, accounting for 36–45% of the total emissions.

The average carbon footprint value for handicraft products is 4.225 kg CO_2e/kg product (1.151 kg C/kg product). The eco-cost of preventing environmental burdens caused by the manufacture of handicraft products is 1.173 €/kg product. No studies have been conducted hitherto regarding similar-use products that are made of neither bamboo materials nor other materials. Researchers may think that the manufacture of small items, such as handicraft products, has low carbon footprints and eco-costs; however, our results are contradictory in this regard. In comparison with other bamboo-based products in this report, the carbon footprint and eco-costs of the handicrafts were the highest. This was mainly caused by the use of fossil energy for transportation and packaging paperboards. We found that three key sources of carbon emissions from the handicraft production were the use of recycled board and paper for packing, truck transportation and electricity, accounting for 30.53%, 32.82% and 26.71% of total emissions, respectively (Figure 8). Similarly, the eco-costs of the mentioned items were 16.67%, 44.44% and 19.44%, respectively (Figure 9). The average weight of the handicraft product is just 0.3 kg; however, it has high-dimensional design spaces (47x47x15 mm). This means that high carbon emissions per product from transportation occur due to the limited capacity of truck transportation. Handicraft products also require approximately 0.8 kg of recycled board and paper for packaging, which significantly contributes to both carbon footprint and eco-cost. Furthermore, fresh bamboo material was transported to the company; however, approximately 80% of raw materials were wasted during manufacturing processes. This means that 80% of emissions were allocated to the transportation of bamboo waste. Finally, we found that manufacturing companies in general, including Duc Phong Company, typically use coal-produced industrial electricity to manufacture their target products, which releases more CO_2 than hydroelectricity and solar electricity. As such, to reduce carbon footprint and eco-costs in the future, the company should use hydroelectricity and solar electricity in the handicraft production process and explore innovative alternatives with respect to dimensional design and packaging materials.

The total carbon footprints of the kitchen countertop and strand-woven mat are -0.4742 kg CO_2e/kg product and -0.7037 kg CO_2e/kg product, respectively (see Table 11). In cubic measurements, these equal to -355.65 kg CO_2e/m^3 product, and -703.70 kg CO_2e/m^3 product. The carbon footprint assessment was based on categories such as electricity, truck transportation, freight shipping and board and paper recycling among others (see Appendix 1). We found that the production of kitchen countertop panels and strand-woven mats entails significant demand for industrial electricity, which is approximately 54.5% of the total carbon footprint for both cases (see Figure 8). Glue application and truck transportation used in the manufacture of these products are all below 20% of the total carbon footprint. In comparison with similar products, the carbon footprint of the kitchen countertop panel is higher than that of the multi-layer panel (-0.3383 kg CO_2e/kg product) (Van der Lugt and Vogtländer, 2015), which is made of the raw bamboo materials of *Phyllostachys pubescens* and side-pressed an in natural colour. Similarly, strand-woven bamboo-based outdoor products also stored carbon in the final products at -0.118 kg CO_2e/kg product (Van der Lugt and Vogtländer, 2015), less than that of the strand-woven bamboo mat. Therefore, carbon stored in two above-mentioned products has a smaller effect on the environment in terms of capturing CO_2 in the final products than the multi-layer panel and the outdoor product. Van der Lugt and Vogtländer (2015) also summarised the carbon footprint of other materials commonly used in buildings and constructions and found that bamboo-based products in China have the lowest environmental impact in comparison with plastics and metals. For instance, the total carbon footprints of PVC (Idemat2014 database), steel (Idemat2014 database), aluminium (Idemat2014 database) and concrete (Idemat2014 database) are 2.104 kg CO_2e per kg product, 1.838 kg CO_2e per kg product, 11.580 kg CO_2e per kg product and 0.231 kg CO_2e per kg product, respectively. Our results highlight the importance of bamboo-based products in Viet Nam with respect to reducing CO_2 emissions into the atmosphere and reducing environmental impacts, which is similar to bamboo-based products in China.

