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Environmental Impact Assessment of Anti-Corrosion Coating Life Cycle Processes for Marine Applications

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Abstract: In the present study, the life cycle assessment (LCA) of uncoated steel and alkyd-coated steel (using the sol–gel method) systems subjected to the marine atmosphere is performed to examine their environmental impacts. The LCA findings demonstrate a notable 46% reduction in the overall environmental impact of the coated system compared to the uncoated system. The findings of the sensitivity analysis indicate that a decreased mean time between repair and maintenance, along with an augmented quantity of coating, results in adverse environmental consequences. Furthermore, the LCA outcomes highlight the significant environmental impacts associated with 3-glycidyloxypropyltrimethoxysilane and n-propanol within the coated system. Hence, there is a need for the development of commercial coatings with bio-based products to develop a greener solution.

Keywords: life cycle assessment; anti-corrosion; sol–gel coating; marine atmosphere; environmental impact

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1. Introduction

Carbon steel is used as a structural material for ships since it possesses superior properties, such as high strength, toughness, machinability, and low cost. However, due to its ferrous (Fe) content, it has poor corrosion resistance. Steel corrosion weakens the structural integrity over time and eventually leads to its failure [1]. The estimated costs to overcome the issues related to steel corrosion in countries like Japan and the USA correspond to 4% of their gross domestic product (GDP) [2]. Several researchers reported the use of different protective coatings to improve the life span of offshore steel structures [3–5]. From the past few decades, aluminum (Al)-based coatings have been used to prevent steel from corrosion since they are economical, non-toxic, and have cathodic electrochemical protection [6–8]. However, the usage of Al coating has limitations under highly humid environments and extreme temperature fluctuations, as it exhibits a high rate of corrosion under such circumstances. Recently, superhydrophobic coatings (SHC) have attracted the attention of engineers and scientists due to their superior properties [9–11]. The higher water contact angles (WCA > 150°) make SHCs an excellent water repellent. This inherent property supports them to employ in various applications such as anti-icing [12], anti-corrosion [13,14], self-cleaning [15,16], anti-splashing [17], and drag reduction [18].

The ship structure comprises a pre-treated steel substrate, a primer over the substrate, and a topcoat over the primer [19]. Generally, the substrate is pre-treated to clean the contaminants from the surface and improve the adhesion of the coating. The primer helps to protect the water permeation and serves as a carrier of various species, like cathodic protectors, anodic passivation, or inhibitors employed with specific functions. Conventionally, epoxy and silica-based primers with Zn powder as a pigment were employed in marine environments. Additionally, to protect the primer from accidental scratching and UV irradiation, an epoxy, alkyd, or vinyl film topcoat is generally applied [20]. Silane-based organic–inorganic hybrid coatings (alone or in combination with TiO_2, ZrO_2, Al_2O_3,

CeO_2, and Fe_2O_3 nanoparticles) demonstrated excellent corrosion protection in an aqueous environment [21]. Metal–organic frameworks (MOFs) have great potential to be used as a functional additive in polymer-based coatings. MOFs exhibit a tailorable structure of metal ions and organic linkers. MOFs possess a large loading capacity of corrosion inhibitors, which assist in mitigating the rate of corrosion. Due to these advantages, MOFs-polymer-based coating gained importance for steel corrosion protection [22].

