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Environmental Impact Analysis in the Cement Industry with Life Cycle Assessment Method

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ABSTRACT

PT A is a cement industry that produces slag, portland cement, and composite portland cement. This research aims to examine the environmental impacts of the cement industry by applying the life cycle assessment method. The methods used in this research are divided into goal and scope, life cycle inventory, life cycle impact assessment, and interpretation. This research uses SimaPro software for data processing. In carrying out impact assessments using life cycle assessment, several methods are used such as CML IA Baseline V3.05, Impact 2002+, EPD 2018, and cumulative energy demand. The results show that there are two types of impacts. Primary impacts include global warming, eutrophication, acidification, and stratospheric thinning. Meanwhile, secondary impacts are photochemical oxidation, abiotic depletion of fossils and non-fossils, terrestrial and aquatic ecotoxicity, carcinogenicity, toxicity, water consumption, land use change, and non-renewable energy depletion.

Keywords: life cycle assessment, cement industry, environmental impact, clean production.

INTRODUCTION

The cement industry is a vital sector in the development of a country's infrastructure and economy. Along with population growth and urbanization, the demand for cement is increasing. Cement is the most widely used artificial material for buildings and infrastructure (Putri and Rimantho, 2022). Based on the Cembureau Activity Report (2023), global cement production will reach 4.1 billion tons in 2022. As an energy and resource-intensive industry, the cement industry is associated with various environmental problems such as global warming, air pollution, land use change, and depletion of natural resources. This makes the cement industry one of the activities that causes environmental problems. According to Gan et al. (2017), around 40% of global Green House Gases (GHG) come from consumption in the building sector. According to Pahlevi et al. (2023), the cement industry is one of the largest contributors to air pollution in the world due to its high level of energy consumption and potential dust emissions. According to the European Commission in 2010, the cement industry requires heat and electricity energy up to around 40% of the total operational costs spent on energy procurement (Vito et al., 2011).

The cement industry not only produces the main product but also produces by-products such as rubbish, waste, and emissions (Farahdiba et al., 2021). Emissions produced by the cement industry include NOx, SO_2, PM, and CO (Kuenen et al, 2016). The cement industry sector can consume almost 12–15% of total energy use in the industrial sector and is responsible for around 7% of global CO_2 emissions (Tun et al, 2020). The same opinion was also expressed by Mokhtar and

Nasooti (2020), if the cement industry uses up to 15% of energy with total CO_2 emissions of 5–7%. This is because in making cement, around half of the CO_2 is released when decarbonizing limestone and the other half comes from the use of fossil fuel energy and electricity. Research conducted by Gutierrez et al. (2017), stated that GHG emissions in the form of CO_2 contribute the most to global warming as an impact from the cement industry which ranges between 98–100%, followed by CH_4 and N_2O with lower numbers but higher characterization factors. This decade, many companies are looking for ways to comply with the environment using prevention strategies and environmental management systems to improve environmental performance within the company. One way that can be done is by implementing the concept of clean production activities which is implemented through a life cycle assessment (LCA) (Nurzamilov and Sitogasa, 2024). According to Hens et al. (2018), clean production is a preventive environmental management strategy that must be applied continuously and continuously in the production process and product life cycle to reduce negative risks to the environment and humans. The LCA method aims to identify and calculate the use of natural resources and the discharge of emissions or waste into the environment to be used as a reference for environmental improvement (Panggabean et al., 2023). The LCA study refers to the ISO 14040:2016 standard which consists of four stages, namely determining objectives and scope, inventory analysis, impact analysis, and interpretation (Setiawan et al., 2021).

In this research, the author took the case study of PT A. PT A is a cement industry that produces slag, portland cement, composite portland cement, and white clay with a production of 3.4 million tons per year. Cement production at PT A uses a dry process with a suspension preheater. A suspension preheater is a tool that functions to preheat the kiln feed so that some of the material can be calcined. The advantage of using this process is that it can minimize fuel use, use a kiln with a shorter size, and easier maintenance (Febrianto et al., 2022). The activities that have been operating at PT A consist of 2 activities, namely the cement factory and the mining of limestone raw materials. This research aims to examine the environmental impacts arising from the cement industry by applying the LCA method.

METHODS

This research was conducted in the PT A cement industry in February – March. The method used in this research was divided into four, namely goal and scope, life cycle inventory, life cycle impact assessment, and interpretation. The first stage is goal and scope or determining the goal and scope to provide references and research limitations from the study and collection of primary and secondary data. The limitation of this research is the cement production stage. The unit function used is 900,000 tons of cement (Figure 1).The

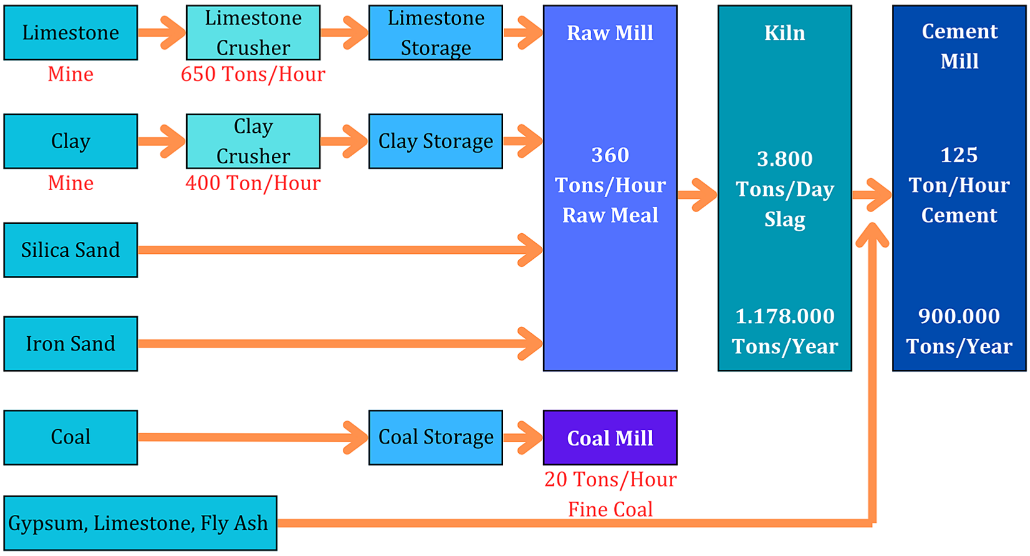


Figure 1. PT a cement production process

second stage is life cycle inventory or data inventory collection. Primary data was obtained based on conditions in the PT A cement industry in the production section and other data on the life cycle of the product system studied. Meanwhile, secondary data is obtained from generally available databases such as journals (Table 1).