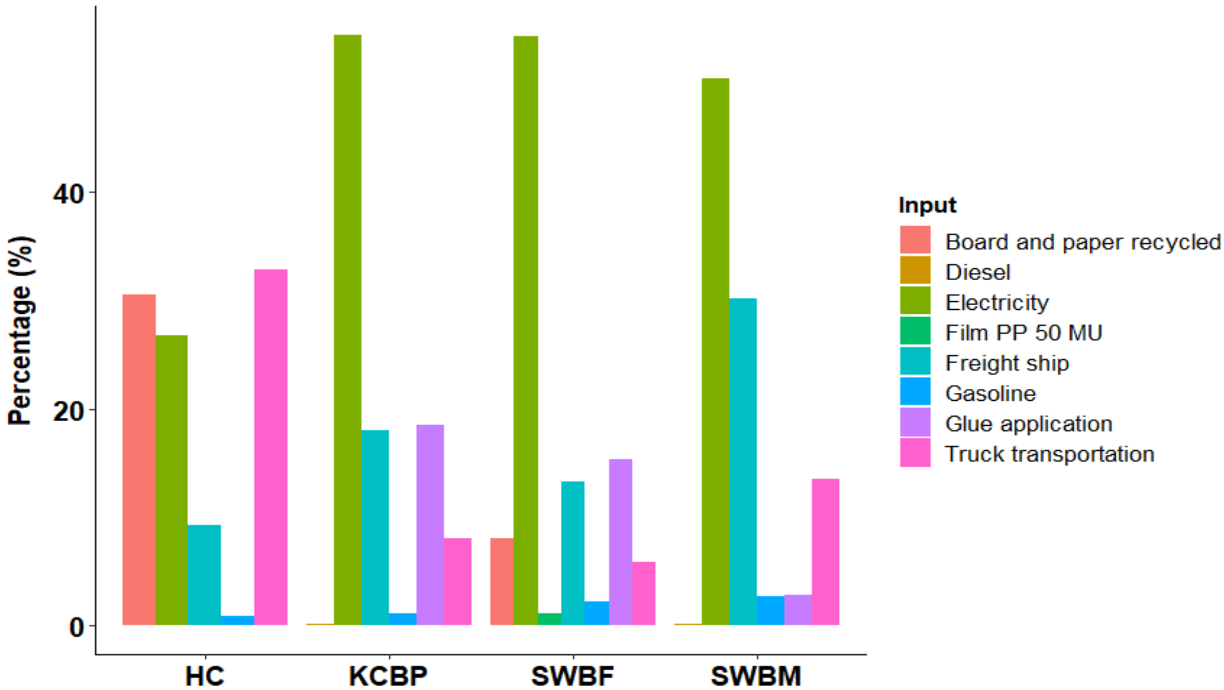

Figure 8. The percentage of carbon footprint by inputs to produce selected products

Note: HC = Handicraft, KCBP = Kitchen countertop bamboo panel, SWBF = Strand woven bamboo flooring, SWBM = Strand woven bamboo mat.

