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RESEARCH ARTICLE

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Environmental Impact of Limestone Mining Using A Life Cycle Assessment Method

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ABSTRACT

The extraction of limestone for cement production can adversely affect the environment. An inquiry is underway to examine the environmental ramifications of limestone mining to formulate strategies to mitigate these effects. This study aims to assess the ecological impact indicators of the limestone mining process by utilizing the LCA method based on CML-IA-baseline data from the openLCA software. The results indicate that crushing is a significant area of focus, contributing the most extensive value. The ratio of Ammonium Nitrate to diesel oil in adherence to guidelines is 94.5 to 5.5%. Particular emphasis is placed on assessing raw materials, especially during the loading and hauling stages. In conclusion, the research findings reveal environmental impact indicators with standardized values, such as abiotic depletion, abiotic depletion of fossil fuels, acidification, eutrophication of freshwater aquatic ecotoxicity, global warming 100a, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation, and terrestrial ecotoxicity.

Introduction

Limestone mining is a crucial process in the production of cement, a key component in the construction industry. However, the extraction of limestone can have significant environmental impacts, including depletion of natural resources, pollution, and habitat destruction. The use of cement in buildings ranks second only to water fields [1]. To produce 1 ton of cement requires 1.4 tons of limestone, 0.37 tons of clay, 0.03 tons of silica sand, and 0.05 tons of iron sand [2]. At the same time, the production manager at the factory said that cement is made from 84 to 87% limestone, 5.5% clay, 8.45% silica sand, and 1.35% iron sand. The selection of research on limestone mining is because in producing cement, limestone is the highest volume material taken from nature whose existence cannot be renewed. Limestone mining activities cause several final impacts on the environment, such as global warming, climate change, and depletion of the ozone layer, which will become a severe environmental problem in a certain period. Still, this research will analysis the preventive impact first.

The impact on the environment is evidenced by the increasing effect of anthropogenic greenhouse gas emissions by 35% from 1990 to 2010 [3]. Therefore, efforts to accelerate the reduction of greenhouse gas emissions are becoming increasingly urgent. The benefits of the research are expected to contribute to efforts to achieve the Indonesian government's greenhouse gas emission reduction target of 834 million tons

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of CO_2eq if done by its efforts and 1,787 million tons of CO_2eq if done with international cooperation [4] by implementing activities by the government's commitment to reduce greenhouse gas emissions by 29 to 41% by 2030 [5]. At the global level, in 2021, the industrial sector contributed around 21% of total greenhouse gas emissions [6]. The industrial sector includes the chemical industry, metallurgy, and manufacturing production. One of the manufacturing products is the cement commodity; the cement industry subsector emits emissions estimated at 98% of total global CO_2 emissions [7]. The same researchers further explained that the production of non-metallic minerals, mainly limestone, produces 44% of CO_2 emissions, and the dominant greenhouse gas emitting industry comes from the Asian continent, around 52% in 2010.

Based on literature studies in the last ten years (2013–2023), from the limestone mining research map, it is known that there are five groups of topics: 1) The environmental impact of pollution and waste [8–13]; 2) The mine waste management group [14]; 3) The use of information technology in mining group [15]; 4) The feasibility of using former mine sites group [16]; and 5) The blast environmental issues group [17]. Past research, however, has produced several benefits to the repertoire of knowledge that still needs to be broadened to the five groups above. Thus, there has yet to be much research that explains the categories of environmental impacts caused by limestone mining. Therefore, this research offers novelty to cover these shortcomings by analyzing the impact of limestone mining from the perspective of energy used with the Life Cycle Assessment (LCA) method. The novelty of this research is that it analysis the environmental impact categories of the limestone mining process with the life cycle method based on the Centrum voor Milieuwetenschappen in Leiden-Impact Assessment (CML-IA) baseline database model.

This research aims to analyze environmental impact categories using the LCA method based on CML-IA-baseline data with the open LCA software application. The CML-IA-baseline database contains characterization factors in synthesizing the impact categories studied as required by Guidelines for the Preparation of a Life Cycle Assessment Report Year 2021 [18] concerning the company's performance assessment program in environmental management including abiotic depletion, abiotic depletion of fossil fuels, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming 100a, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation and terrestrial ecotoxicity. The open LCA application was chosen because this software can be accessed without having a special license. Analysis of the limestone production process is becoming increasingly important in preserving the environment; this is done because of concerns from experts about the environmental impacts of mining exploration activities in general. This study was conducted to answer questions regarding categorizing and quantifying the effects of limestone mining activities. The results of the midpoint impact analysis will be explained in the results and discussion section.

Materials and Methods

Materials

The tools used were a set of computers and portable detonators. The materials used were limestone, urea, diesel oil, dynamite, Ammonium Nitrate powder, and Fuel Oil commonly abbreviated as ANFO.

