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Sustainable Management of Mediterranean Superyacht Marinas: A Comparative Assessment of Environmental Practices and Policy Implications

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Abstract: The Mediterranean superyacht industry significantly contributes to the region's economy, but its rapid growth has raised serious environmental concerns. This study compares the emissions, waste management, and biodiversity protection of two marinas located in Sicily, Italy, and the Balearic Islands, Spain. A survey assessing the carbon footprint and water quality was distributed to the management of the marinas. The collected data were analysed and translated into tonnes of CO_2 equivalent using emission factors. By calculating the carbon and water footprints of the two marinas, this study aimed to understand the environmental impact of port-related operations. The JMarinas Environmental Decision Support System and a P-Mapping/Pareto approach were used to identify pollutant sources, following Pareto's principle. The findings indicated that the primary operations of the marina sector are the main sources of pollution, with significant contributions from supporting activities. This study clarifies the origins of CO_2 and pollution in marina operations, enabling the authors to recommend the close supervision of all recreational boating activities to reduce CO_2 emissions and environmental degradation. By adopting these recommendations, policymakers, marina operators, and yacht owners can ensure the long-term sustainability of Mediterranean marinas.

Keywords: superyacht marinas; sustainable marina management; cross-border regulatory frameworks; coastal zone management; environmental policy

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1. Introduction

Europe's extensive inland waterways (over 37,000 km) and coastline (more than 70,000 km) support a vibrant recreational boating industry. Over 48 million Europeans participate in marine activities, including 36 million boat owners, supported by more than 10,000 marinas offering over 1 million berths [1,2]. The Mediterranean, with its rich biodiversity and economic importance, is a major hub for this activity but faces increasing environmental pressures due to the growth of the superyacht industry.

Superyacht marinas contribute significantly to regional economies through job creation and tourism. However, these benefits come at a high environmental cost, especially in areas already impacted by overfishing, climate change, and marine pollution [3]. The Mediterranean Sea is one of the top destinations for boating tourism, supported by a vast network of marinas for boat building, repairs, and maintenance [4,5]. Italy, Spain, and France alone provide over 400,000 berths across 940 marinas, with boating tourism contributing EUR 28 billion annually and supporting 234,000 jobs in the EU [4].

While motorboats dominate the Mediterranean fleet, superyachts represent around 10% of leisure vessels and have a disproportionately high economic impact. The region accounts for 70% of the global market for superyacht charters, and large yachts have grown at a rate of 3.5% annually [2]. Italy, Turkey, and France collectively represent nearly half the global superyacht market [6]. Italy's 57 shipyards account for 21% of the global market, and its high-quality marinas host an impressive 2900 superyacht berths—the highest in the Mediterranean. This economic growth drives infrastructure improvements at ports to accommodate large yachts and support local economies. These countries' marinas operate in an increasingly competitive environment where sustainability is emerging as a critical success factor. Environmental impact is no longer just a regulatory concern but a unique selling point, especially as consumer awareness of ecological issues grows [3].

However, despite their dominance in the sector, the industry still lacks comprehensive systems for classifying and managing the pollution generated by marina operations [2]. The rapid expansion of nautical tourism has raised environmental concerns, particularly in marine protected areas (MPAs). Rising boat densities, such as 4.5 boats per hectare in Spain's Cap de Creus MPA [5], strain ecosystems. Popular destinations like the Gulf of Saint Tropez can see over 350 recreational vessels and 100 superyachts on peak days [4]. In parts of the Mediterranean, marina densities exceed 100 moorings per kilometre of coastline, with superyacht traffic exceeding 100 h per square kilometre annually, creating significant ecological pressure [4,7].

Superyachts, due to their size and energy demands, are major contributors to marine and atmospheric pollution. Diesel engine emissions, including nitrogen oxides (NO_x) and sulphur oxides (SO_x), combined with untreated wastewater, threaten water quality and biodiversity [8–10]. Sensitive habitats like seagrass meadows and coral reefs, critical for carbon sequestration and marine biodiversity, face physical damage and pollution from unmanaged yachting activities [11].

This study focuses on the marinas of Sicily, Palermo (Italy), and the Balearic Islands, Alcudia Bay (Spain), two key Mediterranean destinations with rich maritime traditions and strategic significance. According to the 2019 European Union Tourism Trends Report, the Mediterranean remains one of the most sought-after regions for nautical tourism. Both Sicily and the Balearic Islands hold unique positions in this context: Palermo as a cultural and logistical hub in the central Mediterranean and the Alcudia Bay as a premier destination renowned for its natural beauty and thriving yachting industry. Moreover, local and regional governments in these areas are actively working to enhance their maritime infrastructures and promote sustainable nautical tourism under the European Union's Research and Innovation Smart Specialization.

Italy and Spain's marinas are increasingly adopting sustainable practises to address these challenges. Tools like Green Process Mapping (P-Mapping) help identify sources of environmental waste and guide mitigation efforts [12]. At the same time, green business process management (GBPM) integrates sustainability into operational workflows, ensuring that business strategies align with environmental goals [13]. However, the adoption of these approaches remains fragmented and largely experimental [14].

Marina operators are also turning to lean manufacturing principles to reduce emissions and resource use while maintaining profitability. These strategies have proven effective in cutting pollution and improving efficiency [15,16]. For example, the application of Porter's Value Chain can help marinas identify core and support activities that drive sustainability, providing a roadmap for reducing their environmental impact [17].

Many Mediterranean countries lack cohesive regulatory frameworks or fail to enforce existing regulations [18]. Marinas often prioritise economic growth over environmental sustainability, resulting in inadequate waste management and emission control that allow pollution to accumulate and harm biodiversity and water quality [18]. Stronger environmental management practises are needed to address these challenges [2].

2. Methodology

2.1. Study Sites

This study investigated the environmental management practises of two marinas in the Mediterranean region: Marina A in Palermo, Sicily, Italy, and Marina B in Alcudia Bay, Mallorca, Spain (Figure 1). These marinas were deliberately selected to represent contrasting operational models and regulatory frameworks, allowing for a robust comparative analysis. Marina A is characterised as a high-traffic facility with traditional management practises, capable of accommodating approximately 600 yachts up to 70 m in length. This marina experiences significant yacht traffic, particularly during peak tourist seasons, and serves as a prime example of a facility with limited sustainability integration.

