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Reduction of the methane emissions on livestock ships to mitigate greenhouse gas emissions and promote future maritime transport sustainability

Mamdouh ELMALLAH [1*], Mohamed SHOUMAN [1], Mohamed ELGOHARY [2]

[1] Department of Marine Engineering Technology, College of Maritime Transport & Technology, Arab Academy for Science, Technology, and Maritime Transport, Egypt.
[2] Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Egypt.
*E-mail: mamdouhelmallh664@gmail.com; mamduohelmallah@aast.edu

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ABSTRACT: One of the main causes of climate change and global warming is greenhouse gas emissions. Livestock makes up 15% of the world's greenhouse gases (GHG), whereas maritime shipping accounts for 3%. Cattle can produce about 500 grams of methane a day per cow. This study demonstrates that livestock ships are an extremely high source of methane emissions. This study also offers innovative scientific techniques for lowering methane gas emissions from livestock ships, techniques that you, as researchers, scientists, environmentalists, and policymakers, can help implement. The MV Gelbray Express Livestock ship was selected to investigate the overall emissions generated by the main engine and the livestock on board. Main engine CO_2 emissions and livestock CO_2 equivalent emissions are theoretically calculated during 24-hour sailing under engine full load and livestock full capacity. The study revealed that livestock CO_2 equivalent emissions account for 43% of the total CO_2 emissions emitted by the engine and the livestock. ZELP (Zero Emissions Livestock Project) has patented a unique catalytic technique for capturing and neutralizing methane generated during enteric fermentation in ruminant animals such as cows to decrease livestock methane emissions. Theoretical results show that using the ZELP mask reduces CO_2 equivalent emissions by 58 000 kg per day at a livestock capacity of 4000 cattle onboard the MV Gelbray Express Livestock ship.
Keywords: climate change; international maritime organization; Zero Emissions Livestock Project.

Redução das emissões de metano em navios de transporte de gado para mitigar as emissões de gases com efeito de estufa e promover a sustentabilidade marítima transporte futura

RESUMO: Uma das principais causas das mudanças climáticas e do aquecimento global são as emissões de gases de efeito estufa. A pecuária representa 15% dos gases de efeito estufa (GEE) do mundo, enquanto o transporte marítimo é responsável por 3%. O gado pode produzir cerca de 500 gramas de metano por dia por vaca. Este estudo demonstra que os navios de transporte de gado são uma fonte extremamente alta de emissões de metano. Este estudo também oferece técnicas científicas inovadoras para reduzir as emissões de gás metano de navios de transporte de gado, técnicas que você, como pesquisadores, cientistas, ambientalistas e formuladores de políticas, pode ajudar a implementar. O navio de transporte de gado MV Gelbray Express foi selecionado para investigar as emissões gerais geradas pelo motor principal e pelo gado a bordo. As emissões de CO_2 do motor principal e as emissões equivalentes de CO_2 do gado são calculadas teoricamente durante a navegação de 24 horas sob carga total do motor e capacidade total do gado. O estudo revelou que as emissões equivalentes de CO_2 do gado são responsáveis por 43% das emissões totais de CO_2 emitidas pelo motor e pelo gado. O ZELP (Zero Emissions Livestock Project) patenteou uma técnica catalítica exclusiva para capturar e neutralizar o metano gerado durante a fermentação entérica em animais ruminantes, como vacas, para diminuir as emissões de metano do gado. Resultados teóricos mostram que o uso da máscara ZELP reduz as emissões de CO_2 equivalente em 58.000 kg por dia em uma capacidade de gado de 4.000 cabeças de gado a bordo do navio MV Gelbray Express Livestock.
Palavras-chave: mudança climática; organização marítima internacional; Projeto Pecuária Emissão Zero.

1. INTRODUCTION

Nowadays, global climate change is a significant issue. It caused the planet's average yearly temperature to rise gradually, which started with the Industrial Revolution (MIKHAYLOV et al., 2020). The primary source of greenhouse gas (GHG) emissions into the atmosphere is the production and consumption of energy. Global warming and climate change have been dramatically impacted by the rise in emissions caused by the increased usage of fuel-burning energy sources (ELMALLAH et al., 2023). By 2050, the world's temperature is expected to rise by roughly 1.5 degrees Celsius; by 2100, it will rise by 2-4 degrees (MEINSHAUSEN et al., 2009). As a result, international policies and the majority of research have focused on reducing global warming through implementing laws, using innovative technologies, and using clean, renewable energy sources.

Carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NOx), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur oxides (SOx) are the six GHGs listed in the Kyoto Protocol. CO_2, CH_4, and NOx contribute over half of the GHG impact. Between 1990 and 2014, global annual CO_2 emissions rose from 22.15 Gt to 36.14 GT, and CH_4 emissions rose from 6.67 to 8.01 Gt CO_2 equivalent (LIU et al., 2019).

