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Assessing the environmental impact of ceramic tile production in Thailand

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Ceramic tiles are one of the most widely used materials in both commercial and residential buildings. As environmental problems increase, the need for environment-friendly building design increases. To achieve this, architects and engineers need reliable data on the environmental impacts of various building materials—including ceramic tiles. This paper reports the results of environmental impact assessment of ceramic tile production in Thailand. Key impact categories, including fossil fuel impact, global warming, ozone depletion, ecotoxicity, and human toxicity were assessed. The results showed that when assessed by EDIP methodology, the global warming impact value of 3.73E+3 kg CO_2-eq per megagram (Mg) of ceramic tile is quite prominent and is rather high compared with existing data in current literature. The human toxicity impact value is also significant. The values of the other impact categories were also determined and found to be relatively high. When assessed using the Eco-indicator 99 methodology, the results showed that the fossil fuel category was the most affected with a value of 8.62E+1 Pt per Mg of ceramic tile, followed by respiratory inorganics and climate change. Raw materials transportation stage yielded the highest environmental impact values. It is thought that the key factors responsible for the relatively high impact values are the process technologies employed and the long transportation distances of the raw materials. It was concluded that the environmental impact values of ceramic tile production in this study are different from, and in most cases higher than, the values presented in current literature.

Key-words : Ceramic tile, Ceramic production, Environmental impact, Life cycle assessment

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1. Introduction

Ceramics are widely used as building materials, and it has been estimated that, when all types of ceramics are included, they constitute around 50% of the materials in existing buildings worldwide.[1] The manufacture of such materials, from raw material production and processing, through forming and transportation, inevitably consumes natural resources, materials and energy, and generates various types of environmental impacts. Information about the impacts of individual materials is of great assistance to architects and engineers in their attempt to contribute towards sustainable development. Selecting appropriate building materials so that the environmental impacts are minimized is one of the key activities that respective professionals could adopt in order to achieve sustainability goals. To date, a number of attempts have been made to quantify such impacts of various building materials.[2)–6)]

Ceramics are of particular interest as far as the environmental impact of building materials is concerned. Manufacturing ceramic products employs highly energy-intensive processes, as well as a number of chemicals, thus generating a significant amount of waste and pollution.[7)–10)] Given the above, it is imperative that the environmental impacts of ceramic building materials should be examined and quantified so that as much detailed information as possible is available to practicing architects and engineers.

There have been several investigations attempting to assess the environmental impacts of ceramic products in recent years. The United States Environmental Protection Agency (USEPA) has collected and compiled available data from research work and ceramic production plants and found that ceramic tile production emitted an average of 300 kg CO_2/Mg, 1.6 kg CO/Mg, 0.27 kg NO_x/Mg, 2.4 kg SO_2/Mg and 0.23 kg HF/Mg.[11)] Goldoni and Bonoli[7)] employed the Life Cycle Assessment (LCA) methodology to assess the environmental impacts of the ceramic sector and concluded that the impacts were mostly from raw material extraction and the firing processes. They also noted that different plants employing different production technologies produced different impacts. The National Institute of Standards and Technology (NIST) in the United States developed an Environment Resource Guide that compiled the data on the environmental impact of various materials, including ceramics.[12)] The data indicated that ceramic tiles resulted in a global warming potential of 8.06E+02 kg CO_2-eq/Mg, and acidification of 3.07E+02 kg H^+ moles-eq/Mg. In a study of housing in Scotland, Asif et al.[5)] found that the material that had the most impact on the environment was concrete (65%), followed by ceramics (14%), and wood (13%). Bovea et al.[13)] assessed the environmental impact of red clay for use in the ceramic industry and found that material movement was one of the key activities contributing to such impact. Advances in production technologies led to a considerable reduction in the environmental impacts of ceramic building materials.[7),8),14)] The use of fabric filters were found to be effective in reducing environmental impacts due to ceramic production.[14)] Increasingly sophisticated market demand for ceramic products, however, could lead to the need for higher firing temperatures and more chemicals being used in the process, thus causing even greater impacts on the environment.[9),15)]

Ceramic tiles are used extensively in buildings—both as structural materials and for decorative purposes. In Thailand, for

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example, consumption of ceramic tiles is over 140 million square meters annually, and the demand is increasing.[16] However, environmental impact assessments specifically concerning ceramic tiles are rather limited in open literature. Nicoletti et al.[9] investigated the impact of ceramic tile production on the environment and found that global warming, human toxicity, and acid rain were affected. The firing stage of the production process was found to have the greatest impact. Timellini and co-workers[15] investigated the environmental impact of ceramic tiles and concluded that progress had been made through process improvements, including the use of fabric filters. Examination of the figures for the environmental impact of ceramic tiles from various sources by several authors[17)–20)] revealed that the impact values were quite different from one source to another. For example, the global warming potential value resulting from ceramic tile production according the database in BEES is 8.06E+02 kg CO_2-eq/Mg,[12] while the value from the database in SimaPro is 4.94E+02 kg CO_2-eq/Mg.[17] The global warming potential value resulting from ceramic tile production in China was found to be as high as 1.62E+04 kg CO_2-eq/Mg.[21] There are many reasons that lead to such differences, including the process technologies employed, plant locations, and assessment methodologies. This suggests that ceramic tiles produced by different firms have different environmental impacts, and that one cannot use existing data directly, as given, without considering the source of the data and/or production details.