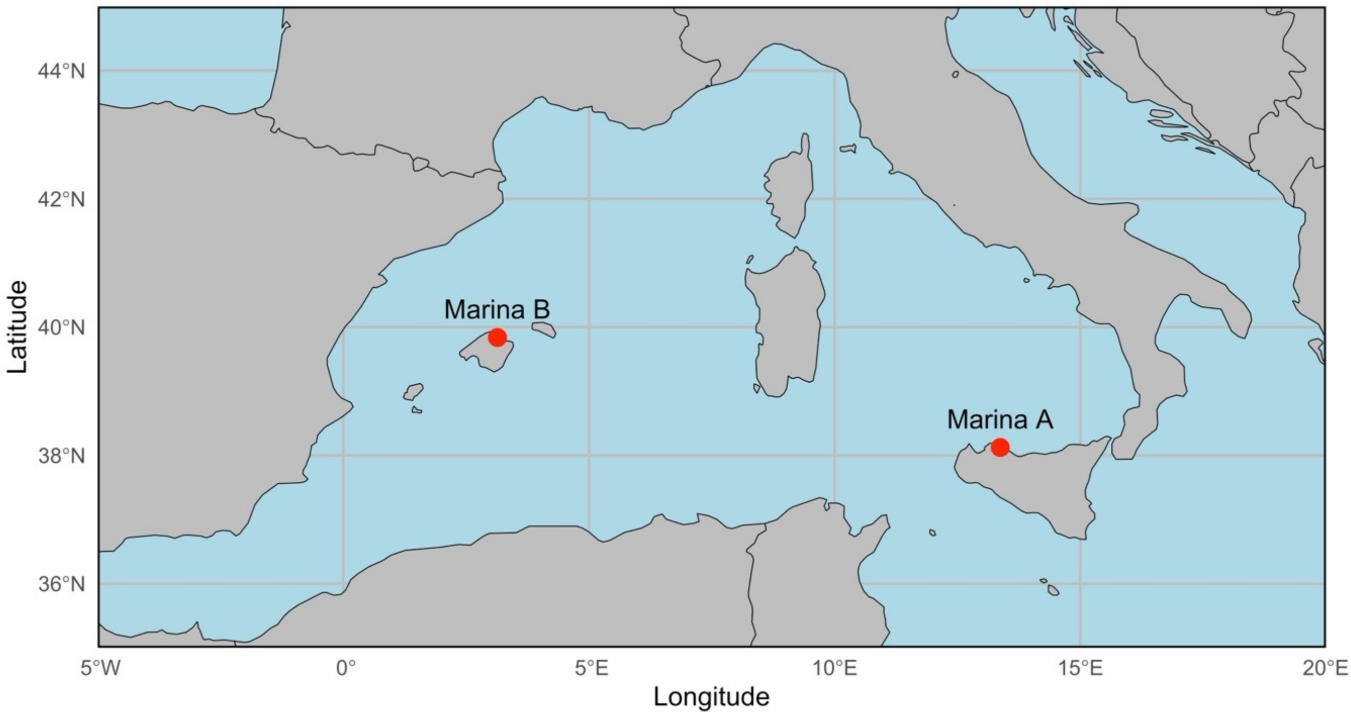

Figure 1. The locations of Marina A (Sicily) and Marina B (Mallorca).

In contrast, Marina B prioritises sustainability and is equipped with 745 moorings, a 12,000 m^2 dry dock, and a 150-ton travel lift. It exemplifies a proactive approach to environmental management, with measures such as energy-efficient lighting systems and wastewater recycling mechanisms. This comparative approach aimed to elucidate the effectiveness of different management strategies in mitigating environmental impacts within diverse regulatory and tourism contexts. The scope of the study included the evaluation of carbon and water footprints for the year 2022, emphasising the influence of operational models on environmental performance.

Industry standards, environmental assessments, and prior research on Mediterranean marina management informed these two case studies, which aid in better understanding the potential ecological effects of various management strategies, particularly in Mediterranean superyacht marinas. The methodologies adhered to ISO 14040 [19] and 14044 [20] guidelines, ensuring systematic and rigorous data collection and analysis. Carbon footprint (CF) calculations followed ISO 14067 [21], and those of carbon equivalents followed the GHG Protocol system.

Palermo Bay's Marina A can accommodate approximately 600 yachts up to 70 m in length. It experiences high yacht traffic, particularly during peak tourism seasons [4].

Marina B, situated in Alcudia Bay, boasts 745 moorings ranging from 6 to 30 m in length, a 12,000 m dry dock, and a 150-tonne travel lift [10]. Volvo Penta's advanced hybrid electric propulsion powers every boat that is available for rent or charter.

This study analyses the 2022 environmental performance of both marinas, focusing on carbon and water footprints. While existing research often concentrates on water quality aspects of marina operations, this study adopts a more holistic approach, examining greenhouse gas emissions and the broader environmental impact. The selection of these marinas allows for a direct comparison of contrasting management strategies and their capacity to mitigate environmental pressures.

2.2. Environmental Risk Assessment

To assess the environmental risks associated with marina operations, this study employed the Environmental Decision Support System (EDSS) Jmarinas [22], adapted specifically for the context of Mediterranean marinas. The EDSS framework incorporates the Multiple Attribute Decision Making (MADM) theory, which systematically evaluates environmental risks by integrating multiple attributes, both qualitative and quantitative. This approach ensures a thorough understanding of the environmental pressures exerted by marina activities.

The attributes assessed included the following:

1. Direct and indirect emissions: the quantification of Scope 1 (e.g., emissions from on-site fuel consumption), Scope 2 (e.g., emissions from purchased electricity), and Scope 3 (e.g., emissions from supply chains and visitor activities) greenhouse gas emissions.
2. Wastewater discharge: an evaluation of untreated effluents and their impacts on local biodiversity and water quality.
3. Proximity to ecologically sensitive zones: an assessment of the risks posed to marine protected areas (MPAs), including seagrass meadows and coral reefs (Figure 2).

