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Analysis of the Carbon Footprint of Academic Gowns: A Case Study of Thai University

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Abstract

The apparel industry has a significant impact on climate change due to the substantial amount of greenhouse gas (GHG) emissions. Academic gowns commonly used in Thailand may be a significant contributor to high GHG levels due to apparel consumption. The objective of this study was to quantify the carbon footprint (CF) of an academic gown for bachelor degree students worn during the commencement ceremony at a private Thai university. The evaluation complies with the national guidelines on Carbon Footprint of Product (CFP) established by the Thailand Greenhouse Gas Management Organization (TGO) in line with ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification. Considering only a single impact category: climate change, GHG emissions were calculated for the entire product life cycle, including raw material acquisition, production process, distribution, use, and the end-of-life (EoL) treatment, and relevant transportation/delivery. Data in this study were collected from the entrepreneur producing academic gowns for rental purposes. The numerical results revealed that CFP of an academic gown with a length of 40 inches, weighing 1,284.30 g, is 42.7 kgCO_2-eq over its entire life cycle with 39.71% contributing from use phase and EoL treatment. The stages of raw material acquisition, use phase and production process caused most of the emissions at 41.08%, 33.69% and 18.49%, respectively. The carbon footprint of this gown serves as an important baseline data to enhance design development and the production process for emission reductions.

Keywords: *academic gown; carbon footprint; climate change; decarbonization policy; design development*

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) published a special report on the impacts of global warming of 1.5 degrees (IPCC, 2018). At the country level, national and regional governments have set targets for achieving carbon neutral and net zero emissions along with strategies and roadmaps to accomplish such targets (Climate Watch, n.d.; Zandt, 2021). The Thai government has announced the target to achieve carbon neutrality and net zero emissions by 2050 and 2065, respectively (United Nations Development Programme, 2023).

All sectors, including government and private agencies, have committed to achieving the national targets. Universities as higher education institutions have played an important role by declaring their targets and by launching projects, research and activities for better understanding and promoting this issue (Berchin et al., 2021). Thailand Greenhouse Gas Management Organization (TGO) was established in 2007 to support the Thai climate change target. TGO has developed guidelines and related schemes for carbon footprint assessment and sustainability. The TGO (2022a) guidelines for Carbon Footprint for Organizations (CFO) have been developed as "Corporate carbon footprint assessment guidelines" in line with ISO 14064-1 (2018) and GHG Protocol (2001, 2004).

The national guidelines on Carbon Footprint of Product (CFP) TGO (2020) have been also developed by TGO in line with ISO 14067:2018 Greenhouse gases - Carbon Footprint of Products – Requirements and guidelines for quantification (International Standard Organization ISO., 2018). CFP is defined as Greenhouse Gas (GHG) emissions of a product through its life cycle stages, including raw material acquisition, the production process, distribution, use and EoL treatment as well as relevant transportation at each stage. Apparel products in Thailand could be evaluated in terms of CFP compliance with TGO protocol (Thailand Greenhouse Gas Management Organization (TGO), 2020) and the assigned Product Category Rule (PCR) (Thailand Greenhouse Gas Management Organization, 2015). The values in the national emission factor divided by the industry sector for CFP TGO (2022b) are used as national emission factors (EF) to calculate CFP for products in Thailand in cases where suppliers cannot provide the emission data for their products or materials.

United Nations Framework Convention on Climate Change (UNFCC) indicated that the impact of the fashion industry, including the production of all clothes which people wear, contributes around 10% of global GHG emissions due to its long supply chains and energy intensive production. The fashion industry consumes more energy than that of the aviation and shipping industries combined (United Nations Framework Convention on Climate Change (UNFCC), 2018).

The trend of research studies related to the apparel industry is upward, presented in systematic literature review in 2023 (Rahman et al., 2023). There were 20 papers published on "fashion and sustainability" in 2010, and the number of papers increased to 171 papers in 2021. The number of research publications related to this field in Asia with the highest population of consumers was still low compared to Europe and North America (Rahman et al., 2023). There were 12 case studies from 2016 to 2021, mostly conducted by companies in Europe and the United States. This indicated that sustainable practices and fashion development were studied particularly in Europe and the United States, with fewer studies conducted in Asia.

In 2021, A review on environmental footprint focused on sustainability scoring label in apparel to communicate to consumer (Gonçalves, & Silva, 2021). The review suggested that the quantification methodology scoring sustainability of fashion products should be in measurable KPIs and be convertible to A-E label to provide simple information for consumers about the most sustainable products (Gonçalves, & Silva, 2021). The environmental indicator most used in various apparel research studies was the impact on global warming, for which the definition of boundaries, allocation criteria and process consideration were necessary. Environmental LCA (Life Cycle Assessment) results, measured in kgCO_2-eq for various products—including knit shirts, T-shirts, sweaters, jeans, and PEF footwear—considering both usage and end-of-life (EoL) treatment, were presented in Gonçalves, & Silva (2021).

Table 1 Selected products with their climate change impact published in studies during 2009 - 2023

Year	Products	Climate Change Impact per functional unit and percentage of use phase and EoL treatment
2009	White long-sleeved shirt (Systain Consulting GmbH, 2009)	10.75 kgCO_2-eq, Use phase and EoL 33%
2013	Gore Jacket (Gore, & Associates GmbH, 2013)	72.7 kgCO_2-eq, Use phase and EoL ~35%
2013	Pale shade shirt (recycled polyester) (Dejpichai et al., 2013)	3.56 kgCO_2-eq, Use phase and EoL 68.5% in case of using a washing machine and ironing
2015	Levi's 501 Jean, a pair of jeans branded Levi and Strauss Co. (Levi Strauss, & Co., 2015)	33.4 kgCO_2-eq, Use phase and EoL 40 %
2015	Chinese cotton shirt (Wang et al., 2015)	8.77 kgCO_2-eq, Use phase 11 %
2016	Batik shirt (Siriwan, & Suwan, 2016)	3.59 kgCO_2-eq, Use phase and EoL 9.55 %
2018	Polyester knit shirt (Gonçalves, & Silva, 2021; Moazzem et al., 2018b)	28 kgCO_2-eq, Use phase and EoL 75 %
2018	Polyester T-shirt (Moazzem, et al., 2018a)	20.56 kgCO_2-eq, Use phase and EoL 31.4%
2023	Cotton T-shirt (Liu et al., 2023)	5.7 kgCO_2-eq, Use phase and EoL 44.7%
2023	Polyester T-shirt (Liu et al., 2023)	9.2 kgCO_2-eq, Use phase and EoL 32.8%
2023	Viscose T-shirt (Liu et al., 2023)	6.7 kgCO_2-eq, Use phase and EoL 39.4%

Several studies, presented in Table 1, have published the climate change impact of fashion products from 2009 to 2023. GHG emissions ranged from 3.56 to 72.7 kgCO_2-eq per piece, with the use phase and EoL treatment accounting for 9.55% to 75% of total GHG emissions.