Eco-cost is a measure used to indicate the environmental burden of a product on the basis of the prevention of that burden (Vogtländer and Baetens, 2010). The eco-costs of the kitchen countertop panel and strand-woven mat are 0.0161 €/kg product (12.075 €/m^3 product) and –0.0486 €/kg product (-48.6 €/m^3 product), respectively. Electricity is the most important eco-cost of the kitchen countertop panel at approximately 36% (see Figure 9), while the most significant eco-cost source in the case of the strand-woven mat is over 44.2%. These total eco-costs are significantly lower than those of the multi-layer panels, which ranges from 0.055 €/kg product to 0.081 €/kg product (Van der Lugt and Vogtländer, 2015). The differences in carbon footprint and eco-cost can be explained by energy consumption for transportation and the amount of glue applied to final products. The freight transport using 28-tonne trucks in ton.km/kg and the weight of glue in the manufacturing process of the kitchen countertop panel are 0.233 ton.km/kg product and 0.011 kg/kg product (see Table 5). Similarly, those in the strand-woven bamboo mat are 0.233 ton.km/kg product and 0.028 kg/kg product (see Table 9). By contrast, the two inputs used for the manufacture of strand-woven bamboo beams are significantly higher than those of the kitchen countertop panel and the strand-woven bamboo mat, equivalent to 0.702 ton.km/kg product and 0.066 kg/kg product, respectively (Van der Lugt and Vogtländer, 2015). Thus, the short distance in freight transportation and limited glue application on the final products affect the carbon footprint and eco-costs of the bamboo-based products. In comparison with other construction and building materials, the eco-costs of the kitchen countertop panel and the strand-woven bamboo mat (Table 11) are significantly lower than PVC (0.73 €/kg product), steel (0.68 €/kg product), aluminium (4.35 €/kg product) and concrete (0.06 €/kg product) (Van der Lugt and Vogtländer, 2015).

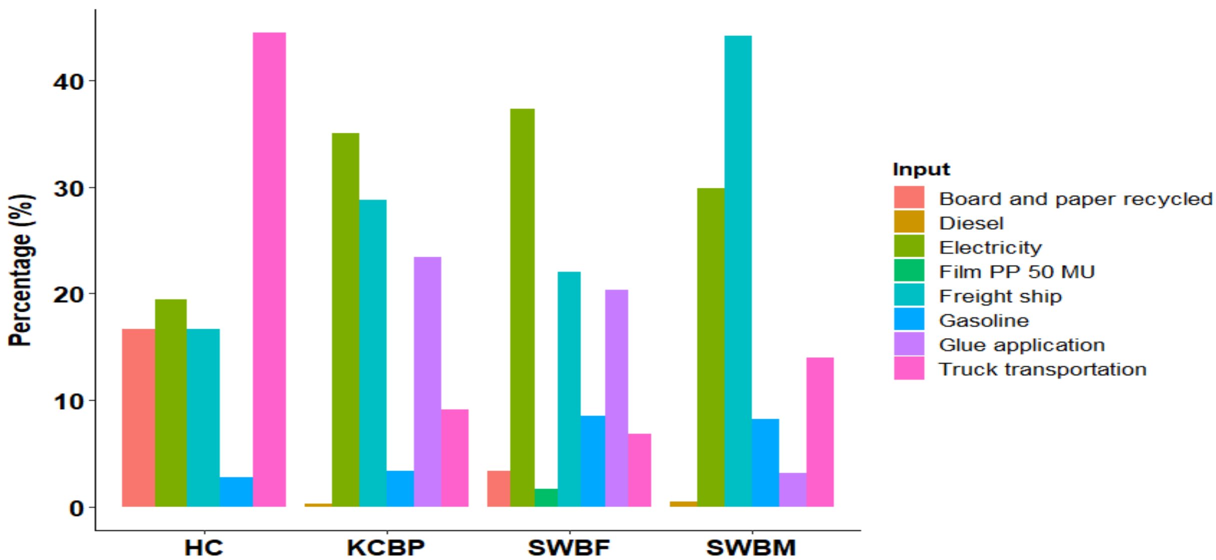

Figure 9. The percentage of Eco-costs by inputs to produce selected products

Note: HC = Handicraft, KCBP = Kitchen countertop bamboo panel, SWBF = Strand woven bamboo flooring, SWBM = Strand woven bamboo mat.