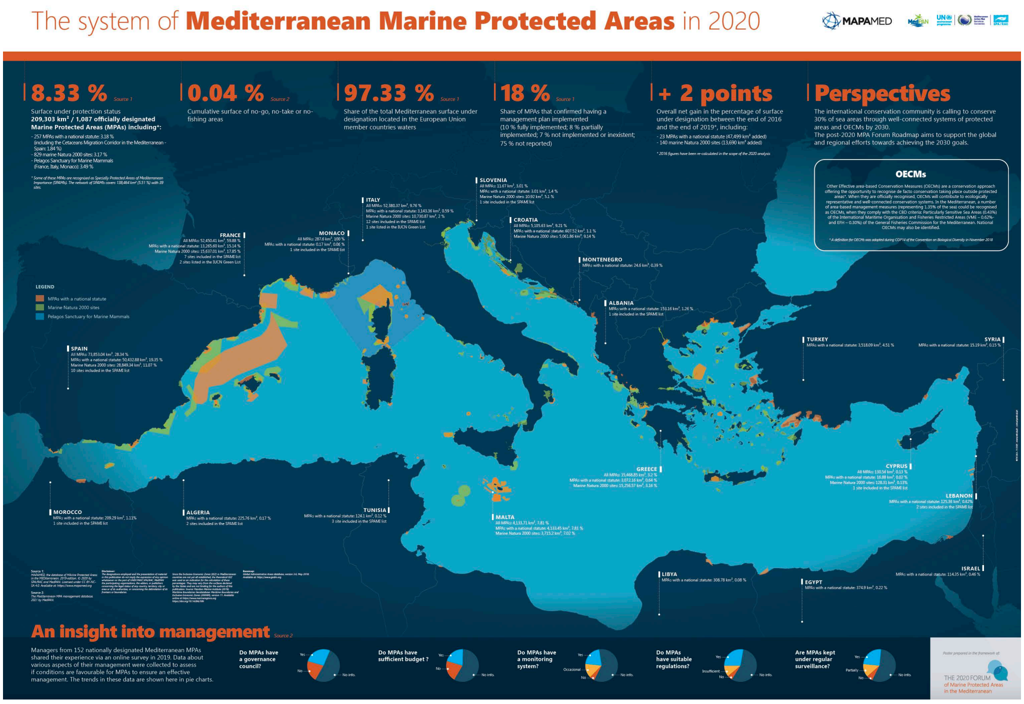

Figure 2. The system of Mediterranean marine protected areas in 2020 (source https://medpan.org/en/system-mediterranean-mpas-2020 (accessed on 18 December 2024)).

The MADM framework enabled a systematic weighting of these attributes to prioritise interventions. By quantifying the ecological risks, the framework facilitated the identification of the most significant environmental challenges faced by Marina A and Marina B. The integration of this structured decision-making model provided a clear basis for comparing the ecological performance of the two marinas.

The NO_x and SO_x emissions, CO_2 emissions generated by diesel-powered yachts and ancillary marina operations (such as fuel dispensing and ship repairs), wastewater output and biodiversity impact (primarily due to uncontrolled anchoring and inadequate ballast water management) were input into JMarinas.

The yearly percentage changes for NO_x emissions, CO_2 emissions, and the biodiversity index was calculated using the following formula:

$$Percentage\ change = \left(\frac{Current\ Year\ Value - Previous\ Year\ Value}{Previous\ Year\ Value}\right) \times 100$$

We calculated the yearly *percentage changes* for both Marina A and Marina B for each of the environmental metrics over the 2020 to 2030 period. The method employed integrates historical data, responses from marina operators, and predictive modelling techniques. Emissions trends were calculated using regression models, factoring in expected increases in marina traffic and technological advancements in propulsion systems.

2.3. Green P-Mapping and the Pareto Principle

To identify key sources of pollution and assess the effectiveness of different management strategies, this study employed an extended Green P-Mapping approach for both Marina A and Marina B. This technique dissects marina operations into individual activities, classifying each as value-adding or non-value-adding (e.g., transport, storage, delays) and quantifying the associated waste generation. The analysis further incorporates the Pareto principle, focusing on the few activities that generate the most significant environmental impacts. This modified P-Mapping method finds pollution sources in each marina's value chain by replacing traditional cost efficiency metrics with environmental sustainability indicators. It does this by connecting specific operations to the damage they cause the environment. This detailed process-based analysis, considering both direct and indirect sources of pollution, is crucial for identifying targeted areas for improvement in each marina's environmental management strategy.

The P-Mapping technique, or Process Mapping, analyses processes by breaking them into individual activities to identify inefficiencies and environmental impacts. Activities are classified as value-adding (e.g., manufacturing or quality checks) or non-value-adding (e.g., unnecessary movement or idle time). By extending this method, it becomes possible to highlight sources of pollution and resource waste. For example, the analysis may reveal that activities in a cleaning station consume excessive water and produce chemical-laden wastewater, requiring careful management and mitigation.

The Pareto principle (80:20 rule) is a valuable tool for focusing on critical environmental issues [23]. It posits that a small proportion of causes often accounts for the majority of effects. For example, in a shipyard, 80% of energy consumption might stem from just 20% of its processes, such as welding or refrigeration. By identifying and targeting these key contributors, operators can prioritise efforts to reduce their environmental footprints. Globally, carbon emissions reflect this principle, with a small number of industries or countries responsible for the majority of outputs, necessitating targeted interventions for maximum impact [24].

2.4. Data Collection and Analysis

Marina operations supervisors were asked to fill out an online questionnaire (Table 1) to provide details on (i) fossil fuel usage for vehicles and fixed installations; (ii) electricity consumption; (iii) fuel usage related to waste management, employee commutes, and supplier deliveries; and (iv) water usage and waste management. The interviews were structured based on P-Mapping and Porter's Value Chain model, focusing on environmental aspects to determine the carbon and water footprints. The study aimed to gain a clear understanding of marina operations' environmental impact and identify all pollution sources. Porter's Value Chain was used as an exploratory tool because it typically maps activities that create value. A green perspective was adopted to highlight pollution sources and environmental issues.