Thailand had GHG emissions of 278.50 MtCO2-eq, or 3.9 tCO2-eq/head in 2021 (Ritchie et al., 2020). Climate Change Management and Coordination (CCMC) developed the Thailand GHG Emission Inventory System (TGEIS) and reported the proportion of emissions in each sector in 2019 as follows: energy 69.96%, industrial process and production accounted for 10.28%, agriculture 15.23%, and waste 4.53% (Climate Change Management and Coordination Division, 2019). Recent research has focused on the carbon footprint of apparel, such as shirts, T-shirts, jackets, etc. but there is no research on the CFP of academic gowns used for graduation ceremonies. In general, most graduates use an academic gown only once in their lifetime. Most gowns are rented and worn once a year, resulting in substantial GHG emissions per use. Therefore, academic gowns should be improved and redesigned. There were approximately 270,000 bachelor degree graduates in the academic year 2021 in Thailand (Ministry of Higher Education, Science, Research and Innovation, 2021). Thus, design development for academic gowns could reduce GHG emissions significantly. According to Thai ministerial regulations, academic gowns for private institutions of higher education (Office of the Council State, 2012) are classified into three types: Type I: mesh robe with a one-piece open-fronted garment faced and bordered with a velvet or felt band, Type II: black pleated collar robe faced and bordered with a velvet or felt band, Type III: black or colour robe faced and bordered with a velvet or felt band.

In this study, the evaluation was conducted to determine the GHG emissions contributing to climate change from the black heavy gowns with hoods (Type II) used at a private Thai university. This university has integrated sustainability into every aspect, such as education, curriculum development, administration, research and development, etc. In recent years, this university has supported and funded many research and development projects to promote sustainability in all domains such as energy return and carbon investment of wind farms (Tantawat et al., 2023), sustainable development policy based on energy consumption (Sutthichaimethee et al., 2023), sustainable career development for college students (Wang et al., 2023), electric vehicles and environment (Nirukkanaporn, & Petcharaks, 2019), health risks from air pollution (Thanvisitthpon et al., 2021), education for sustainable development (Chiang, & Chen, 2022), energy storage owner in an electricity structure (Petcharaks et al., 2023), etc. This study contributes to sustainability research in apparel industry, enhancing the field's knowledge base at this university.

2. Objectives

The objective of this study was to quantify the carbon footprint of a bachelor's degree academic gown (Type II) worn in the annual commencement ceremony at a private Thai university.

3. Materials and methods

The quantification of this CFP study aligns with the national guidelines on product carbon footprint (CFP) (Thailand Greenhouse Gas Management Organization, 2020), complying with ISO 14067: 2018 (International Standard Organization ISO, 2018), and adopting PCR for apparel made from textile (Thailand Greenhouse Gas Management Organization, 2015). National emission factors (EF), as divided by industry sector in the CFP TGO (2022b), are utilized to calculate CFP for products in Thailand when suppliers cannot provide emission data for their products or materials.

In methodological framework, the calculation of GHG emissions is conducted through a life cycle consisting of four phases: goal and scope, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation (TGO, 2020; International Standard Organization ISO, 2018). LCI includes the compilation and quantification inputs and outputs for a product for each stage throughout its life cycle. LCIA evaluates the magnitude and significance of environmental impacts for a product system. Life cycle interpretation analyzes findings from LCI and LCIA related with goal and scope, leading to conclusions and recommendations (International Standard Organization ISO, 2018). The calculation covers all stages of life cycle: raw material acquisition, production process, distribution, use, and EoL treatment, and relevant transportation/ delivery. This CFP study is quantified under boundaries from the cradle to grave or Business to Consumer (B2C), complying with PCR for apparel made from textile (Thailand Greenhouse Gas Management Organization, 2015). The CFP study considers only the impact on climate change, quantified in mass of CO_2-eq per functional unit of academic gowns.

3.1 Goals and Scope

3.1.1 Goals

The objective of this study was to quantify the carbon footprint of an academic gown using empirical data collected from an entrepreneur producing academic gowns for rental purposes.

This CFP study may be useful for various stakeholders. The findings provide researchers information for further investigation and understanding, aid designers for redesigning with sustainable product design and raw material selection, support management team in developing decarbonization policies and transition towards a low-carbon society, and provide instructors and students with valuable lessons and information for educational purposes.

3.1.2 Product Boundary

This specific product was academic gowns (Type II) for students of medium size, at a length of 40 inches as shown in Figure 1. The academic gown is a black open-fronted robe with wide sleeves and a neck hook fastening. It is adorned with two 7.5 cm wide velvet bands along the front and two 5 cm velvet bars on each sleeve, representing faculty colors. A separate hood is made of the same black fabric, lined with purple satin (the university colour), bordered by black velvet, and accented with golden ribbon trim. It is produced for rental purposes with approximately five uses over a life span of five years. The annual commencement ceremony at this university is held for a cohort of approximately 1,500 bachelor's degree graduates per year. Each gown has distinctive color bands and bars representing various academic programs. Academic gowns, consisting of a robe and hood, are produced and rented by an entrepreneur with a contract for a 5-year term.

Each year, academic gown sets were individually packed into paper bags, each labeled with a specific code for the specific registered graduate, a specific size and specific bands and bars. They were delivered to the university a few weeks before the commencement ceremony. After their use, all of the gown sets were returned and transported back to the entrepreneur's factory and examined in a manual inspection to separate those in damaged condition and those in good condition. The gown sets in good condition were then cleaned, exposed to sunlight for drying and stored in a storeroom for future reuse.