According to climate impact and global warming, CH4 is considered 30 times equivalent to CO_2 (IPCC, 2021). Due to the ongoing growth in emissions and atmospheric concentrations of CH_4, early reduction of CH4 would significantly increase the chances of mitigating global warming (MAR et al., 2022). Approximately 3% of the world's GHG emissions are produced by maritime transport (LINDSTAD et al., 2021).

In 2018, the International Maritime Organization (IMO) adopted the Initial Strategy on reduction of greenhouse gas (GHG) emissions from ships, which commits the IMO to reduce the overall GHG emissions of shipping by at least 50% by the year 2050 (SERRA; FANCELLO, 2020). The IMO controversy focused on mitigating the emissions of CO_2 from the ship's main engine, which is considered the first direct source of emissions. However, other crucial indirect emission sources exist, especially in livestock ships. Livestock produces about 15 percent of the total emissions of greenhouse gases (KRÓLICZEWSKA et al., 2023). Compared to 2010, agricultural CH_4 emissions are expected to rise roughly 30% in 2050. The rising human population and demand for animal protein are the causes of these increases (REISINGER et al., 2021).

Livestock methane emissions are 90% through burps and only 10% through animal manure, resulting from enteric fermentation (BROUČEK, 2014). Domesticated animals, such as cattle, sheep, and goats, naturally produce CH_4 during their physiological digestive processes. A cow emits 500 g of methane emissions daily, which is high, especially for livestock ships carrying more than 4000 cattle. To decrease the negative impacts of methane emissions from the livestock industry, ZELP (Zero Emissions Livestock Project), a startup company in the UK, invented a methane-reduction device and certification system. ZELP has created a patented wearable apparatus that instantly oxidizes methane emissions into carbon dioxide (GROVE; CLOUSE, 2021).

As the IMO is concerned about providing low-emission shipping by implementing many regulations regarding the ship's propulsion system and its energy and operational measures, it is also essential to be concerned about indirect emission sources, especially the emissions caused by livestock ships. This study demonstrates the CO_2 emissions of the main engine and the CH_4 emissions of the livestock onboard the MV Gelbray Express Livestock ship.

The study represents the total CO_2-eq emissions of the main engine and livestock during a 24-hour sailing period under full engine load and full livestock capacity. The study also highlights the significant environmental effects of using the ZELP burp-catching mask.

2. MATERIAL E METHODS

The primary source of air pollution and the greenhouse effect in the maritime industry is the excessive worldwide production of greenhouse gases (mostly carbon dioxide, CO_2, and methane, CH_4), particularly due to the burning of fossil fuels for energy and power generation.

This has ultimately led to several hazards impacting people's daily lives, such as global warming and climate change (JEFFRY et al., 2021). Numerous strategies, such as Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU), reducing the use of fossil fuels, and promoting the use of clean and renewable energy, have been contributed to tackle and conquer the sharp increase in GHG emissions (HUSSIN; AROUA, 2020; ALQARNI et al., 2021).

Maritime transport remains the most economical means of shipping goods around the globe and continues to be the backbone of global trade. More than four-fifths of all trade, by volume, is transported by sea. These days, the use of fossil fuels by maritime vessels is equivalent to around 2.2 million barrels of oil equivalent (MBOE) or over 1000 million tons of carbon dioxide equivalent ($MtCO_2eq$) (SANTOS et al., 2022).

There are several approaches to reducing emissions in the maritime sector; some emphasize using alternative energy, while others emphasize other decarbonization strategies (XING et al., 2020; AL-ENAZI et al., 2021). To reduce GHG in the maritime sector, most studies took into account the ship's propulsion system and looked at the key features of several propulsion systems in terms of fuel consumption and emissions production, while other studies assessed how operational research methods were used in the energy sector (FAZLOLLAHI et al., 2012; FAZLOLLAHI; MARÉCHAL, 2013; HWANGBO et al., 2017; HUAN et al., 2019; SANGAIAH et al., 2019).

The IMO plays a significant role in decreasing GHG emissions caused by shipping. As stated in the IMO Initial Strategy, the organization is committed to lowering greenhouse gas emissions from international shipping and will persist in its efforts to phase them out over the next century. The Initial Strategy aims to mitigate the volume of total annual greenhouse gas emissions from international shipping by at least 50% by 2050, compared to 2008. The IMO recently implemented stricter controls on international maritime transport activities.

To reduce greenhouse gas (GHG) emissions, the IMO has started to implement obligatory measures such as the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP), the Energy Efficiency Operational Indicator (EEOI), and the Energy Efficiency Existing Ship Index (EEXI). Enhancing energy efficiency, lowering the Carbon Intensity (CI) of new ships, enhancing the Energy Efficiency Design Index (EEDI), and improving the Energy Efficiency Operation Index (EEOI) are the major methods used to accomplish the goals (REHMATULLA et al., 2017; JOUNG et al., 2020).

In their implementations, the IMO primarily focuses on lowering GHG emissions from the primary engine; however, other parameters also significantly impact the environment. Livestock ships have a magnificent source of CH_4 that needs to be considered. Cattle are considered a major source of global methane emissions. Figure 1 shows the sources of global human-induced methane emissions. The agriculture source represents 40%,33% of livestock and 27% of rice cultivation (MUNDRA; LOCKLEY, 2023).