The use of palm stearin in the synthesis of alkyd resins results in a more environmentally friendly and economical production process, reducing energy consumption and chemical pollution. This method supports sustainable practices by conserving natural resources and minimizing harmful emissions compared to traditional solvent-based methods [23]. The synthesis of Hydroxy Urethane modified alkyd resins from renewable resources offers a greener and less toxic method to enhance chemical resistance, thus promoting environmentally friendly coating solutions. This innovation improves the alkali resistance of alkyd resins while maintaining key film properties, contributing to more sustainable production practices [24]. Alkyd paint contains less volatile organic compounds (VOCs) and uses fewer toxic solvents, making it a more sustainable and environmentally friendly alternative. The alkyd paint exhibits superior mechanical and thermal properties comparable to conventional paints [25]. Alkyd coatings possess good adhesion, corrosion resistance, flexibility, and durability. The selection of the resin is based on various factors such as performance (water resistance, chemical resistance, resistance to ultraviolet radiation, etc.), processing requirements (substrate material, substrate surface conditions, coating material, etc.), chemical characteristics (of pigments, solvents, additives, etc.), method of application (dipping, spray coating, etc.), and economic feasibility [26]. Laco et al. [27] reported that modified alkyd resin, with the addition of a low volume of polyaniline, improved corrosion resistance compared to thermoplastic polymers. This improvement was attributed to the conductive ability of polyaniline. To integrate the experimental findings, Kowalski et al. [28] performed the life cycle cost (LCC) analysis of the steel barrier structure installed on a bridge coated with various corrosion protection coatings, such as hot dip galvanizing, a three-layer paint coating, and a double-layer coating consisting of zinc. Their study outlines that the metallic coating produced using hot dip galvanizing provides financial benefits in the long term. Ingham [29] carried out an life cycle assessment (LCA) for different coating systems, which includes a new marine coating product (XGIT-Fuel, manufactured by Graphite Innovation and Technologies, Halifax, NS, Canada), cuprous-oxide-based anti-fouling coating (BRA640), and poly(dimethyl siloxane)-based anti-fouling coating (INT1100SR). This study revealed that the BRA640 system has the most prominent environmental impact due to the significant shipping emissions in the service phase and the release of cuprous oxide into the marine environment. Alkyd coatings, known for their good adhesion and durability, offer significant anti-corrosion performance by forming a protective barrier that prevents chloride-induced corrosion on metal surfaces, making them a cost-effective option for transportation agencies [30]. Guo et al. [31] demonstrated that despite the accelerated failure process under cathodic polarization, alkyd coatings exhibited notable durability, showing resilience, and maintaining a significant level of protection in both static and flowing seawater conditions over extended immersion periods. In another study, Seddik et al. [32] highlighted the superior performance of alkyd coatings enhanced with cysteine-modified swelling clay, which provided durable corrosion protection and significantly improved the impedance and charge transfer resistance of brass surfaces. In practical marine applications, uncoated steel is typically not used due to its high susceptibility to corrosion. However, for the purposes of this study, uncoated steel was included as a baseline to effectively compare the environmental impacts of using alkyd coatings. Similar assumptions are supported by studies such as Suer et al. [33], which highlights the application of LCA methodologies to assess the environmental impacts of both uncoated and coated steel, and Adsetts et al. [34], which underscores the necessity of coatings in harsh environments to prevent corrosion. Alkyd coatings significantly extend the lifespan of steel structures by providing a protective barrier, thereby reducing the frequency of maintenance and overall environmental impact.

The published literature shows that alkyd coating possesses excellent resistance to oxidation and corrosion in marine environments. Hence, in the present study, LCA of uncoated and alkyd sol–gel coated systems is performed to investigate the environmental impacts. The experimental data considered in the present study to perform LCA were referred to from the published article [35]. Moreover, the sensitivity analysis is performed considering parameters such as the coating mean time between repair and maintenance and the coating amount.

2. Materials and Methods

2.1. Materials

As the ship structure is made up of carbon steel (bare steel), it is considered a System 1. In comparison, the ship structure coated with an alkyd-based anti-corrosion coating (developed by Tecnalia, Donostia-San Sebastián, Serbia [35]) is considered System 2. The inventory details considered for both systems are mentioned in Section 2.1.1 [35,36].