The third stage is life cycle impact assessment, where at this stage an assessment is carried out regarding the impacts caused by cement production. The software used in LCA analysis is SimaPro. In conducting impact assessments using LCA, several methods can be used, such as CML IA Baseline V3.05, Impact 2002+, EPD 2018, cumulative energy demand (CED), and the Intergovernmental Panel on Climate Change (da). However, in this research, the methods that will be used are only CML IA Baseline V3.04, Impact 2002+, EPD 2018, and CED. Finally, the fourth stage is interpretation, which is useful for providing statements regarding the impacts caused by the cement industry using LCA analysis.

RESULT AND DISCUSSION

Life-cycle inventory

Provision of raw materials

The raw materials used for making cement at PT A are divided into three groups, namely:

a) Main raw materials

The main raw materials consist of limestone ($CaCO_3$) and clay ($2SiO_3 \cdot 2H_2O$). Limestone and clay are obtained from quarries. Limestone is crushed using a single shaft hammer crusher with a capacity of 650 tonnes/hour, while clay is crushed using a roll crusher with a capacity of 500 tonnes/hour. The products resulting from the breakdown are stored in each stockpile and storage:

b) Supporting raw materials (corrective). The supporting raw materials consist of silica sand (SiO_2) and iron sand (Fe_2O_3).

c) Additional raw materials. Additional raw materials consist of gypsum ($CaSO_4 \cdot 2H_2O$).

Grinding of raw materials

Grinding raw materials is a stage to obtain a homogeneous mixture of materials with a fine grain size. Limestone and clay originating from mining are transported using dump trucks to the respective crusher units (limestone and clay) to be reduced in size (size reduction). The aim is to facilitate chemical reactions and the process of drying raw materials using hot gas media originating from the hot gas generator and/or hot gas from the combustion process in the clinic. The main raw materials (limestone and clay) are raked using a reclaimer from each stockpile and storage. The results of the raking are then spilled onto a series of conveyor belts. A certain amount of supporting material is mixed with the main raw material on the conveyor belt and then fed into the vertical raw mill. The mixed ingredients then undergo a grinding and drying process in a vertical raw mill until they become raw flour as the product. The raw meal product is then sucked in by a fan and passes through a separator to obtain a standard level of material fineness. The hot gas mixed with the raw meal is then separated using 4 cyclones. The raw meal which has been separated from the hot gas is then fed into the Continuous Flow Silo (CF Silo). Raw meals will be homogenized

Table 1. Secondary data collection

No	Data	Data type	Data source
Input			
1	Limestone	Primary	Direct observation
2	Clay	Primary	
3	Diesel fuel	Primary	
4	Chemicals, oil, grease, and NH_4NO_3	Primary	
5	Mine area	Primary	
Output			
6	Air emissions	Primary	Direct observation
7	Toxic and hazardous waste (LB3 waste)	Primary	
8	Non-toxic and hazardous waste (non-LB3 waste)	Primary	
9	Product	Primary	

in the CF Silo and stored, and ready to be fed to the kiln. Vertical raw mills can also operate by simply grinding clay material to produce white clay according to market needs and demands. The production process is the same as raw meal production, only the raw meal and white clay storage areas are different.

Burning raw meal

Raw meal in the CF Silo is fed to the rotary kiln via a series of bucket elevators to be burned. The rotary kiln has a length of 75 m and a diameter of 4.5 m. The processes that occur at this stage include initial heating of the feed in the preheater (drying, calcination, dehydration, and decomposition), burning in the rotary kiln (clinkerization process), and cooling in the grate cooler (quenching) so that a clinker product is produced. The resulting clinker product is then stored in the Clinker Silo.

Cement grinding

The raw materials used for making cement consist of clinker, gypsum, limestone, trass, and fly ash as additional materials. The clinker in the clinker silo is transported into the clinker bin using a pan conveyor. Likewise, gypsum, limestone, and trass that will be used are also stored in the bin. The raw material composition is removed from each bin using a dosimat feeder including a conveyor belt to the cement grinding unit. The tube mill grinding process takes the form of a crushing or rough grinding process in a roller press to a certain size and is continued with a fine grinding or grinding process in a tube mill containing ball steel as a grinding medium. After this material undergoes a grinding process and comes out of the tube mill, fly ash material is added as an addictive material. The product that has come out of the tube mill and mixed with the fly ash material is sent to the separator. In this separator, all materials undergo a separation process by rotating and sucking. The fine material, which is a cement product, will be separated from the reject material which is still rough. The fine cement product material is continued for storage in cement silos via equipment, namely air slides and bucket elevators. Meanwhile, the rejected material that is still rough will return to the tube mill cement grinding unit. The vertical cement mill grinding process is a close circuit grinding system and the material output uses an air-swept mill system. The inlet section of the vertical cement mill is equipped with a metal detection system to prevent metal material from entering the vertical cement mill because it can damage the vertical cement mill and cause the grinding process to stop. If the vertical cement mill feed is detected to contain metal, the feed will be bypassed to the waste bin. Next, the material enters the vertical cement mill through the rotary airlock. The water content in the material is removed or evaporated by using hot gas from the combustion process in the kiln. The ground material is sucked out using a fan, and through a separator to separate the fine material from the coarse material at the top of the vertical cement mill and then enters the dust capture device (bag filter) to be separated from the carrier air. Some of the gas that comes out of the bag filter is recycled back to the vertical cement mill using an exhaust fan and the other part is channeled to the stack. The vertical cement mill is also equipped with a recycling system in the form of a conveying system which functions to circulate material that has not been finely ground back into the vertical cement mill. The vertical cement mill is also equipped with fresh air or a hot gas damper to make up gas that enters the vertical cement mill. Vertical cement mills can also be equipped with water sluice to minimize false water entering the vertical cement mill and water injection to maintain the operational stability of the vertical cement mill. The grinding results or cement products that come out of the bottom bag filter are transported using a flux slide transport and bucket elevator to an airtight cement silo for storage. The cement produced meets the chemical and physical requirements for cement with a minimum fineness of 3,800 cm^2 per gram (SNI requires a minimum of 2,800 cm^2 per gram). Next, the cement is removed from the cement silo using a flux slide into the steel silo.