An environment impact assessment of ceramic tiles has never been conducted in Thailand. The objective of this work is to quantitatively assess the impacts resulting from ceramic tile production for a typical Thai manufacturing firm, employing the Life Cycle Assessment (LCA) methodology. Both relative and absolute impact values were to be determined, and the resulting impact values compared with those existing in current literature.

2. Methodology

2.1 Background

This research was conducted in a ceramic manufacturing plant in Thailand. The plant from which the necessary data was measured and collected is a medium-sized firm, typical of the Thai ceramic industry, located in an industrial area near Bangkok. The average production capacity of the firm is 2900 m^2 of ceramic tile/month. The firm produces many different types of ceramic tiles, differing in dimensions, texture, and color. For the purpose of the present study, one megagram (Mg) of double-fired glazed plain white and pink ceramic tiles, size 98 mm × 98 mm × 5 mm thick, was chosen as the unit of analysis. The average weight of the ceramic tile was 10.57 kg/m^2.

The scope within which the current study was conducted is as shown in **Fig. 1**. The process chain of ceramic tile manufacturing can be divided into nine stages: transportation of raw materials, body preparation, forming, drying, biscuit firing, glazing preparation, glazing, glost firing, and packing of finished products. The scope here is limited to raw material transportation, manufacturing, and packing of final products. The focus of this study is on assessing the impacts of the actual ceramic tile manufacturing. The impacts due to production of raw materials, factory construction, machinery and equipment in the plant are not included.

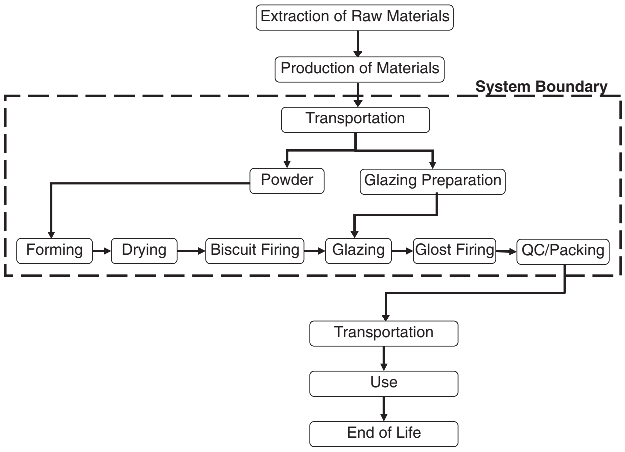

Fig. 1. Scope of study.

The raw materials transportation stage includes the transportation of all raw materials directly from suppliers (raw materials production plants and relevant dealers) to the plant. Sources of raw materials and their respective transportation distances are as shown in **Table 1**.

2.2 Production details

The production of ceramic tiles starts with body preparation. In the body preparation stage, the raw materials are mixed in a ball mill (capacity 15 T/h, 125 HP) for 10–12 h before transforming into slip and being taken to a spray dryer (capacity 3 T/h, 160 HP). The slip is dehydrated and combined in the form of small balls with 6–7% humidity. Thereafter, they fall to the dryer bottom and are then transported via a conveyor system to be stored in a silo.

Glazing material is prepared by mixing the raw materials (feldspar, color stain, zirconium, various chemicals, and frit) in a ball mill. The necessary raw materials for the production of 1 Mg of ceramic tiles and for glazing material are shown in **Table 2**. The weighted average of the frit compositions are shown in **Table 3**.

Ceramic tiles are then formed by a pressing operation using a hydraulic press with a metal mould, 98 mm × 98 mm in size,

Table 1. Sources of raw materials and transportation distances

Raw Materials	Sources	Distances (km)	Raw Materials	Sources	Distances (km)
Soapstone A	Nakhon Nayok	107	Unwashed Kaolin B	Surat Thani	644
Soapstone C	Nakhon Nayok	107	White Clay	Surat Thani	644
Pottery Stone A	Lampang	599	Ball Clay MRD	Lampang	599
Pottery Stone B	Kanchanaburi	128	Frit	Bangkok	42
Green Stone A	Saraburi	107	Feldspar	Tak	426
Green Stone B	Saraburi	107	Kaolin	Ranong	568
Unwashed Kaolin A	Prachin Buri	136	Zirconium	Bangkok	42
Washed Kaolin	Lampang	599	Alumina Ball	Bangkok	42