Location and Research Time

The research was conducted from February 2023 to July 2023, at the time of the research mining was being carried out at the quarry D mine site. Other quarry locations such as quarry A, quarry B, and quarry C have been mined earlier, precisely in mid-1975. Quarry D consists of 5 mining zones, namely zone A, zone B, zone C, zone D and zone E. Quarry D, which consists of zone A and zone B, is a mountainous area dominated by limestone, covering an area of about 30 hectares of a total area of more than 124,270.80 hectares. This mountainous area with a hilly topography with a type A climate has high rainfall in the dry season with strong winds and heavy equipment vehicles going back and forth causing air pollution which has a negative impact on the village around the mine site. The mining site is geographically located in Cikukulu Village, Lulut Village, Klapanunggal Sub-district, Bogor Regency, West Java Province. This location is located between Latitude 6°26'44" LS and Longitude 06°53'31.7” East. The distance to the capital city of Jakarta is ± 34 km. The location of quarry D is at an altitude of 136 meters above sea level, temperature 25 to 32 °C, relative humidity ± 84%. The average annual rainfall is 4,000 to 4,500 mm per year. This area is owned by Perhutani whose ownership status is controlled by the company with the status of business use rights with a certain contract extension period according to mutual agreement. A map of the study area is presented in Figure 1.

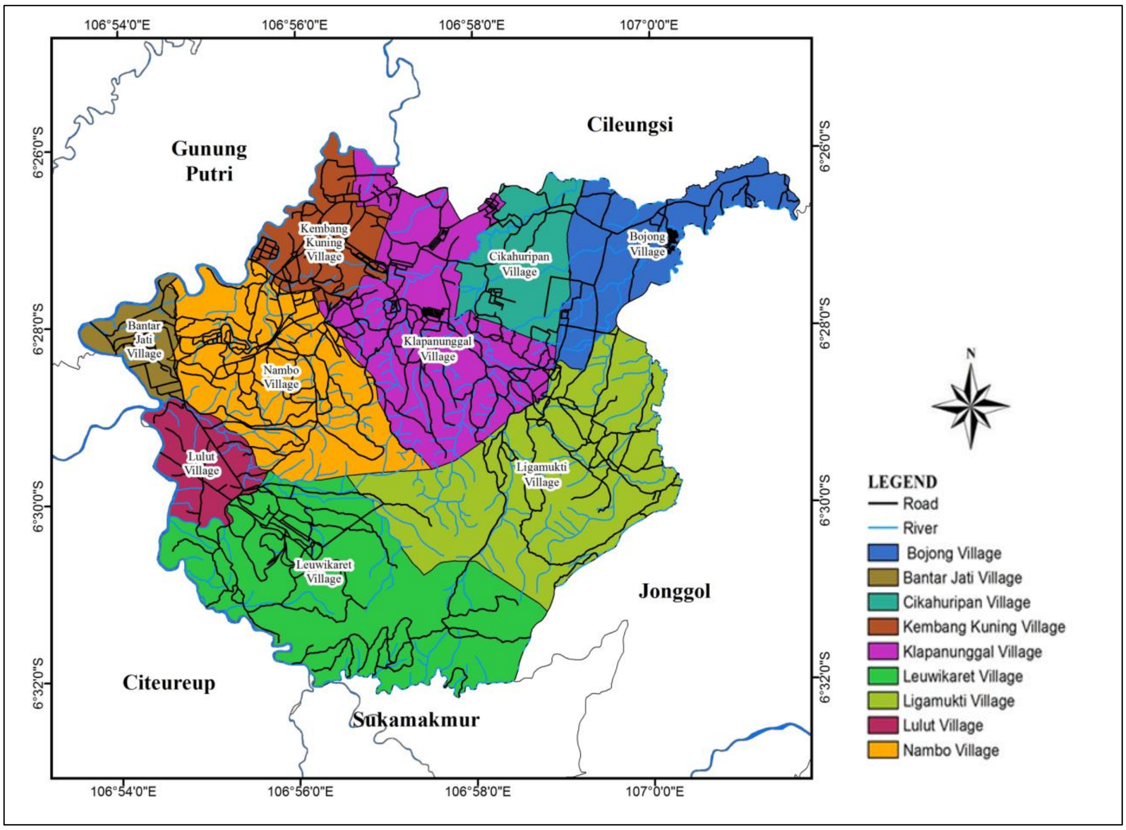


Figure 1. Lulut Village, Klapanunggal Bogor Regency, West Java.

Method

This research mainly uses secondary data from the company last year, which includes data on raw materials, products, and emissions in the production process. The environmental impact analysis was conducted using openLCA software version 1.11.0. The limestone mining process consists of five work sequences: drilling, blasting, loading, hauling, and crushing (Figure 2). First, blast hole drilling is the first work done after land clearing using a bulldozer, which aims to clear the land of grass, trees, and foreign objects in the mining area. Stripping the topsoil at a depth of 30 cm from the ground surface and other mining zones is done at the beginning. Drilling of blast holes is done using a hydraulic drilling machine at the quarry D location, which is divided into two zones, A and B. Each zone consisted of 15 blast holes (Figure 3a and Figure 3b); the depth of the blast hole was ± 15 m, and the diameter of the blast hole was 4 inches with a spacing distance of 5 m between blast holes and 3 m from the edge of the cliff.