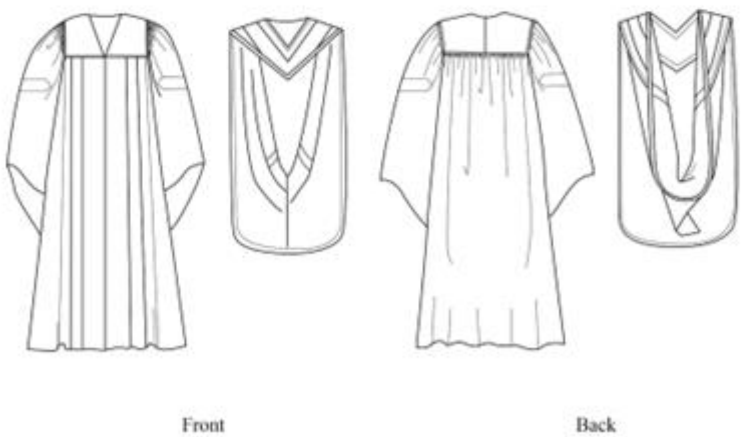


Figure 1 An academic gown sketched by the authors

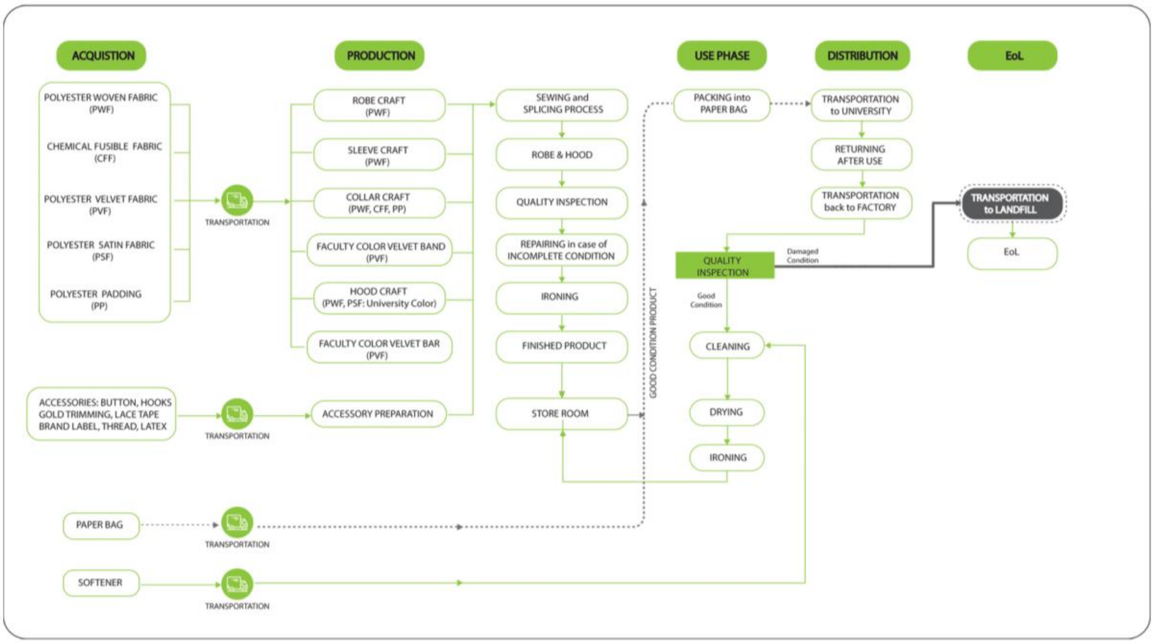


Figure 2 System boundary of carbon footprint of an academic gown (B2C)

3.1.3 Functional Unit

The functional unit of an academic gown is defined as 1 set consisting of a robe and hood, with specific size and weight.

3.1.4 System Boundary

The carbon footprint study of an academic gown covers the complete life cycle from cradle to grave. The boundary system includes five stages: raw material acquisition, the production process, distribution, the use phase, and end-of-life (EoL) treatment as shown in Figure 2. Electricity, waste and wastewater are included in this system as energy input and waste output, however, they are not displayed in this simplified figure.

3.2 Life Cycle Inventory

3.2.1 Primary Data

In this study, primary data were collected by observation of the entrepreneur's demonstration of production of an academic gown including craft (tailoring), sewing, ironing, and cleaning at the entrepreneur's premises. Raw materials and waste were weighed by a digital weighing scale. To obtain precise data, light accessories weighing less than 100 g used in the gown were brought to the university laboratory and weighed using a precision digital weighing scale. The data for raw material acquisition, transportation, distribution, the use phase, EoL treatment, electricity, and tap water were collected.

3.2.2 Secondary Data

GHG emission factors as secondary data for materials, energy, water, transportation, and waste management are obtained from national CFP Emission Factor (Thailand Greenhouse Gas Management Organization, 2022b), the national product category rule for apparel made from textile textile (Thailand Greenhouse Gas Management Organization, 2015), and the national product category rule for packaging (Thailand Greenhouse Gas Management Organization, 2019). Selected GHG emission factors used for this study are shown in Appendix, Table A2.

3.2.3 Assumption

The assumptions in this CFP study were:

i) Most students rented academic gowns instead of buying or having them tailor-made.

ii) Academic gowns had a five-year lifetime.

iii) The EoL treatment of academic gowns were sent to landfills.

iv) The distance between factory and landfill is 40 km, using six-wheeled garbage truck, with a carrying capacity of 11 tons, specified in national guideline on CFP (Thailand Greenhouse Gas Management Organization, 2020).

v) All raw materials were obtained from suppliers in Sampeng market in Thailand, thus transportation of raw materials was determined from suppliers to the factory.

vi) Students did not clean academic gowns before and after using them.

vii) Distances for transportation between factory- suppliers and factory- university were obtained from https://www.google.co.th/maps.

3.3 Life Cycle Impact Assessment (LCIA)

The calculation of GHG emissions is conducted throughout product life cycles mentioned in Section 3.1.4 and relevant transportation (TGO, 2020; Inter-national Standard Organization ISO, 2018). It is important to conduct mass balance in the production process.

GHG emissions depend on the activities and the emission factor (EF). Raw material acquisition, resource depletion, and disposal cause the emission of seven GHG components: CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 and NF_3. Each component impacts the 100- year Global Warming Potential (GWP) differently as shown in Table 2. In general, GHG emissions can be calculated from equation (1) Greenhouse Gas Protocol (GHG Protocol) (2011), International Standard Organization ISO. (2018), TGO (2020), which is the multiplication of activity data *i* (AD_i) with emission factor *i* (EF_i) obtained from equation (2) GHG Protocol (2011), Myhre et al. (2013). Activity data include the amounts of all input and output materials, waste materials, disposal, transportation, use phase, water and energy. EF_i includes all seven components of GHG (CO_2 and non-CO_2) in $kgCO_2$ equivalent by multiplying the mass of material/resource *i* per unit (M_i) with the emission factor (f_x) of each GHG component *x* corresponding to that material/resource and the 100-yr GWP (GWP_x) of each GHG component (GHG Protocol, 2011; Myhre et al., 2013). The GWP_x in equation (2), is the 100-year emissions of a given component, relative to emissions of an equal mass of CO_2. The selected emission factor EF_i used in this study and the recycle rate for disposal in Thailand are shown in appendix Table A1- A2, TGO (2015, 2019, 2022a, 2022b). The mathematical formulations for each stage are presented as follows.

The calculation of GHG emissions throughout the system boundary is presented as follows:

$$EM_i = AD_i EF_i \quad (1)$$

where EM_i is GHG emissions for activity data *i* ($kgCO_2$-eq),

AD_i is activity data of material/resource *i* per unit emitting GHG components (kg, kWh, L), and

EF_i is GHG emission factor of material *i* ($kgCO_2$-eq/unit) which is calculated as follows:

$$EF_i = \sum_{x=1}^{7} M_i f_x GWP_x \quad (2)$$

where EF_i is GHG emission factor of material *i* ($kgCO_2$-eq/unit),

M_i is mass of material /resource *i* in one unit (kg, kWh, L),

f_x is emission factor of material/ resource emitting GHG component *x* ($kgGHG_x$/unit), and

GWP_x is 100-year global warming potential of GHG component *x*.

Total GHG emissions are calculated from Equation (3).

$$EM_{Tot} = EM_{RM} + EM_{PP} + EM_{Dt} + EM_{UP} + EM_{Dp} \quad (3)$$

where EM_{Tot} is total GHG emissions ($kgCO_2$-eq),

EM_{RM} is GHG emissions from raw material acquisition ($kgCO_2$-eq),

EM_{PP} is GHG emissions from production process ($kgCO_2$-eq),

EM_{Dt} is GHG emissions from distribution process ($kgCO_2$-eq),

EM_{UP} is GHG emissions from use phase ($kgCO_2$-eq),

EM_{Dp} is GHG emissions from disposal ($kgCO_2$-eq).