Table 2. Raw materials for producing 1 Mg of ceramic tile

Body Materials		Glazing Materials	
Category	Quantity (kg)	Category	Quantity (kg)
White Clay	426.11	Frit	84.96
Ball Clay	106.15	Kaolin	5.66
Pyrophillite	338.51	Feldspar	12.68
Pottery Stone	87.61	Zirconium	0.16
Limestone	87.51	Alumina Ball	0.22
		STTP	0.09

Table 3. Frit compositions (average values for white and pink tiles)

Compounds	Percent	Compounds	Percent
PbO	4.36	SiO_2	55.82
SrO	2.18	ZrO_2	6.91
MgO	1.27	Al_2O_3	11.27
K_2O	2.55	Na_2O	4.00
BaO	0.91	CaO	5.45
TiO_2	0.18	ZnO	4.55
Fe_2O_3	0.36	SnO_2	0.18

Table 4. Energy consumption (per 1 Mg ceramic tile)

Unit Process	Electric Energy (kWh)	Fuel (l)	Thermal Energy	Total (MJ)	%
Transportation	NC	876.14	NC	31,909	59.79
Body Preparation	195	168.12	49.01	9,794	18.35
Glazing Preparation	18.07	36.42	NC	1,493	2.80
Forming	32.64	NC	NC	300	0.56
Drying	NC	NC	NC	0	0.00
Biscuit Firing	20.15	NC	78.15	3,804	7.13
Glazing	8.14	NC	NC	75	0.14
Glost Firing	45.03	NC	87.61	4,471	8.38
Packaging	NC	41.82	NC	1,523	2.85
Total				53,369	100

Source: Information from the business operator
1 kWh = 9.2 MJ
LPG (Propane + Butane) = 46.3 MJ/kg
Furnace oil = 38.3 MJ/l
Diesel = 36.42 MJ/l
Transportation by 28-ton truck consuming oil at the rate of 0.2 l/Tkm
NC: No Consumption

Table 5. Details of pollution measurements

Pollution Types	Sampling Methods	Analytical Techniques	Standards
Particulate	Isokinetic	Gravimetric	US.EPA Method 5
Carbon Monoxide	Gas Bag	Non-Dispersive Infrared Detection	US.EPA Method 10
Carbon Dioxide	—	Flue Gas Analyzer	US.EPA Method 3A
Sulfur Dioxide	Isokinetic	Titrimetric	US.EPA Method 8
Sulfuric Acid	Isokinetic	Titrimetric	US.EPA Method 8
Oxides of Nitrogen	Vacuum Flask	Colorimetric	US.EPA Method 7
Lead	Isokinetic	AAS	US.EPA Method 12
Cadmium	Isokinetic	AAS	US.EPA Method 29
Copper	Isokinetic	AAS	US.EPA Method 29
Chromium	Isokinetic	AAS	US.EPA Method 29
Mercury	Isokinetic	Cold Vapour AAS	US.EPA Method 29
Fluoride	Midget Impinger	Ion Chromatography	US.EPA Method 26

before being conveyed to the kiln for drying. The dryer used in the plant is a tunnel kiln and the temperature is set at approximately 100°C. Tiles are dried in the kiln for 28 h. This process, however, cannot reduce the humidity to below 1%. They are therefore subsequently put on a conveyor to the biscuit firing process. Biscuit firing (capacity 0.98 T/h) helps reduce the humidity before glazing, thus enhancing the absorptive capacity of the tiles. The temperature of the biscuit firing is 1120°C and the firing time is approximately 38 h. The thermal energy for the tunnel kiln is from LPG combustion. Ceramic tiles from the tunnel kiln are conveyed to the first glazing facility for base glazing to prevent surface bubbles, and then to the second glazing facility for thicker glazing. After being glazed, the tiles are put in a protective box, or "saggar," before being put into another tunnel kiln for glost firing (capacity 1.4 T/h). The purpose of glost firing is to melt the glazing. The temperature in the kiln is 990°C and the firing time is approximately 29 h. LPG is used as the kiln fuel.

After being fired, the ceramic tiles are conveyed to the quality checking and size separator station. The tiles are classified as either Grade A or Grade B, and those remaining are regarded as damaged tiles. The tiles are then packed in cardboard boxes (one square meter or 0.011 Mg of tiles per box) glued by workmen and then put on pallets for transportation on to dealers.

2.3 Data collection

All the data required for environmental impact assessment was collected at the plant using on-site measurements and from the actual manufacturing practices of the plant, from March 2008 to February 2009. The data was collected in accordance with ISO 14040:2006 and ISO 14044:2006 standards.

The type and quantity of raw materials for the production of 1 Mg ceramic tiles are summarized in Table 2. Frit compositions were analyzed using the X-ray fluorescence (XRF) technique and are shown in Table 3.

The energy used in the production process is of four forms: electrical energy, fuel oil, LPG, and furnace oil. The amount of energy consumption for each production stage is shown in **Table 4**.