Cement packing

Cement products are transported to steel silos for the packaging process. Cement is packaged using special cement bags with a load of 50 kg using cement packer equipment. Cement products that have been packaged are ready to be marketed by truck or train. Apart from that, cement is also marketed in big bags containing 1 ton and bulk cement which is transported using tank trucks.

Life-cycle impact assessment

Life cycle assessment (LCA) is an assessment tool used to evaluate the potential impact of a product on the environment throughout its lifetime. The LCA assessment was carried out based on Minister of Environment and Forestry Regulation Number 1 of 2021 concerning life cycle assessment aspects, product category rules of the Indonesian Cement Association (ASI), and Guidelines for Preparing Life Cycle Assessment Reports by the PROPER-KLHK Secretariat. The LCA analysis carried out at PT A used the CML IA Baseline V3.05, Impact 2002+, EPD 2018 and CED methods. The following is the issue identification PT A in Table 2.

Global warming potential

The cement industry is a significant contributor to greenhouse gas emissions, especially carbon dioxide (CO_2). The cement manufacturing process involves burning fossil fuels such as coal and natural gas, which produces direct CO_2 emissions. Apart from that, cement production can also produce emissions of methane gas (CH_4) and nitrogen oxide (N_2O) through chemical processes that occur in making clinker (Fig. 2).

From the data above, it is known that the highest contributor to limestone mining comes from CO_2 amounting to 65.576%, CH_4 amounting to 47.653%, and N_2O amounting to

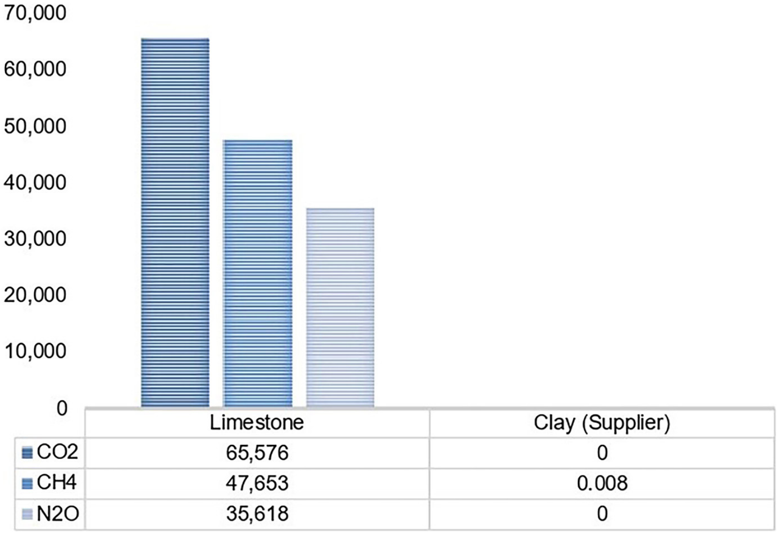


Figure 2. Contributor global warming potential

Table 2. Issues identification in PT A

No	Impact	Type	Limestone mine (%)	Limestone clay (Supplier) (%)
1	Global warming potential	Primary	100	0.0013
2	Eutrophication	Primary	99.93	0.0011
3	Acidification	Primary	100	0
4	Stratosphere thinning	Primary	100	0
5	Photochemical oxidation	Primary	99.91	0.009
6	Fossil fuel depletion	Secondary	100	0
7	Abiotic depletion	Secondary	100	0
8	Terrestrial ecotoxicity	Secondary	100	0
9	Aquatic ecotoxicity	Secondary	99.96	0
10	Carcinogenic	Secondary	100	0
11	Toxicity	Secondary	100	0
12	Water consumption	Secondary	99.96	0
13	Land change	Secondary	99.94	0
14	Non-renewable energy	Secondary	99.98	0.03

35.618%. The CH_4 contribution to clay mining is 0.008%. The impacts of CO_2, CH_4, and N_2O emissions from the cement industry include contributions to global warming, extreme climate change, and environmental damage.