Table 1. The requested information from the two marinas.

Question	General Information	Unit	Indicator
Q1.1	Type of marina	Transit/base	–
Q1.2	Number of employers	n°	–
Q1.3	Average daily commute of employees to the marina	km	Carbon
Q1.4	Average daily commute of tourists to the marina	km	Carbon
Q2	Number of berths	n°	–
Q3	Vessel dimensions	m	–
Q4	Activities most frequently carried out by ships	Open-ended question	Carbon/Water
Q5.1	Separate waste collection	Yes/no	–
Q5.2	Frequency of waste collection	Times/year	Carbon
Q6	Developed by who	Open-ended question	–
Q7	Frequency of these tasks	Times/year	Carbon
Q8	Hot water supplying system	Open-ended question	Carbon
Q9	Electric	kWh	Carbon
Q10	Diesel	litres	Carbon
Q11	Water	m^3	Water
Q12	Suppliers	n°	Carbon
Q13	Frequency of visits	Times/year	Carbon
Q14	Vehicle type	Open-ended question	Carbon
Q15	Number of employees	n°	Carbon
Q16	Bar, cafeteria, restaurant, etc.	Type	Carbon/Water
Q17	Quantity	n°	–
Q18	Source of energy	Type	Carbon
Q19.1	Quantity	n°	Carbon
Q19.2	Type of vehicle	Carbon	

A systematic approach to data collection is essential to ensure the information's accuracy and completeness. To this end, a web-based survey is developed, with most questions being primary and open-ended. Three questions are multiple choice: question 10 addresses Scope 1, pertaining to the marina's fuel usage; questions 8, 9, and 18 cover the marina's electricity usage; and the remaining questions, estimating the fuel used by visitors', suppliers', and waste managers' vehicles, cover Scope 3.

2.5. Model Adaptation

The initial model illustrated a yacht charter enterprise as a sequence of activities (or processes), each facilitating value creation that eventually benefits the consumer. The model classified the activities into two categories: (i) primary activities and (ii) support activities. The proposed adaption omitted services like launching docks, winter storage, minor repairs, and maintenance from the value chain, as these amenities did not contribute to the value flow but instead represented the value itself. Due to the prevalence of logistics and marketing activities across different flows, the operations box did not replicate them but rather diversified them according to the type of service provided.

Only four value chain activities substantially contributed to the environmental pressure identified in this case study. The corresponding Pareto ratios for transportation (99.6/0.4), storage (99.8/0.2), delays (98/2), and green waste (99/1) identified in our investigation are presented in Table 2. This pattern is anticipated based on the probability calculation that underpins the environmental pressure derivation of the Van Straalen–Aldenberg integral (overlaps of distribution tails). This statistical cause remains unidentified. In retrospect, it would have been unexpected to discover non-skewed results, considering that Newman's analysis indicated analogous outcomes across multiple scenarios. The situation in which all primary activities contribute uniformly to the mixing influence universally, or where they hold equal significance, would be quite unusual. Based on the current results and accuracy level, we advocate applying the findings in practise by categorising them into three classes: despite certain uncertainties, the method can assist in identifying a class of chemicals unlikely to cause harm in the European Union water body, a class for which this is feasible (contingent on circumstances), and a class of chemicals that are likely to pose harm.

Table 2. Extended Process Mapping [4]. Note: O—operations, I—termed inspections, T—transports, S—storage, D—delays, G—green waste, n.a.—not applicable.

Task	O	I	T	S	D	G	Notes
Load	n.a.	n.a.	10 s	n.a.	n.a.	n.a.	n.a.
Process	60 s	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Check thickness	n.a.	20 s	n.a.	n.a.	n.a.	n.a.	n.a.
Clean	n.a.	5 s	n.a.	n.a.	n.a.	n.a.	n.a.
Unload	n.a.	n.a.	10 s	n.a.	n.a.	Disposal of contaminate isopropanol (100 L weekly)	1 in 5 require isopropanol cleaning
Warehouse	n.a.	n.a.	100 m	<48 h	WTG forklift, 30 min	Diesel fuel (100 L daily) and forklift emissions	Forklift emissions refill; 1000 L in storage
Pareto ratio	-	-	98.9%/0.4%	98.9%/0.2%	97%/1.5%	98%/1%	-

2.6. Analysis

The operational performance, utilising P-Mapping and Porter's Value Chain, seeks to demonstrate the beneficial impact on the implementation of the carbon reduction value chain in recreational boat marinas. The measurement model is evaluated for validity and reliability prior to testing the structural model. Consequently, construct reliability, convergent validity, and discriminant validity were assessed for each indicator. The composite reliability (CR) coefficient was employed to assess construct dependability.

Indicators were rated based on individual reliability utilising partial least squares (PLS). Composite reliability was employed to evaluate the reliability of the constructions. The path connection was statistically significant, as all standardised regression weights exceeded 0.1. Consequently, it can be deduced that the primary and supporting activities were essential for implementing a value chain with a reduced carbon footprint and that the determinants of strategic environmentalism can forecast the adoption of a sustainable value chain.

The incorporation of complex analytical frameworks and evidence-based decision-making tools guarantees that the offered approaches are both efficient and scalable.

3. Results

The results of this study, drawn from the comparison between Marina A and Marina B, demonstrate significant differences in environmental performance across several key metrics, including emissions, wastewater management, and biodiversity preservation. The P-Mapping and JMarinas Environmental Decision Support System provide a detailed understanding of how different management practises affect overall environmental sustainability.

3.1. P-Mapping

Green P-Mapping and Porter's Value Chain frameworks informed the questionnaire, providing a comprehensive dataset on operations that allowed for a detailed assessment of carbon and water footprints. The data gathered (see Table 2) enabled a detailed, process-based analysis of pollution sources, reflecting both direct operational impacts and indirect influences from supporting activities (e.g., supplier deliveries, visitor transport). This integrated approach is essential given the existing research gap in comprehensively assessing greenhouse gas emissions and total environmental impact within the context of marina operations.