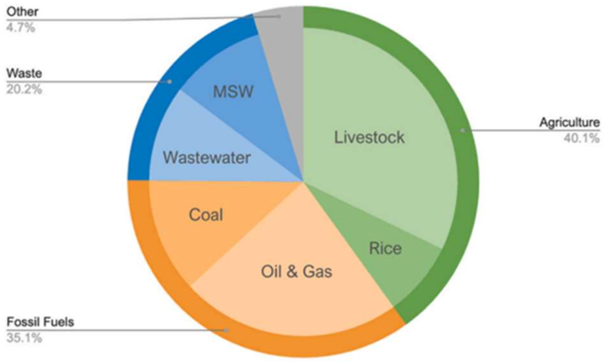

Figure 1. Sources of global human-induced methane emissions.
Figura 1. Fontes de emissões globais de metano induzidas pelo homem.

To encourage the transition towards a sustainable maritime transport sector, Policymakers should start to pay more attention to the harmful environmental impact of cattle emissions onboard livestock ships. Growing methane levels cause stratospheric water vapor to rise, lowering the ozone layer. This is because stratospheric water vapor causes polar stratospheric clouds and hydrogen oxide radicals (HOx), accelerating ozone depletion (REVELL et al., 2016; MUNDRA; LOCKLEY, 2023).

Microbiological digestion in the rumen emits 90% of livestock methane emissions through breathing (Burping) (THORPE, 2008; KUMARI et al., 2016; CHOW et al., 2020; MUNDRA; LOCKLEY, 2023;). ZELP mask is a novel strategy to decrease the environmental impact of livestock methane. Produced by ZELP™, this wearable device is utilized to identify, capture, and catalytically oxidize methane (MUNDRA; LOCKLEY, 2023). An adjustable harness covers the cow's head, and the mask initiates the oxidation process by detecting burps through sensors.

This study provides a new method to decrease the methane emissions on livestock ships since the methane environmental impact is 30 times greater than the CO_2 impact. Encouraging livestock ships to require mask-wearing among their cows will reduce the impact of methane by 30 times since the burp-catching masks will convert methane to carbon dioxide. Figure two shows the design of the mask.

Figure 2. Design of the ZELP burp-catching mask.
Figura 2. Design da máscara anti-arrotos ZELP.

In this study, the MV Gelbray Express Livestock ship is selected to study the total emissions generated by the main engine and the cattle onboard. MV Gelbray Express is the third livestock carrier built by Cosco Guangdong Shipyard, based in China. Vroon Offshore Services, a Dutch company, contracted with Cosco Guangdong Shipyard to build six livestock ships at an estimated cost of $28.25 million in 2011. With five decks and a total gross pen area of around 4,500 m², the vessel can accommodate about 4,000 cattle weighing 350 kg each. Around 495 m² of deck area can hold up to 1,200 m³ of feed. Table 1 shows the generalship particulars.

Table 1. Ship particulars MV Gelbray Express carrier.
Tabela 1. Dados do navio transportador MV Gelbray Express.

GENERAL	
Year built	2014
Builder	Cosco Guangdong, China
Flag	Portugal
IMO	9621211
PRINCIPAL DIMENSIONS	
Length Overall (LOA)	134.80 m
Beam Moulded	19.60 m
Depth	14.80 m
Summer Draft	6.80 m
MACHINERY & PROPULSION	
Main Engine	6090 kW Wartsila W7X35
Service speed Auxiliary Engines	16.75 knots
Auxiliary Engines	3 x 1100 kW
Shaft Generator	1050 kW
Bow Thruster	750 kW
TONNAGES	
Dead Weight Tonnage (DWT)	5225 t
Scantling Draft	6.8 m
Design Draft	5.8 m
Gross Tonnage	10421 t
Net Tonnage	3126 t
CARGO CAPACITIES & EQUIPMENT	
Total Gross Pem Area	4511 m²
Number of Decks	5
Deck Space Fodder	495 m²
Fodder (Silo)	1200 m³

MV Gelbray Express is propelled by 6090 kW of power produced by Wärtsilä X35 engines. The smallest low-speed engine in Wärtsilä's lineup is the Wärtsilä X35. It is a low-speed, electronically controlled two-stroke marine engine that is among the most efficient in its class. Compact engine size, straightforward engine operation, and the ability to power ships with shallow draft requirements were the key goals in the design of the Wärtsilä X35. The engine's power output ranges from 3,475 to 6,960 kW, with a cylinder arrangement of 5-8 cylinders. The specific fuel consumption (SFC) of the engine is 170 g/kWh. Table 2 shows the main engine characteristics of MV Gelbray Express.

Table 2. The characteristics of the main engine.
Tabela 2. Características do motor principal.