Eutrophication

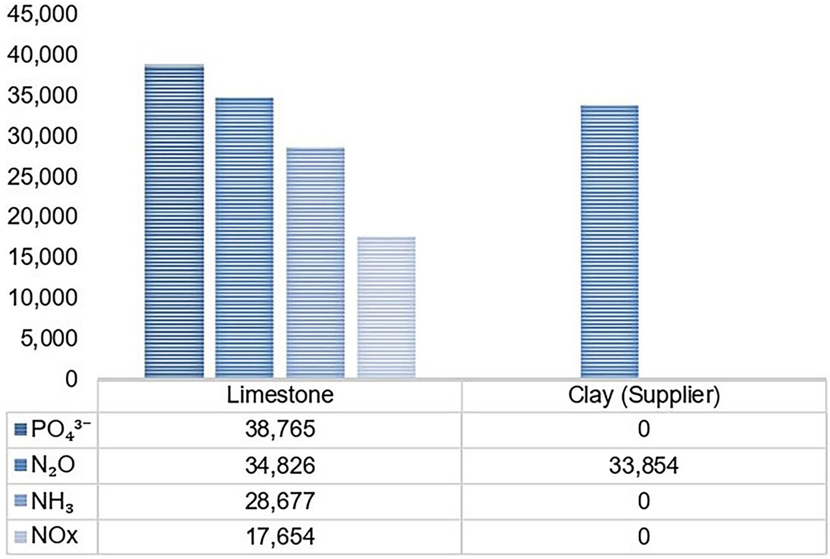
Eutrophication is a condition where there is an increase in nutrients such as phosphorus (PO_4^{3-}) and nitrogen (NH_3, NOx) in the aquatic environment, which can cause excessive growth of algae and aquatic plants. Emissions from the cement industry, such as PO_4^{3-}, N_2O, NH_3, and NOx, can contribute to eutrophication in the aquatic environment (Fig. 3). PO_4^{3-} is an emission from the cement industry that can increase phosphorus concentrations in water and is the main factor causing eutrophication. N_2O emissions from the cement industry, although in a smaller proportion than CO_2, CH_4, and N_2O, can still contribute to eutrophication due to its effect as a greenhouse gas that can accelerate global warming. NH_3 emissions from the cement industry can also cause eutrophication because ammonia can stimulate the growth of algae and aquatic plants. Meanwhile, NOx can also contribute to eutrophication because nitrogen is an important nutrient for the growth of aquatic plants and algae. In the data above, it is known that the highest contributors are PO_4^{3-} of 38,765 in limestone, N_2O of 34,826 in limestone and 33,854 in clay, NH_3 of 28,677 in limestone, and NOx of 17,654 in limestone.

Acidification

Acidification is one of the impacts of mining activities carried out by PT A. Emissions that arise include SO_2, NH_3, and NOx. SO_2 emissions from the mining process can react with water and air to form sulfuric acid, which can then cause acid rain and result in a decrease in soil and water pH. NH_3 emissions can also react with air and form ammonium acid which can contribute to the acidification process (Fig. 4). Meanwhile, NOx emissions can react with air and water to form nitric acid, which can also cause environmental acidification. The impacts of acidification include damage to water and soil ecosystems, reduced soil quality for agriculture, and disruption to human and animal health. The highest percentage of contributors is SO_2 of 57.432%, NH_3 of 38.981%, and NOx of 26.543% for limestone.

Stratosphere thinning

The thinning of the stratosphere layer comes from NH_4NO_3 emissions and the use of fuel during the limestone and clay mining process. NH_4NO_3 emissions can contribute to the depletion of the stratospheric ozone layer through chemical reaction processes that produce nitrate compounds and nitrogen oxides that damage the ozone layer (Fig. 5). From the data above, it is known that methane bromotrifluoro halon 1301 has the largest contribution to stratospheric depletion in both types of mines, namely 79.896%. Meanwhile, the amount of methane bromochlorodifluoro halon 1211 was 30.145%.



	Limestone	Clay (Supplier)
■ PO_4^{3-}	38,765	0
■ N_2O	34,826	33,854
■ NH_3	28,677	0
■ NOx	17,654	0