3.3.1 Raw Material Acquisition GHG emissions from raw material acquisition are calculated from Equations (4) and (5).

$$EM_{RM} = \sum_{i=1}^{Nm} EF_i m_i + EM_{Tp,RM} \quad (4)$$

$$EM_{Tp,RM} = \sum_{i=1}^{Nm} \frac{m_i}{1000} EF_{Tp,sf} D_i + \sum_{i=1}^{Nm} \frac{m_i}{1000 \cdot LCC_{truck}} EF_{Tp,fs} D_i \quad (5)$$

Table 2 The 100-yr Global Warming Potential AR5 of each GHG component (Myhre et al., 2013; Thailand Greenhouse Gas Management Organization, 2022a)

GHG Components	Chemical Formula	GWP 100-yr AR5 (2014)
Carbon dioxide	CO_2	1
Methane (fossil Methane)	CH_4	28 (30)
Nitrous oxide	N_2O	265
Hydrofluorocarbons	HFCs	4-12,400
Perfluorocarbons	PFCs	6,630-11,100
Sulfur hexafluoride	SF_6	23,500
Nitrogen trifluoride	NF_3	16,100

where EM_{RM} is GHG emissions from raw material acquisition ($kgCO_2$-eq),

EF_i is GHG emission factor of material i ($kgCO_2$-eq/unit),

m_i is material used to be component of academic gown i (kg),

N_m is number of materials,

$EM_{Tp,RM}$ is GHG emissions from material transportation ($kgCO_2$-eq).

$EF_{Tp,sf}$ is GHG emission factor of transportation using 100% loading four-wheeled truck from source to factory ($kgCO_2$-eq/tkm),

D_i is distance from source of material i to factory, 19.33 km,

$EF_{TP,fs}$ is GHG emission factor of transportation using 0% non-load four-wheeled truck from factory to source ($kgCO_2$-eq/km), and

LCC_{truck} is load carrying capacity of four-wheeled truck transporting material from source to factory, (7 ton).

3.3.2 Production Process

GHG emissions from production process are calculated from Equations (6)-(8).

$$EM_{PP}=EF_{EE}\sum_{j=1}^{Neqp} p_j t_j + EM_{Dp,PP}+EM_{Tp,fl} \quad (6)$$

$$EM_{Dp,PP}=\sum_{k=1}^{Nwm} EF_k wm_{k,PP}(1-RR_k) \quad (7)$$

$$EM_{Tp,fl}=\sum_{k=1}^{Nwm}\frac{wm_{k,pp}}{1000}EF_{Tp,fl}D_{lf}+\sum_{k=1}^{Nwm}\frac{wm_{k,pp}}{1000\cdot LCC_{dp,truck}}EF_{Tp,lf}D_{lf} \quad (8)$$

Where EM_{PP} is GHG emissions from production process ($kgCO_2$-eq),

EF_{EE} is GHG emission factor of electricity (grid mixed in Thailand) ($kgCO_2$-eq/kWh),

p_j is rated electrical power of equipment j (kW),

t_j is production time using equipment j (h),

N_{eqp} is number of equipment,

$EM_{Dp,PP}$ is GHG emissions from disposal in production process ($kgCO_2$-eq), and

$EM_{Tp,fl}$ is GHG emissions from transportation of disposal from factory to landfill ($kgCO_2$-eq).

EF_k is GHG emission factor of wasted material k ($kgCO_2$-eq/unit),

$wm_{k,PP}$ is wasted material k from production process (kg), and

RR_k is recycle rate of wasted material k (percent/100).

$EF_{TP,fl}$ is GHG emission factor of transportation using 100% loading six-wheeled garbage truck from factory to landfill ($kgCO_2$-eq/tkm),

D_{lf} is distance from factory to landfill 40 km (specified in national guideline on CFP (Thailand Greenhouse Gas Management Organization, 2020))

$EF_{TP,lf}$ is GHG emission factor of transportation using 0% non-load six-wheeled garbage truck from landfill to factory ($kgCO_2$-eq/km) and

$LCC_{Dp,truck}$ is load carrying capacity of six-wheeled garbage truck transporting wasted material from factory to landfill, (11 ton).

3.3.3 Distribution Process

GHG emissions from the distribution process are calculated from Equation (9) with five cycles of transporting academic gowns between the university and the factory, and each cycle comprising transporting academic gowns from factory to university and transporting them back from university to factory after usage.

$$EM_{Dt}=10\left(\frac{M_{ag}}{1000}EF_{Tp,fu}D_{fu}+\frac{M_{ag}}{1000\cdot LCC_{Truck}}EF_{Tp,uf}D_{fu}\right) \quad (9)$$

where EM_{Dt} is GHG emissions from transportation of finished product between factory and university in the distribution stage ($kgCO_2$-eq),

M_{ag} is mass of finished product, academic gown (kg),

$EF_{Tp,fu}$ is GHG emission factor of transportation using 100% loading six- wheeled truck from factory to university ($kgCO_2$-eq/tkm),

D_{fu} is distance from factory to university 21.1 km,

$EF_{Tp,uf}$ is GHG emission factor of transportation using 0% non-load six-wheeled truck from university to factory ($kgCO_2$-eq/km), and

LCC_{truck} is load carrying capacity of six-wheeled truck transporting academic gown between university and factory, (8.5 ton).

3.3.4 Use Phase

Academic gowns are used for rental five times. Emissions are calculated from Equations (10) - (13). Emissions from other materials acquisition, electricity, waste management for the use phase are thus multiplied by five whereas emissions from wastewater for cleaning are multiplied by four due to four cleaning cycles after each use.

$$EM_{UP}=5\sum_{q=1}^{Nom}EF_q om_q+5EF_{EE}\sum_{j=1}^{Neqp}p_j t_j+5EM_{Dp,UP}+4EM_{WW,UP}+5EM_{Tp,om}+5EM_{Tp,fl} \quad (10)$$

$$EM_{Dp,UP}=\sum_{l=1}^{Nwom}EF_l wom_{l,UP}(1\text{-}RR_l) \quad (11)$$

$$EM_{WW,UP}=(EF_{WW,collect}+EF_{WW,Treatment})\cdot WW_{UP} \quad (12)$$

$$EM_{Tp,om}=\sum_{m=1}^{Nom}\frac{om_m}{1000}EF_{Tp,sf}D_m+\sum_{m=1}^{Nom}\frac{om_m}{1000\cdot LCC_{truck}}EF_{Tp,fs}D_m \quad (13)$$

Where EM_{UP} is GHG emissions from use phase ($kgCO_2$-eq),

EF_q is GHG emission factor of other material q ($kgCO_2$-eq/unit),

om_q is other material q used in use phase (kg),

N_{om} is number of other materials,

EF_{EE} is GHG emission factor of electricity (grid mixed in Thailand) ($kgCO_2$-eq/kWh),

p_j is rated electrical power of equipment j (kW),

t_j is production time using equipment j (h),

N_{eqp} is number of equipment,

$EM_{Dp,UP}$ is GHG Emissions from disposal in use phases ($kgCO_2$-eq),

$EM_{WW,UP}$ is GHG Emissions from wastewater in use phases ($kgCO_2$-eq),

$EM_{Tp,om}$ is GHG Emissions from transportation of other material between source and factory ($kgCO_2$eq),

$EM_{Tp,fl}$ is GHG emissions from transportation of disposal from factory to landfill ($kgCO_2$-eq) using equation (8),

EF_l is GHG emissions factor of wasted other material l ($kgCO_2$-eq/unit),

$wom_{l,UP}$ is wasted other material l from use phase (kg),

RR_l is recycle rate of wasted other material l (percent/100),

N_{wom} is number of wasted other material,

$EF_{WW,collect}$ is GHG emission factor of collecting wastewater ($kgCO_2$-eq/m^3),

$EF_{WW,treatment}$ is GHG emission factor of treatment wastewater ($kgCO_2$-eq/m^3),

WW_{UP} is wastewater from use phase (m^3),

om_m is other material m used in use phase (kg),

$EF_{Tp,sf}$ is GHG emission factor of transportation using 100% loading four- wheeled truck from source to factory ($kgCO_2$-eq/tkm),

D_m is distance from source of other material m to factory, 19.33 km,

$EF_{TP,fs}$ is GHG emission factor of transportation using 0% non-load four-wheeled truck from factory to source ($kgCO_2$-eq/km), and

LCC_{truck} is load carrying capacity of four-wheeled truck transporting other material from source to factory, (7 ton).