Air pollution from the kiln and spray dryer chimneys was measured in accordance with USEPA standards. Particulate matter, carbon monoxide, carbon dioxide, sulfur dioxide, sulfuric acid, oxides of nitrogen, lead, cadmium, copper, chromium, mercury, and fluoride were measured. Details of pollution types, sampling methods, analytical techniques, and relevant standards are shown in **Table 5**. The types and quantities of air pollution measurements are summarized in **Table 6**.

The water used in the plant is fully recycled and thus has no environmental impact. The water, however, is treated as part of

Table 6. Air quality measurements (per 1 Mg ceramic tile)

Categories	Body Prep. (kg)	Biscuit Firing (kg)	Glost Firing (kg)	Total (kg)
Particulate Matter	0.27	0.26	0.23	0.76
Carbon Monoxide	0.05	0.03	0.01	0.09
Carbon Dioxide	484	1,045	969	2,498
Sulfur Dioxide	1.69	0.07	0.03	1.79
Sulfuric Acid	0.03	0.01	0.05	0.09
Nitrogen Oxides	0.35	0.21	0.19	0.75
Lead	1.20E−03	2.93E−04	2.18E−03	3.67E−03
Cadmium	8.51E−07	5.72E−06	1.03E−05	1.68E−05
Copper	6.81E−05	3.18E−05	6.94E−05	1.69E−04
Chromium	1.36E−04	1.48E−04	2.05E−03	2.34E−03
Mercury	2.47E−05	4.92E−06	2.65E−06	3.23E−05
Fluoride	8.51E−07	5.06E−07	3.36E−07	1.69E−06

the recycling process to improve water quality and to comply with the regulatory requirements of the Thai authorities.

2.4 Inventory analysis

Data collection was conducted separately for each of the production stages. The inputs were divided into raw materials and energy for manufacturing and transportation; the outputs were the products and production waste, water pollution, and air pollution. Production waste, such as damaged tiles or particles can be reused in the body preparation in proportions specified by the plant. Waste water is treated and fully recycled. The data from the nine stages was processed and expressed in terms of the quantity of raw materials, energy consumption, and pollution in the production of 1 Mg ceramic tiles. Respective numbers are shown in **Fig. 2**. Data derived from the inventory analysis was verified by means of mass and energy balance.

2.5 Impact assessment

2.5.1 EDIP methodology

The EDIP (Environmental Design of Industrial Products) methodology[22] was used to assess the midpoint indicators for environmental impacts (i.e., the potential for such impacts). The units of EDIP impact values are in the forms of reference substances that cause particular impacts. For example, CO_2 is the reference substance for global warming. Since other substances also contribute to global warming, they are presented as CO_2-equivalents or CO_2-eq. The unit of Global Warming Potential (GWP) is therefore CO_2-eq. The total value of GWP is expressed in terms of CO_2-eq and includes the actual CO_2 value and other CO_2-eq values contributed by other substances. Other environmental impacts employ other reference substances. For example, CFC-11 is used as the reference substance for ozone depletion, SO_2 for acidification, and so on. The impact values in the EDIP methodology are calculated according to the relationship in Eq. (1):[22]

$$\mathrm{EP}_j = \Sigma(\mathrm{Q}_i \times \mathrm{EF}_{ij}) \tag{1}$$

where

EP_j: Environmental impact potential for an environmental problem (j)

Q_i: Quantity of substance (i)

EF_{ij}: Equivalency factor of the substance (i) impact the environmental problem[22]

An example to demonstrate the steps in EDIP calculation is shown in **Fig. 3**. The example shows how the GWP of the transportation stage is calculated. The final value of GWP is the sum of GWP for all individual stages. The values of other impact potentials are obtained in the same way. One liter of diesel production in Thailand has the potential to cause global warming of 0.508 kg CO_2-eq.[23] From Fig. 3, the total GWP from the transportation stage is 2949.18 kg CO_2-eq.

2.5.2 Eco-indicator 99 methodology

The impact values from the Eco-indicator 99 methodology[24] are measures of the endpoint indicators of environmental impacts. They are indicators of the impacts on human health, ecosystem quality, and resources. The unit of the impact values using this methodology is in "points" (Pt). One Pt is equivalent to 1/1000 of the average European environmental impact in one year. Normalization and weighting are required in the Eco-indicator 99 methodology to take into account the differences in temporal effects and the severity of the effect of the substance, respectively. The impact values in Eco-indicator 99 methodology are calculated using the relationships in Eqs. (2)–(4).[24] The damage scores (DP) of various impact categories are first calculated using Eq. (2):

$$\mathrm{DP}_{ij} = \mathrm{Q}_i \times \mathrm{DF}_{ij} \tag{2}$$

where

DP_{ij}: Scores for the damage categories j and substance i

Q_i: Quantity of substance i (kg)