2.1.1. Life Cycle Assessment (LCA) Methodology

The environmental impacts of System 1 and System 2 are studied using the cradle-to-gate LCA approach [37]. The LCA modeling of both systems is performed using the GaBi software (version 10), and the inventory is referred from the GaBi database [38]. Life cycle impact assessment (LCIA) is a phase of LCA that evaluates the significance of potential environmental impacts based on the life cycle inventory data collected [39]. It involves translating emissions and resource use into environmental impact categories, such as global warming potential or eutrophication, providing a comprehensive understanding of a product's environmental performance [40]. The Centrum voor Milieukunde Leiden (CML) methodology is employed for LCIA. The CML method is a widely recognized framework that categorizes environmental impacts into midpoint indicators, facilitating a comprehensive analysis of environmental burdens throughout the lifecycle of a product. This methodology is specifically designed to align with European environmental policies and regulations, ensuring relevant and accurate impact assessments [41]. The CML method's detailed and structured approach allows for consistency and comparability in LCA studies, making it a preferred choice for regional assessments [42]. In the present study, the protection of a 1 m^2 surface area of steel is considered a functional unit [43,44]. The life of the bare ship structure (System 1) is assumed to be 10 years [45]. Whereas the effective life of the coating (System 2) is assumed to be 5 years. Since, every five years, repair and maintenance of the ship structure is generally scheduled [46]. The boundary considered in the present LCA study for both uncoated and coated systems is depicted in Figure 1.

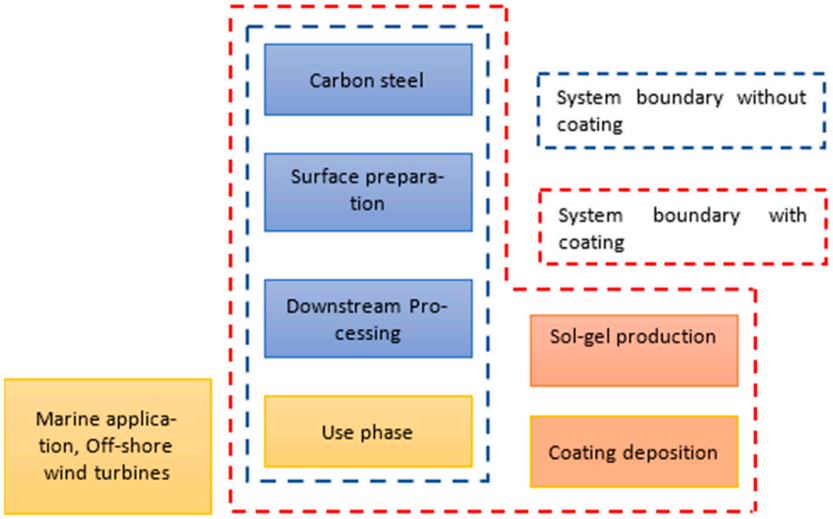


Figure 1. Boundary of the uncoated and coated systems considered in the present LCA study.

2.1.2. Life Cycle Inventory (LCI) for Production of Carbon Steel (System 1) and Steel Substrate Coated with Anti-Corrosion Coating (System 2)

The LCI data for System 1 are obtained from the GaBi database [38]. Whereas the life cycle of System 2 is divided into the following six different stages: (1) production of carbon steel substrate; (2) surface preparation, which includes degreasing, i.e., removal of oil impurities and dirt; (3) synthesis of alkyd coating using sol–gel approach; (4) deposition of alkyd coating on steel substrate; (5) thermal curing for proper adhesion of coating; and (6) use of coated specimen under corrosive atmosphere. The key parameters and major assumptions made for the alkyd-coated system are summarized and presented in Table 1.

Table 1. Key process parameters and assumptions made in the present LCA study.

Life Cycle Processes	Main Assumptions Made and Referred Data Sources
1. Production of carbon steel substrate	LCI data for the production of carbon steel material were referenced from the GaBi database [38]
2. Surface cleaning and preparation, shot blasting of cleaned surface	LCI data for the preparation of the surface (degreasing and cleaning) and the shot blasting process were referenced from the literature [47,48]
3. Synthesis of alkyd coating	LCI data for the synthesis of the coating material were referenced from the literature [49]
4. Application of coating by immersion (dipping process)	LCI data for the deposition of the coating material using the immersion method were referenced from the literature [50]
5. Thermal curing for proper adhesion of coating	LCI data for thermal curing were referenced from an industrial process reported in the literature [50]
6. Use of coated specimens under corrosive environments	The maximum life of the anti-corrosion coating was considered based on previously published literature [35,51]

Figure 2 depicts the cradle-to-gate LCA model for System 2. It starts with raw material acquisition and proceeds through the production, coating process, and use phase. This model excludes transportation and end-of-the-life phases.