3.3.5 EoL Treatment

GHG emissions from EoL treatment are calculated from Equations (14) and (15).

$$EM_{Dp}=M_{ag}\cdot EF_{DP,ag}+EM_{Tp,DP} \quad (14)$$

$$EM_{Tp,Dp}=\frac{M_{ag}}{1000}EF_{Tp,fl}D_{lf}+\frac{M_{ag}}{1000\cdot LCC_{Dp,Truck}}EF_{Tp,lf}D_{lf} \quad (15)$$

Where EM_{Dp} is GHG emissions from disposal ($kgCO_2$-eq),

M_{ag} is mass of finished product, academic gown (kg),

$EF_{DP,ag}$ is GHG emission factor of unusable academic gown ($kgCO_2$-eq/kg),

$EM_{Tp,Dp}$ is GHG emissions from transportation of disposal (unusable academic gown) ($kgCO_2$-eq),

$EF_{TP,fl}$ is emission factor of transportation using 100% loading six-wheeled garbage truck from factory to landfill ($kgCO_2$eq/tkm),

D_{lf} is distance from factory to landfill 40 km (specified in national guideline on CFP (Thailand Greenhouse Gas Management Organization, 2020))

$EF_{TP,lf}$ is emission factor of transportation using 0% non-load six-wheeled garbage truck from landfill to factory ($kgCO_2$-eq/km) and

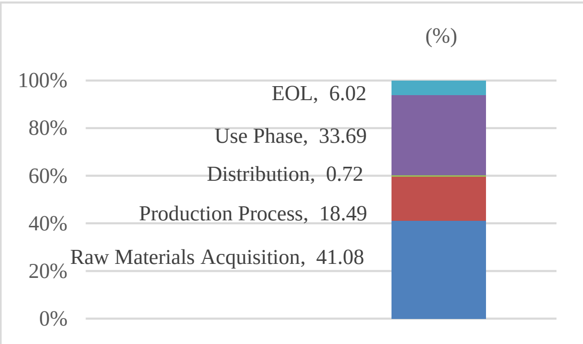
$LCC_{Dp,truck}$ is load carrying capacity of six-wheeled garbage truck transporting wasted material from factory to landfill, (11 ton).

4. Results and Discussions

The results of the quantification of the CFP revealed that an academic gown with length of 40 inches, weighing 1,284.30 g, released GHG emissions 42.72 $kgCO_2$-eq over its entire life cycle, which was almost four times its own weight, with 39.71% contribution from use phase and EoL treatment. GHG emissions for each stage are shown in Figure 3, 41.08% (17.55 $kgCO_2$-eq) of total emissions arose from raw material acquisition, 33.69% (14.39 $kgCO_2$-eq) from the use phase, 18.49% (7.90 $kgCO_2$-eq) from the production process, 6.02% (2.57 $kgCO_2$-eq) from EoL treatment and 0.72% (0.31 $kgCO_2$-eq) from transportation five times between entrepreneur's location and the university at a distance of 21.1 km. For EoL treatment, unrecyclable gowns were disposed of in a landfill.

The majority of raw materials were polyester fabric weighing 1,255.61 g accounting for 83.67% of the total material shown in Table 3. This polyester fabric with a high emission factor of 12.3011 $kgCO_2$-eq/kg released GHG emissions 15.45 $kgCO_2$-eq or 36.15% of total GHG emissions. The next one was chemical fusible fabrics with the emission factor of 15.4007 $kgCO_2$-eq/kg, and a mass of 100.96 g or 6.73% of the total material, releasing GHG emissions 1.55 $kgCO_2$-eq or 3.64% of total GHG emissions. The overall material input was 1,500.59 g whereas the finished product weighed 1,284.30 g equivalent to 85.59% of input.

Resource depletion such as electricity and water are shown in Table 4. GHG emissions during the production process and the use phase were mainly from electricity consumption, 34.33 kWh releasing GHG emissions 20.55 $kgCO_2$-eq or 48.13% of total GHG emissions. Wastewater from the cleaning process was released to city treatment plants. The electricity used for sewing machines, irons, boilers, lighting and fans is shown in Table 5. The highest GHG emissions were from the boiler converting water into steam for the ironing process.



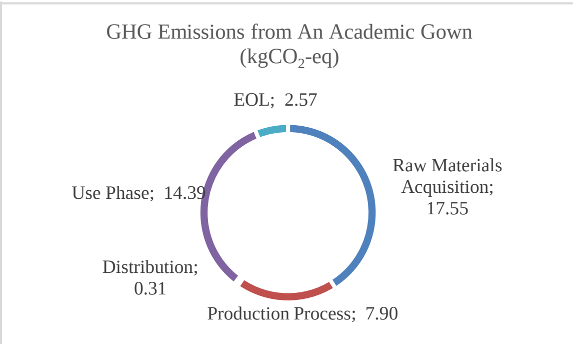


Figure 3 Carbon footprint of an academic gown at each stage in $kgCO_2$-eq and percentage

Table 3 Raw materials for the production of an academic gown

Raw Material	g	%
Fabric woven from polyester yarn	1,255.61	83.67
Chemical fusible fabrics	100.96	6.73
Polyester Padding	77.20	5.15
Other Accessories	66.82	4.45
Total	**1,500.59**	**100.00**

Table 4 Resource depletion for an academic gown

Resource	Unit	Production Process	Use Phase	Total
Electricity	kWh	12.51	21.82	34.33
Water	L	0.42	2.68	3.10

Table 5 Breakdown of electricity used in the production process and use phase of an academic gown

Equipment	Electricity			
	Production Process (kWh)	Use Phase (kWh)	Subtotal (kWh)	Subtotal (%)
Sewing machine	1.13	0	1.13	3.28
Iron	1.8	7.2	9	26.21
Boiler	3.2	12.8	16	46.60
Lighting	3.02	0.86	3.89	11.33
Fan	3.36	0.96	4.32	12.58
Total	**12.51**	**21.82**	**34.33**	**100.00**