Second, two pieces of dynamite were inserted in each blast hole with a weight of 200 grams of dynamite with an explosive power of 4 to 6 MJ/kg [19], gel-shaped dynamite wrapped around Fire Retardant Cable with six mm^2 NYA type connected to a detonator that uses battery current. When the dynamite is inserted into the blast hole, the position of the dynamite is checked to determine whether it is at the bottom of the blast hole or still stuck by inserting a non-metal deep stick so that there is no friction between ANFO powder, which is explosive with metal surfaces that can trigger an early explosion. After ensuring that the dynamite is at the bottom of the blast hole, it is then stockpiled by inserting fine rock powder from drilling into the blast hole to compact the blast hole to produce maximum explosive power and produce relatively many boulders with dimensions smaller than 1 m^2, if the boulders have a size greater than 1 m^2, they will be broken with a vibrator before being taken to the stone crusher. Blasting is carried out every day at around 12.00 WIB a clock, the chemical reaction at the time of blasting ANFO mixture with a composition of 94.5% Ammonium Nitrate (NH_4) and 5% Fuel Oil according to the equation: $3NH_4NO_3 + CH_2 \rightarrow 3N_2 + CO_2 + 7H_2O$ [20].

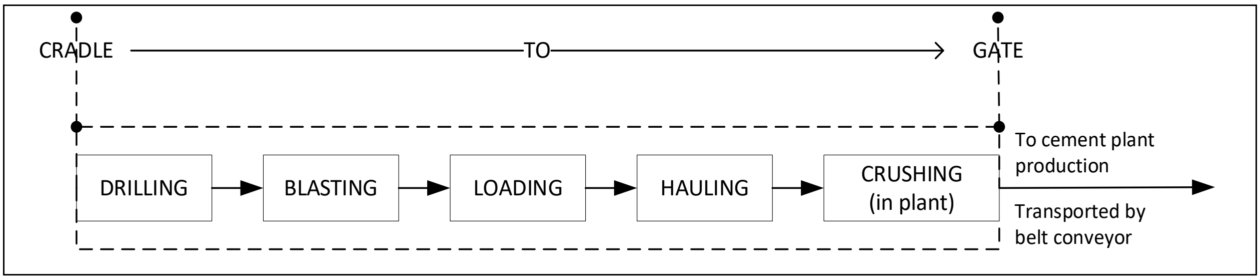


Figure 2. Mining workflow and research scope system.

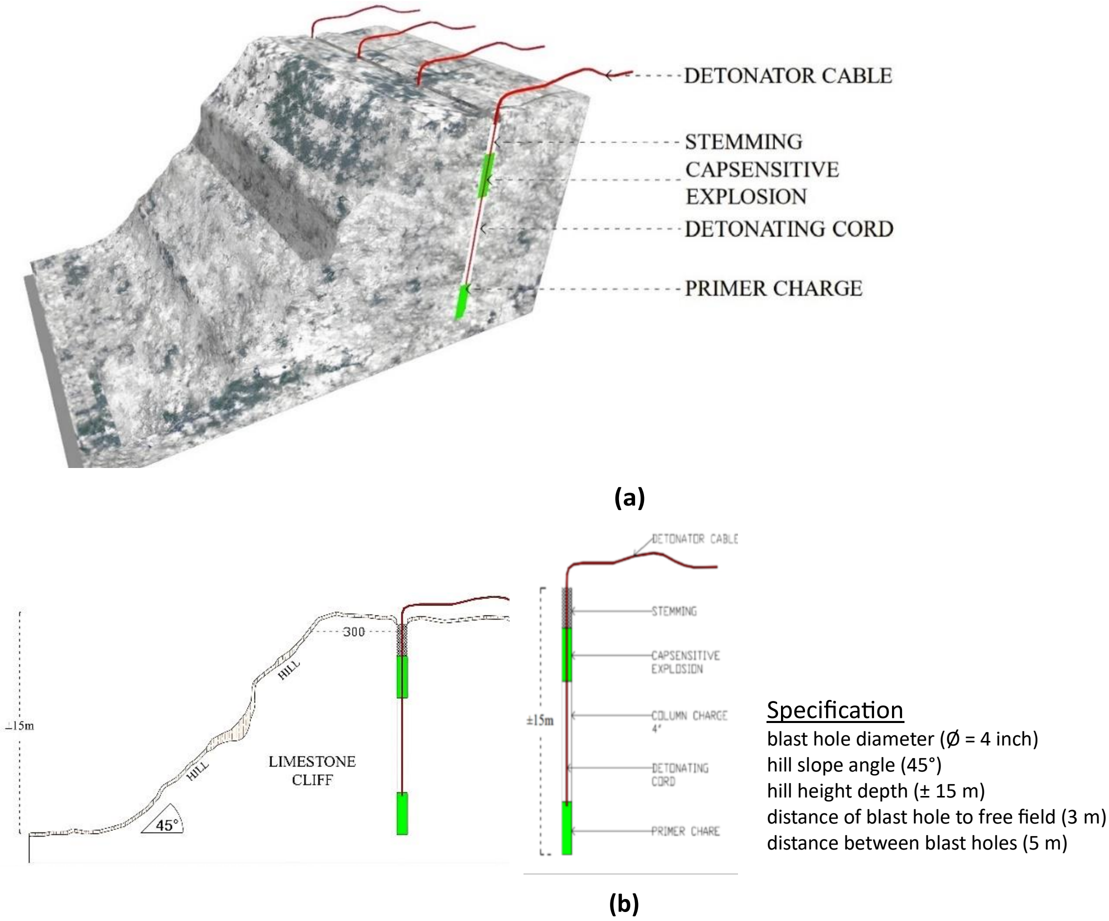


Figure 3. Blast hole geometry in limestone mining (a), detail of blast hole (b).