DF_{ij}: Damage factor of the substance i that impacts the damage categories j[24]

Damage scores are then normalized using Eq. (3):

$$\mathrm{NP}_{ij} = \mathrm{DP}_{ij} \times \mathrm{NF}_{ij} \tag{3}$$

where

NP_{ij}: Normalized scores for the damage categories j and substance i

NF_{ij}: Normalization damage factor of the substance i that impacts the damage categories j[24]

Normalized scores are then weighted to get weighted scores using Eq. (4):

$$\mathrm{WP}_j = \Sigma(\mathrm{WF}_{ij} \times \mathrm{NP}_{ij}) \tag{4}$$

where

WP_j: Weighted scores of all substances for the damage categories j

WF_{ij}: Weighted damage factor for damage categories j and substance i[24]

An example to demonstrate the calculation steps for Eco-indicator 99 impact values is shown in **Fig. 4**. The example shows how the climate change category impact value as a result of transportation is calculated. The final value of climate change is the sum of the values from all the individual stages. The values of other impact categories are re-calculated in the same way.

Because LCA-based analysis demands many calculations, computer programs for calculating the various numerical values are required. In this paper, the data in Tables 1–6 was used as inputs for impact assessments and SimaPro 7.1 LCA software was used for assessing the environmental impacts.

3. Results

The results of environmental impact assessment using EDIP methodology are shown in **Table 7**. It is notable that the values for global warming and human toxicity are significant and particularly high compared with similar data in current literature.

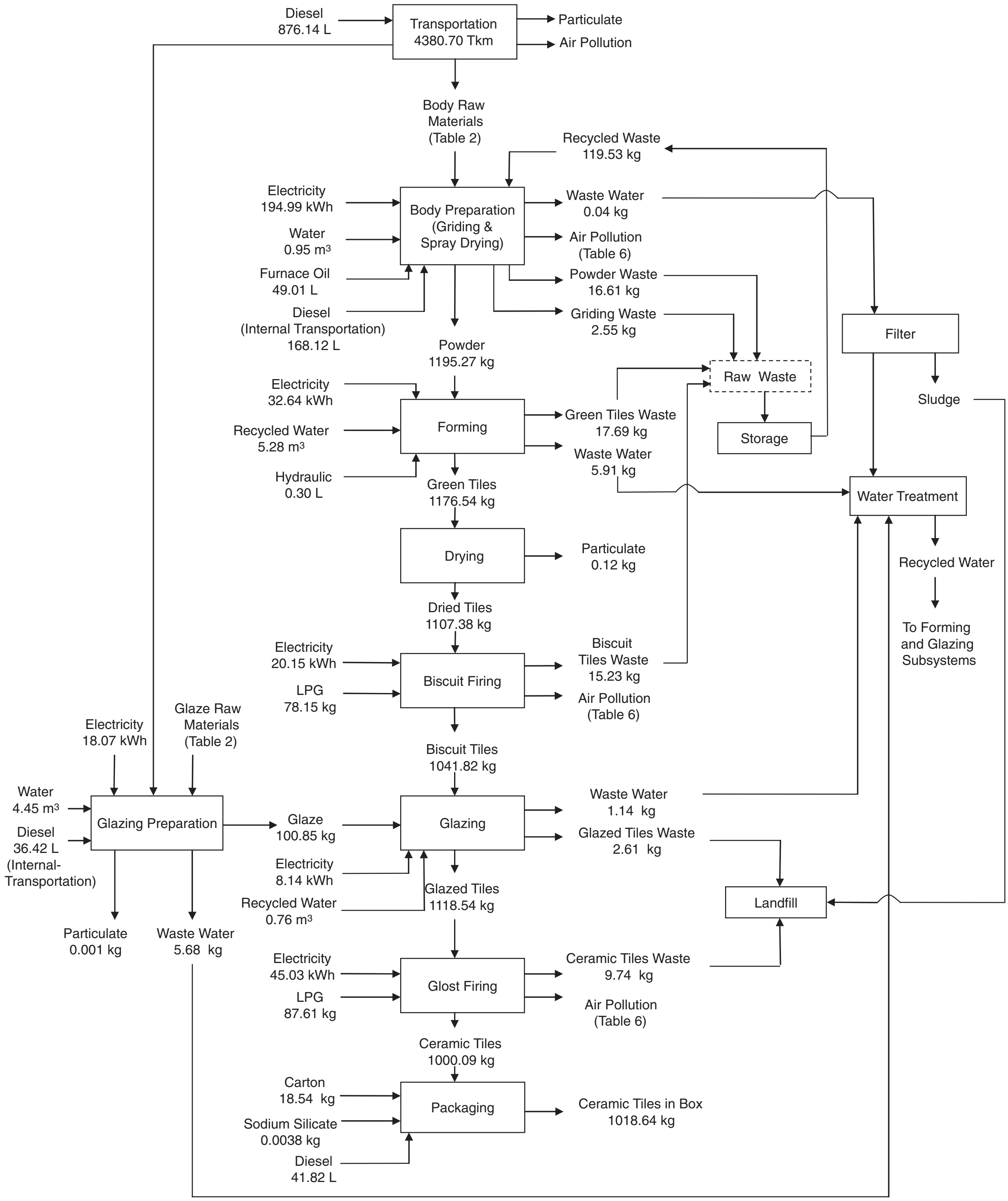

Fig. 2. Inventory data for 1 Mg ceramic tile processing (excluding extraction and production of raw materials).