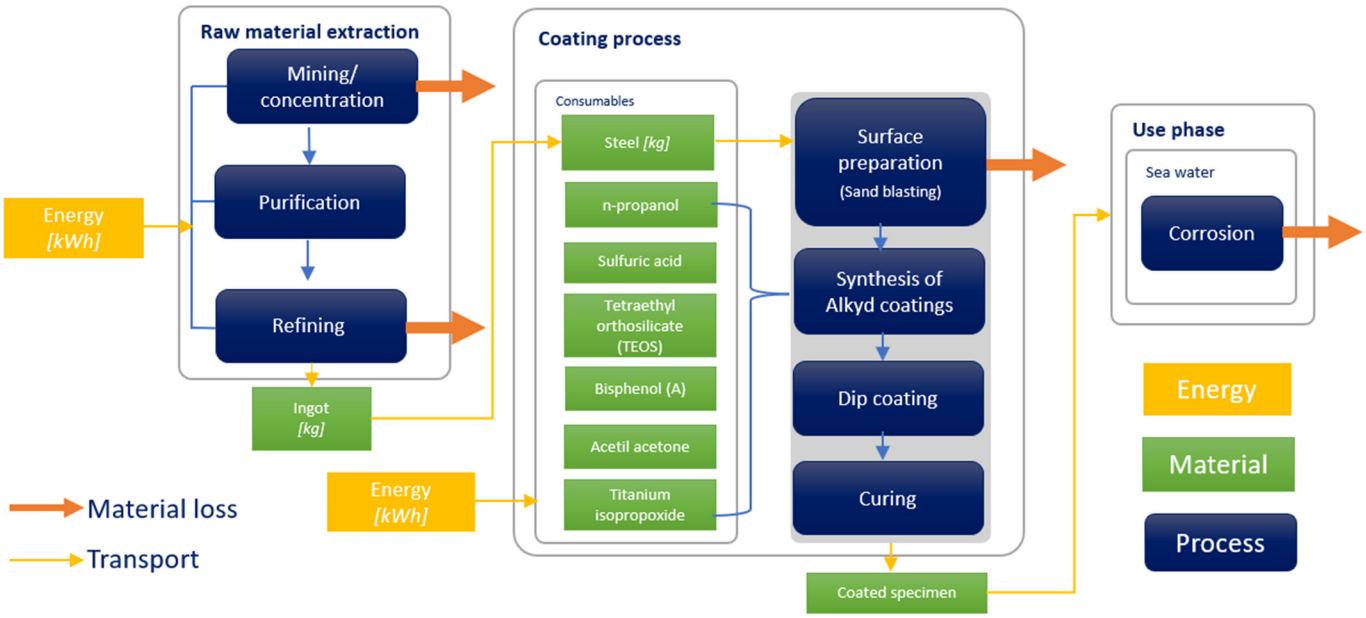


Figure 2. Cradle-to-gate LCA model for System 2.

The geometry of the specimen used to evaluate the surface area, the mass of the uncoated specimen (System 1), and the mass of the coated specimen (System 2) were

referenced from the literature [35]. A correlation between the specimen surface area and mass was carried out to obtain the required inputs corresponding to the functional unit of 1 m^2. The masses for the uncoated (System 1) and coated specimens (System 2) with 1 m^2 surface area are presented in Table 2.

Table 2. Mass of material for uncoated and coated systems (1 m^2 functional unit).

System ID	Area of Steel	Mass (kg)
System 1	1 m^2	15
System 2	1 m^2	15.2

The LCI data for the production of one kg of alkyd coating are presented in Table 3 [49]. Additionally, the electrical energy consumption during the synthesis and deposition of the coating on the steel substrate is referenced from published literature [52,53].

Table 3. LCI data to produce one kg of alkyd coating.