The Pareto principle, which posits that a small number of causes account for most effects, played a key role in this analysis. Applied to marina operations, this principle identified a disproportionate environmental impact from a few high-intensity processes. For instance, a detailed breakdown revealed that energy-intensive activities, such as refrigeration in storage areas and engine testing, accounted for approximately 80% of energy use, despite representing only 20% of the operational processes. Similarly, activities like hull coating heavily concentrated the generation of hazardous waste, with solvent-based paints and cleaners significantly contributing to environmental degradation.

Quantifying these impacts using the Green P-Mapping approach provided concrete data for each process. Refuelling activities at Marina A, for example, emitted an estimated 0.8 metric tonnes of CO_2 daily and consumed 300 kWh of energy, while hull painting at Marina B generated 50 litres of hazardous waste per maintenance cycle. Such insights allowed for targeted recommendations, such as transitioning to low-emission fuels, implementing energy-efficient storage systems, and adopting eco-friendly, biodegradable cleaning agents.

By linking specific operations to their environmental consequences, the analysis provided actionable insights in areas requiring immediate attention. For instance, the adoption of closed-loop water recycling systems could optimise water-intensive cleaning processes, and the integration of renewable energy could enhance energy-intensive refrigeration systems. These targeted interventions are in line with the main goal of the Green P-Mapping method, which is to find activities that have a big effect on the environment and make changes that lower their environmental impact while keeping operations running smoothly.

This methodology demonstrates the potential for a data-driven approach to environmental management, offering marina operators a framework for prioritising sustainability alongside operational goals. The application of environmental sustainability indicators instead of cost metrics marks a shift in focus, emphasising ecological outcomes and long-term resource preservation in the maritime industry.

3.2. JMarinas

The modelling results for Marina A reveal elevated levels of NO_x, SO_x, and CO_2 emissions (see Figure 3). With over 80% of the yachts using diesel-powered engines and no enforced emission controls, Marina A exceeded regional emission thresholds by up to 30%. CO_2 emissions from ancillary operations, such as fuel stations and yacht repairs, further compounded the problem, leading to a significant rise in local air pollution. Wastewater discharge, untreated or poorly managed, resulted in a 40% increase in nutrient pollution, contributing to the eutrophication of nearby waters.

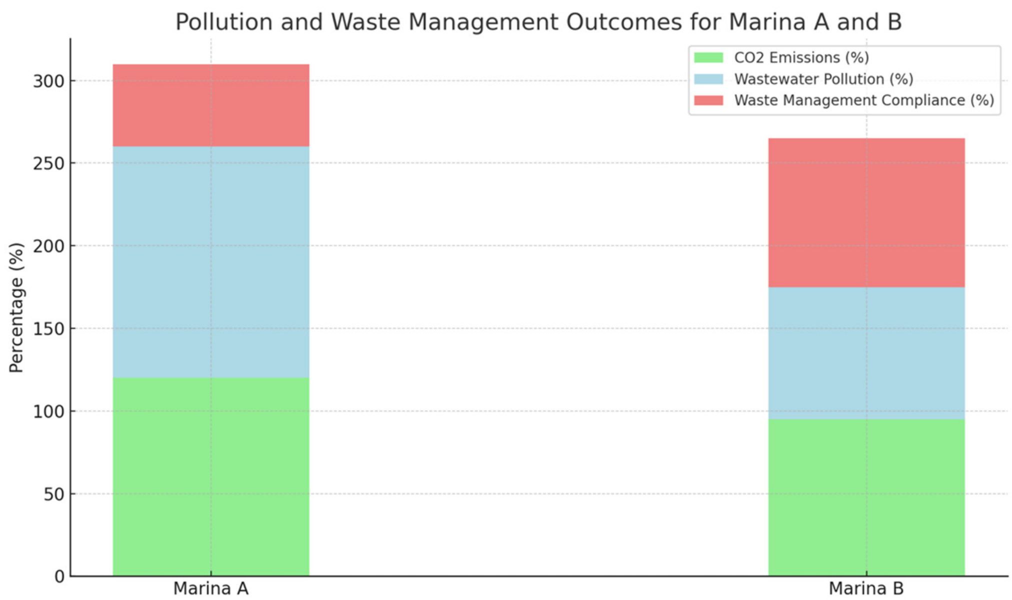

Figure 3. JMarinas output for Marina A and B.

In contrast, Marina B's adoption of hybrid propulsion systems and renewable energy sources significantly reduced emissions. Marina B's energy-efficient marina operations, which included solar-powered charging stations for yachts, reduced NO_x and SO_x emissions by 50% and CO emissions by 25% compared to Marina A. Advanced treatment plants at Marina B ensured highly efficient wastewater management, preventing the release of nutrient-rich wastewater into the surrounding marine environment. This led to a 60% reduction in nutrient pollution levels at Marina B, significantly reducing the risk of harmful algal blooms. Figure 4 highlights biodiversity indices, with Marina B exhibiting higher resilience.