The results of the assessment using the Eco-indicator 99 methodology, both for overall production and for individual production stages are shown in **Table 8**. The fossil fuels impact category has the highest value followed by respiratory inorganics and climate change when assessed by this methodology. The transportation stage yields the highest total impact value followed by glost firing and biscuit firing. The drying stage has the least environmental impact since waste heat was reused for this process.

4. Discussion

The results of the present study show that environmental impact values due to ceramic tile production in this particular case are quite high compared with those described in the current literature. The CO_2-eq value, the measure of global warming potential, of 3.73E+03 kg CO_2-eq/Mg is also very much higher than the NIST value of 8.06E+02 kg CO_2-eq/Mg and the

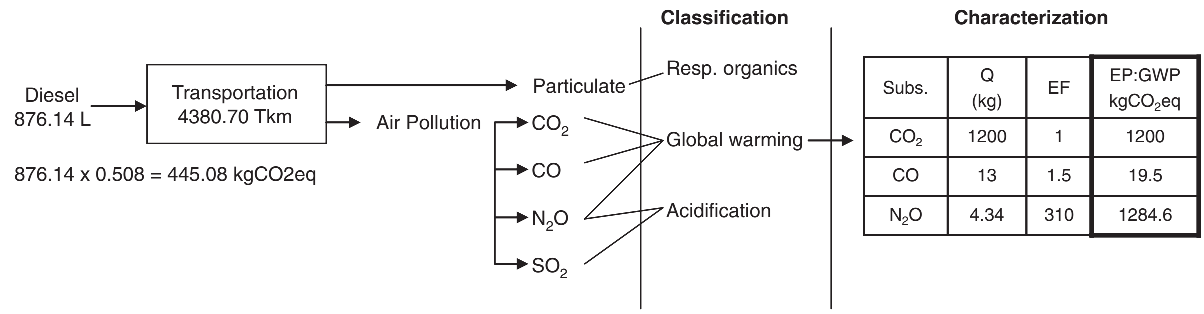

Fig. 3. Steps in EDIP calculation.

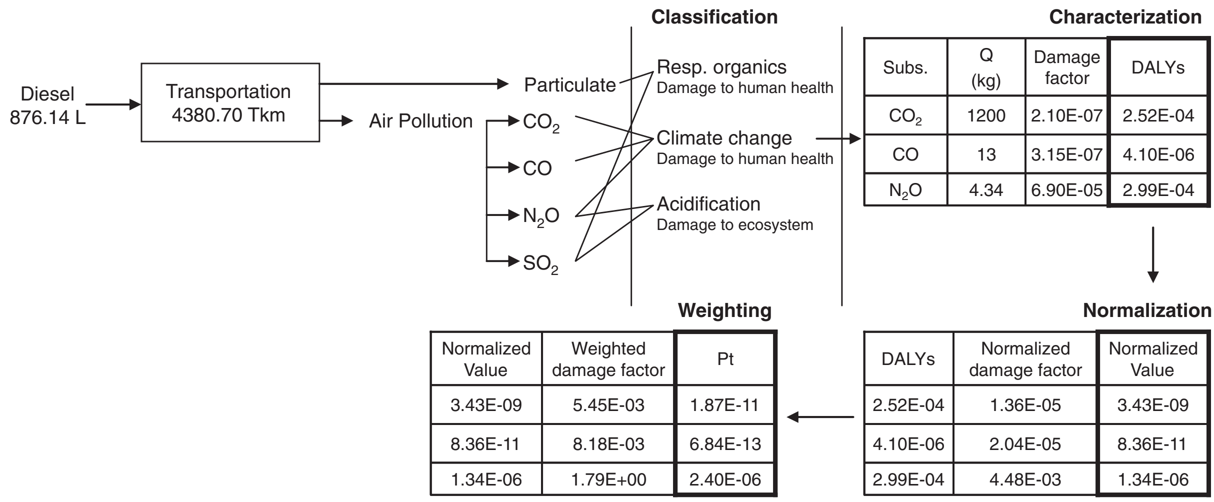

Fig. 4. Steps in Eco-indicator 99 calculation.