Figure 3. Contributor eutrophication

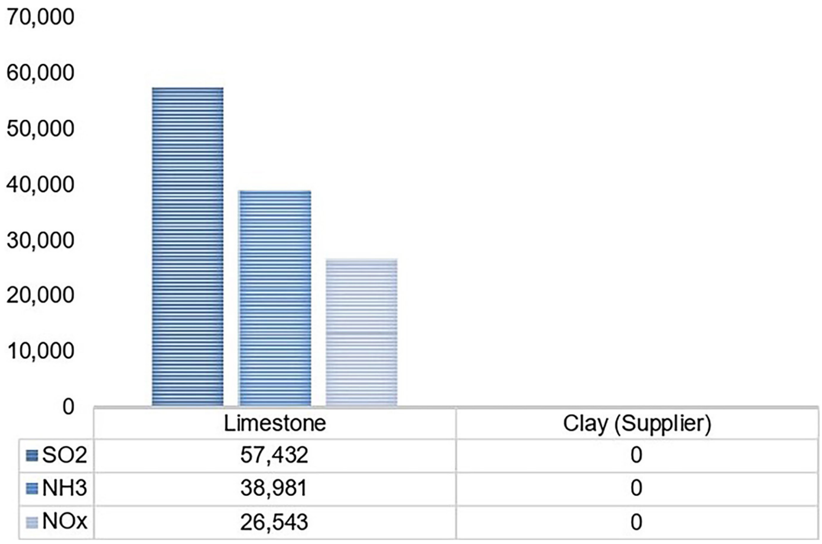


Figure 4. Contributor acidification

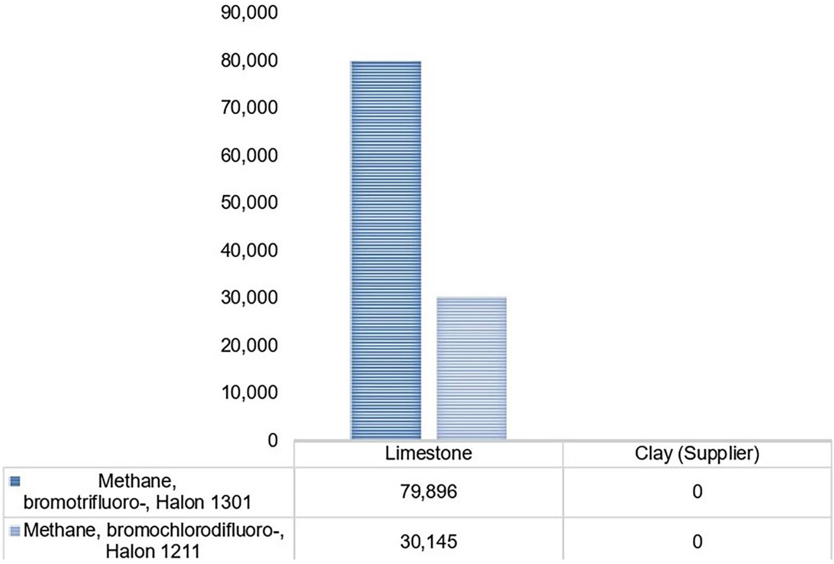


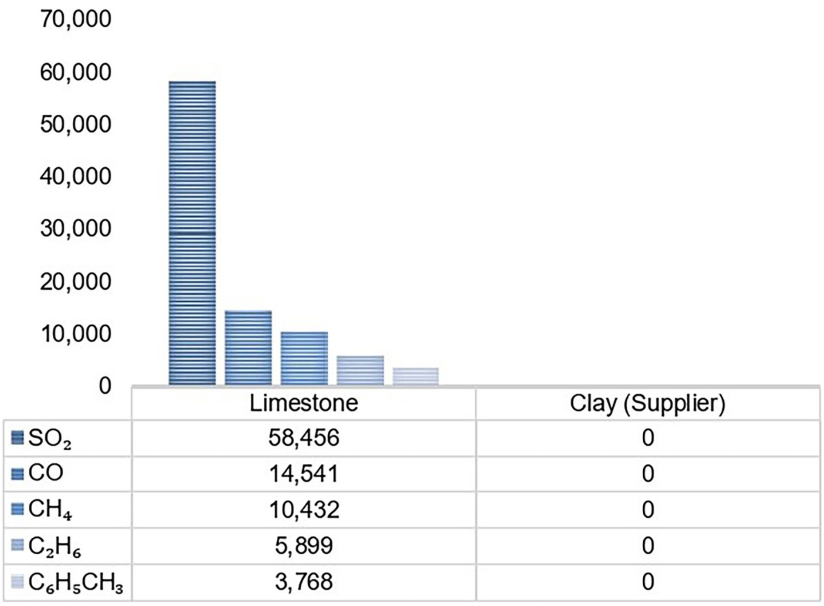
Figure 5. Contributor stratosphere thinning

Photochemical oxidation

Photochemical oxidation comes from the emissions of SO_2, CO, CH_4, C_2H_6, and $C_6H_5CH_3$. SO_2 contributes to the formation of sulfuric acid and fine particulate matter, which can affect air quality and respiratory health (Fig. 6). CO is a toxic compound that can interfere with the blood's ability to carry oxygen, cause poisoning, and affect air quality. CH_4 is a powerful greenhouse gas and can contribute to global warming and climate change. C_2H_6 is a precursor for the formation of tropospheric ozone, which is a secondary air pollutant that is dangerous for human and plant health. The final emission is $C_6H_5CH_3$ which is an organic compound that causes irritation of the respiratory tract and harms indoor air quality. The highest percentage of contributors was SO_2 of 58.456%, CO of 14.541%, CH_4 of 10.432%, C_2H_6 of 5.899, and $C_6H_5CH_3$ of 3.768% for limestone and 2.654% for clay.

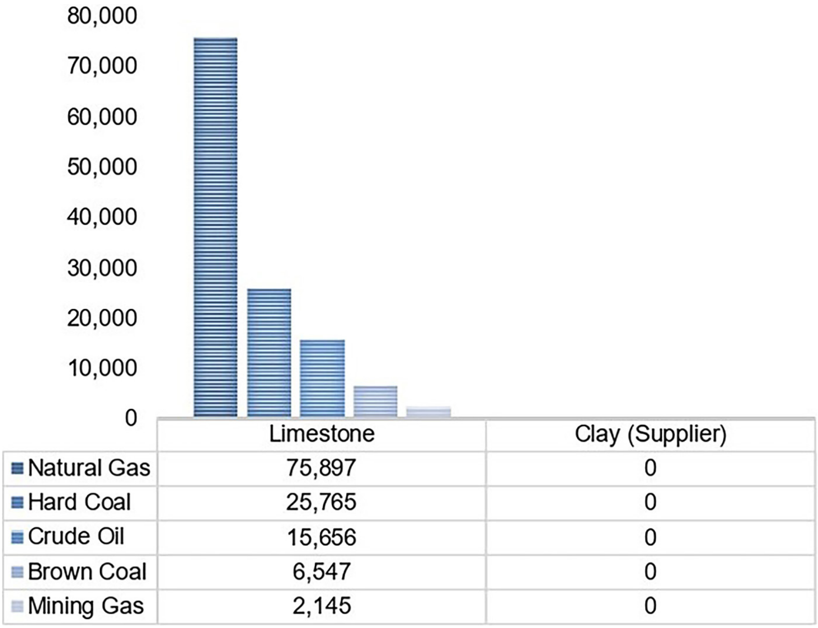
Abiotic depletion of fossils and non-fossils

The depletion of abiotic impacts such as fossils and non-fossils is caused by the use of crude oil, natural gas, coal, and other materials. The process of extraction, processing, and use of fossil fuels can produce greenhouse gas emissions and other environmental pollution



	Limestone	Clay (Supplier)
SO_2	58,456	0
CO	14,541	0
CH_4	10,432	0
C_2H_6	5,899	0
$C_6H_5CH_3$	3,768	0

Figure 6. Contributor photochemical oxidation



	Limestone	Clay (Supplier)
Natural Gas	75,897	0
Hard Coal	25,765	0
Crude Oil	15,656	0
Brown Coal	6,547	0
Mining Gas	2,145	0

Figure 7. Contributor abiotic depletion (fossils)

(Fig. 7). From the data above, it is known that natural gas in limestone mines has the highest contribution of 75.897%, followed by high coal (hard coal) at 25.765%, crude oil at 15.656%, low coal (brown coal) at 6.547%, and mining gas. (mine gas) of 2.145%. The main contributors to non-fossil abiotic depletion in the cement industry include the use of non-renewable non-fossil materials such as minerals, chemicals, and metals in various production processes (Fig. 8). From the data above, it is known that tellurium has the largest contribution to limestone mining, namely 75.812% followed by gold at 23.756%.