The total carbon footprint and eco-costs of strand woven bamboo flooring are -0.2615 kg CO_2e/kg product (-313.80 kg CO_2e/m^3 product and 0.0721 €/kg product (86.52 €/m^3 product). Electricity input covers the highest proportion of the total carbon footprint (approximately 55%) and the total eco-costs (37.2%) in the manufacturing stages (see Figures 10 and 11). Previous studies have examined the LCAs of flooring products made of bamboo raw materials. For example, Gu, Zhou, Mei, Zhou and Xu (2019) studied the LCA of bamboo scrimber flooring in China and concluded that the product is a negative carbon-emission product with a carbon footprint of -14.89 kg CO_2e/m^3 product. Another study indicated that the carbon footprint of ply flooring ranges from -0.3491 kg CO_2e/kg product to -0.4653 kg CO_2e/kg product or -220 kg/m^3 product on average, depending on thickness, colour and design style of products (Van der Lugt and Vogtländer, 2015). The authors also concluded that the eco-costs of the product are 48 €/m^3 product. In comparison with these results, the carbon footprint in this study is lower. This is also true with respect to non-renewable carbon-intensive materials, including PVC, steel, aluminium and concrete.

The comprehensiveness of LCA projects depends on the scope, objectives and available resources of each study. Some studies have included additional inputs, such as emissions to air, emissions to water, and waste for deeper LCAs (Jönsson, Tillman and Svensson, 1997). Other studies have focused on core inputs such as transportation, energy, materials for production process and the products' end of life (Gu et al., 2019; Van der Lugt and Vogtländer, 2015). Our study followed the latter, and thus it has some limitations in terms of a lack of additional inputs for a comprehensive LCA of bamboo-based products.

In Viet Nam, Decision 11/2011/Q -TTg was issued in 2011 by the Prime Minister on an incentive policy to promote bamboo and rattan development. According to INBAR (2016), the bamboo export value of Viet Nam is worth 85 million USD, accounting for 5% of the global export value. Of this value, around 50% derives from woven bamboo products. While producing handicraft products from bamboo has a long history, the development of bamboo-based products for construction and buildings remains limited. Bamboo-based products are mainly exported, while the domestic market seems oblivious. The use of bamboo-based products for construction and buildings remains limited in Viet Nam as wood-based products continue to prevail. Changing from the use of wood-based products to bamboo-based products in construction and other uses may help to alleviate the pressure on forests and contribute to reducing emissions. Promotion of the consumption of bamboo-based products on the domestic market may be achieved by improving access to the market, the use of sustainable material sources and processing technology and the addition of value across the supply chain as well as the raising of awareness.

Conclusion and recommendations

Bamboo in Viet Nam is commonly used to produce handicraft products and panels for home-use and construction. While bamboo-based handicraft production has a long history, the manufacture of bamboo-based panels and energy products has only recently developed. *Bambusa longissima* and *Dendrocalamus barbatus* in Nghe An and Thanh Hoa province are major bamboo species used in handicraft and panels production.

The carbon footprint was assessed for four (4) bamboo-based products, including handicraft products (in Duc Phong Company), kitchen countertop panels, strand-woven flooring, and strand-woven mats (in BWG bamboo Viet Nam Company). The carbon footprint of the handicraft products, the kitchen countertop panels, the strand-woven flooring, and the strand-woven mat are 3.6641 kg CO_2e/kg product, -0.4742 kg CO_2e/kg product, -0.2615 kg CO_2e/kg product and -0.7037 kg CO_2e/kg product, respectively. The eco-costs of these products are 1.173 €/kg product, 0.0161 €/kg product, 0.0721 €/kg product and -0.0486 €/kg product, respectively. The key sources of carbon emissions for the handicraft production are the transportation of bamboo materials to factories, accounting for 32.82% of the total emissions, followed by the use of recycled board and paper for packing (30.53%) and electricity consumption (26.71%). The major emission sources in the production of kitchen countertop panels, strand-woven flooring and strand-woven mats are the consumption of electricity (estimated 50.53%–54.50%), freight shipping (13.23%–30.15%) and glue application (2.73%–18.42%). The carbon footprints and eco-costs of bamboo-based panels for home-use and construction are much lower than non-renewable carbon intensive materials, including plastics and metals. This implies that the use of bamboo-based products has positive environmental impacts compared to the use of plastics and metal materials with respect to climate change mitigation.