Materials	Quantities (kg)
n-Propanol	0.286
3-Glycidyloxypropyltrimethoxysilane, (GPTMS, 98% purity)	0.315
0.1 M H_2SO_4 in water (total)	0.071
Tetraethyl orthosilicate (TEOS, purity 98%)	0.094
Poly (bisphenol A-co-epichlorohydrin), glycidyl end-capped	0.161
Acetil acetone	0.018
Titanium isopropoxide	0.051
Electricity consumption	
Sand blasting of steel substrate	3 kWh/m^2 [52]
Stirring and Heating by ultrasound reactor (1 h at 40 °C)	0.7 kWh/L [52]
Sol–gel deposition by dip coating	0.44 kWh/m^2 [52]
Curing	0.126–0.1488 kWh/m^2 [53]

In this LCA study, a sensitivity analysis was performed considering the following two parameters: the span between coating repairs and maintenance and the amount of coating used. The experimental study observed a five-year lifespan for the alkyd coating [35,51]. However, these experiments need to accurately represent atmospheric corrosion, accounting for factors such as wet and dry climate cycles, UV radiation, ozone, and air pollutants. To address these factors, a ±25% variation in the coating repair and maintenance span relative to the five-year lifespan was considered, and corresponding changes in environmental impacts were studied.

The amount of coating used is another significant parameter affecting environmental impact. According to the experimental study, 10 mL of coating volume is required to coat 1 m^2 steel surface [35]. However, factors such as coating deposition techniques, the number of layers (base, intermediate, and topcoat), and loss of coating to the surroundings can lead to variations in the required amount of coating. To investigate this, a scenario with a ±25% variation in the amount of coating relative to the 10 mL/m^2 baseline was considered, and corresponding changes in environmental impacts were analyzed.

3. Results and Discussion

3.1. LCIA

The LCIA results for System 1 and System 2 are summarized in Table 4 and represented in Figure 3. The results are normalized to that of the system with the highest impact in the respective category. Among all listed categories in Table 4, ADF, GHG, POCP, AP, FAETP, and EP were found to have significant contributions to the total environmental impact. The steel production process contributes 95% of the total environmental burden in System 1 [54–56].

Table 4. Life cycle impacts (with 1 m^2 steel) for System 1 and System 2.

Impact Category	Unit	System 1	System 2
ADE	kg Sb eq.	0.001156	0.0004163
ADF	MJ	792	766.85
AP	kg SO_2 eq.	0.2584	0.15231
EP	kg Phosphate eq.	0.02164	0.011957
FAETP	kg DCB eq.	0.3568	0.2024
GHG	kg CO_2 eq.	64.4	43.896
HTP	kg DCB eq.	12.24	4.212
MAETP	kg DCB eq.	7440	3511
ODP	kg R11 eq.	8.12×10^{-11}	2.74×10^{-10}
PCOP	kg Ethene eq.	0.0172	0.010691
TETP	kg DCB eq.	0.2624	0.11458

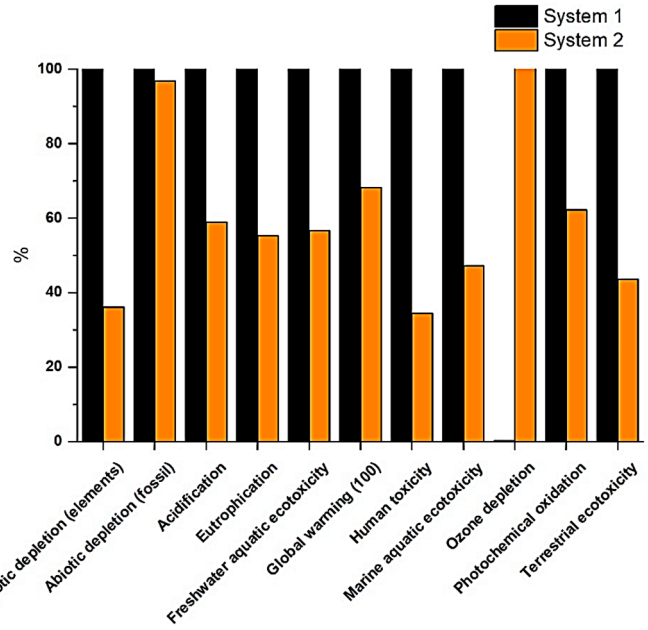


Figure 3. LCIA results for System 1 and System 2.