Third, limestone chunks from blasting are loaded onto dump trucks using 33-wheel loaders with a bucket capacity of 6 tons. Fourth, transportation to the location of the rock-breaking machine utilizing a dump truck carrying 68 tons of limestone boulders per trip. Fifth, rock breaking using jaw crusher and double shaft hammer type machines driven by 1,200 kW electric motor. The crusher reduces limestone to a size smaller than 50 mm^2 with a production fraction of 2,400 tons/hour. The reduced-size limestone is temporarily stored before being sent by a belt conveyor to the production plant, which is about 4.5 km from the location of the crushing machine.

Data Collection

Primary data was collected from field observations and field notes through unstructured, open-ended interview techniques with company staff at the mine site. Interviews were conducted to explore data on heavy equipment, specifications and types of explosives, and the electricity usage of stone-crushing machines. In contrast, secondary data were obtained from literature studies, data from company documents on the characteristics of explosives usage, and archival data in the form of monitoring fuel consumption by heavy equipment during mining activities and transportation of mining products.

Research Stages

The research consists of four stages, namely: 1. literature study by conducting reviews of journals relevant to the research topic; 2. Field observations were conducted to evaluate and compare the literature study results with the implementation; 3. Interviews were conducted by recording important information regarding data on the use of heavy equipment, explosives, fuel oil consumption, and electricity usage data; 4. Researchers analyzed the data with openLCA to determine the environmental impacts that occur.

Data Analysis

Calculation of diesel oil consumption for machine start-up is calculated based on the number of hours the machine is started until the machine is turned off. Data was obtained for the period February to July 2023. The fuel used is diesel or Industrial Diesel Oil (IDO). At the same time, the Indonesian government recommends biofuel (B35) as a more environmentally friendly diesel oil mixture by Government Regulation No.106.K/EK.05/DJE/2023 [21].

LCA is an internationally recognized concept and is systematically defined in the International Organization for Standardization (ISO) 14040 and 14044 [22], SNI (*Standar Nasional Indonesia*) ISO 14040:2016 and SNI ISO 14044:2017 on Guidelines for the Preparation of Life Cycle Assessment Reports [23] and Minister of Forestry and Environment Regulation No. 1 Year 2021 [18]. Technically, LCA is a tool to quantify (input and output) raw materials, energy, and emissions from a product or service. This case study assumes that there are no by-products in the production process. Figure 4 is a life cycle assessment framework of the LCA method, which consists of four stages: namely definition, goals and scope, inventory analysis, impact assessment and interpretation.

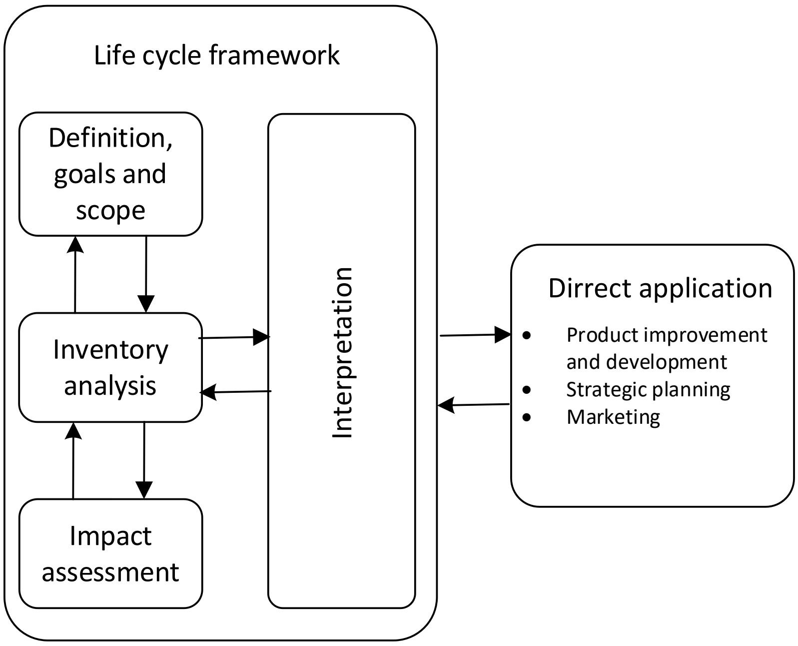


Figure 3. Life cycle assessment framework.

Definition, goal and scope

The research aims to analyze the impacts caused by limestone mining based on the energy used. Research analysis on the limitations and scope of cradle to the gate as shown in Figure 3, this scope with consideration of the impact caused by the mining process starting from the beginning of drilling (cradle) until the limestone is ready to exit the crusher in the plant (gate). The unit of function used to provide a quantitative description in the reference unit system is 1 ton of limestone fractions [24].

