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CARBON FOOTPRINT STUDY ON COAL-BASED ENERGY SYSTEMS IN THE FISHERIES PROCESSING INDUSTRY IN BALI

Kajian Jejak Karbon Pada Sistem Energi Berbasis Batu Bara Dalam Industri Pengolahan Hasil Perikanan di Bali

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ABSTRACT

The fish processing industry is one of the main contributors to regional economic activity in coastal areas. However, its dependence on fossil fuels, especially coal, poses significant environmental problems, especially related to greenhouse gas (GHG) emissions. This study aims to assess the carbon footprint resulting from coal combustion in a fish processing plant in Bali during the operational period. Parameters observed include daily coal consumption, coal ash residue, total CO_2 emissions, and specific carbon footprint. Data analysis revealed a total coal consumption of 765,430 kg, resulting in total CO_2 emissions of 1,382,964.3 kg. The average specific carbon footprint was calculated to be 3.98 kg CO_2/kg product, indicating high carbon intensity relative to industry energy efficiency benchmarks. The study also analyzed the relationship between production output and emissions, as well as the correlation between coal ash production and carbon efficiency. Findings showed inconsistencies between energy use and production levels, with several examples of high emissions accompanied by low output, indicating operational inefficiencies. The results highlight the urgent need for mitigation strategies, including improving boiler efficiency, transitioning to low-carbon fuels, implementing emission control systems, and utilizing coal ash as a secondary feedstock. This research provides baseline data for environmental management planning and contributes to broader efforts in industrial decarbonization and sustainable fish processing practices.

Key words: Carbon Footprints, CO_2 Emissions, Coal, Energy Management, Fish Processing Industry

ABSTRAK

Industri pengolahan ikan merupakan salah satu penyumbang utama kegiatan ekonomi regional di wilayah pesisir. Namun, ketergantungannya pada bahan bakar fosil, khususnya batu bara, menimbulkan masalah lingkungan yang signifikan, terutama terkait emisi gas rumah kaca (GRK). Studi ini bertujuan untuk menilai jejak karbon yang dihasilkan dari pembakaran batu bara di pabrik pengolahan ikan di Bali selama periode operasional. Parameter yang diamati meliputi konsumsi batu bara harian, residu abu batu bara, total emisi CO_2, dan jejak karbon spesifik. Analisis data mengungkapkan total konsumsi batu bara sebesar 765.430 kg, yang menghasilkan total emisi CO_2 sebesar 1.382.964,3 kg. Jejak karbon spesifik rata-rata dihitung sebesar 3,98 kg CO_2/kg produk, yang menunjukkan intensitas karbon yang tinggi relatif terhadap tolok ukur efisiensi energi industri. Studi ini juga menganalisis hubungan antara hasil produksi dan emisi, serta korelasi antara produksi abu batu bara dan efisiensi karbon. Temuan menunjukkan ketidakkonsistenan antara penggunaan energi dan tingkat produksi, dengan beberapa contoh emisi tinggi disertai dengan hasil rendah, yang menunjukkan inefisiensi operasional. Hasilnya menekankan kebutuhan mendesak akan strategi mitigasi, termasuk peningkatan efisiensi boiler, transisi ke bahan bakar rendah karbon, penerapan sistem pengendalian emisi, dan pemanfaatan abu batu bara sebagai bahan baku sekunder. Penelitian ini menyediakan data dasar untuk perencanaan pengelolaan lingkungan dan berkontribusi pada upaya yang lebih luas dalam dekarbonisasi industri dan praktik pengolahan ikan yang berkelanjutan.

Kata Kunci: Jejak Karbon, Emisi CO_2, Batubara, Manajemen Energi, Industri Pengolahan Ikan

INTRODUCTION

The fisheries processing industry plays a strategic role in supporting food security, increasing the added value of fisheries commodities, and providing employment in various coastal areas of Indonesia, including Bali Province (Nugraha et al., 2025; Nugraha et al., 2025). As an area with quite large potential for fish catching and cultivation, Bali has a number of fish processing units (UPI) that produce processed products such as dried fish, smoked fish, fish floss, as well as frozen and canned products that are marketed locally or exported abroad (Putri et al., 2023; Utari et al., 2024).