With regards to System 2, for the ADF impact category, the potential contribution of various factors was observed, i.e., steel production 70%, GPTMS 12%, n-propanol 5%, bisphenol 4%, followed by steel blasting 2%. Similarly, for the FAETP impact category, various factors contributed, i.e., steel production 72%; steel blasting 14%; GPTMS 5%; n-propanol 3%, followed by bisphenol 2%. For the GHG impact category, various factors contributed, i.e., steel production 78%, GPTMS 10%, steel blasting 3%, and n-propanol 2%. For POCP and EP impacts, steel production contributes 80%, GPTMS contributes 7%, followed by steel blasting 4% [56].

The highest negative impact for ODP was observed due to the emissions from the consumption of fossil fuels (in the form of electricity) and chemicals used for the synthesis of coatings [57–59]. From the LCIA results shown in Figure 3, overall, a 46% reduction in the total environmental impact is observed for System 2 compared to System 1.

3.2. Sensitivity Analysis

The sensitivity analysis for the mean time between repair and maintenance of ship coating over five years with ±25% variation is shown in Figure 4. The variation in mean time between repair and maintenance of ship coating greatly affects ADP (fossil), GWP, ODP, and POCP environmental impacts. A decrease in the meantime between repair and maintenance of ship coating causes an increase in the above-listed environmental impacts

and vice versa. The results showed 20 to 24% negative environmental impact for ADP (fossil), GWP, and POCP with reduced mean time between repair and maintenance of ship coating compared to the reference five-year period, as shown in Figure 4a,b,d. This can be attributed to the higher consumption of chemicals in the synthesis of alkyd coatings [57]. The negative 31% ODP impact was observed in the case of a reduced mean time between repair and maintenance of ship coating (refer to Figure 4c). It originates from the chemicals used for coating, pre-treatment of the substrate, and energy used in various life cycle phases [45]. In addition, about 12 to 15% positive impact for ADP (fossil), GWP, and POCP was observed for the increased mean time between repair and maintenance of ship coating compared to the reference five-year period [51].