Terrestrial ecotoxicity and aquatic ecotoxicity

The depletion of terrestrial and aquatic biota is caused by emissions from PT A such as aluminum, copper, and zinc emissions. Emissions of aluminum, copper, and zinc can result in increased concentrations of aluminum in soil and water, which can poison plants, animals, and microorganisms (Fig. 9).From the data above, it is known that the largest contribution

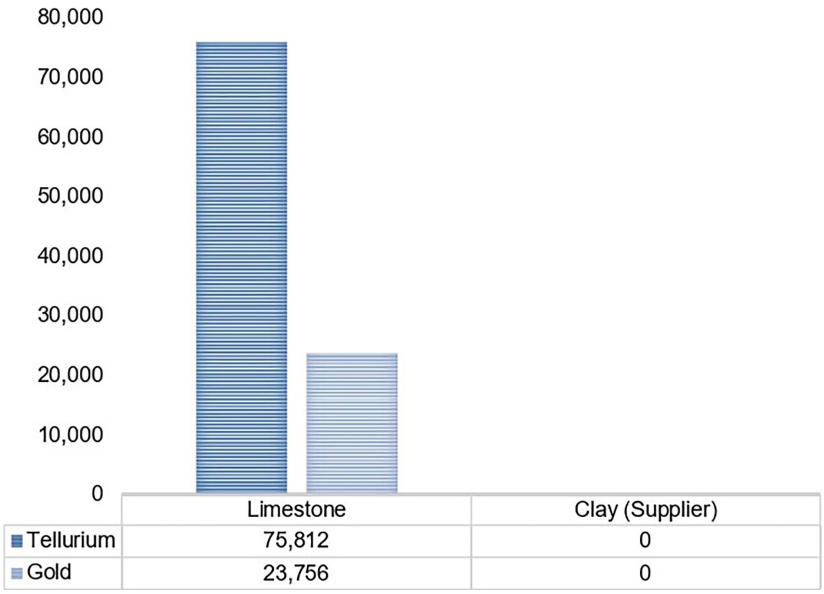


Figure 8. Contributor abiotic depletion (non-fossils)

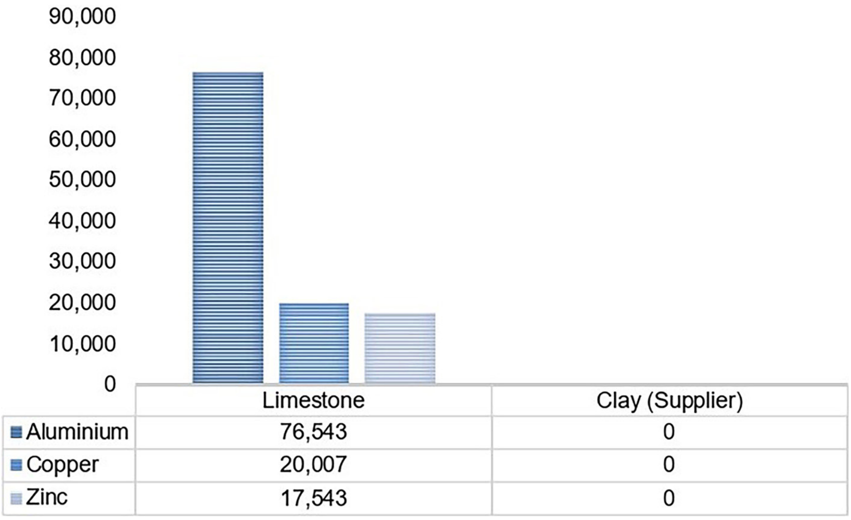
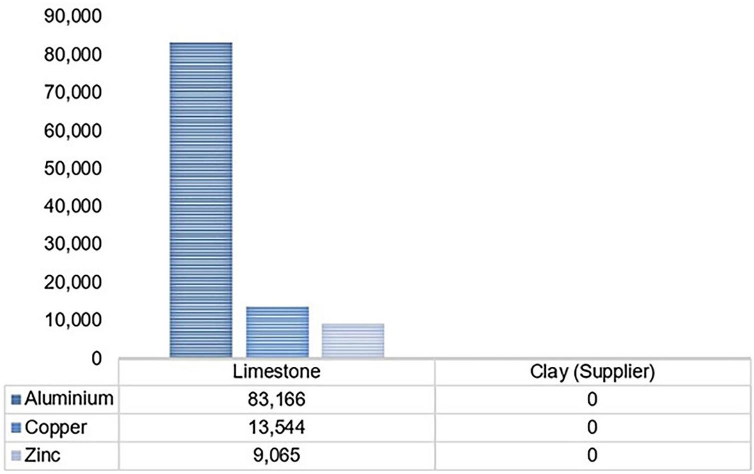


Figure 9. Contributor terrestrial ecotoxicity

that disrupts terrestrial and aquatic conditions is aluminum at 76.543%, followed by copper at 20.007%, and zinc at 17.543% (Fig. 10). The data shows that aluminum has the largest contribution to influencing toxicity in the aquatic environment at 83.166%, followed by copper at 13.544%, and zinc at 9.065%.