However, behind its contribution to the regional economy, fish processing industry activities also have an impact on the environment, especially through the use of fossil energy sources such as coal. This is also almost found in several other marine and fisheries activities (Nugraha, 2020; Suryanto et al., 2017, 2019). In the processing process, coal is generally used as fuel for drying, heating, and sterilization processes due to its high availability and relatively low operational costs (Arrieta & González, 2019; Cao et al., 2023; Chen et al., 2024; Drewnowski et al., 2015; MOJA et al., 2023; Shabir et al., 2023; Xu et al., 2015; Yudhistira et al., 2023; Zeng et al., 2022). The use of this coal produces greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), which contribute significantly to increasing the industry's carbon footprint and global climate change (Arrieta & González, 2019; Beyer et al., 2024; Cao et al., 2023; Mazzetto et al., 2023; Rosalina et al., 2023).

Environmental problems due to coal combustion are becoming increasingly crucial to examine, considering that Bali as a world tourist destination has a high commitment to sustainable and environmentally friendly industrial practices (Kurniawan et al., 2024; Wiratama et al., 2016). The local government has also encouraged business actors, including the fisheries sector, to implement green economy principles and reduce dependence on fossil-based energy.

In this context, the study of the carbon footprint of the coal-based energy system in the fisheries processing industry is very important. The carbon footprint is a quantitative measure of the total GHG emissions produced directly or indirectly from an activity or process, usually expressed in carbon dioxide equivalent (CO_2) (Admaja et al., 2020; Dapas, 2015; Mubekti, 2016; Rahayu et al., 2023; Zuhria & Azmi, 2023). Through this approach, it can be seen how much each stage of the production process contributes to carbon emissions, as well as strategies that can be applied to reduce it (Grealey et al., 2022; Herawati et al., 2024; Ismail, 2020; Kiehle et al., 2023; Kohli et al., 2023; Mancini et al., 2016).

Given the urgency of the climate change issue and demands for efficiency and industrial shortages, this study aims to analyze the magnitude of the carbon footprint generated from the coal-based energy system in the fisheries processing industry in Bali. The results of this study are expected to be the basis for taking carbon emission mitigation policies in the fisheries sector, as well as encouraging the transition to a cleaner and more sustainable energy system.

METHODS

This research is a quantitative descriptive study with a case study approach. This approach is used to provide a systematic and factual description of the carbon footprint resulting from the use of coal as an energy source in the fishery product processing process, especially in the boiler system. The research focuses on the identification and quantification of carbon dioxide (CO_2) emissions resulting from coal combustion, as well as an analysis of the potential for combustion waste generated.

This research was conducted in the Province of Bali, which has a number of fishery product processing units that still use coal as the main energy source in the production process, such as drying and sterilization. The research location was selected purposively based on the criteria for using a coal-fired boiler system in its production activities. The research implementation time is planned to take place during the period February to March 2025, which includes field observation activities, data collection, and laboratory analysis if necessary.

Sample of fishery product processing units in Bali that use coal in their production process. The sample was selected using a purposive sampling technique, with the criteria of processing units that actively use coal-fired boilers, have well-documented operational data, and are willing to provide access to the data needed by researchers. With these criteria, it is expected that the data collected truly reflects the real conditions of coal-based energy use in the fishery processing industry.

The types of data collected consist of primary data and secondary data. Primary data include the amount of coal consumption per day or per batch process, the type and volume of coal combustion waste (such as ash and fuel residue), daily or monthly production volume, and the technical characteristics of the boiler system used. Primary data collection is carried out through direct observation in the field, structured interviews with operators or officers, and operational records of the production process. Meanwhile, secondary data is obtained from company documents, production reports, technical references, and literature related to emission factors and energy efficiency standards that apply nationally and internationally.

Data analysis is carried out in two main stages. First, the calculation of carbon dioxide emissions is carried out using the Tier 1 method from the Intergovernmental Panel on Climate Change (IPCC), with formula 1. The standard emission factor used is 2.86 kg CO_2/kg coal, according to the IPCC reference, but can be adjusted if specific characteristic data is available from the type of coal used at the research location. Second, a specific carbon footprint calculation is carried out, namely the amount of carbon emissions produced per kilogram of processed fish products, using formula 2. This result is used for the efficiency and environmental impact of the fossil energy-based production process.

In addition to greenhouse gas emissions, this study also analyzes the characteristics of coal combustion waste generated from the boiler system. The waste in question includes coal ash (bottom ash and fly ash), which is weighed and analyzed descriptively to identify potential contamination and the possibility of its reuse as a construction material, binder, or adsorbent.

This waste data was collected through direct observation and measurement during the combustion process and after the process was completed.

To ensure the validity of the data, triangulation was carried out by comparing the operational ecosystem of coal use with the results of observations in the field. Validation of the emission factor was carried out by comparing the values used with references from the IPCC, the Ministry of Energy and Mineral Resources (ESDM), or relevant scientific journals. In addition, interviews with field operators, boiler technicians, and production managers were used as a form of cross-validation of the quantitative data obtained.