Wärtsilä X35	
Cylinder bore	350 mm
Piston stroke	1550 mm
Speed	142–167 rpm
Mean effective pressure	21.0 bar
Stroke/bore	4.43
Number of cylinders	7
Rated power	6090 kW at 167 rpm
Weight in tonnes	95

553

To show the results of the CO_2-eq emissions, the engine and cattle emissions during a 24-hour sailing under engine full load and livestock full capacity will be calculated. Equation 1 can determine the total emission for ships during a single voyage (AMMAR; SEDDIEK, 2020).

$$EM_{trip,i,f} = \sum\left[t\left(P_w . L_f . P_{f,i}\right)\right] \quad (01)$$

where: EM is the total ship emission, t is the operation trip time in (hours), P_w is the main engine power in (kW), L_f is the load factor, $P_{f,i}$ fuel pollution factor in (g/kWh), i is the type of emission, and f the type of fuel.

Equation 2 determines the fuel carbon content (ELKAFAS et al., 2020). The fuel's carbon content is the primary factor used to determine its pollution factor for CO_2 emissions.

$$P_{CO_2} = SFC . CF \quad (02)$$

where: CF is the conversation factor, and SFC is the specific fuel consumption (g/kwh).

Equation 3 shows the CO_2 emission for the main engine.

$$ME\ CO_2\ emissions = \left\{\sum_{i=1}^{nME} P_{ME(i)} . C_{FME(i)} . SFC_{ME(i)}\right\} \quad (03)$$

where: P_{ME} is the Power output from main engine. C_{FME} is the fuel conversation factor from fuel consumption to CO_2 emission. . SFC_{ME} is the specific fuel consumption for main engines.

Equation 4 shows the total methane emission per livestock capacity.

$$E_{CH4} = M_{CH4} . N_{cattle} \quad (04)$$

The total amount of cattle methane emission is calculated by multiplying the mass of CH_4 emitted by each cow with the total number of cows. Where E_{CH4} is the total CH4 cattle emissionM_{CH4}, the mass of CH_4 emitted per cow, and N_{cattle} is the total number of cows.

A carbon dioxide equivalent (CO_2-e) is a metric measure used to convert amounts of other gases to an equivalent amount of carbon dioxide with the same Global Warming Potential (GWP) to compare emissions from different greenhouse gases based on their GWP. Million Metric Tons of Carbon Dioxide Equivalent (MMTCDE) is the standard way to represent carbon dioxide equivalents. Equation 5 shows the CO_2-e of CH_4 gas.

$$MMTCDE_{CH4} = MMT_{CH4} . GWP_{ch4} \quad (05)$$

The carbon dioxide equivalent of methane is calculated by multiplying its tons by the corresponding GWP. Where $MMTCDE_{CH4}$ is the million metric tonnes of carbon dioxide equivalents, MMT_{CH4} is the million metric tonnes of CH_4, and GWP_{ch4} is the global warming potential of CH_4.

3. RESULTS

Figure 3 shows the CO2 emission of the main engine. Figure 4 represents the amount of livestock methane emissions. The maximum CH_4 emissions is about 2000 kg per day at a livestock capacity of 4000 cattle.

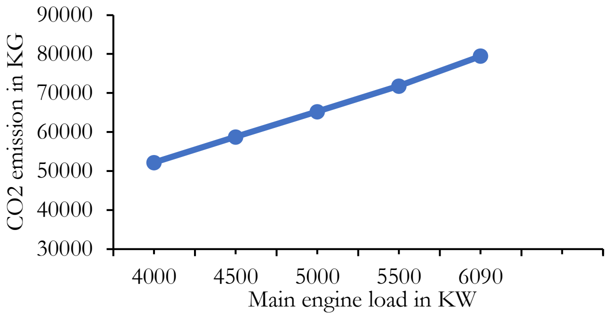

Figure 3. CO_2 emission of the main engine.
Figura 3. Emissão de CO_2 do motor principal.

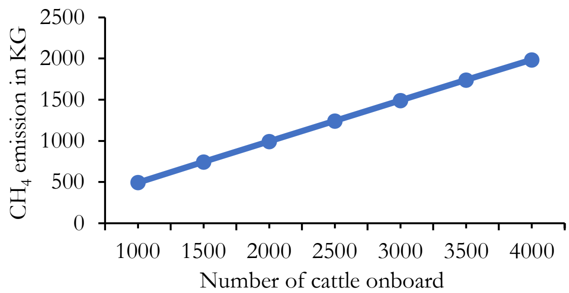

Figure 4. Methane emissions from cattle.
Figura 4. Emissões de metano do gado.

Figure 5 shows the CO_2-eq emissions generated by livestock onboard. The CO_2-eq at full capacity of livestock is about 60000 kg, which is about 75% of the engine's maximum CO_2 emissions. These results indicate the high danger of livestock emissions since they are as high as the CO_2 emissions of the main engine.