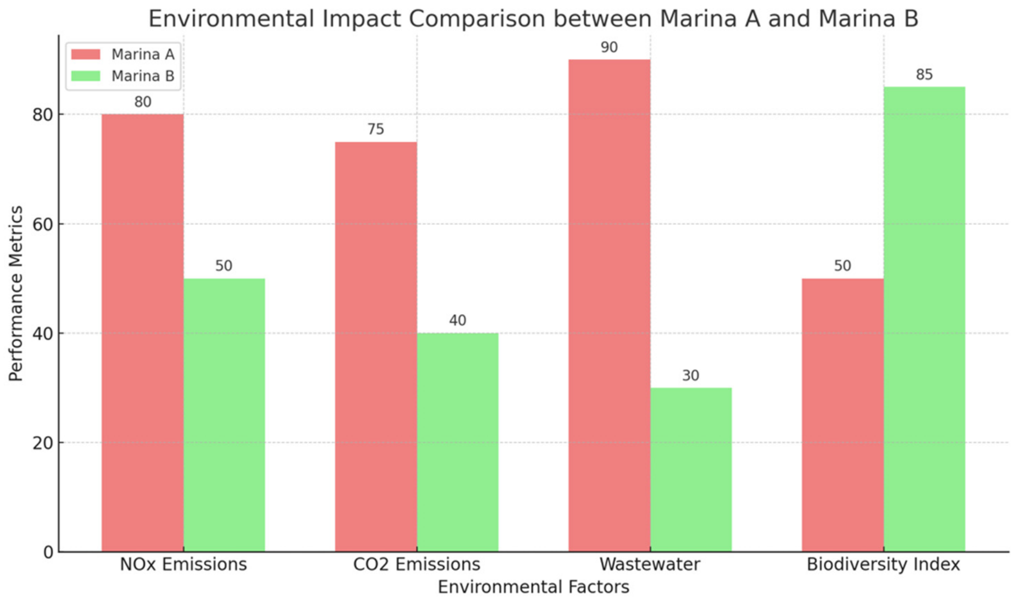

Figure 4. Environmental impact comparison between Marina A and Marina B.

The quantitative model confirmed that adopting sustainable technologies and stricter pollution controls, as seen in Marina B, can drastically improve environmental outcomes, particularly in high-traffic areas like the Mediterranean.

The results, presented in Table 3, highlight the differences in environmental performance between the two marinas, which present contrasting approaches to environmental management. The reliability of the data collected will be assessed through established statistical methods (CR values above 0.7, SD below 1, and the mean score above 2.5 on a 5-point scale). Structural equation modelling was employed to analyse the relationships between operational performance and the adoption of reduced calculated value chains in each marina, accounting for the significant differences in management approaches.

Table 3. Carbon and water footprints of the 2 studied marinas.

	Units	Marina A	Marina B
Carbon Footprint	t CO_2 eq	53.2	487.8
Water Footprint	m^3	1610	465

Table 4 presents the main characteristics of the two marinas in relation to their annual day-to-day operation, which contributes to their carbon and water footprints.

Table 4. Main characteristics of the two marinas studied.

Marina	Marina A	Marina B
Number of boats	50	145
Monthly diesel consumption (L)	1088.3	1345
Electricity consumption (kwh)	12,168	41,143.10
No of suppliers	40	65
No of workers	15	8

This comparative analysis of the environmental performance of Marina A and Marina B has revealed distinct operational characteristics and their consequential environmental impacts. Both marinas serve a similar clientele and operate within comparable geographical contexts, yet their approaches to environmental management differ significantly.

Maintenance and Storage: Marina B's proactive investment in electric forklifts and streamlined supply chain management resulted in considerably lower greenhouse gas emissions associated with maintenance and equipment transport compared to Marina A, which relies on fossil fuel-powered vehicles. Both facilities demonstrated effective material storage, preventing significant pollution from accidental releases.

Mooring Operations: While both marinas experience high traffic, Marina B's optimised mooring procedures and well-trained staff led to significantly shorter engine run times during mooring, resulting in lower emissions. Marina A's processes, while sufficient for operational efficiency, are less focused on minimising fuel consumption during these operations.

Boat Hauling and Launching: The operational procedures for boat hauling and launching were comparable across both marinas, with no significant difference observed in emissions.

Mooring Place Allocation: Marina B's sophisticated booking and berth allocation system minimised unnecessary boat movements and engine idling, contrasting with Marina A, where inefficiencies in allocation processes resulted in higher fuel consumption for repositioning vessels.

Pier Management: Both Marinas employed video surveillance; however, Marina B implemented supplementary preventive measures, such as proactive inspections, to further reduce pollution risks from moored vessels.

Boat Maintenance: Marina B's commitment to environmentally friendly cleaning products and waste management practises resulted in significantly lower hazardous waste generation than Marina A.

Waste Management: Marina B's superior waste management systems, including rigorous hazardous waste disposal, resulted in a noticeably smaller overall environmental footprint compared to Marina A.

External Service Providers: Both marinas utilise external contractors; however, Marina B's stricter selection criteria prioritised environmentally responsible businesses, resulting in a lower overall impact from outsourced services.

This highlights the significant impact of proactive environmental management. Marina B's integrated strategy, incorporating green technologies, efficient processes, and stringent regulatory compliance, resulted in substantially lower environmental impacts compared to Marina A's more conventional approach. These findings emphasise the critical role of sustainable practises in mitigating the environmental pressures associated with high-traffic marina operations.

3.3. Risk Assessment Findings

The analysis revealed notable differences between Marina A and Marina B in terms of environmental trends (see Figure 5). Marina A, due to its outdated infrastructure and minimal enforcement of environmental regulations, posed a high risk for several key factors:

1. Pollution risk. Unregulated emissions and wastewater discharge primarily cause high levels of air and water pollution.

2. Biodiversity risk. The nearby seagrass meadows and coral reefs are experiencing significant habitat destruction and biodiversity loss.
3. Invasive species risk. Ineffective ballast water management increases the risk of introducing invasive species.

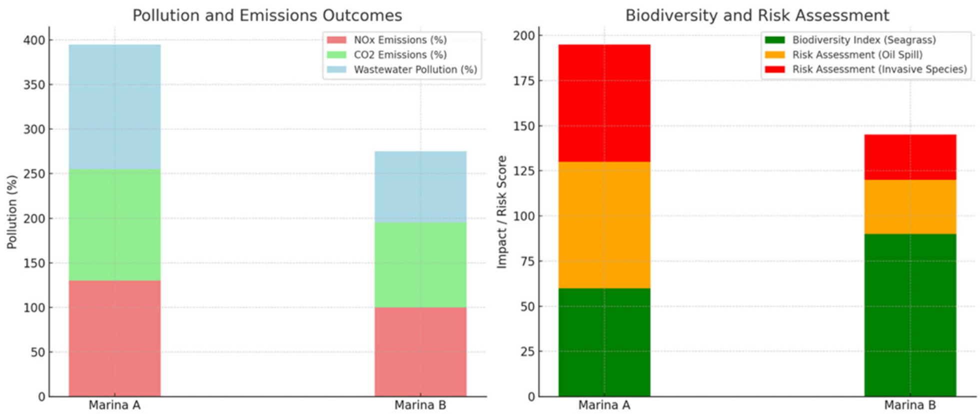

Figure 5. Marinas' risk outcome.