With this systematic approach and method, it is hoped that the study will be able to provide a comprehensive picture of the magnitude of the carbon footprint generated from the use of coal in the fishery processing industry in Bali, as well as provide appropriate recommendations for emission mitigation efforts and the transition to more environmentally friendly energy.

$$CO_2 Emissions\ (kg) = Coal\ Consumption\ (kg)\ x\ CO_2\ Emissions\ Factor\ (kgCO_2/kg\ of\ coal) \quad 1$$

$$Specific\ Carbon\ Footprint = \frac{Total\ CO_2\ Emissions}{Total\ Processed\ Product\ (kg)} \quad 2$$

RESULTS

Daily Energy Consumption

This study examines greenhouse gas (GHG) emissions resulting from the use of sub-bituminous coal in a boiler system in a fishery product processing industry unit in Bali. Observations were conducted for 17 consecutive days to obtain a representative picture of energy consumption and combustion waste. The data collected included the amount of coal used each day and solid waste in the form of ash from combustion.

The results of the observations showed that daily coal consumption varied between 38,000 kg and 50,500 kg per day. Total consumption for 17 days was recorded at 792,130 kg of coal, with a daily average of 46,654.71 kg/day. Meanwhile, solid waste generated from the combustion process was around 10% of the total fuel used, resulting in a total ash waste of 79,213 kg or around 4,665 kg/day.

Type of Coal and Emission Factor Used

The type of coal used in the production process in this company is sub-bituminous coal, which has the characteristics of medium calorific value and high relative humidity. Based on the Intergovernmental Panel on Climate Change (IPCC) guidelines, the CO_2 emission factor for sub-bituminous coal is 96,100 kg CO_2 per terajoule of energy. With an average calorific value of 18.8 MJ/kg, the factor obtained is the actual emission. This factor is used as a reference in calculating the total carbon dioxide emissions produced from coal combustion activities during 17 days of observation.

$$CO_2\ Emissions\ per\ kg\ of\ coal = \frac{96,100\ x\ 18.8}{1,000,000}) = 1.80668\ kgCO_2/kg$$

Greenhouse Gas Emission Estimation

The calculation results show that during 17 days of production activities, this processing industry produced a total of 1,382,964.3 kg of CO_2 from the combustion of 765,430 kg of sub-bituminous coal. With a total processed product of 347,330 kg, a specific carbon footprint of

3.98 kg CO_2 per kg of product was obtained. This value shows the large contribution of GHG emissions from one production facility in a relatively short time.

This value means that every 1 kg of processed fish product produced from the production process produces almost 4 kg of carbon dioxide released into the atmosphere. This figure is quite high for the fishery processing industry, especially when compared to renewable energy or gas-based processing processes, which can produce a carbon footprint of <2 kg CO_2/kg of product in an efficient system.

This high carbon footprint is due to the full dependence on coal as the main energy source, which is known to have a high carbon emission intensity compared to other fossil fuels such as natural gas. In addition, variations in combustion efficiency and production ratios can also affect the carbon footprint per unit of product.

This specific carbon footprint has a significant impact on the company's environmental hatred and reputation. In the context of global regulations and sustainable industry trends, this value can be the basis for evaluating and justifying the energy transition towards a more efficient and low-carbon system. For example, replacing part of the coal consumption with biomass, biogas or renewable energy sources, optimizing boiler efficiency and utilizing waste heat to increase output per unit of energy.

$$Total\ CO_2\ Emission = 765.430\ x\ 1.80668 = 1{,}382{,}964.3\ kgCO_2$$

$$Specific\ Carbon\ Footprint = \frac{1{,}382{,}964.3}{347{,}330} = 3.98\ kgCO_2\ per\ product$$