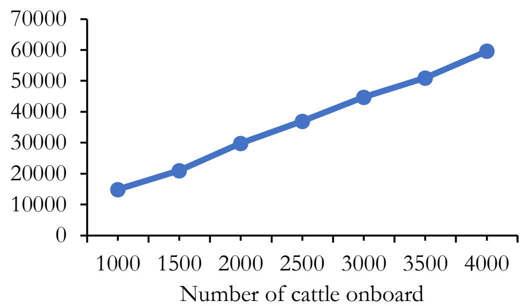

Figure 5. CO_2-eq emissions of cattle.
Figura 5. Emissões de CO_2 equivalente do gado.

Figure 6 shows a comparison between CO_2 engine emissions and CO_2-eq livestock emissions. These emissions are calculated at full livestock capacity and a different engine's load. The environmental impacts of livestock emissions are just as hazardous as those from engine emissions.

Figure 7 shows the total CO_2-eq emissions of the engine and cattle together. The cattle CO_2-eq emissions are 43% of the total emissions. The maximum CO_2-eq engine emissions are about 80000 kg per day, and the maximum CO_2-eq livestock emissions are about 60000 kg per day.

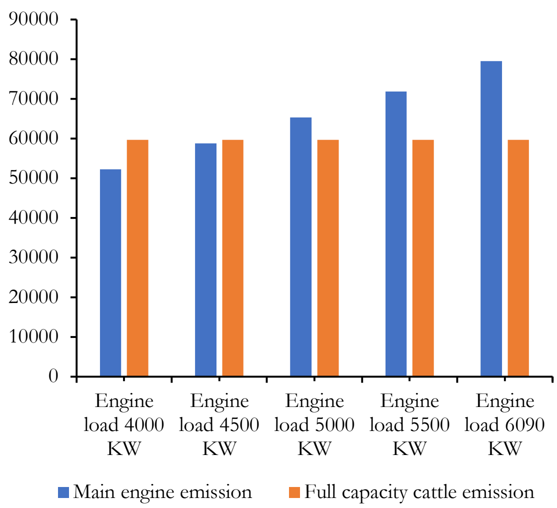

Figure 6. CO_2-eq emissions from engines and cattle.
Figura 6. Emissões de CO_2 equivalente do motor e do gado.

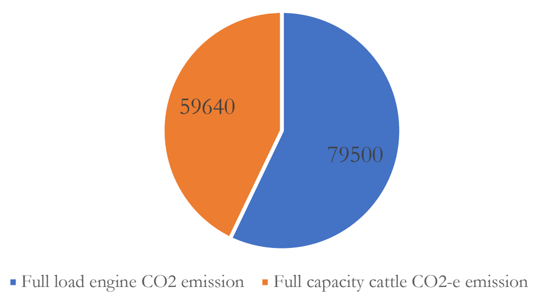

Figure 7. Total CO_2-eq emission (in kg) during 24 hours of sailing at full livestock capacity and full engine load.
Figura 7. Emissão total de CO_2 equivalente (em kg) durante 24 horas de navegação com capacidade máxima de gado e carga máxima do motor.

Figure 8 shows the CO_2-eq of livestock methane emissions using the ZELP burp-catching mask. The findings demonstrate the huge reduction of cattle methane CO_2-eq emissions during the use of the ZELP mask. The maximum CO_2-eq of cattle methane emissions without using the ZELP mask is about 60000 kg per day, while the maximum CO_2-eq of cattle methane emissions while using the ZELP mask is about 2000 kg per day. The ZELP mask enhanced the reduction of CO_2-eq emissions by 58000 kg. These findings prove the importance of this novel innovation and the development and application of this technology as a mandatory regulation for these ships.

Figure 9 shows the total CO_2-eq emissions of the engine and the cattle using the ZELP mask. The results are calculated after 24 hours of sailing under the engine's full load and the livestock's full capacity while using the ZELP mask, illuminating the huge reduction in CO_2-eq livestock emissions.

Figure 10 shows the total CO_2-eq emissions of the engine and cattle together. The cattle CO_2-eq emissions during using ZELP are 2.4% of the total emissions. Figure 11 shows the livestock CO_2-eq emissions with and without the ZELP mask.

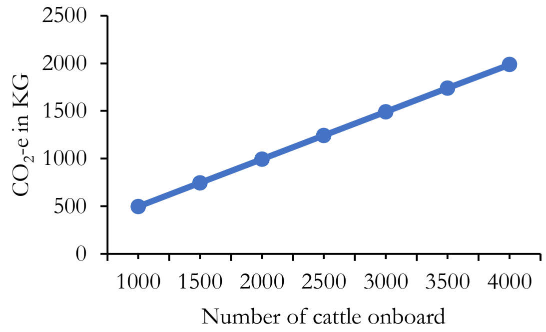

Figure 8. CO2-eq of livestock methane emissions during the use of the ZELP.
Figura 8. Emissões de CO2-eq de metano do gado durante o uso do ZELP.