Table 6 GHG emissions contributing to climate change from various clothing types

Items	Year	Total GHG Emissions ($kgCO_2$-eq)	Use Phase (%)	Production Process (%)	Material Acquisition (%)	Distribution (%)	EoL Treatment (%)
Gore Jacket (Gore, & Associates GmbH, 2013)	2013	72.7	35%	65%			
A pair of jeans (Levi Strauss & Co., 2015)	2015	33.4	37%	63%			
Chinese cotton shirt (Wang et al., 2015)	2015	8.77	11.14%	56.87%	31.99%		
Polyester T-shirt (Moazzem et al., 2018a)	2018	20.56	30.35%	28.94%	39.68%		1.03%
White long-shirt* (220g) (Systain Consulting GmbH, 2009)	2009	10.75	31%	30%	12%	25%	2%
Pale shade shirt, recycle polyester (180 g) (Dejpichai et al., 2013)	2013	3.56	53.65%	3.09%	26.40%	1.97%	14.89%
Batik shirt (150 g) (Siriwan, & Suwan, 2016)	2016	3.59	8.95%	15.35%	74.8%	0.30%	0.6%
Academic gown (1,284.3 g)	2023	42.72	33.69%	18.49%	41.08%	0.72%	6.02%

Note *Production process (28 %production, 2 %packaging), distribution (3% transportation, 8 %distribution, 14% catalog)

The carbon footprints of products (CFPs) may not be directly comparable due to nonidentical quantification requirements, different system boundaries, and variations in the inclusion of inputs and outputs. However, GHG emissions in Table 6 were intended to provide an overview of the CFPs of various clothing types. GHG emissions across various clothing types revealed a range of 3.56 – 72.7 $kgCO_2$-eq per piece as shown in Table 6. Clothing care during the use phase caused emissions of 8.95%-53.65% of the total GHG emissions. This was the most significant stage due to the resource consumption such as electricity usage for washing and drying machines and ironing, tap water, detergent and producing wastewater. Following the clothing use phase, material acquisition was the next important stage with contributions from fabric woven from yarn, the dyeing process, and cotton cultivation. GHG emissions in the production process of various clothing range of 3.09% - 56.87% resulting from a variety of methods from manual to automated control machines in factories. For example, a pair of jeans, predominantly using cotton for fiber production, emitted a total of 33.4 kgCO_2-eq, with the significant phases for climate change impact and energy from consumer care or use phase (37%), and fabric production (27%) (Levi Strauss, & Co, 2015).

GHG emissions in each stage of four types of clothing, academic gown, batik shirt (Siriwan, & Suwan, 2016), white long-shirt (Systain Consulting GmbH, 2009), and pale shade shirt (Dejpichai et al., 2013), are shown in Figure 4, highlighting the most significant stages: material acquisition, production process and the use phase. An academic gown used a lot of material weighing 1,500.59 g representing 41.08% of total GHG emissions whereas a batik shirt used cotton woven fabric and a complex dyeing process resulting in 74.8% of the total GHG emissions. In the production process of an academic gown, the complexity of design with pleats collar and shoulder, and a complicated hood lengthened the production duration, increasing energy consumption in production process resulting in high emissions of 18.49%. Whereas white long-shirts were responsible for emissions of 30% in production process, due to the lack of grid supply in Bangladesh, the location of the production factory for the suppliers. The electricity was generated onsite using natural gas (Systain Consulting GmbH, 2009). In the production process, pale shade shirts and batik shirts were responsible for 3.09% and 15.35% of emissions, respectively. In distribution phase the gown emitted 0.72% from transportaion the rental gown from the factory storeroom to the university. Whereas other clothing emitted 0.3-25% for distribution phase.

During the use phase, the gown was responsible for quite high GHG emissions at 33.69%, whereas other clothing items were in the range from 8.95% to 53.65% since the rental gown was packed, rented, used, cleaned, and ironed with great effort after each annual use. For EoL treatment, GHG emissions ranged from 0.6% to 14.89% of their total GHG emissions. Assuming 100% disposal after the end of life, the gown contributed 6.02% of its total GHG emissions as shown in Figure 4.

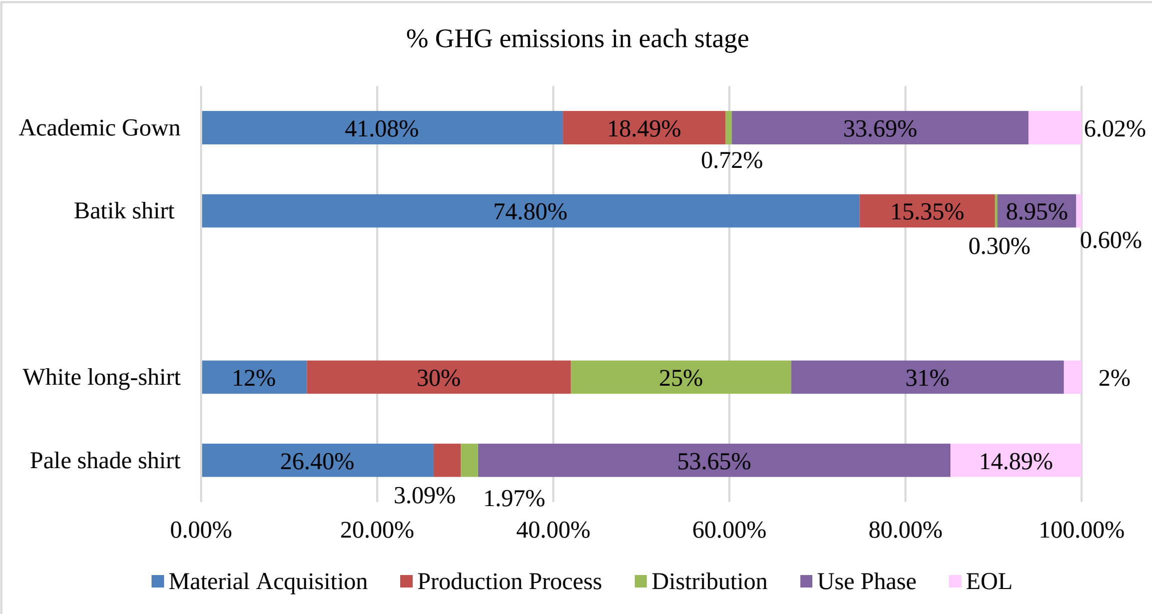


Figure 4 GHG emissions in each stage among four various clothing type

Table 7 GHG emissions contributing to climate change from transportation for various clothing

Items	Year	Total GHG Emissions ($kgCO_2$-eq)	GHG Emissions from Transportation	
			($kgCO_2$-eq)	(%)
White long-shirt (Systain Consulting GmbH, 2009)	2009	10.75	0.29	3%
Chinese cotton shirt (Wang et al., 2015)	2015	8.77	0.227*	2.59%
Batik shirt (Siriwan, & Suwan, 2016)	2016	3.59	0.012	0.33 %
Polyester T- shirt (Moazzen et al., 2018a)	2018	20.56	0.89	4.33%
Academic gown	2023	42.72	0.359	0.84%

Note *excluding transportation of cotton

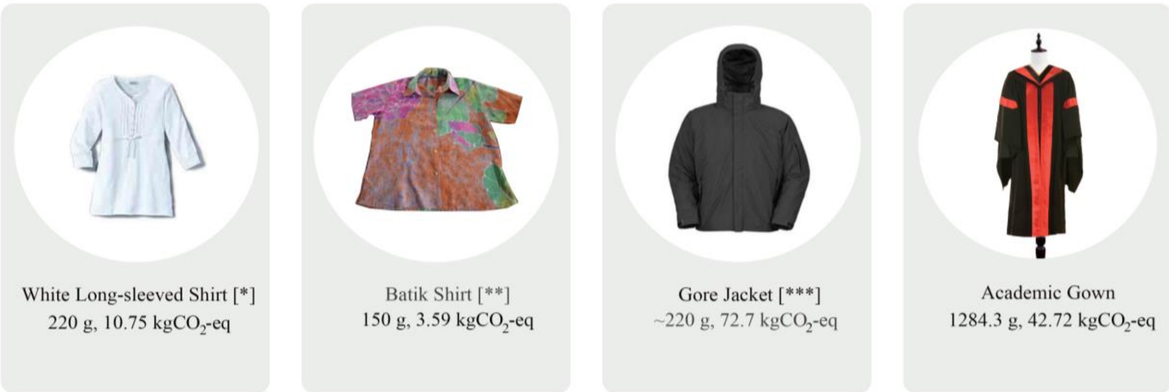


Figure 5 GHG emissions from various clothing types.
[*] Systain Consulting GmbH, 2009, [**] Siriwan, & Suwan, 2016, [***] Gore, & Associates GmbH, 2013.