The graphical analysis in this study provides a comprehensive overview of the energy performance, carbon emissions, and solid waste generated from coal-based production processes in the fishery processing industry during a 17-day observation period. Figure 1 presents data on the total daily carbon dioxide (CO_2) emissions generated from coal combustion in the boiler industry. The graph shows that the total CO_2 emissions per day fluctuate quite significantly, with the lowest value recorded on the 13th day at 71,725 kg CO_2, while the highest value was recorded on the 10th day at 91,237 kg CO_2. This variation reflects differences in the volume of coal burned each day and indicates that the intensity of carbon emissions is highly dependent on the level of production activity and the efficiency of the combustion process carried out. Furthermore, Figure 2 displays the specific carbon footprint value, namely the amount of CO_2 emissions produced per kilogram of product produced each day. This graph provides a deeper perspective on the efficiency of energy use in producing output. There is a fairly sharp reflection from day to day, where the highest value was recorded on day 9 at 6.49 kg CO_2 per kg of product, while the lowest value was found on day 13 at 2.52 kg CO_2 per kg of product. This shows that although the total emissions on day 9 were not the highest, the low production volume caused the emissions per unit of product to increase drastically. Conversely, on day 13, high production accompanied by relatively low energy consumption resulted in an optimal specific carbon footprint value. This graph illustrates the importance of maintaining consistent production efficiency to control the overall carbon footprint. Figure 3 shows a comparison between coal consumption and daily production output in the form of a double bar graph. This graph shows that energy consumption is not always linear to production results. The most striking example can be seen on day 10, where the amount of coal used reached 50,500 kg but only produced an output of 15,250 kg, indicating a very inefficient energy conversion. On the other hand, the 13th day shows a more ideal condition, namely with coal consumption of 39,700 kg capable of producing an output of 28,508 kg. This analysis helps identify days with the highest and lowest operational efficiency, and provides an important basis for starting equipment performance and operational strategies implemented. Meanwhile, Figure 4 illustrates the relationship between total CO_2 emissions and daily production output in the form of a scatter plot. From the distribution pattern of data points, it can be seen that the relationship between the two variables is not always linear. Several points indicate low production but accompanied by high emissions, indicating energy waste and potential inefficiencies in the combustion system. Conversely, there are also points that show a balance between the amount of emissions and output, indicating better system efficiency. This analysis is important in producing whether increased production is followed by a proportional increase in emissions or actually produces unnecessary emissions because the combustion system is not optimal.