Inventory analysis

At this stage, the inputs, and outputs of the product throughout its life cycle are compiled and quantified, detailed in Figure 5. Inputs consist of limestone, energy, and transportation that enter the process, while outputs are comprised of products and emissions. Emissions are substances or compounds released into the environment (air, water, soil).

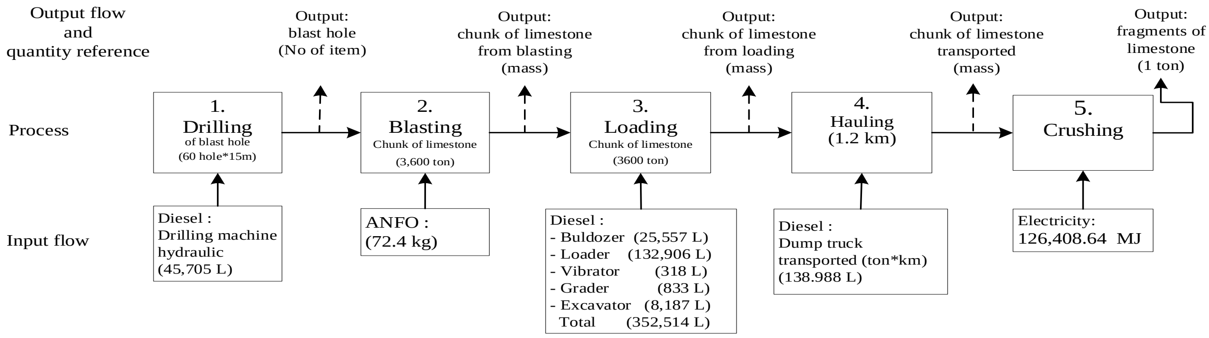


Figure 5. Inventory of input and output data of limestone fraction production.

Impact assessment

In the life cycle impact assessment stage, all inputs and outputs in the life cycle inventory stage are linked to potential environmental impacts to evaluate the magnitude and significance of the potential ecological impacts of the product system throughout the life cycle of the product being assessed in their respective categories [25]. The process input and output inventory are the characterization values [18] of material, energy, and transportation. Figure 6 shows the flow chart and system boundaries of the study. The openLCA application is used to analyze the environmental impact categories from the data obtained in the inventory analysis stage [26]. Meanwhile, the CML-IA-baseline database [24] was used to analyze the environmental impact category indicators from the output of each mining process unit. The CML-IA-baseline impact assessment model [27] was selected to calculate the midpoint impact category of the studied system. The category analysis results were then normalized to compare the impact indicators with each other.

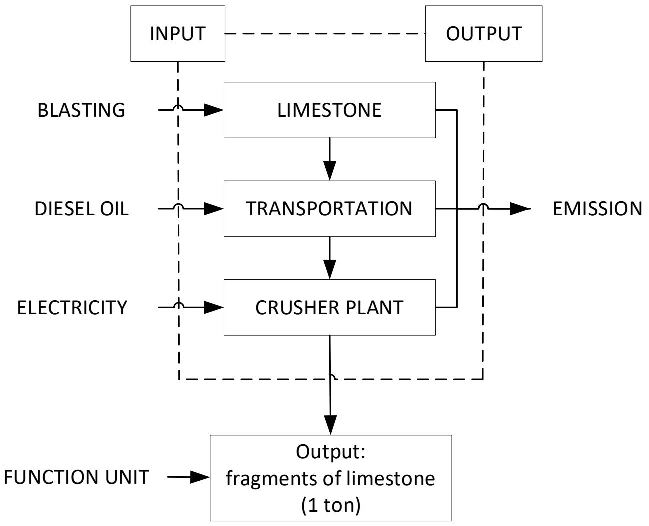


Figure 6. Flowchart and mining system constrains.

The life cycle impact assessment has several stages: characterization, normalization, weighting, and finally, determining the most impactful ranking [28]. Each impact assessment aims to identify the magnitude of environmental impacts resulting from the production process. In this study, the environmental impact assessment was carried out in characterization and normalization. The characterization stage is a stage that will display the impact value but still tends to be relative [18], because the characterization stage is directly carried out by comparing the results of the life cycle inventory against each category in the method used. The normalization stage is needed to equalize the overall units of each impact category from the method used. In the normalization stage, the impact value, still in the form of a characterization value, is multiplied by the normalization factor so that each impact category contained in a method has the same unit; this is by the output of the analysis results from the open LCA system. The purpose of equalizing the unit of each impact value is to compare the impact value of each impact category in the impact assessment method. After obtaining the impact value that has passed the normalization stage in each impact category and process unit, the impact value can be compared with other impact values because the units are the same. The purpose of comparing the impact value after the normalization stage is to determine the largest impact category in the production process.

Interpretation

The last stage of the LCA method is the interpretation stage. Discussions on the analysis results, analysis of impact causes, identification of crucial issues, data limitations, hotspots, conclusions, recommendations, or suggestions, and evaluation of the obtained results in the life cycle assessment are related to the interpretation of findings from the three preceding stages [26]. The stage examines the results to understand the factors influencing the environmental indicator categories. Constructive solutions and recommendations can be provided at this stage to improve the mining system's performance through intervention strategies or better production process management scenarios by optimizing inputs in each mining process unit to reduce adverse impacts [29].