Our general recommendations are that the use of bamboo products should be promoted, appropriate and incentivising policies should be prepared and implemented to mobilise investment from the private sector and to encourage the use of bamboo products. It is also important to effectively implement awareness of the environmental benefits associated with the use of bamboo products. The development of bamboo product production will contribute to climate change mitigation and poverty reduction for local communities. Enhancing downstream processing factories and clustered supply chains will help to improve resource efficiency and reduce the emissions associated with transportation from forest site to factory.

Specifically, there are possibilities for the reduction of emissions at production level for the assessed bamboo-based products. For handicraft products, the following recommendations are made: (1) to enhance the efficiency of material transportation from forest sites to factories. This can be improved through the pre-processing of bamboo materials rather than conducting all processing at the factory; (2) to use recycled papers for packaging with a low carbon footprint; and (3) to improve the efficiency of bamboo material use (as around 80% of bamboo materials are wasted) and electricity use during the processing and manufacture of handicraft products. Bamboo waste should be considered as input material for energy production (energy pellets, charcoal etc.); and (4) the construction of downstream processing factories that consume bamboo residue to produce durable products will help to reduce systematic emission.

Regarding bamboo-based products produced by BWG, one possible means of reducing emissions would be to focus on the efficiency of electricity use in operating machinery. This relates to the arrangement of processing stages in a more connected and completed production chain.

Further assessment and research should be considered to support the elaboration of the mentioned recommendations. These include (1) assessing the possibilities of using bamboo waste from handicraft production for energy generation. This should focus on bamboo disposal availability, the possible use of the waste for energy production and cost-benefit analysis of using the waste as input materials for energy purposes; (2) assessing the potential for production and use of bamboo-based panels for home use and construction for the domestic market, including the requirements of bamboo-based products for construction, market analysis etc.; and (3) policy analysis to identify barriers and motivations for the development of the bamboo sector.

References

Davidse, G., Soderstrom, T.R. and Ellis, R. (1986). 'Pohlidium petiolatum (Poaceae: Centotheceae), a new genus and species from Panama', *Systematic Botany*.pp 131-144 DOI:10.2307/2418952.

Dung, N.Q, Nguyen Nghia Bien, Pham Tuan Anh, Nguyen Thi Thanh Hai, Vu Ngoc Sinh, Dinh Van De and Pham Quang Vinh. (2019). 'Remote sensing-based regional bamboo resource assessment: Viet Nam. INBAR Working Paper No. 80', Bamboo resource assessment in Viet Nam

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., . . . Suh, S. (2009). 'Recent developments in life cycle assessment', *Journal of Environmental Management,* 91(1), 1–21.

Gu, L., Zhou, Y., Mei, T., Zhou, G. and Xu, L. (2019). 'Carbon footprint analysis of bamboo scrimber flooring—Implications for carbon sequestration of bamboo forests and its products', *FORESTS,* 10(1), 51.

Hanh, D.T.M, J. G., Pham Bach Viet and Vignes-Lebbe, R. (2018). *Viet Nam bamboo resources conservation for sustainable development*. Retrieved from https://worldbamboo.net/wbcxi/papers/Diep, MyHanh, J. Gurgand, Pham Bach Viet, Regine Vignes-Lebbe.pdf

Hunter, I. R. (2002). 'Bamboo resources, uses and trade: the future?', *J Bamboo Rattan,* 2, pp1–19.

INBAR. (2019). Key facts of bamboo in Viet Nam. Retrieved from https://www.inbar.int/country/viet-nam/?fbclid=IwAR17OF3MR7ZvMlEf31cwrsd9HBYpTgs8E9wIfL0IOGzqWtqQeJ2lscb7dJA - 2

INBAR (2016). An Overview 2016: Bamboo and Rattan Products in the International Market https://www.inbar.int/wp-content/uploads/2020/05/1534489167.pdf

IPCC. (2006). *IPCC guidelines for national greenhouse gas inventories. 4. Agriculture, forestry and other land use*: IGES.