Table 7. Environmental impact of 1 Mg ceramic tile (EDIP methodology)

Impact category	Unit	Total
Global warming (GWP 100)	kg CO_2	3.73E+03
Ozone depletion	kg CFC11	2.86E−04
Acidification	kg SO_2	1.03E+01
Eutrophication	kg NO_3	1.35E+01
Photochemical smog	kg ethene	1.08E+00
Human toxicity air	m^3	8.29E+05
Human toxicity water	m^3	5.03E+01
Human toxicity soil	m^3	3.26E−01
Ecotoxicity water chronic	m^3	2.51E+03
Ecotoxicity water acute	m^3	2.55E+02
Ecotoxicity soil chronic	m^3	1.99E+01

IDEMAT 2001 Project value of 4.94E+02 kg CO_2-eq/Mg.[12),17)] The reasons for such differences are thought to be the production technologies employed, as well as the nature of the raw materials used and the long transportation distances. The double-fired, slow thermal cycle process, together with relatively high firing temperatures results in high energy consumption, and high air pollution. This explanation is in line with those suggested by other investigators.[9),15)] The differences are thought to be due to the fact that in the production of ceramic tiles the NIST values were derived using 75% recycled windshield glass as a raw material, less energy was consumed because of the single-firing process employed, and the shorter raw material transportation distance of 482 km. The IDEMAT 2001 Project assessed the environmental impacts of ceramics production in

Table 8. Environmental impact (Pt) of 1 Mg ceramic tile (Eco-indicator 99 methodology)

Impact Category	Transp.	Body Prep.	Forming	Drying	Biscuit Firing	Glazing Prep.	Glazing	Glost Firing	Packaging	Total
Carcinogens	1.72E−02	1.13E+01	9.31E−03	0.00E+00	2.08E−02	3.60E−01	2.32E−03	3.99E−02	6.36E−02	1.18E+01
Resp. organics	5.02E−02	2.20E−03	6.37E−05	0.00E+00	5.90E−03	3.34E−03	1.59E−05	6.66E−03	2.61E−03	7.10E−02
Resp. inorganics	7.45E+00	1.78E+01	2.86E−02	2.56E−03	1.57E+00	8.29E−01	7.14E−03	1.51E+00	4.60E−01	2.96E+01
Climate change	1.13E+00	5.16E+00	2.67E−02	0.00E+00	4.37E+00	1.93E−01	6.67E−03	4.09E+00	1.51E−01	1.51E+01
Radiation	0.00E+00	3.62E−02	9.91E−05	0.00E+00	6.12E−05	1.60E−03	2.47E−05	1.37E−04	2.88E−03	4.10E−02
Ozone layer	0.00E+00	4.88E−03	1.21E−05	0.00E+00	7.46E−06	4.63E−04	3.01E−06	1.67E−05	4.57E−04	5.84E−03
Ecotoxicity	1.46E−02	4.39E+00	6.23E−03	0.00E+00	1.46E−01	1.37E−01	1.55E−03	1.39E+00	1.11E−01	6.20E+00
Acidification/Eutrophication	1.05E+00	3.92E+00	4.21E−03	0.00E+00	2.69E−01	1.69E−01	1.05E−03	2.74E−01	7.51E−02	5.76E+00
Land use	2.96E−01	1.15E+00	5.40E−03	0.00E+00	4.06E−02	6.98E−02	1.35E−03	4.92E−02	4.26E−01	2.04E+00
Minerals	4.03E−03	1.86E+00	3.56E−03	0.00E+00	2.74E−03	4.79E+00	8.88E−04	5.52E−03	3.15E−02	6.69E+00
Fossil fuels	5.57E+01	1.30E−01	2.16E−01	0.00E+00	9.70E+00	4.69E+00	5.38E−02	1.10E+01	4.72E+00	8.62E+01
Total	1.04E+02	7.00E+00	3.00E−01	2.56E−03	1.61E+01	1.12E+01	7.48E−02	1.84E+01	6.04E+00	1.61E+02

the Netherlands, which also used the single-firing process. However, details of the production process are not available. Comparing the amount of CO_2 released with the corresponding USEPA value,[11] it is evident that the figure from the present work is far higher (2,498 vs. 300 kg/Mg). The NO_2 released is about twice the USEPA value, and is thought to result from the same causes.

Regarding the influence of production technology on environmental impacts, direct comparison with existing data is not possible due to the lack of information concerning production details and differences in the scope of the studies from which the data was derived. Indirect comparisons are possible, however. The impact value from this study, excluding the raw materials transportation stage, of 57 Pt is about twice the value from the ETH project (27.9 Pt). This despite the fact that both the transportation of raw materials and products were included in the ETH study. The ETH project was the project for assessing environmental impacts of ceramics production in Western European countries during 1990–94, which employed the more advanced single-firing technology.[25]

The CO_2-eq value of the present work is, however, much lower than the recent work by Li and coworkers,[21] who studied the impact of ceramic tile production in China and found that the CO_2-eq value, excluding raw material transportation, was 1.62E+04 kg CO_2-eq/Mg. In their study, the single-fired process was employed. Several raw materials and chemical substances were used in the production of ceramic tiles. Light diesel oil was mostly used as fuel. The types of raw materials and fuel used seem to be important factors influencing the global warming potential in ceramic tile production.