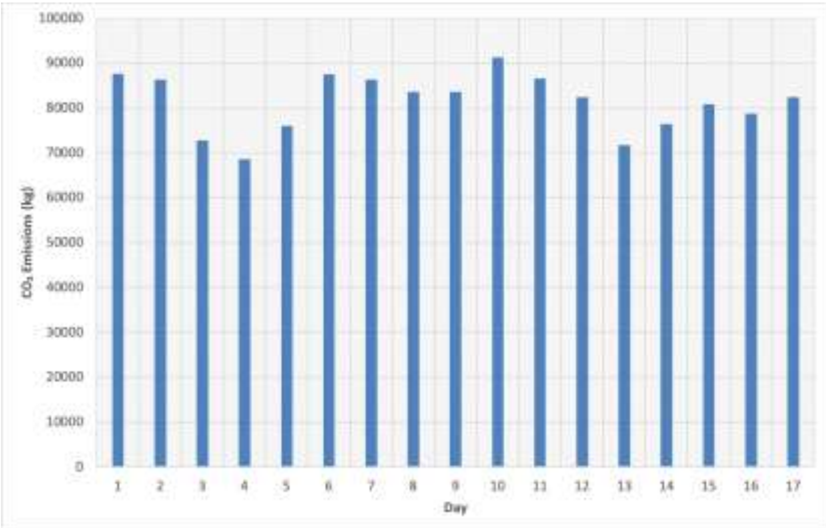

Figure 1. Total CO_2 Emissions per Day

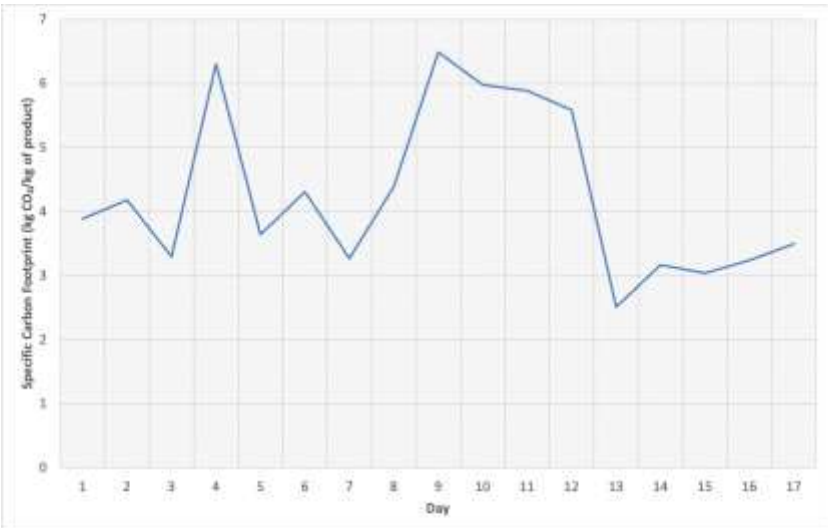

Figure 2. Specific Carbon Footprint per Day

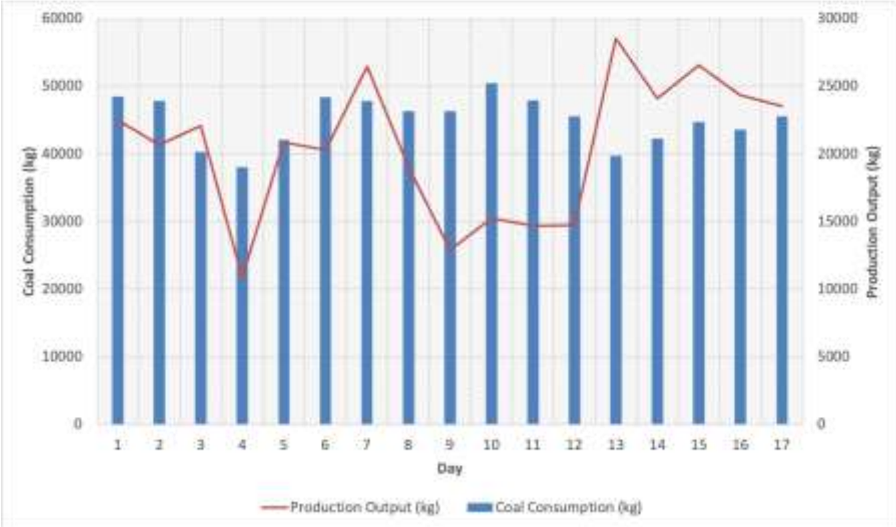

Figure 3. Coal Consumption vs Production Output

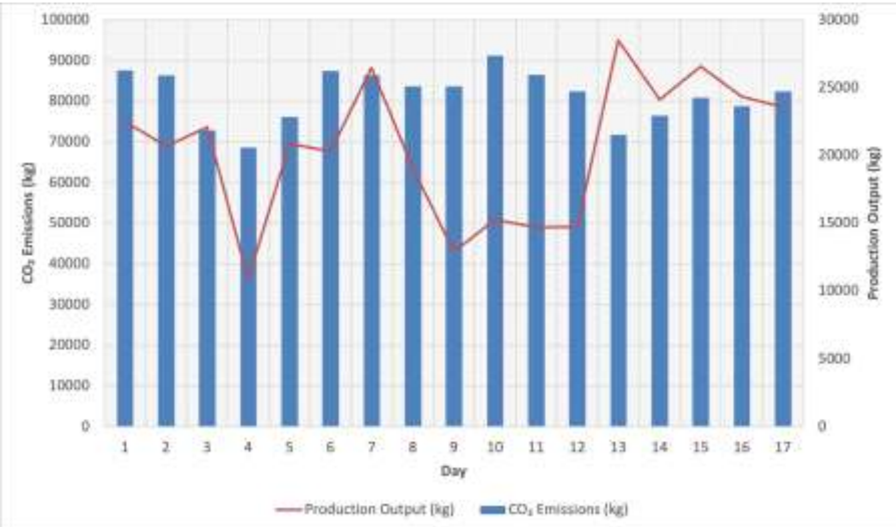

Figure 4. CO_2 Emissions vs Production Output

Combustion Ash Waste

Coal ash waste is a solid residue from the combustion process of fossil fuels, in this case sub-bituminous coal, in the boiler industry. This type of waste is generally divided into two main forms, namely fly ash (fine particles carried by exhaust gas) and bottom ash (coarse residue left at the bottom of the combustion furnace). The ash waste contains a number of inorganic compounds such as silica (SiO_2), alumina (Al_2O_3), and heavy metals such as arsenic, chromium, and mercury in low to moderate concentrations.

During the 17-day observation period, the total coal consumption was recorded at 765,430 kg, and the total solid waste from combustion reached 76,543 kg. This shows that around 10% of the mass of coal burned turns into ash, which is consistent with the general characteristics of sub-bituminous coal which produces solid residues in the range of 8–12%. The daily average ash waste reached 8,505 kg/day, with variations following the daily fuel consumption pattern.

The production of large amounts of ash waste can pose environmental risks if not managed properly. Fly ash, if not effectively captured by emission control devices such as electrostatic precipitators (ESPs) or baghouse filters, can be released into the air and cause particulate air pollution (PM10 and PM2.5) to humans, which has adverse effects on health. Meanwhile, the disposal of bottom ash to open land or rivers can pollute the soil and air, especially if the ash contains heavy dissolved metals. In addition to direct contamination, the accumulation of ash waste also requires a large enough space. If left to pile up without processing or utilization, this ash can cause long-term problems such as damage to environmental aesthetics and potential material landslides.