The interpretation of environmental impacts is done by summing up the Life Cycle Impact Assessment (LCIA) values for each ecological impact category to obtain the total environmental impact value. The results of impact interpretation can be used to compare similar products from other studies or make decisions based on the generated ecological impacts. In the case study of producing 1 ton of crushed limestone using the CML-IA-baseline database, the total environmental impact value can be calculated by summing the normalization values of each impact category. The significant impacts to produce 1 ton of crushed limestone using the CML-IA-baseline method are abiotic depletion of fossil fuels (3.80E+14) and marine aquatic ecotoxicity (1.94E+14) and global warming potential 100a (4.18E+13). Other environmental impacts, such as abiotic depletion (2.09E+08), ozone layer depletion (2.27E+08), and photochemical oxidation (3.68E+10), have relatively minor impacts on the environment.

Based on the normalized impact category results to produce 1 ton of crushed limestone, the types of impacts with the most significant magnitude are abiotic depletion of fossil fuels, marine aquatic ecotoxicity, and global warming potential 100a. This indicates that in efforts to improve limestone production, the focus should be on reducing the use of diesel fuel, which is a fossil fuel. Using alternative fuels would likely have more significant environmental benefits. Biodiesel (B35) and solar and wind energy are the fuel with the most tremendous potential.

Results and Discussion

Analysis and Evaluation of Results Based on the CML-IA-Baseline Model Database

Before developing recommendations, analysis, and evaluation of the data that has been processed are first carried out [4]. Data analysis produces a model used to create intervention strategies or improvement scenarios for critical issues so that they can be formulated into policies that can be implemented logically. After obtaining the value of environmental impact indicators, they can be compared with the literature study results as evaluation material. The impact indicator values are obtained by comparing the coverage of ecological impact indicator values with research from Bendouma et al. [30] in Algeria with the ReCiPe 2016 database and Kittipongvises [13] in Thailand with the IMPACT 2002+ database, as shown in Table 1. In terms of geography, it also determines whether the impact is regional or global.

Table 1. Comparative analysis of impact categories of producing 1 ton of limestone fractions.

No	Indicator	Value			Unit
		Result of research	[13]	[30]	
1	Abiotic depletion (ADP)	1.28E-07	-	-	Kg-Sb-eq
2	Abiotic depletion (ADP fossil)	6.15E+00	-	-	MJ
3	Acidification (AP)	1.00E-03	1.43E-02	5.86E-09	kg SO_2 eq
4	Eutrophication (EP)	2.00E-04	1.37E-04	6.34E-11	kg PO_4 eq
5	Fresh water aquatic ecotoxicity (FWAE)	2.54E-02	-	5.97E-13	kg 1.4-Db-eq
6	Global warming (GWP 100a)	1.17E-01	2.76E+00	-	kg CO_2 eq
7	Human toxicity (HT)	4.69E-02	-	6.33E-08	kg 1.4-Db-eq
8	Marine aquatic ecotoxicity (MAE)	7.93E+01	-	2.72E-13	kg 1.4-Db-eq
9	Ozone layer depletion (ODP)	7.94E-08	1.75E-07	-	kg CFC-11-eq
10	Photochemical oxidation (POP)	5.07E-05	-	-	kg C_2H_4 eq
11	Terrestrial ecotoxicity (TEP)	2.40E-04	1.60E+01	2.76E-11	kg 1.4-Db-eq

Normalization of Impact Indicator Values

The evaluation of impact indicator category values after normalizing the mining process based on the CML-IA-baseline ranges from 3.80E+14 to 2.09E+08, shown in Table 2. Abiotic depletion of fossil fuels results from the depletion of non-renewable abiotic resources, especially fossil resources, which includes all categories of fossil fuels, including the raw materials for making the fuels themselves. Marine aquatic ecotoxicity is dominated by fluoride from air emissions from the electricity supply and non-ferrous metal manufacturing sectors and water emissions from sewage treatment plants. GWP 100a is the impact produced due to an increase in temperature on the Earth's surface; an increase in Earth's temperature results in climate change. Global Warming is triggered by the rise in greenhouse gases in the atmosphere. The total impact generated from the worldwide warming impact category in the production process is 4.18E+13.

Human toxicity is the potential toxicity of chemicals released into the environment to human health. This is based on the level of chemical content in a compound, which, if accumulated into the environment, will also impact human health. The total impact generated from the human toxicity category is 2.58E+12. Freshwater aquatic ecotoxicity is the toxic impact of chemicals on an ecosystem, in this case, freshwater, causing loss of biodiversity and or extinction of species. Terrestrial ecotoxicity is dominated by pesticide emissions to agricultural soils, sulfuric acid, and steam used during conversion. Marine ecotoxicity is entirely dominated by emissions of heavy metals and sulfuric acid, primarily to air. Acidification is when sulfur dioxide (SO_2) gas reacts or mixes with water in the atmosphere, resulting in acid rain. This process is triggered by gases that can cause acid deposition, such as Nitrogen Oxides (NO_x) and sulfur oxides (SO_x). The total impact of the acidification category is 2.39E+11.