One major factor that leads to the higher values of environmental impact is the long transportation distance of raw materials. The energy consumed by transportation is around 60% of the total energy consumption. This results in higher potential values—particularly the CO_2-eq value. This is in general agreement with the previous work by Nicoletti et al.[9] and the World Bank Group[10] who found that greenhouse gas emissions, especially CO_2, were mainly associated with the use of energy.

Regarding the contribution of individual production stages, the transportation stage has the highest impact value, followed by glost firing, biscuit firing, glazing preparation, and spray drying. Excluding the raw materials transportation stage, glost firing consumes the largest amount of energy and yields the greatest environmental impact. This despite the fact that glost firing is accomplished at lower temperatures and in a shorter time than biscuit firing. The reason is that in glost firing, the tiles need to be placed in protective boxes, or "saggars," to avoid damage to the tiles. Additional energy is required for heating the saggars. Furthermore, a smaller amount of tiles can be fired in each cycle in glost firing stage compared with the biscuit firing stage. The results are different from those in previous works by Hocenski et al.[26] who found that the atomizing or spray drying stage produced the highest environmental impact and the work by Li and coworkers[21] who found that the glazing stage yielded the highest impact. The reason for such discrepancy is thought to be due to differences in the nature of the manufacturing technologies and process parameters employed in production, as suggested by Goldoni and Bonoli.[7]

It can be seen from the results of our work and those of others that there are several causes of the different environmental impact potential, such as production technology, manufacturing practices, raw material sources that affect the transportation distance, and the amount and type of energy used in production. Upgrading production technology would indeed improve environmental impacts. In reality, however, this cannot be easily accomplished due mainly to economic reasons, particularly for small and medium-sized firms in less developed countries like Thailand. The use of rather outdated technologies is expected to remain widespread for some time to come. Prudent manufacturing practices and appropriate energy saving measures that help to reduce the consumption of energy would reduce environmental impacts if changes in production technology are not feasible.

5. Conclusion

Environmental impacts of Thai ceramic tiles, produced by a typical Thai manufacturing firm, were assessed by EDIP and Eco-indicator 99 methodologies. When assessed by EDIP methodology, global warming and human toxicity were found to be the most affected, with values of 3.73E+03 kg CO_2-eq/Mg and 8.29E+05 m^3/Mg, respectively. The values are different from and rather high compared with those available in current literature. Such discrepancies are thought to be due to differences in the nature of the production technologies employed, process parameters, and the nature and quantity of the chemicals employed in production. The location of the plant relative to the raw materials sources, and hence the transportation distances involved, also contribute significantly to environmental impacts. Other impact values, such as acidification, eutrophication, ozone depletion, ecotoxicity etc., are also different from, and in most cases higher than, existing data.

When assessed using Eco-indicator 99 methodology, the impact category with the highest value is fossil fuels (8.62E+01 Pt) followed by respiratory inorganics (2.96E+01 Pt), and climate change (1.51E+01 Pt). The transportation stage yields the highest impact value followed by glost firing, biscuit firing, and glazing preparation. The values of such impacts are also different from those in current literature.

The rather high impact values for the fossil fuels and global warming categories in the present study are due primarily to three reasons: long distances involved in raw materials transportation, the production technologies employed, and high firing temperatures. The transportation accounts for almost three-quarters of the total energy consumed.

The nature of the chemicals used in the process is the major cause of the relatively high values of respiratory inorganics and ecotoxicity. Heavy metals, such as arsenic, copper, cadmium, chromium, zinc etc., in the chemicals are the root causes of such impacts. Modification or changing the compositions of the chemicals would ameliorate these problems. It was concluded that ceramic tiles produced from different sources (i.e., different plants or countries) yield different environmental impacts.

6. Recommendations

In order to improve the environmental friendliness of ceramic tiles, the following recommendations are proposed:

(1) Double-firing technology should be changed to single-firing technology where possible. The single-firing process not only reduces energy consumption, hence environmental impacts, but also reduces production time.

(2) Manufacturing plants should be located as near to the raw material sources as possible in order to minimize the transportation distance of raw materials to the plants.

(3) Development of body materials that can be fired and sintered at lower temperature than the currently available materials would reduce energy consumption in the

production of ceramic tiles and help reduce environmental impacts.

(4) Good manufacturing practices and appropriate energy-saving measures, though not dramatic for individual activities, can add up to substantial environmental impact reduction over the long term.

(5) Use of chemicals that contain heavy and poisonous metals such as arsenic, cadmium, copper, chromium, etc., should e avoided These metals are harmful to both human beings and eosystems.

(6) Designers, architects and engineers, and cosumers should select locally produced ceramic tiles where possible to reduce the transportation distances of the finished products.

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