Figure 5 presents data on the amount of coal ash waste produced each day. Given that ash waste is a direct result of coal combustion, this graph pattern shows a very strong correlation with coal consumption graph. The value of ash waste ranges from 3,800 kg to 5,050 kg per day. Although it looks consistent, broadcasting on the amount of waste should be considered as an indicator of increasing pollution loads and potential environmental risks. This graph is very useful for preparing solid waste management plans, including fly ash utilization strategies for building material industries such as alternative bricks and cement, while supporting a circular economy approach. Meanwhile, Figure 6 contains two important indicators, namely the specific carbon footprint and the amount of coal ash waste, in one graph with two different axes. This graph provides a simultaneous analysis of two forms of environmental impacts: greenhouse gas emissions and solid waste pollution. In several days of observation, it can be seen that the high amount of direct ash waste with an increase in the specific carbon footprint indicates inefficient combustion in terms of both energy and environment. However, there are also several days where the high amount of waste is not in line with the carbon footprint, indicating that operational efficiency is influenced by other factors such as boiler load settings, fuel quality, and production intensity. This graph is important to understand the trade-offs that occur in fossil fuel-based production processes, as well as being a starting point for designing a cleaner and more sustainable production system. Biorefinery from the use of fly and bottom ash can be seen in Table 1. The use of fly ash and bottom ash as alternative raw materials in various applications shows significant potential in supporting sustainable development and more efficient industrial waste management. Fly ash is widely used as a substitute for cement in the manufacture of concrete and geopolymers because of its pozzolanic properties that can increase the strength and durability of concrete, while reducing carbon emissions. In addition, fly ash is also used in soil stabilization and the production of environmentally friendly bricks. Meanwhile, bottom ash is used as a base material for roads, embankments, and covers for final disposal sites (TPA), because its physical and geotechnical properties support these functions. Findings from various studies accompanied by references and source links show that the use of this combustion ash not only reduces the environmental impact of waste accumulation, but also contributes to reducing the use of conventional natural resources. Therefore, the integration of fly ash and bottom ash in technical applications is a strategic step in realizing a circular economy in the construction and infrastructure sector.