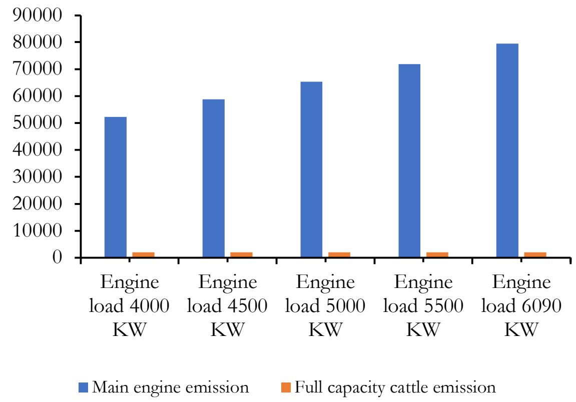

Figure 9. CO_2-eq emissions of the engine and the cattle during the use of the ZELP mask.
Figura 9. Emissões de CO_2-eq do motor e do gado durante o uso da máscara ZELP.

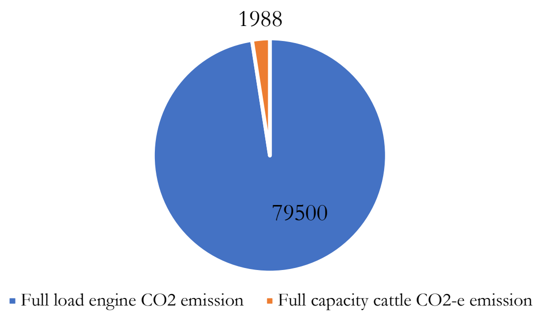

Figure 10. Total CO2-e emission in KG during 24 hours of sailing at full livestock capacity and full engine load using ZELP mask.
Figura 10. Emissão total de CO2-e em KG durante 24 horas de navegação com capacidade máxima de gado e carga máxima do motor usando máscara ZELP.

4. DISCUSSION

This study compares cattle methane emissions and main engine emissions and highlights the high amount of cattle methane emissions on livestock ships. It also highlights the positive environmental impact of using the ZELP burp-catching mask to reduce methane emissions on livestock ships and the importance of developing and considering this novel strategy in maritime transport regulations. The results show a high percentage of livestock emissions among the total emissions caused by the main engine and the livestock onboard the MV Gelbray Express.

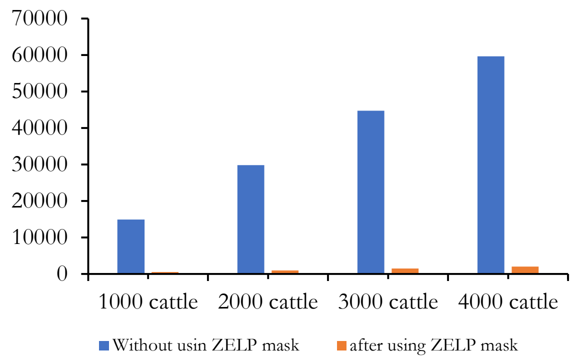

Figure 11. Livestock CO_2-eq emissions with and without the ZELP mask.
Figura 11. Emissões de CO_2 equivalente da pecuária com e sem a máscara ZELP.

The results demonstrate the role of ZELP masks in reducing livestock CO_2-eq emissions. Figure three shows the main engine's CO_2 emissions. The highest amount of CO_2 can be reached during sailing at an engine load of 6090 kW. The results show that the engine CO_2 emissions are about 80000 kg at engine load 6090 kW and about 52224 kg at engine load 4000 kW. Table three clarifies the results of the theoretical CO_2-eq calculations per 24 hours of sailing under engine full load and livestock full capacity.

Table 3. Theoretical results of CO_2-eq emissions without the use of ZELP mask.
Tabela 3. Resultados teóricos das emissões de CO_2-eq sem o uso da máscara ZELP.

Engine full load	6090 KW
Cattle capacity	4000 Cattle
Main engine CO_2 emission	79500 Kg
Cattle CO_2-e emission without the use of ZELP	59640 Kg
Cattle emissions as a percentage of the total emissions of CO_2-eq	43%

Table 4 demonstrates the results of the theoretical CO_2-eq calculations per 24 hours of sailing under engine full load and livestock full capacity while using the ZELP mask.

Table 4. Theoretical results of CO_2-eq emissions during the use of ZELP mask.
Tabela 4. Resultados teóricos das emissões de CO_2-eq durante o uso da máscara ZELP.

Engine full load	6090 KW
Cattle capacity	4000 Cattle
Main engine CO_2 emission	79500 Kg
Cattle CO_2-e emission without the use of ZELP	1988 Kg
Cattle emissions as a percentage of the total emissions of CO_2-eq	2.4%

5. CONCLUSIONS

The world is presently making scientific, political, and environmental contributions towards mitigating climate change and global warming. Climate change and global warming are triggered by releasing GHG emissions into the atmosphere. Reducing methane emissions could achieve the 1.5°C global warming target outlined in the Paris Agreement.

The IMO is working hard to develop legislation and plans that contribute to lowering emissions in the maritime sector, slowing down the predicted rise in emissions. The livestock vessel is one of the most popular vessels employed in maritime transportation.