Marina B, however, showed much lower risk scores across all categories, reflecting its commitment to sustainable practises:

1. Pollution risk. Reduced emissions and effective wastewater treatment significantly lowered pollution risks.
2. Biodiversity risk. Strict no-anchoring zones and eco-mooring systems greatly minimised the impact on sensitive habitats.
3. Invasive species risk. Strong ballast water management policies and regular monitoring helped prevent the introduction of non-native species.

The risk matrices developed for each marina highlight the substantial environmental benefits of implementing comprehensive sustainability measures (Figure 5). Marina B serves as a model for best practises, with low-risk scores reflecting the successful integration of green technologies and regulatory compliance. The following are the calculated yearly percentage changes (Figure 6) for each environmental metric in Marina A and Marina B from 2020 to 2030:

1. NO_x Emissions:
   (1) Marina A: +3.13% to +2.44% (steady increase).
   (2) Marina B: −2.74% to −3.64% (steady decrease).
2. CO_2 Emissions:
   (1) Marina A: +2.94% to +2.33% (steady increase).
   (2) Marina B: −2.67% to −3.85% (steady decrease).
3. Biodiversity Index:
   (1) Marina A: −5.0% to −16.67% (significant decline).
   (2) Marina B: +1.25% to +2.06% (steady improvement).

Figure 7 presents the environmental trends for NO_x, CO_2 emissions, and the biodiversity index for the period 2020–2030. Marina A experienced an increase in both NO_x and CO_2 emissions, while Marina B experienced a decrease. Consequently, Marina A experienced a decrease in the biodiversity index, while Marina B experienced the opposite trend.

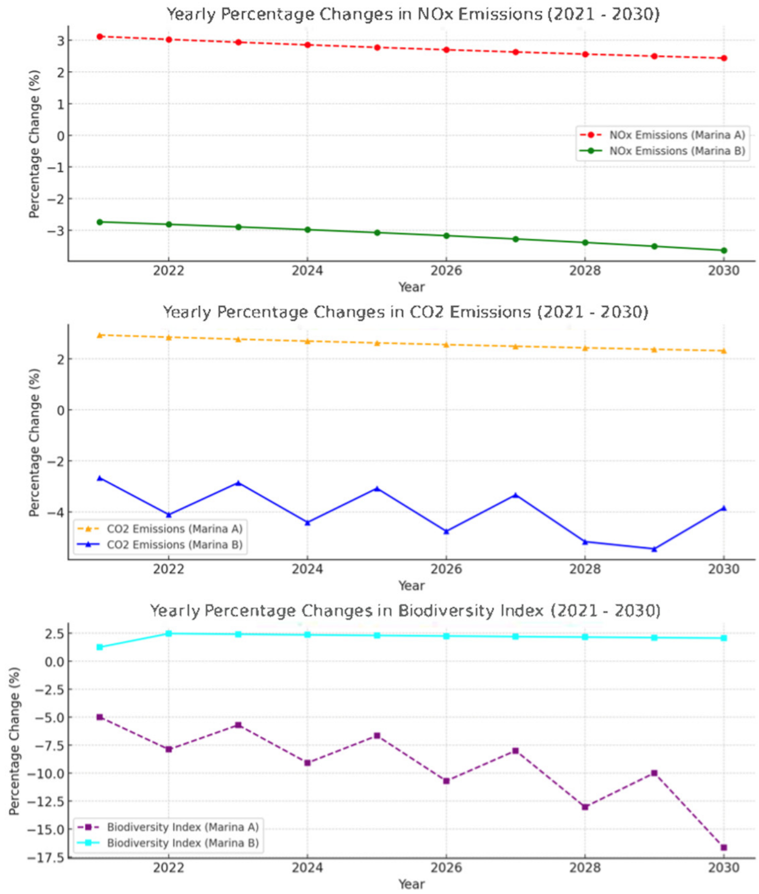

Figure 6. Yearly percentage value change for NO_x, CO_2 and biodiversity index.

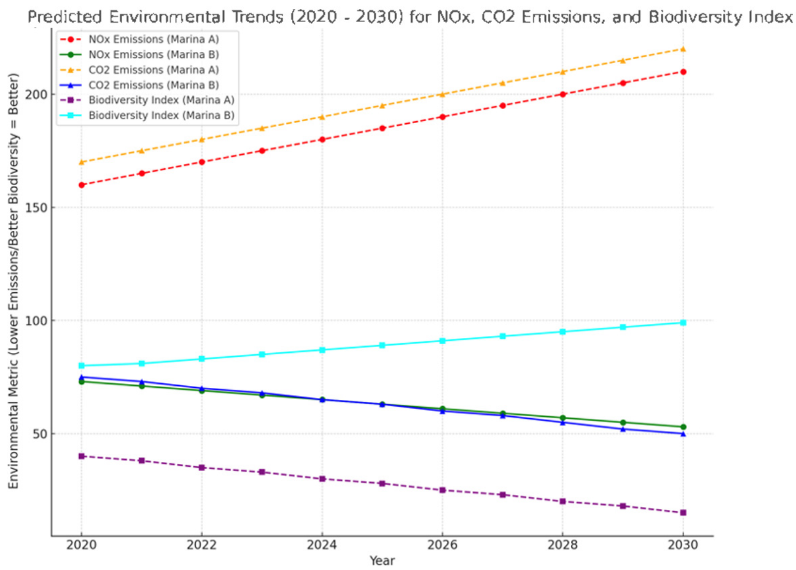

Figure 7. Predicted environmental trends over 10-year scenario.