Jönsson, Å., Tillman, A.-M. and Svensson, T. (1997). Life cycle assessment of flooring materials: case study. *Building and Environment,* 32(3), pp245–255.

Khoi, C. (2020). A significant increase in the export of bamboo-based products. Retrieved from https://thoibaokinhdoanh.vn/thi-truong/xuat-khau-may-tre-tang-truong-manh-1066059.html?fbclid=IwAR22mvrPvaRuNBgNbOXCEt6ZqrF50mOHI4V3AAS4tbTi9Ld3V0BKmg73e-U

Lee, U., Han, J. and Wang, M. (2017). 'Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways', *Journal of Cleaner Production,* 166, pp335–342.

Li, T., Zhang, H., Liu, Z., Ke, Q. and Alting, L. (2014). 'A system boundary identification method for life cycle assessment', *The International Journal of Life Cycle Assessment,* 19(3), pp646-660.

MARD. (2018). Data on forest area change Retrieved from http://www.kiemlam.org.vn/Desktop.aspx/List/So-lieu-dien-bien-rung-hang-nam/?fbclid=IwAR1PUcqbKRBP2_FLikSb69FW4zMeV7Xo6bq2-GQZ_3W8IotDVLA7qG5R5ww. http://www.kiemlam.org.vn/Desktop.aspx/List/So-lieu-dien-bien-rung-hang-nam/?fbclid=IwAR1PUcqbKRBP2_FLikSb69FW4zMeV7Xo6bq2-GQZ_3W8IotDVLA7qG5R5ww

MARD. (2019). *The manufacturing industry of wood and NWFPs products for exporting in 2018 - Achievement, lessons learned, and solutions in 2019.* Retrieved from https://goviet.org.vn/bai-viet/viet-nam-xuat-nhap-khau-go-2018-mot-nam-nhin-lai-va-xu-huong-2019-8947.

MARD. (2020). *Decision No. 1423/QĐ-BNN-TCLN dated 15 April 2020 on promulgation of national forest area as of December 2019*. Hanoi.

Nghia, N.H. and Tien, T.V. (2010). Bamboo resources of Viet Nam. Retrieved from http://vafs.gov.vn/en/2010/12/bamboo-resources-of-Viet Nam/?fbclid=IwAR0fyKfSwHZOow6T-hNK5zca9t3Q7iUgwhT9c9V7PQ3h9zb-hXAX2gfghhs

Sam, D.D (1994). *Shifting cultivation in Viet Nam: its social, economic and environmental values relative to alternative land use*. International Institute for Environment and Development. London, UK. https://pubs.iied.org/7505IIED/

Selvan, T. (2018). *Bamboo Resources, Their Status, Conservation and Strategies for Improvement*. In: Forest, Climate Change and Biodiversity. Kalyani Publisher.

International organization for standardization (ISO) (2006). *Environmental management: Life cycle assessment; requirements and guidelines*. ISO 14040:2006. Retrieved from https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

STATISCA. (2020). Viet Nam: Growth rate of real gross domestic product (GDP) from 2009 to 2021. Retrieved from https://www.statista.com/statistics/444616/gross-domestic-product-gdp-growth-rate-in-Viet Nam/

Thang, P.V. (2016). *Bamboo utilization and development direction towards the strategy plan of action of the ASEAN cooperation on forest products development in Viet Nam*. ASEAN Regional Workshop on Bamboo Utilization, Bogor, Indonesia, 16-18 November 2016. Retrieved from https://www.forda-mof.org//files/Viet Nam_AWGBW.pdf

Tian Lin, Loc Manh Khoa., Nguyen Khac Lam, Dang Thi Thuy. (2019). Report on Lung bamboo value change assessment. FLORISH, Nghe An, Viet Nam.