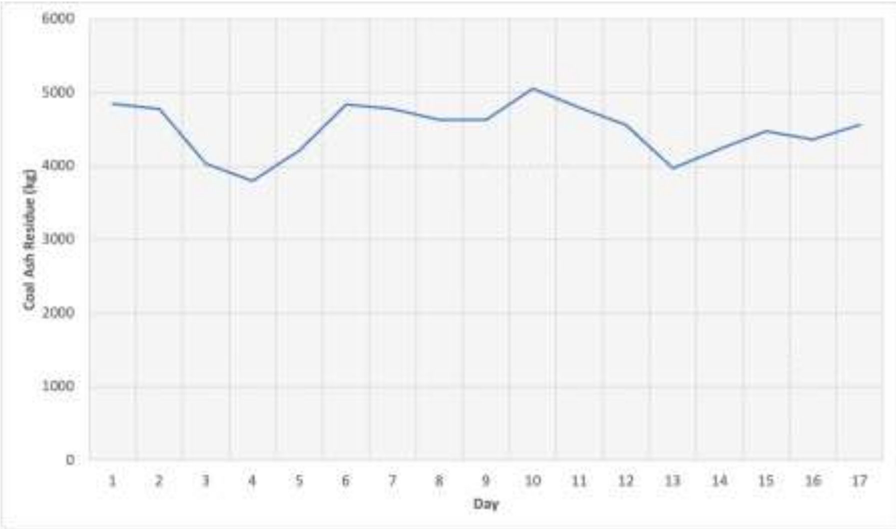

Figure 5. Coal Ash Residue per Day

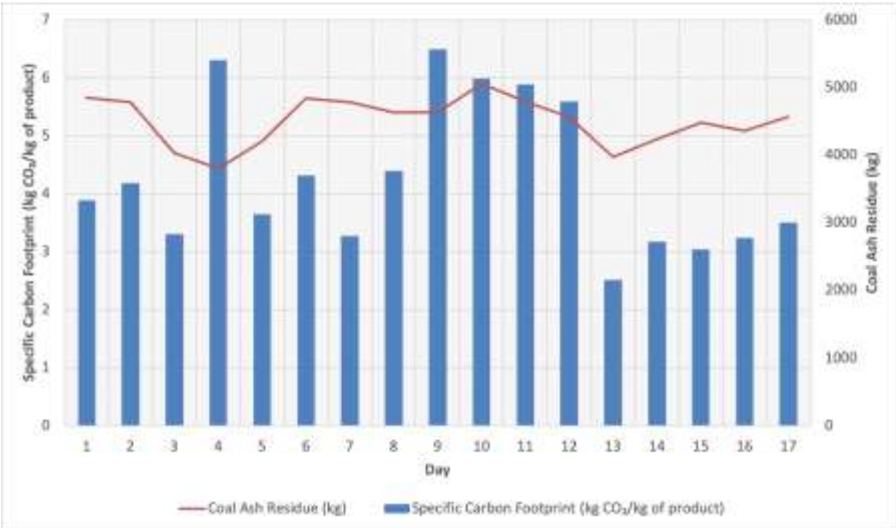

Figure 6. Specific Carbon Footprint vs Coal Ash Residue

DISCUSSION

Carbon Footprint and Solid Waste Evaluation from Coal Use in the Fisheries Processing Industry

The study results show that the use of sub-bituminous coal as the primary energy source in fishery product processing in Bali results in a relatively high carbon footprint. During the 17-day observation period, total carbon dioxide (CO_2) emissions reached 1,382,964.3 kg from the combustion of 765,430 kg of coal. This value equates to a specific carbon footprint of 3.98 kg CO_2 for every kilogram of processed product produced. This figure is relatively high, especially when compared to production systems using low-carbon energy sources such as natural gas or renewable energy, which in efficient systems generally produce emissions below 2 kg CO_2/kg of product. These high emissions reflect the complete dependence on coal as a fuel, which is known to have a high carbon intensity.

Significant fluctuations in coal consumption and daily production output during the observation period indicate variations in combustion efficiency and the effectiveness of the production process. For example, on the 10th day, the volume of coal used reached a peak of 50,500 kg, yet only 15,250 kg of product was produced, indicating highly inefficient energy conversion. Conversely, on the 13th day, with coal consumption of 39,700 kg, the industry was able to produce 28,508 kg of product, demonstrating significantly improved operational efficiency. This underscores the importance of consistent operational management and optimal boiler load management to minimize emissions per unit of product.

Analysis of the specific carbon footprint also shows that low production volumes on certain days, even though emissions do not significantly increase, can lead to an increase in the carbon footprint per kilogram of product. This occurs because combustion continues at high capacity while product output decreases, resulting in disproportionate energy consumption and emissions. In other words, energy efficiency significantly determines the environmental impact of the production process.

In addition to greenhouse gas emissions, this study also highlights the impact of solid waste from coal combustion, namely fly ash and bottom ash. During the research period, coal ash waste reached 76,543 kg, or approximately 10% of the total coal used. This waste contains inorganic compounds such as silica (SiO_2), alumina (Al_2O_3), and heavy metals in low to moderate concentrations, which can pose environmental risks if not managed properly. Fly ash that is not captured by emission control systems can be released into the air and cause particulate matter pollution (PM10 and PM2.5), while bottom ash disposed of in the open environment has the potential to pollute soil and water.

However, the potential use of coal ash waste within a circular economy approach opens up opportunities for environmental impact mitigation. Fly ash can be used as a cement substitute in concrete and geopolymer production, as well as as a soil stabilization material. Bottom ash can be used as a base material for road construction and landfill cover. This utilization not only reduces waste accumulation but also helps reduce conventional natural resource consumption and carbon emissions from the construction industry.

Taking the overall findings into account, it is clear that the coal-based fisheries processing sector contributes significantly to carbon emissions and the potential for solid waste pollution. Therefore, a comprehensive mitigation strategy is needed, ranging from optimizing boiler combustion efficiency and implementing emission control technologies such as electrostatic precipitators (ESPs) and flue gas desulfurization (FGD), to a gradual transition to low-carbon energy sources such as biomass or compressed natural gas (CNG). Furthermore, regular carbon audits, sustainable waste management, and employee training and engagement in environmentally friendly practices are also crucial elements in driving the transformation towards a greener industry.

These mitigation measures will not only reduce immediate environmental impacts but also provide long-term benefits for companies, such as increased energy efficiency, compliance with environmental regulations, and a strengthened reputation with consumers and business partners. With an integrated approach that encompasses technical, managerial, and social aspects, the fisheries processing industry in Bali can begin to move towards a sustainable and globally competitive production system.