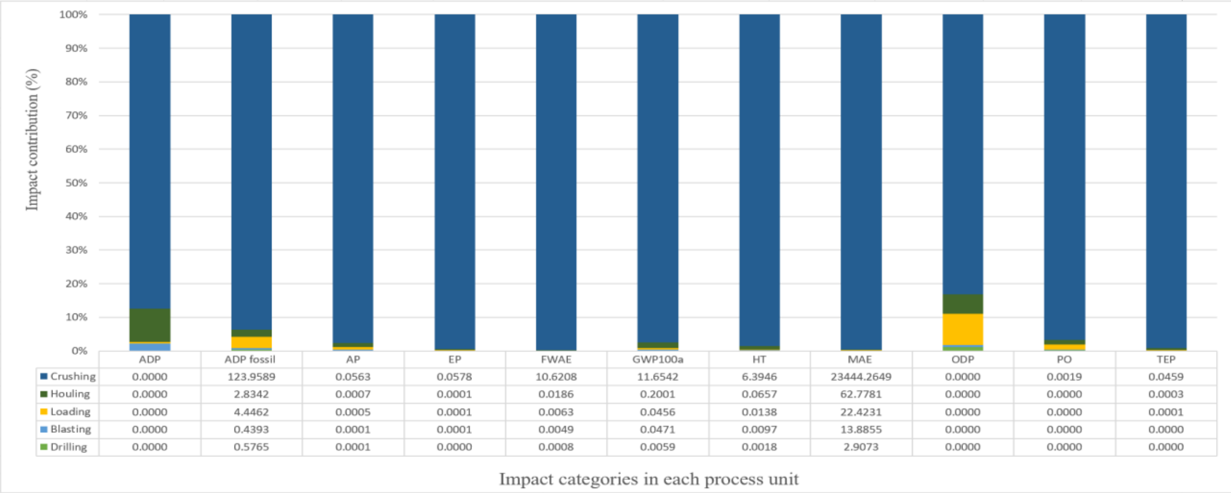
Eutrophication is an example of water pollution caused by abundant nutrients in the water, resulting in algae growth in the aquatic ecosystem. What can cause eutrophication is the presence of nitrate, Nitrogen Oxide (NO_x), and ammonia in the water ecosystem. The total impact resulting from the eutrophication category is 1.58E+11. Photochemical oxidation is air pollution that is still related to smog in the air that contains NO_2 and O_3. Therefore, these conditions can cause health problems in living things. The total impact of the photochemical oxidation category is 3.68E+10. Ozone layer depletion is a condition where the ozone layer is depleted, which results in radiation from UV-B rays to the earth's surface. This condition has many adverse effects on life and land and water ecosystems. The total impact generated from the ozone layer depletion category is 2.27E+08. Abiotic depletion is the impact generated due to the depletion of non-renewable abiotic resources that can damage the ecosystem if these resources are no longer available due to the dependence of humans who still use these resources. The total impact resulting from the abiotic deletion category is 2.09E+08. The value above impacts the production of 1 ton of limestone fractions in the crushing process unit.

Table 2. Normalization of impact categories for the production of 1 ton of limestone fractions.

No	Indicator	Value	Rank
1	Abiotic depletion (ADP)	2.09E+08	11
2	Abiotic depletion fossil fuels (ADP fossil)	3.80E+14	1
3	Acidification (AP)	2.39E+11	7
4	Eutrophication (EP)	1.58E+11	8
5	Fresh water aquatic ecotoxicity (FWAE)	2.36E+12	5
6	Global warming (GWP 100a)	4.18E+13	3
7	Human toxicity (HT)	2.58E+12	4
8	Marine aquatic ecotoxicity (MAE)	1.94E+14	2
9	Ozone layer depletion (ODP)	2.27E+08	10
10	Photochemical oxidation (POP)	3.68E+10	9
11	Terrestrial ecotoxicity (TEP)	1.09E+12	6

Process Unit Contribution to Impact

The total impact contribution value is the sum of indicators in each unit of the limestone fraction production process, each of which is drilling 3.49E+00, blasting 1.44E+01, loading 2.69E+01, hauling 6.59E+01 and crushing 2.36E+04. The life cycle impact assessment results can determine the impact contribution value or hotspot generated from each production process unit. From the results of the analysis, it can be seen that the most significant total hotspot value comes from the crushing process unit with a total impact value of 2.36E+04. The magnitude of the contribution occurs in the crushing process unit. Therefore, the crushing process unit will be studied in more depth to find out what components are the most dominant cause of the crushing process unit becoming a hotspot for immediate intervention action. Especially for LCA on chemical products, such as ammonium nitrate, it is essential to report and document transparently. The contribution of chemicals to impacts related to the product life cycle stage and each process unit. This can help identify potential problems in processing inventory results (LCI) and impact analysis (LCIA).



	ADP	ADP fossil	AP	EP	FWAE	GWP100a	HT	MAE	ODP	PO	TEP
Crushing	0.0000	123.9589	0.0563	0.0578	10.6208	11.6542	6.3946	23444.2649	0.0000	0.0019	0.0459
Houling	0.0000	2.8342	0.0007	0.0001	0.0186	0.2001	0.0657	62.7781	0.0000	0.0000	0.0003
Loading	0.0000	4.4462	0.0005	0.0001	0.0063	0.0456	0.0138	22.4231	0.0000	0.0000	0.0001
Blasting	0.0000	0.4393	0.0001	0.0001	0.0049	0.0471	0.0097	13.8855	0.0000	0.0000	0.0000
Drilling	0.0000	0.5765	0.0001	0.0000	0.0008	0.0059	0.0018	2.9073	0.0000	0.0000	0.0000

Figure 4. Environmental impact contribution of each production process unit.