Trang, D.M.T. (2020). 'Development of method and estimates of carbon foot print for rice production in Red River Delta' PhD Thesis (in Viet Namese). Viet Nam Institute of Meteorology, Hydrology and Climate Change, Hanoi.

Trieu, D. T. (2010). 'The characteristics of Dendrocalamus plantations in Thanh Hoa province', *Viet Nam Journal of Forest Science*. 4 (2010): 66-74.

Truong, L. X. (2015). *Carbon storation of different Luong (Dendrocalamus barbatus) plantation models in Thanh Hoa provinces*. Journal of Forestry Science and Technology. 4(2015): 50-56.

Van der Lugt, P. and Vogtländer, J. (2015). The environmental impact of industrial bamboo products. Life cycle assessment and carbon sequestration. *Report Number: INBAR Technical Report, 35*.

Van der Lugt, P., Vogtländer, J., Van Der Vegte, J. and Brezet, J. (2012). 'Life cycle assessment and carbon sequestration; the environmental impact of industrial bamboo products'. Paper presented at the Proceedings of the IXth World Bamboo Congress.

Verchot, L., Lasco, K., Ogle, S., Raison, J., Li, Y., Martino, D., . . . Smith, P. (2006). IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 6 Grassland. Intergovernmental Panel on Climate Change, vol. 4: Agriculture. *Forestry and Other Land Use*.

Viet Nam Yellow Pages (2019): Bamboo and Rattan products - Manufactures and Wholesales (2019). Hanoi, Viet Nam: Viet Nam Yellow Pages JSC. Retrieved from https://www.yellowpagesvn.com/categories/23610/bamboo-and-rattan-products-manufacturers-and-wholesalers.html?page=1&fbclid=IwAR0ezY87W5ORHx43l_mYoy4xa8uvBVbeqBaXMqLrLCiCrijeU3PPI9zHP1

Vo, D. and Viet, K. (2019). Approximately 80,000 hectares of Luong in Thanh Hoa province: An important resource for livelihood of local mountainous farmers. Retrieved from https://nongnghiep.vn/xu-thanh-co-8-van-hecta-luong-bai-1-cuu-canh-cho-dong-bao-vung-cao-d252781.html

Vogtlander, J. and Van der Lugt, P. (2014). 'The environmental impact of industrial bamboo products: Life-cycle assessment and carbon sequestration', *INBAR Technical Report No. 35*.

Vogtländer, J. G. and Baetens, B. (2010). *LCA-based Assessment of Sustainability: The Eco-costs-Value Ratio EVR*: VSSD.

Vorontsova, M. S., Clark, L. G., Dransfield, J., Govaerts, R. and Baker, W. J. (2016). *World Checklist of Bamboos and Rattans: In Celebration of INBAR's 20th Anniversary*: Beijing.

Appendix

Appendix 1: Carbon footprint and eco-cost of different products by input sources

Product type	Input	Carbon footprint		Eco-costs	
		CO2e/FU	CO2e/kg	Eco-costs/FU	Eco-costs/kg
SWLBM	Electricity	88.270	0.171	18.720	0.036
	Glue application	4.740	0.009	1.990	0.004
	Transportation	23.610	0.046	8.770	0.017
	Freight shipping	53.360	0.104	27.660	0.054
	Gasoline	4.540	0.009	5.120	0.010
	Diesel	0.160	0.000	0.290	0.001
	Total	**174.680**	**0.339**	**62.550**	**0.122**
KCBP	Electricity	16.390	0.308	3.480	0.065
	Glue application	5.540	0.104	2.320	0.044
	Transportation	2.420	0.046	0.900	0.017
	Freight shipping	5.410	0.102	2.860	0.054
	Gasoline	0.300	0.006	0.330	0.006
	Diesel	0.010	0.000	0.030	0.001
	Total	**30.070**	**0.566**	**9.920**	**0.187**
SWBF	Electricity	1.030	0.424	0.220	0.091
	Glue application	0.290	0.119	0.120	0.049
	Transportation	0.110	0.045	0.040	0.016
	Freight shipping	0.250	0.103	0.130	0.054
	Gasoline	0.040	0.016	0.050	0.021
	Film PP 50 MU	0.020	0.008	0.010	0.004
	Board & paper recycling	0.150	0.062	0.020	0.008
	Total	**1.890**	**0.778**	**0.590**	**0.243**
HC	Electricity	0.350	1.167	0.070	0.233
	Transportation	0.430	1.433	0.160	0.533
	Freight shipping	0.120	0.400	0.060	0.200
	Gasoline	0.010	0.033	0.010	0.033
	Board & paper recycling	0.400	1.333	0.060	0.200
	Total	**1.310**	**4.367**	**0.360**	**1.200**