This study aimed to determine the emissions rate from the main engine and the livestock on board the MV Gelbray Express Livestock ship during the 24-hour sailing period. The analysis demonstrates that livestock CO_2-eq emissions are higher than 60,000 kg per day at a capacity of 4000 cattle.

The results emphasize that the main engine's CO2-eq emissions are about 80.000 kg during a 24-hour sailing period at full engine load. According to the study, livestock emissions are massive and practically as hazardous as engine emissions. The ZELP mask reduced CO_2-eq emissions by 58,000 kg.

These results highlight the significance of this innovative innovation and the need to develop and implement this technology as a mandatory policy for these sorts of ships. These theoretical results illuminate the importance of cooperation between policymakers and ZELP to provide maritime sustainability by decreasing the impact of emissions on livestock ships.

6. REFERENCES

ELKAFAS, A. G.; ELGOHARY, M. M.; SHOUMAN, M. R. Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ships. **Environmental Science and Pollution Research**, v. 28, p. 15210-15222, 2021. https://doi.org/10.1007/s11356-020-11639-6.

AL-ENAZI, A.; OKONKWO, E. C.; BIÇER, Y.; AL-ANSARI, T. A review of cleaner alternative fuels for maritime transportation. **Energy Reports**, v. 7, p. 1962-1985, 2021. https://doi.org/10.1016/j.egyr.2021.03.036

ALQARNI, D. S.; LEE, C. W.; KNOWLES, G. P.; VOGT, C.; MARSHALL, M.; GENGENBACH, T. R.; CHAFFEE, A. L. Ru-zirconia catalyst derived from MIL140C for carbon dioxide conversion to methane. **Catalysis Today**, v. 371, p. 120-133, 2021. https://doi.org/10.1016/j.cattod.2020.07.080

AMMAR, N. R.; SEDDIEK, I. S. Enhancing energy efficiency for new generations of containerized shipping. **Ocean Engineering**, v. 215, e107887, 2020. https://doi.org/10.1016/j.oceaneng.2020.107887

BROUČEK, J. Production of Methane Emissions from Ruminant Husbandry: A Review. **Journal of Environmental Protection**, v. 5, n. 15, p. 1482-1493, 2014. https://doi.org/10.4236/jep.2014.515141

CHOW, W. L.; CHONG, S.; LIM, J. W.; CHAN, Y. J.; CHONG, M. F.; TIONG, T. J.; CHIN, J. K.; PAN, G. T. Anaerobic Co-Digestion of Wastewater sludge: A review of potential Co-Substrates and operating factors for improved methane yield. **Processes**, v. 8, n. 1, e39, 2020. https://doi.org/10.3390/pr8010039

ELMALLAH, M.; ELGOHARY, M. M.; SHOUMAN, M. R. The effect of air chamber geometrical design for enhancing the output power of oscillating water column wave energy converter. **Marine Technology Society Journal**, v. 57, n. 1, p. 122-129, 2023. https://doi.org/10.4031/mtsj.57.1.14

FAZLOLLAHI, S.; MARÉCHAL, F. Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP). **Applied Thermal Engineering**, v. 50, n. 2, p. 1504-1513, 2013. https://doi.org/10.1016/j.applthermaleng.2011.11.035

FAZLOLLAHI, S.; MANDEL, P.; BECKER, G.; MARÉCHAL, F. Methods for multi-objective investment and operating optimization of complex energy systems. **Energy**, v. 45, n. 1, p. 12-22, 2012. https://doi.org/10.1016/j.energy.2012.02.046

GROVE, H.; CLOUSE, M. Zero net emissions goals: Challenges for boards. Corporate Board: **Role, Duties & Composition**, v. 17, n. 2, p. 54-69, 2021. https://doi.org/10.22495/cbv17i2art5

HUAN, T.; FAN, H.; LEI, W.; GUO-QIANG, Z. Options and evaluations on propulsion systems of LNG carriers. In: **Propulsion Systems**. IntechOpen eBooks, 2019. https://doi.org/10.5772/intechopen.82154

HUSSIN, F.; AROUA, M. K. Recent trends in the development of adsorption technologies for carbon dioxide capture: A brief literature and patent reviews (2014-2018). **Journal of Cleaner Production**, v. 253, e119707, 2020. https://doi.org/10.1016/j.jclepro.2019.119707

HWANGBO, S.; LEE, I.; HAN, J. Mathematical model to optimize design of integrated utility supply network and future global hydrogen supply network under demand uncertainty. **Applied Energy**, v. 195, p. 257-267, 2017. https://doi.org/10.1016/j.apenergy.2017.03.041

IPCC: **Climate Change 2021**: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2021.