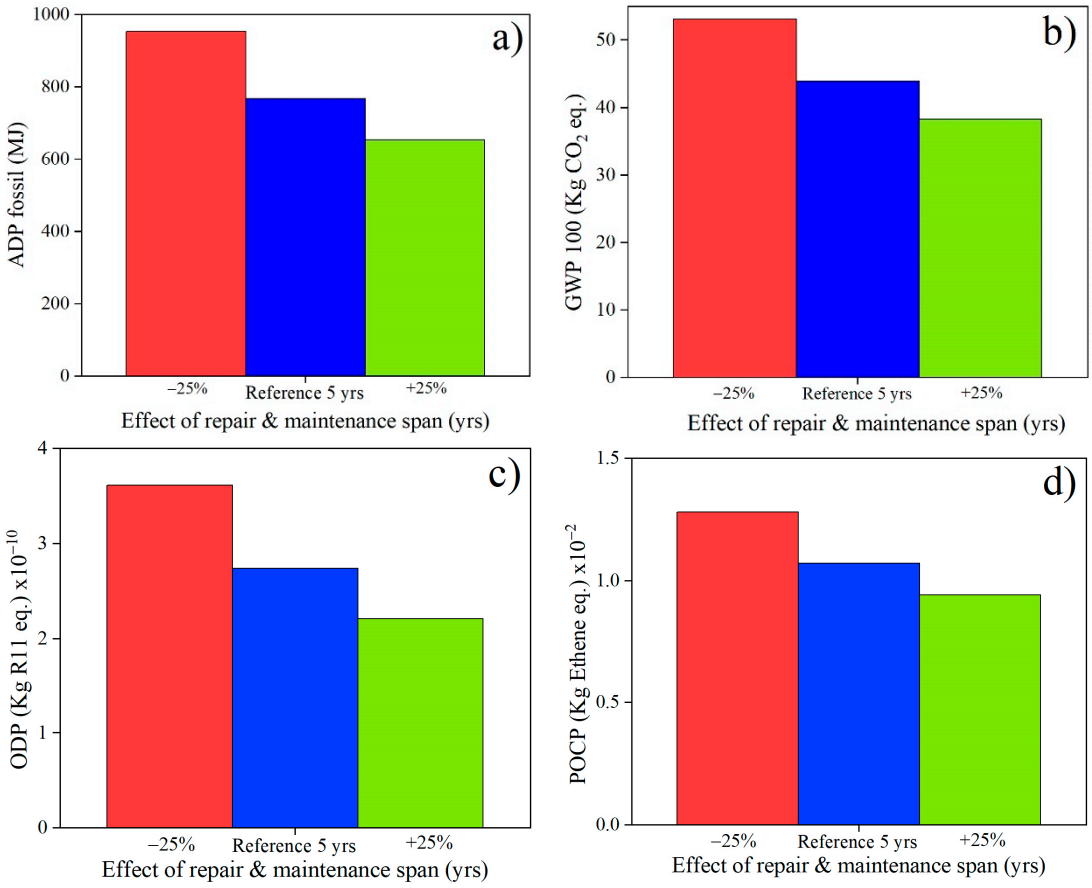


Figure 4. Sensitivity analysis for ±25% variation in mean time between repair and maintenance of ship coating; reference of a 5-year period: (**a**) ADP, (**b**) GWP, (**c**) ODP, and (**d**) POCP.

In the referred experimental study [35], a 10 mL/m^2 amount of coating was used; considering this, the sensitivity analysis is performed with ±25% variation in the amount of coating. The obtained sensitivity analysis results for ADP (fossil), GWP, ODP, and POCP are depicted in Figure 5a–d. The variation in coating amount shows an influence on ADP (fossil), GWP, ODP, and POCP impact categories. The reduction in the amount of coating showed a decrease in the environmental impacts and vice versa. It is directly related to the amount of chemicals used in the synthesis of alkyd coating [60]. The results show about 4% and 6% variation in ADP (fossil), GWP, and POCP, with −25% and +25% variation in the amount of coating, respectively, as shown in Figure 5a,b,d. Whereas 9% and 19% variation in ODP is observed with −25% and +25% variation in the amount of coating, respectively (Refer Figure 5c). The maximum variation in ODP (both on the negative and positive side) was observed due to the amount of chemicals and the energy consumed during different life cycle phases [57].