Appendix 2: Carbon footprint (cradle to gate) of several products

ID	Products	Carbon footprint value	Reference
1	Bamboo scrimber flooring (emissions for production) in China (kg CO_2e/m^3 product)	252.65	Lei Gu et al (2019)
2	Bamboo scrimber flooring (carbon stored in the product) in China (kg CO_2e/m^3 product)	267.54	Lei Gu et al (2019)
2	*3-layer laminated bamboo board, 2440 x 1220 x 20 mm (700kg/m³)* (kg CO_2e/m^3 product)	712,600.00	P. van der Lugt and J.G. Vogtländer (2015)
3	Compression of rough bamboo fibres, *1,900 X 110 X 140 mm (1,080 kg/m³)* (kg CO_2e/m^3 product)	989.28	P. van der Lugt and J.G. Vogtländer (2015)
4	Flattened bamboo, *3-ply flooring board, 1210x125x18 mm, 1,819 kg/m³* (kg CO_2e/m^3 product)	1,127.78	P. van der Lugt and J.G. Vogtländer (2015)
5	Construction products produced from *Larix principis-rupprechtii* in China **(**kg CO_2e/m^3 product)	567.64	Fei Lun et al 2016
6	Furniture products produced from *Larix principis-rupprechtii* in China **(**kg CO_2e/m^3 product)	1,497.25	Fei Lun et al 2016
7	Panel products produced from *Larix principis-rupprechtii* in China **(**kg CO_2e/m^3 product)	838.68	Fei Lun et al 2016
8	Rice production in Guangdong province, China (kg CO_2e/ton rice)	2,504.20	Xiaoming Xu et al (2013)
9	Rice production in Hunan province, China (kg CO_2e/ton rice)	2,326.47	Xiaoming Xu et al (2013)
10	Rice production in Heilongjiang province, China (kg CO_2e/ton rice)	1,889.97	Xiaoming Xu et al (2013)
11	Rice production in Sichuan province, China (kg CO_2e/ton rice)	1,538.90	Xiaoming Xu et al (2013)
12	Rice production in Thai Binh, Viet Nam – Traditional practice (kg CO_2e/ton rice)	3,150.00	Trang, D.M (2020)
13	Rice production in Thai Binh, Viet Nam – System of Rice Intensification practice (kg CO_2e/ton rice)	2,925.00	Trang, D.M (2020)
14	Rice production in Thai Binh, Viet Nam – large row mixed with narrow row practice (kg CO_2e/ton rice)	2,940.00	Trang, D.M (2020)
15	Coffee production in Latin American countries - Traditional polycultures and commercial polycultures (kg CO_2e/ton coffee nut)	6,750.00	Henk Rikxoort et al. (2014)
16	Coffee production in Latin American countries - Shaded monocultures, and unshaded monocultures (kg CO_2e/ton coffee nut)	9,900.00	Henk Rikxoort et al. (2014)

INBAR

INTERNATIONAL BAMBOO AND RATTAN ORGANISATION

www.inbar.int

@INBAROfficial