JEFFRY, L.; ONG, M. Y.; NOMANBHAY, S.; MOFIJUR, M.; MUBASHIR, M.; SHOW, P. L. Greenhouse gases utilization: A review. **Fuel**, v. 301, e121017, 2021. https://doi.org/10.1016/j.fuel.2021.121017

JOUNG, T.; KANG, S.; LEE, J.; AHN, J. The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. **Journal of International Maritime Safety, Environmental Affairs, and Shipping**, v. 4, n. 1, p. 1-7, 2020. https://doi.org/10.1080/25725084.2019.1707938

KRÓLICZEWSKA, B., PECKA-KIEŁB, E.; BUJOK, J. Strategies Used to Reduce Methane Emissions from Ruminants: Controversies and Issues. **Agriculture**, v. 13, n. 3, e602, 2023. https://doi.org/10.3390/agriculture13030602

KUMARI, S.; DAHIYA, R.; NAIK, S.; HILOIDHARI, M.; THAKUR, I. S.; SHARAWAT, I.; KUMARI, N. Projection of methane emissions from livestock through enteric fermentation: A case study from India. **Environmental Development**, v. 20, p. 31-44, 2016. https://doi.org/10.1016/j.envdev.2016.08.001

LINDSTAD, E.; LAGEMANN, B.; RIALLAND, A.; GAMLEM, G. M.; VALLAND, A. Reduction of maritime GHG emissions and the potential role of E-fuels. **Transportation Research Part D: Transport and Environment**, v. 101, e103075, 2021. https://doi.org/10.1016/j.trd.2021.103075

LIU, D.; GUO, X.; XIAO, B. What causes growth of global greenhouse gas emissions? Evidence from 40 countries. **Science of the Total Environment**, v. 661, p. 750-766, 2019. https://doi.org/10.1016/j.scitotenv.2019.01.197

MAR, K. A.; UNGER, C.; WALDERDORFF, L.; BUTLER, T. Beyond CO2 equivalence: The impacts of methane on climate, ecosystems, and health. **Environmental Science & Policy**, v. 134, p. 127-136, 2022. https://doi.org/10.1016/j.envsci.2022.03.027

MEINSHAUSEN, M.; MEINSHAUSEN, N.; HARE, B.; RAPER, S. C. B.; FRIELER, K.; KNUTTI, R.; FRAME, D. J.; ALLEN, M. Greenhouse gas emission targets for limiting global warming to 2 °C. **Nature**, v. 458, n. 7242, p. 1158-1162, 2009. https://doi.org/10.1038/nature08017.

MIKHAYLOV, A.; MOISEEV, N.; АЛЕШИН, К. А.; BURKHARDT, T. Global climate change and greenhouse effect. **Entrepreneurship and Sustainability Issues**, v. 7, n. 4, p. 2897-2913, 2020. https://doi.org/10.9770/jesi.2020.7.4(21

MUNDRA, I.; LOCKLEY, A. (2023). Emergent methane mitigation and removal approaches: A review. **Atmospheric Environment**, v. X, e100223, 2023. https://doi.org/10.1016/j.aeaoa.2023.100223

REHMATULLA, N., CALLEYA, J.; SMITH, T. The implementation of technical energy efficiency and CO_2 emission reduction measures in shipping. **Ocean Engineering**, v. 139, p. 184-197, 2017. https://doi.org/10.1016/j.oceaneng.2017.04.029

REISINGER, A.; CLARK, H.; COWIE, A.; EMMET-BOOTH, J.; FISCHER, C. G.; HERRERO, M.; HOWDEN, M.; LEAHY, S. C. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? **Philosophical Transactions of the Royal Society A**, v. 379, n. 2210, e20200452, 2021. https://doi.org/10.1098/rsta.2020.0452

REVELL, L. E.; STENKE, A.; ROZANOV, E.; BALL, W. T.; LOSSOW, S.; PETER, T. The role of methane in projections of 21st century stratospheric water vapour. **Atmospheric Chemistry and Physics**, v. 16, n. 20, p. 13067-13080, 2016. https://doi.org/10.5194/acp-16-13067-2016

SANGAIAH, A. K.; TIRKOLAEE, E. B.; GOLI, A.; DEHNAVI-ARANI, S. Robust optimization and mixed-integer linear programming model for LNG supply chain planning problem. **Soft Computing**, v. 24, n. 11, p. 7885-7905, 2019. https://doi.org/10.1007/s00500-019-04010-6

SANTOS, V. A. D.; SILVA, P. P. da; SERRANO, L. The maritime sector and its problematic decarbonization: A Systematic review of the contribution of alternative fuels. **Energies**, v. 15, n. 10, e3571, 2022. https://doi.org/10.3390/en15103571

SERRA, P.; FANCELLO, G. Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping. **Sustainability**, v. 12, n. 8, e3220, 2020. https://doi.org/10.3390/su12083220

THORPE, A. Enteric fermentation and ruminant eructation: the role (and control?) of methane in the climate change debate. **Climatic Change**, v. 93, n. 3-4, p. 407-431, 2008. https://doi.org/10.1007/s10584-008-9506-x

XING, H.; SPENCE, S.; CHEN, H. A comprehensive review on countermeasures for CO_2 emissions from ships. **Renewable & Sustainable Energy Reviews**, v. 134, e110222, 2020. https://doi.org/10.1016/j.rser.2020.110222

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