The transportation of various fabric products ranged from 0.33% to 4.33% of the total GHG emissions depending on the supply chain as shown in Table 7. Batik shirts and academic gowns were produced and distributed locally resulting in a lower percentage whereas the others involved overseas production and distribution resulting in a higher percentage.

GHG emissions contributing to climate change of some fabric products is shown in Figure 5. Gore jackets and academic gowns were designed for special uses. The Gore jacket with a five-year lifetime, and was specially designed to be a waterproof, windproof and breathable jacket. Consumer care, the textile supply chain, distribution and Gore processes including the PTFE fiber supply chain were reflected in the high total emissions of 72.7 $kgCO_2$-eq in which 35% are from the use phase, and less than 0.1% from EoL stage (Gore, & Associates GmbH, 2013). In contrast, an academic gown with a complicated design and five times usage caused the emission of a total of 42.72 $kgCO_2$-eq wiht 33.69% from use phase and 6.02% from EoL stage. Emissions from special products such as Gore jackets and academic gowns were much higher than casual products such as white long-shirts and batik shirts.

The CF of an academic gown, with length of 40 inches, weighing 1,284.30 g was 42.72 $kgCO_2$-eq or 8.54 $kgCO_2$-eq/use consuming raw material 1,500.59 g, electricity 34.33 kWh, tap water 3.10 liters and other resources such as paper bags and softener in the use phase of 100 g per use. The academic gown design used large amounts of polyester fabric particularly in the pleated collar and hood contributing to its heavy weight. This caused discomfort for graduates who may require cooler air, consequently leading to more emissions. The academic gown was medium size. However, the larger size with heavier weight would cause more GHG emissions due to the use of more material and resources. Additionally, the number of uses of academic gowns was only five times in five years compared to other clothing such as T-shirts with 200 uses, resulting in 0.03 $kgCO_2$-eq per use (Horn et al., 2023).

Design development using less fabric, less complexity, lighter weight, and recycled fabric is needed for GHG emission reductions. Alternatively, recycled polyester fabric could be used to reduce GHG emissions as illustrated by the shirt with GHG emissions of only 3.56 kgCO_2-eq in case of using washing machine and ironing Dejpichai et al. (2013) compared to other shirts that caused emissions of 8.77-20.56 kgCO_2-eq as shown in Table 6. The manual cleaning process for academic gowns minimized water usage and employs sunlight for drying instead of drying machines. This resulted in a lower carbon footprint in this process. At the end of lifecycle, academic gowns should be recycled instead of being disposed in landfills. There are many research and studies on textile disposal. Textile waste can be utilized as a resource for new construction products (Tedesco, & Montacchini, 2020). Shredded polyester threads were used to produce a new type of clay bricks whereas wool and cashmere dust were used to replace glass fiber in pre-mixed plaster (Tedesco, & Montacchini, 2020). Different types of clothing waste can be used for a variety of fashion products which may inspire designers in the fashion industry to craft alternatives from garment disposal (Lee, 2023).

Improvement design for academic gowns, with less fabric, less complexity, lighter weight, and recycled fabric is needed for GHG emission reductions. Production process should be improved to shorten the production time to reduce energy consumption from electricity, accounting for 48.13% of total GHG emissions. In addition, energy effiecncy and/ or renewable energy should be determined. This data may stimulate awareness for GHG emission reductions among people in society. This study provided valuable input information that can be integrated into education curricula such as in the Faculty of Fine and Applied Art and core subjects for general education in climate change and global warming impacts for other students. It can raise global warming awareness for students, faculties and staff who may participate in carbon footprint reduction in the future. This study was one of the important activities aligning with university decarbonization policy. It can be used by the university's management team for sustainability initiatives, promoting a low-carbon and sustainable society, positioning the university as a leading organization committed to environmental, social and governance (ESG) goals.

5. Conclusions

This study aimed to quantify the carbon footprint (CF) of an academic gown for bachelor degree students worn during the commencement ceremony at a private Thai university. The quatification complies with the national guidelines on Carbon Footprint of Product (CFP) established by the Thailand Greenhouse Gas Management Organization in line with ISO 14067: 2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification, considering only a single impact category: climate change. The entire life cycle including raw material acquisition, production process, distribution, use, and the end-of-life (EoL) treatment, and relevant transportation/ delivery were taken into consideration in this quantification. Data in this study were collected from the entrepreneur producing academic gowns for rental purposes. An academic gown set with length of 40 inches, weighing 1,284.30 g causes GHG emissions of 42.72 kgCO_2-eq with 39.71% contribution from use phase and EoL treatment. It consumes 1,500.59 g of material, 34.33 kWh of electricity, 3.10 liters of tap water and other resource materials for packaging and cleaning at 500 g or 100 g per use, respectively. The contribution of GHG emissions from each stage is as follows: acquisition of raw materials, the use phase, the production process, the end of life (EoL) treatment, and distribution at 41.08%, 33.69%, 18.49%, 6.02% and 0.72%, respectively. In addition, energy effiecncy and/or renewable energy should be determined to reduce energy consumption from electricity, accounting for 48.13% of total GHG emissions.

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Abbreviation

CF: Carbon Footprint
CFF: Chemical Fusible Fabric
CFP: Carbon Footprint of Product
CFO: Carbon Footprint for Organization
EF: Emission Factor
EM: GHG Emissions
GWP: Global Warming Potential
GHG: Greenhouse Gas
IPCC: Intergovernmental Panel on Climate Change
PCR: Product Category Rule
PP: Polyester Padding
PSF: Polyester Satin Fabric
PVF: Polyester Velvet Fabric
PWF: Polyester Woven Fabric
TGO: Thailand Greenhouse Gas Management Organization