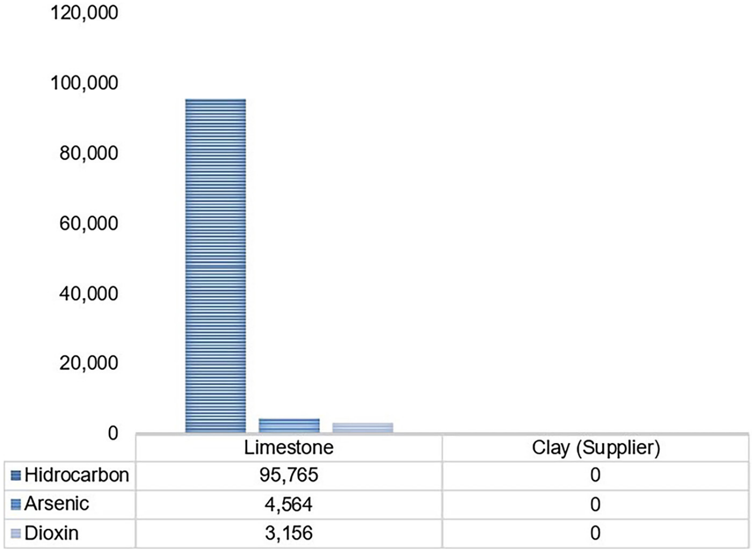
Carcinogenic

Carcinogenic impacts arise due to emissions of hydrocarbons, arsenic, and the dioxin tetrachlorodibenzo-p from industrial activities at PT A. Hydrocarbon emissions from the cement industry, such as exhaust gas from the fuel combustion process, can contain carcinogenic compounds such as benzene, formaldehyde, and polycyclics—aromatic hydrocarbons (PAH). Arsenic emissions from the cement industry, whether from combustion waste or production processes, can contribute to the risk of cancer because arsenic is considered a carcinogenic substance for humans by global health institutions such as WHO and EPA. Tetrachlorodibenzo-p-dioxin emissions are a very dangerous type of dioxin that arises from the combustion and processing processes in the cement industry. TCDD is known to be carcinogenic to humans and can cause various serious diseases (Fig. 11). From the data above, it is known that hydrocarbons have the highest contribution



	Limestone	Clay (Supplier)
Aluminium	83,166	0
Copper	13,544	0
Zinc	9,065	0

Figure 10. Contributor aquatic ecotoxicity



	Limestone	Clay (Supplier)
Hidrocarbon	95,765	0
Arsenic	4,564	0
Dioxin	3,156	0

Figure 11. Contributor carcinogenic impact

to causing carcinogenic impacts. The amount of hydrocarbons was 95.765%, followed by arsenic emissions of 4.564%, and dioxin tetrachlorodibenzo-p of 3.156%.

Toxicity

Toxicity is caused by emissions of thallium and chromium in PT A. Thallium emissions from the cement industry can cause serious environmental pollution. Exposure to thallium can cause damage to the nervous system, impaired heart function, and other health problems. Likewise, with chromium emissions, some forms of chromium, such as chromium VI (Cr^{6+}), are considered carcinogenic and can cause cancer, lung irritation, and skin problems (Fig. 12). From the data above, it is known that the source of toxicity comes from thallium and chromium. Thallium contributed the highest with a value of 55.879% and chromium at 26.431%.

Water consumption

Water usage such as surface water, seawater, and lake water is generally used in cement industry operations for various purposes such as production processes, machine cooling, and other needs (Fig. 13). The percentage of contributors to the impact of water consumption is 100% in limestone mines and 0% in clay mines. This is because the clay comes from suppliers.

Land-use change

The cement industry can cause significant land changes due to the need for land for factory

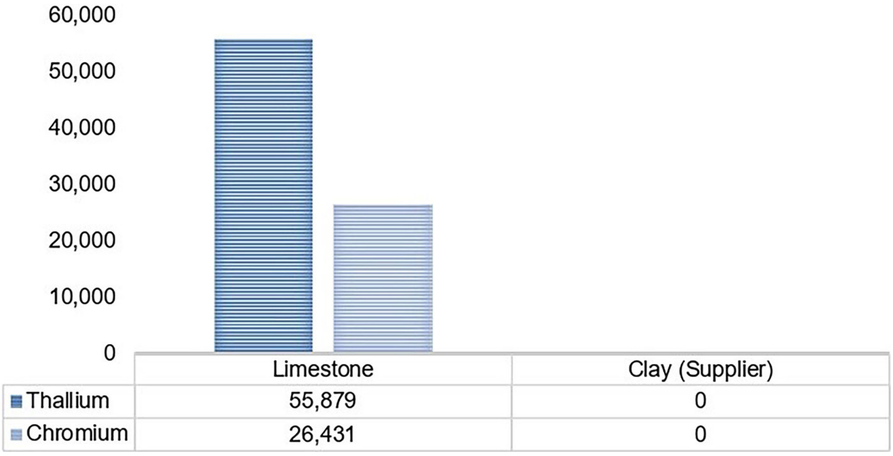


Figure 12. Contributor toxicity

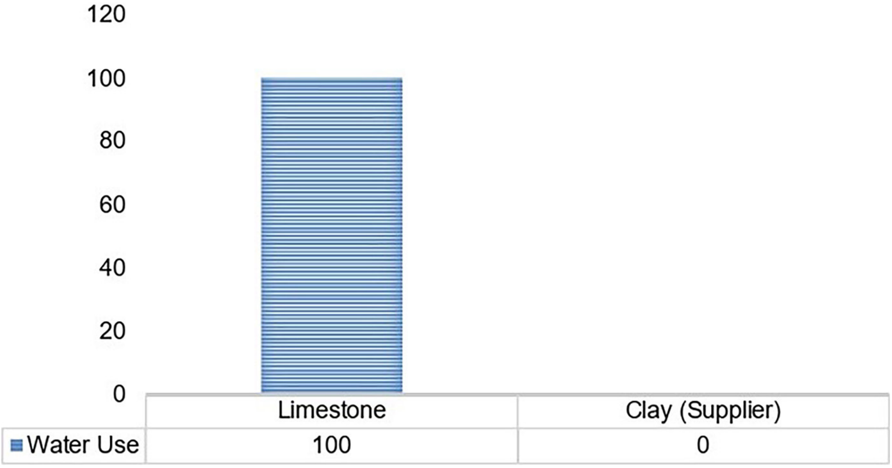


Figure 13. Contributor water consumption

locations, limestone quarries, raw material storage, and other supporting infrastructure. Some of the impacts of land change that can occur due to cement industry activities include:

- Land conversion: land that was originally used for agricultural activities, forests, or other open land can be converted into cement industrial areas, which can change land use and reduce the diversity of natural habitats.
- Use of pipes: the use of pipes during operational activities in the cement industry can affect land layout, especially around industrial facilities. The construction of pipe infrastructure for the distribution of water, waste, or other materials can result in land eviction and changes in land use.
- Land contamination: the use of chemicals, waste, or other pollutants in the cement industry production process can cause land contamination, which can also affect the quality and productivity of the land used (Fig. 14). The percentage of contributors to land use impacts is 100% in limestone mines and 0% in clay mines. This is because the clay comes from suppliers.

Depletion of non-renewable energy

The use of non-renewable energy resources such as coal and crude oil can cause depletion of non-renewable natural resources, increase dependence on fossil energy, and increase risks to future energy supplies. The impact of non-renewable energy is caused by the use of energy such as coal, natural gas, and crude oil in operational processes in the PT A industry. The use of coal, natural gas, and crude oil in the cement industry can produce greenhouse gas emissions such as CO_2, CH_4, and N_2O which contribute to global warming and climate change. In addition, burning coal and crude oil in the cement production process can produce

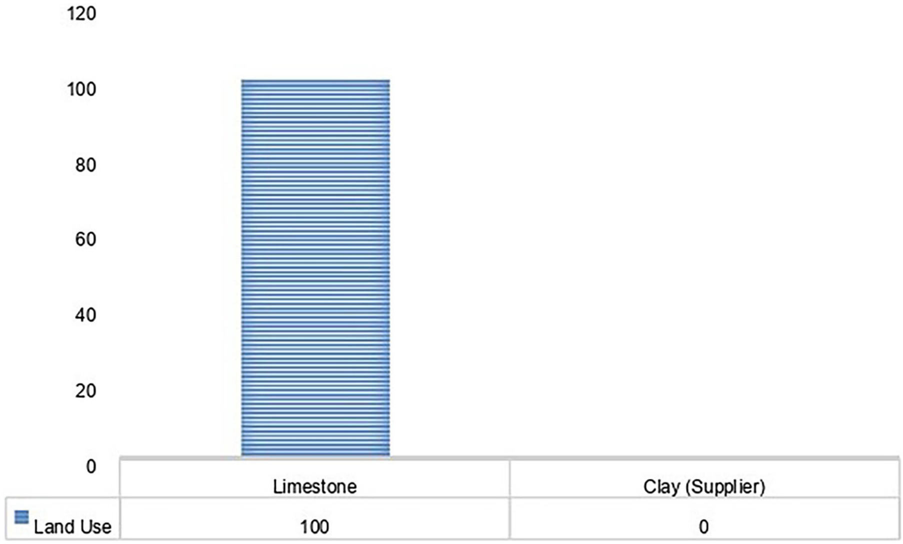


Figure 14. Contributor land use

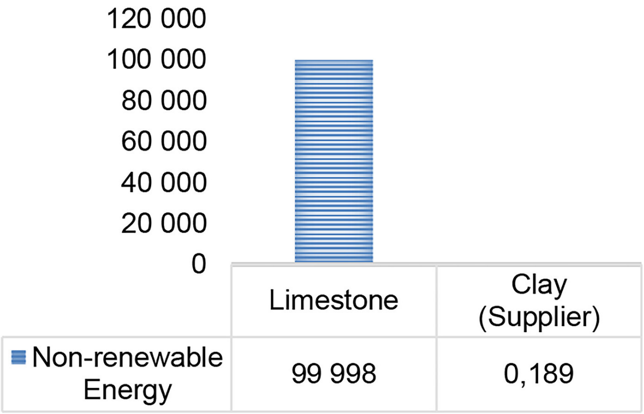


Figure 15. Contributor non-renewable energy

air pollutants such as SO_2, NOx, and fine particulates which can cause air pollution (Fig. 15).

In the data above, it is known that limestone is the highest contributor at 99.998% followed by clay at 0.189%.

From the life cycle impact assessment results, it is known that there are impacts arising from cement industry activities carried out by PT A. The types of impacts are based on Indonesian Ministry of Environment Regulation No. 1 of 2021. The impacts on the cement industry are divided into two types, namely primary impacts (potential global warming, eutrophication, acidification, and stratospheric depletion) and secondary impacts (photochemical oxidation, abiotic depletion of fossils and non-fossils, terrestrial ecotoxicity, and aquatic ecotoxicity, carcinogenicity, toxicity, water consumption, land use, and non-renewable energy).

CONCLUSIONS

In the research, it was discovered that when analyzing environmental impacts, can use the LCA method. The methods used in this research are divided into goal and scope, life cycle inventory, life cycle impact assessment, and interpretation. From the analysis primary impacts that occur in the cement industry at PT A include global warming, eutrophication, acidification, and stratospheric thinning. Meanwhile, secondary impacts that occur at PT A include photochemical oxidation, abiotic depletion of fossils and non-fossils, terrestrial ecotoxicity and aquatic ecotoxicity, carcinogenicity, toxicity, water consumption, land use changes, and non-renewable energy depletion.

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