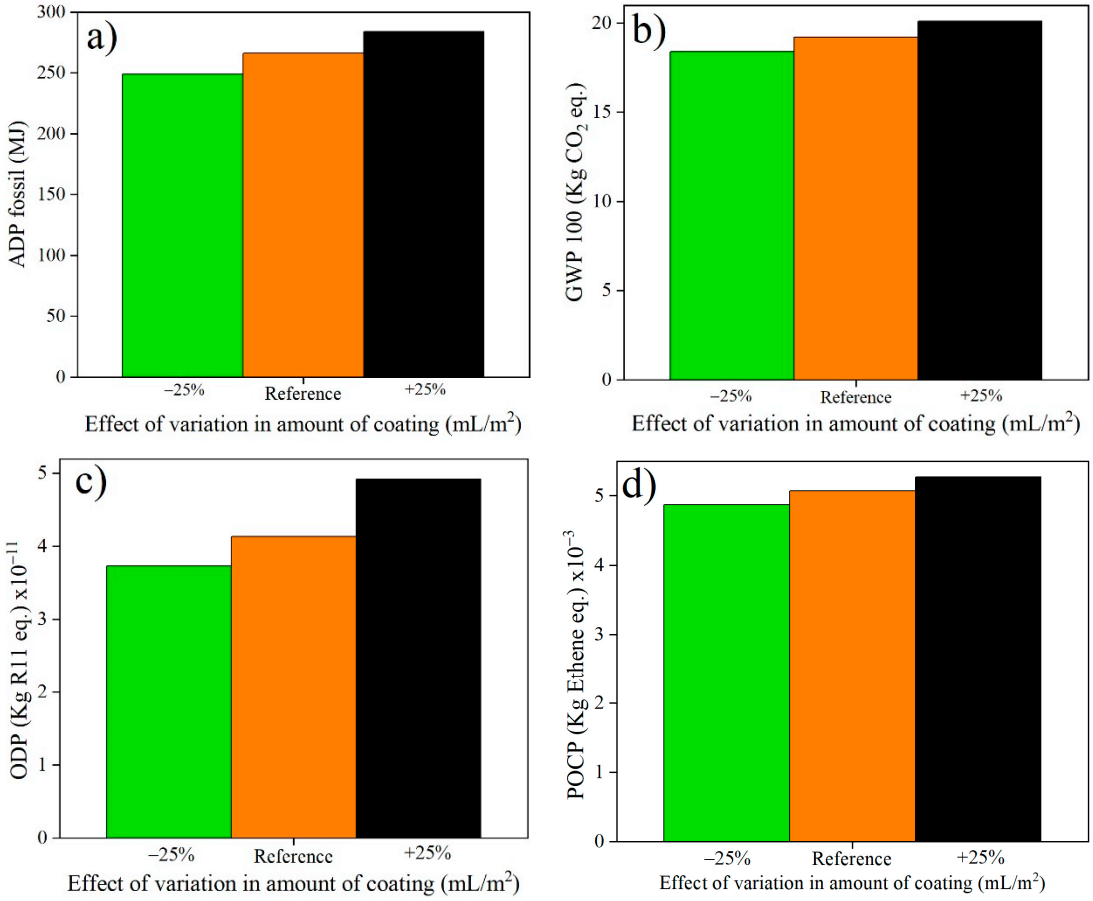


Figure 5. Sensitivity analysis with variation in amount of coating: (**a**) ADP, (**b**) GWP, (**c**) ODP, and (**d**) POCP.

The sensitivity analysis revealed that changes in the meantime between repair and maintenance of ship coatings, as well as variations in coating amounts, significantly impact environmental factors like ADP (fossil), GWP, ODP, and POCP. Decreasing the repair and maintenance interval or increasing coating amounts led to higher environmental impacts due to increased chemical usage, while increasing the repair and maintenance interval or decreasing coating amounts resulted in decreased impacts. These findings emphasize the importance of maintenance strategies and coating application practices in minimizing environmental burdens within the marine industry.

4. Conclusions

This study presents a comprehensive life cycle assessment (LCA) comparing the environmental impacts of uncoated steel and alkyd-coated steel systems prepared using the sol–gel method in a marine atmosphere. The LCA results indicate a substantial 46% reduction in the overall environmental impact of the alkyd-coated steel system compared to the uncoated steel system, underscoring the enhanced environmental performance of the coated system.

Sensitivity analysis further elucidates that a decrease in the meantime between repair and maintenance, coupled with an increased quantity of coating material, exacerbates the environmental impacts. These findings suggest that optimizing the maintenance schedule and the amount of coating applied are critical factors in minimizing environmental burdens.

Moreover, this study identifies 3-glycidyloxypropyltrimethoxysilane and n-propanol as significant contributors to the environmental impacts of the coated system. These substances, integral to the coating process, exhibit high environmental footprints, indicating the necessity for research and development of alternative materials.

The results emphasize the importance of developing and adopting commercial coatings formulated with bio-based products to achieve a greener and more sustainable solution. Future work should focus on the exploration and integration of eco-friendly materials that can provide comparable or superior performance while mitigating environmental impacts.

Overall, the findings from this LCA provide valuable insights for improving the environmental sustainability of protective coatings in marine applications, and they highlight the potential for significant environmental benefits through material innovation and process optimization.

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Abbreviations

LCA	Life cycle assessment	EP	Eutrophication
LCIA	Life cycle impact assessment	FAETP	Freshwater aquatic ecotoxicity
LCC	Life cycle cost	GWP	Global warming (100)
LCI	Life cycle inventory	HTP	Human toxicity
CML	Centrum voor Milieukunde Leiden	MAETP	Marine aquatic ecotoxicity
ADE	Abiotic depletion (elements)	ODP	Ozone depletion
ADF	Abiotic depletion (fossil)	POCP	Photochemical oxidation
AP	Acidification	TETP	Terrestrial ecotoxicity
GPTMS	3-Glycidyloxypropyltrimethoxysilane	TTIP	Titanium isopropoxide
GHG	Greenhouse gas		

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