Nomenclature

AD_i : activity data of material/resource *i* per unit emitting GHG components (kg, kWh, L),
D_{lf} : distance from factory to landfill 40 km (specified in TGO assessment guideline),
D_i : distance from source of material *i* to factory (km),
D_{fu} : distance from factory to university (km),
D_m : distance from source of other material *m* to factory (km),
GWP_x : 100 year global warming potential of GHG component *x*,
$EF_{DP,ag}$: GHG emission factor of wasted academic gown (kgCO_2-eq/kg),
EF_{EE} : emission factor of electricity (grid mixed in Thailand) (kgCO_2-eq/kWh),
EF_i : GHG emission factor of material *i* (kgCO_2-eq/unit),
EF_k : emission factor of wasted material *k* (kgCO_2-eq/unit),
EF_l : GHG emission factor of wasted other material *l* (kgCO_2-eq/unit),
EF_q : GHG emission factor of other material *q* (kgCO_2-eq/unit),
$EF_{TP,fl}$: GHG emission factor of transportation using 100% loading disposal six-wheeled truck from factory to landfill (kgCO_2eq/tkm),
$EF_{Tp,fs}$: emission factor of transportation using 0% non-load four-wheeled truck back from factory to source (kgCO_2-eq/km),
$EF_{Tp,fu}$: emission factor of transportation using 100% loading six-wheeled truck from factory to university (kgCO_2-eq/tkm),

$EF_{Tp,uf}$: emission factor of transportation using 0% non-load six-wheeled truck from university to factory ($kgCO_2$-eq/km),

$EF_{TP,lf}$: GHG emission factor of transportation using 0% non-load disposal six-wheeled truck from landfill to factory ($kgCO_2$-eq/km),

$EF_{Tp,sf}$: GHG emission factor of transportation using 100% loading four-wheeled truck from source to factory ($kgCO_2$-eq/tkm),

$EF_{WW,collect}$: emission factor of collecting wastewater ($kgCO_2$-eq/m^3),

$EF_{WW,treatment}$: emission factor of treatment wastewater ($kgCO_2$-eq/m^3),

EM_i : GHG Emissions for activity data i ($kgCO_2$-eq),

EM_{RM} : GHG Emissions from raw material acquisition ($kgCO_2$-eq),

EM_{PP} : GHG Emissions from production process ($kgCO_2$-eq),

EM_{Dt} : GHG Emissions from distribution process ($kgCO_2$-eq),

EM_{Dp} : GHG Emissions from disposal ($kgCO_2$-eq),

$EM_{Dp,PP}$: GHG Emissions from disposal in production process ($kgCO_2$-eq),

$EM_{Dp,UP}$: GHG Emissions from disposal in use phases ($kgCO_2$-eq),

EM_{Tot} : total GHG Emissions ($kgCO_2$-eq),

$EM_{Tp,Dp}$: GHG Emissions from transportation of disposal ($kgCO_2$-eq),

$EM_{Tp,Dt}$: GHG Emissions from transportation of finished product between factory and university in distribution stage ($kgCO_2$-eq),

$EM_{Tp,fl}$: GHG Emissions from transportation of disposal from factory to landfill ($kgCO_2$-eq),

$EM_{Tp,om}$: GHG Emissions from transportation of other material between source and factory ($kgCO_2$eq),

$EM_{Tp,RM}$: GHG Emissions from material transportation ($kgCO_2$-eq),

EM_{UP} : GHG Emissions from use phase ($kgCO_2$-eq),

$EM_{WW,UP}$: GHG Emissions from wastewater in use phases ($kgCO_2$-eq),

f_x : emission factor of material/resource emitting GHG component x ($kgGHG_x$/unit),

LCC_{truck} : load carrying capacity of four-wheeled truck transporting material from source to factory, (7 ton),

$LCC_{Dp,truck}$: load carrying capacity of disposal six-wheeled truck transporting wasted material from factory to landfill, (11 ton),

m_i : material used to be component of academic gown i (kg),

M_{ag}: mass of finished product, academic gown (kg),

M_i : mass of material /resource i in one unit (kg, kWh, L)

N_{eqp}: number of equipment,

N_m: number of materials,

N_{om}: number of other materials,

om_q : other material q used in use phase (kg),

om_m : other material m used in use phase (kg),

p_j : rated electrical power of equipment j (kW),

RR_k : recycle rate of wasted material k (percent/100),

RR_l : recycle rate of wasted other material l (percent/100),

t_j : production time using equipment j (h),

$wm_{k,PP}$: wasted material k from production process (kg),

$wom_{l,UP}$: wasted other material l from use phase (kg),

WW_{UP} : wastewater from use phase (m^3),

Appendix

Table A1 Recycle rate for disposal in Thai Industry (Thailand Greenhouse Gas Management Organization, 2022a)

Type	Recycle Rate (%)
Paper	77
Plastic	87
Rubber	44

Table A2 Selected GHG emission factors (EF) (Thailand Greenhouse Gas Management Organization, 2015, 2019, 2022b)

	Material/Energy	Detail	unit	GHG EF ($kgCO_2$-eq/unit)	Reference
1	fabric woven from polyester yarn, dyeing process and textile finishing	Mixed ratio polyester fiber > 85%; LCIA method IPCC 2013 GWP 100a V1.03	kg	12.3011	TGO: EF CFP TGO (2022b), sequence no. 269
2	polyester staple fiber (PSF) (polyester padding)		kg	3.4900	TGO: EF CFP TGO (2022b), sequence no. 334
3	polyester fiber, dyeing process (sewing thread)	Mixed ratio polyester fiber > 85%; LCIA method IPCC 2013 GWP 100a V1.03	kg	6.7552	TGO: EF CFP TGO (2022b), sequence no. 263
4	yarn woven fabric, cotton/polyester blend, TC type, dyeing process and textile finishing, (chemical fabric)	Mixed ratio cotton fiber 34% and polyester fiber 66%; LCIA method IPCC 2013 GWP 100a V1.03	kg	15.4007	TGO: EF CFP TGO (2022b), sequence no. 273
5	polyvinyl acetate polymer latex	Ecoinvent, latex, at plant/kg/RER	kg	2.2628	TGO: PCR packaging GHG Protocol (2022), sequence no. 5
6	polyester resin (button raw material)	Polyester resin, unsaturated, at plant	kg	7.4185	TGO: EF CFP TGO (2022b), sequence no. 26
7	Brass (raw material for hook)	Brass, at plant, Ecoinvent 2.2, IPCC 2007 GWP 100a	kg	2.4528	TGO: EF CFP TGO (2022b), sequence no. 692
8	polyester yarn (gold trimming)		kg	4.1300	TGO: EF CFP TGO (2022b), sequence no. 327
9	Polyester knitted fabric (lace tape)	Mixed ratio polyester fiber > 85%; LCIA method IPCC 2013 GWP 100a V1.03	kg	4.5496	TGO: EF CFP TGO (2022b), sequence no. 276
10	Polyvinyl acetate polymer latex	Ecoinvent: latex, at plant/kg/RER	kg	2.628	TGO: PCR for packaging
11	Softener	Ecoinvent 2.0: Silicone emulsion	kg	2.6500	TGO: PCR for apparel made from textile
Energy					
12	electricity, grid mix	electricity, grid mix, year 2016-2018 LCIA method IPCC 2013 GWP 100a V1.03	kWh	0.5986	TGO: EF CFP TGO (2022b), sequence no. 59
Processing					
13	thermoforming, with calendaring (button processing)	Ecoinvent 2.2, IPCC 2007 GWP 100 a	kg	0.8592	TGO: EF CFP TGO (2022b), sequence no. 702
14	casting, brass	Ecoinvent 2.2, IPCC 2007 GWP 100 a	kg	0.0647	TGO: EF CFP TGO (2022b), sequence no. 696