Environmental Implications and Mitigation Strategies

The results of the study show that in a relatively short period of time, namely 17 days, this industry has produced more than 1,383 tons of carbon dioxide emissions from the use of coal as the main fuel. This figure reflects a fairly large carbon footprint for one unit of production, and has the potential to increase sharply if calculated on a monthly or annual scale. Thus, the use of coal in the fishery processing industry in Bali has real consequences for the environment, especially regarding its contribution to the acceleration of global climate change.

Therefore, mitigation steps are needed that are not only technical, but also strategic and sustainable. The mitigation strategy must include changes in the energy system, management of the production process, and regular monitoring and reporting of carbon footprints. Overall, the mitigation strategy for the carbon footprint from coal use must be carried out in an integrated manner, covering technical, managerial, and social aspects. This approach not only reduces the burden of carbon emissions, but can also improve the company's reputation, energy efficiency, and presentation to environmental regulations. With commitment and gradual implementation, the industry. Here are some mitigation strategies that can be implemented gradually:

1. Optimizing boiler combustion efficiency
   The first step that can be taken is to increase the efficiency of fuel combustion in the boiler system. Efficiency results in lower consumption of higher coal and produces greater emissions. Optimization efforts can be carried out with routine boiler maintenance, the use of fuel with low air content, and appropriate temperature and pressure settings. For example, installing an automatic control system to maintain optimal temperature and air flow during the combustion process.
2. Use of emission control technology
   The application of emission control devices such as electrostatic precipitators (ESP) or baghouse filters can help reduce the amount of fine particulates and fly ash released into the air. This technology is able to capture solid particles before the gas is released into the atmosphere, so that in addition to reducing air pollution, it can also reduce the impact of GHG indirectly. In addition, technologies such as flue gas desulfurization (FGD) can be used to capture SO_2 and NO_x emissions which also contribute to global warming.
3. Energy substitution towards low-carbon fuels
   The medium to long-term mitigation step is to reduce dependence on coal and switch to low-carbon energy sources such as biomass, compressed natural gas (CNG), or electricity from renewable energy. For example, the use of biomass from agricultural waste such as rice husks, coconut shells, or sawdust can replace some of the coal consumption. In addition to being more environmentally friendly, local biomass can also support the circular economy in the local area.
4. Utilization of coal ash waste (fly ash & bottom ash)
   Instead of disposing of ash waste into the open environment or landfill, companies can apply a waste-to-resource approach. Ash from coal combustion (especially fly ash) can be used as a mixture of cement, paving blocks, bricks, or mine reclamation materials. This not only reduces the potential for pollution, but also creates added value from previously unused waste.
5. Carbon audit and implementation of environmental management systems
   Companies should periodically conduct carbon audits to determine emission trends over time. This audit can be conducted internally or involving an independent third party, as part of the company's environmental responsibility. In addition, the implementation of an environmental management system based on ISO 14001:2015 will help companies in formulating policies, procedures, and real actions to manage environmental impacts comprehensively and systematically.
6. Employee education and training
   One important aspect in mitigating emissions is building employee awareness and competence. Training and socialization programs on energy efficiency, waste management, and environmentally friendly operational practices need to be carried out routinely. For example, training on efficient combustion techniques or handling of ash residue from combustion can improve environmental performance as well as operational efficiency.
7. Cooperation with local government and communities
   Mitigation measures will also be more effective if supported by local government policies and community involvement. Companies can collaborate with environmental agencies,

academics, or environmental NGOs in order to develop community-based emission reduction programs. For example, companies can participate in CSR tree planting programs as a form of measurable and documented carbon offsets.

CONCLUSION

This study shows that the use of sub-bituminous coal as the main energy source in the fishery processing industry produces significant carbon dioxide (CO_2) emissions. During the 17-day operational period, the total coal consumption was recorded at 765,430 kg with total CO_2 emissions reaching 1,382,964.3 kg. This value shows the high contribution of greenhouse gas emissions from one industrial unit in a relatively short time. The average specific carbon footprint calculated at 3.98 kg CO_2 per kg of product indicates that the production process is still classified as carbon intensive and requires increased efficiency.

Analysis of the relationship between energy consumption, production output, CO_2 emissions, and combustion ash waste shows a collapse on several days, where high energy consumption is not matched by comparable production output. This indicates inefficiencies in the combustion system and production management. On the other hand, the coal ash waste produced directly follows the fuel consumption pattern, indicating the potential for environmental pollution that needs to be managed sustainably.

Based on these findings, it is recommended to implement mitigation strategies such as increasing boiler efficiency, gradually switching to low-carbon energy sources, implementing emission control systems, and utilizing ash waste as a secondary raw material. This study provides a strong basis for more sustainable energy and environmental management policies in the fishery processing industry sector.

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