Impact Cause Analysis

The analysis indicated that the most significant value of the environmental impact indicator was Marine Aquatic Ecotoxicity (MAE) 7.93E+01 kg 1.4-Db-eq followed by Abiotic Depletion Potential fossil (ADP fossil) of 6.15E+00 MJ. At the same time, the smallest was Ozone Layer Depletion (ODP) 7.94E-08 kg-CFC-11-eq followed by Abiotic Depletion (ADP) 1.28E-07 kg-Sb-eq (Table 1). After evaluation, the cause of the high MAE indicator value is the use of ANFO explosives with levels that are too high from the predetermined levels. At the same time, fossil ADP is due to diesel oil consumption for heavy equipment. Hotspots occur in the crushing process unit; this happens because of the use of electrical energy that is still high (coal energy), so it is necessary to evaluate the use of electricity, for example, by replacing it with other types of electrical energy sources (e.g., solar cells) to be more environmentally friendly. The hauling process unit is clearly due to the use of fuel oil; thus, it is necessary to immediately leave fuel oil and switch to biofuel-type biodiesel (B35).

This research has limitations in setting system boundaries, including the quantity and quality of data, mining operations, exhaust emissions, and diesel oil leakage (fugitive). Due to all these aspects, it is difficult to accurately estimate the results, leading to uncertainty in the analysis results. In this context, it is essential to collect data separately on fuel consumption at each stage of the mining life cycle, such as blast-hole drilling, explosive charging, blasting, transportation, specific parameter sensitivities, and all processes associated with mining activities. Hence, it is necessary to inventory the data to the maximum extent to make it more representative as a parameter contributing to the uncertainty of the assessment results. From all the existing limitations, it is necessary to conduct further studies on the environmental impacts of limestone mining up to the effect of damage (endpoint), such as changes in land use, degradation of land functions, changes in groundwater quality, noise, and vibration, air quality, water scarcity, formation of fine particulates, ionizing radiation, biodiversity, and other environmental impacts.

The Benefits of The Research

In the context of research on the environmental impact of producing 1 ton of crushed limestone using the LCA method based on CML-IA-baseline data, the benefits can be outlined as follows: 1) Environmental impact identification: this research aids in identifying the environmental impact of the stages involved in mining and producing 1 ton of crushed limestone. The impacts include abiotic depletion of fossil fuels, marine aquatic ecotoxicity, and global warming potential over 100 years; 2) Prioritizing significant impacts by analyzing and normalizing impact categories, the research provides an understanding of the most significant environmental impacts. This enables the prioritization of management and improvement actions on aspects with substantial impacts; 3) Recommendations for environmental management: the research results serve as a foundation for constructive recommendations related to the ecological management of crushed limestone production.

For instance, they could focus on reducing the use of diesel fuel and consider switching to alternative fuels like biodiesel; 4) In comparing similar products, the total environmental impact values obtained can be used to compare similar products from other studies. This aids in making sustainable and environmentally friendly decisions in the mining industry; 5) The basis for company policies and strategies. The findings from this research can form the basis for formulating company policies and strategies to enhance environmental performance. This includes fuel management and the selection of more sustainable energy sources; 6) A deeper understanding of environmental hotspots through analysis: the research provides a deeper understanding of ecological hotspots or specific areas with significant environmental impacts. This assists in making more valid decisions.

Conclusion

From the inventory results and analysis using the openLCA method based on CML-IA-baseline data, conclusions can be drawn regarding impact categories with normalized values as follows: Abiotic depletion 2.09E+08 kg-Sb-eq, Abiotic depletion fossil fuels 3.80E+14 MJ, Acidification 2.39E+11 kg-SO_2-eq, Eutrophication: 1.58E+11 kg-PO_4-eq, Freshwater aquatic ecotoxicity 2.36E+12 kg 1.4-Db-eq, Global warming 100a 4.18E+13 kg-CO_2-eq, Human toxicity 2.58E+12 kg 1.4-Db-eq, Marine aquatic ecotoxicity 1.94E+14 kg 1.4-Db-eq, Ozone layer depletion 2.27E+08 kg CFC-11-eq, Photochemical oxidation 3.68E+10 kg C_2H_4-eq, Terrestrial ecotoxicity 1.09E+12 kg-1.4-Db-eq. Suggestions based on the analysis: 1) Scrutiny is needed on fuel consumption data as energy in limestone mining due to its significant impact on emissions; 2) Regular updates of emission data from mining should be carried out as a further mitigation action; 3) Commitment from industry stakeholders is essential to achieve emission reduction targets; 4) Exploration of alternative, environmentally friendly explosive materials other than ANFO is needed. Diesel fuel should transition to biodiesel, following government recommendations; 5) Weighing of limestone chunks in the loading, hauling, and crushing processes should be considered.

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