4. Discussion

The comparative analysis of Marina A and Marina B demonstrates the critical role of sustainable environmental management in mitigating the ecological impacts of superyacht marinas. Marina A, with its outdated practises and lack of pollution controls, exhibited elevated levels of emissions and pollution, leading to significant habitat destruction and biodiversity loss. These findings align with previous studies highlighting the risks associated with unmanaged marina operations, particularly in regions with sensitive marine ecosystems [25].

In contrast, Marina B's integration of green technologies, such as hybrid propulsion systems and advanced wastewater treatment plants, resulted in substantial reductions in emissions and pollution. This highlights the effectiveness of sustainable technologies and proactive regulatory compliance [10]. This study's results demonstrate a 50% reduction in NO_x and SO_x emissions and a 25% reduction in CO_2 emissions at Marina B compared to Marina A, reinforcing the importance of technological innovation in reducing the environmental footprint of superyacht marinas. Furthermore, the implementation of eco-friendly mooring systems and no-anchor zones at Marina B effectively protected seagrass meadows and coral reefs, preserving biodiversity and enhancing ecosystem resilience.

Biodiversity loss was notably higher in Marina A due to its lack of protective measures for sensitive habitats. The constant anchoring of yachts in seagrass meadows and nearby coral reefs caused a 40% reduction in seagrass coverage over five years, contributing to a decline in biodiversity indices. The absence of eco-mooring systems exacerbated the destruction of vital habitats that serve as nurseries for marine life. Additionally, invasive species introduced via poorly managed ballast water systems and hull fouling further disrupted local ecosystems, leading to shifts in community structure.

A significant contribution of this study lies in its empirical demonstration of how targeted sustainability interventions yield measurable environmental benefits. The documented 30% improvement in biodiversity scores at Marina B compared to Marina A validated the use of eco-mooring systems, which helped to prevent physical damage to these critical habitats, while proactive ballast water management reduced the introduction of invasive species by 50%. These measures not only prevent physical damage to marine habitats but also curb the introduction of invasive species, which remains a persistent ecological threat in marina environments. Biodiversity preservation efforts, such as creating marine protected areas (MPAs), ensured the continued health of seagrass meadows, which are crucial for carbon sequestration and marine life support. In the Mediterranean, there are more than 1000 designated MPAs that cover 6.5% of the sea. Out of these, 76 MPAs fully protect 0.04% of the sea. These results demonstrate the importance of habitat protection and invasive species management.

This study advances the literature on sustainable marina management by integrating pollution source analysis with operational practises. Unlike previous research, which often assesses environmental impacts in isolation, this study applies a holistic approach that considers both technological and regulatory dimensions. The findings reinforce the necessity of enforcing stricter environmental standards across all marinas to prevent pollution and habitat destruction. Governments and regulatory bodies should implement mandatory eco-certifications, requiring marinas to adopt green technologies such as hybrid propulsion systems and advanced wastewater treatment facilities.

From a managerial perspective, the study provides actionable insights for marina operators, policymakers, and investors. The contrast between Marina A and Marina B highlights the competitive advantage of sustainability-oriented practises. Marina B's ability to reduce emissions and enhance biodiversity protection illustrates how environmental stewardship can serve as a differentiating factor in the luxury yachting industry. Managers can leverage these findings to justify investments in green infrastructure, as the long-term benefits—ranging from regulatory compliance to enhanced market reputation—outweigh the initial costs.

This study highlights the need for cross-border regulatory collaboration as necessary to ensure consistent environmental standards across Mediterranean countries. A Mediterranean-wide council could oversee a unified regulatory framework that harmonises policies on emissions, waste management, and invasive species control [2]. This would prevent marinas in countries with weaker enforcement from continuing to pollute at unsustainable levels. Marinas that adopt sustainable technologies and practises should also receive economic incentives like tax breaks or subsidies. Public recognition through awards and eco-certifications can also motivate marinas to improve their environmental performance, as demonstrated by the success of the Clean Superyacht Marina Campaign [2].

Superyacht marinas contribute significantly to air and water pollution in the Mediterranean, with emissions exceeding those of commercial ports by up to 30% due to the prevalence of large, fuel-intensive vessels [4]. One of the most pressing threats stems from frequent anchoring and the absence of designated mooring zones, which lead to habitat destruction, particularly in sensitive areas such as *Posidonia oceanica* meadows and coralligenous reefs. Over the past 50 years, recreational boating has been a major driver of seagrass decline, reducing coverage by an estimated 34% [26].

The study also sheds light on managerial challenges related to pollution control. The discharge of black and grey water from recreational crafts raises substantial environmental challenges. Black water often harbours harmful pathogens, while grey water can instigate algal blooms and contaminate marine organisms [27]. The inconsistency in regulatory standards across EU member states exacerbates these problems. Marine litter, primarily plastics from recreational boating, poses a significant threat to marine wildlife, contributing to entanglement, ingestion, and habitat degradation [28]. Additionally, while antifouling paints have regulatory oversight, they continue to release toxic substances like copper and zinc into the water, adversely affecting aquatic organisms at even low concentrations [29].

Recreational vessels also play a role in the unintentional spread of invasive species through anchor fouling and hull contamination. Studies reveal that many leisure vessels carry non-native species, raising concerns about local biodiversity and ecosystem stability [30]. Wastewater discharges from yachts, including greywater and blackwater, introduce harmful nutrients and pathogens into the marine environment, often overwhelming local water treatment facilities. This leads to issues like eutrophication, harmful algal blooms, and oxygen depletion, threatening marine biodiversity [31]. Although research into advanced wastewater treatment technologies shows promise for reducing nutrient loads, their application across Mediterranean marinas remains inconsistent [32].

The Mediterranean Sea faces a particularly acute threat from non-indigenous species (NIS). Introduction rates of NIS to the Mediterranean are notably high, exceeding the average for European waters (Figure 8). While transport vectors, such as stowaways in shipping, remain a primary pathway for NIS introduction across all European seas, the Mediterranean's unique geographic position and high level of maritime activity likely contribute to this elevated risk. This necessitates focused biosecurity measures within Mediterranean marinas, particularly those catering to leisure boats, to mitigate the risk of NIS spread and protect the region's biodiversity.

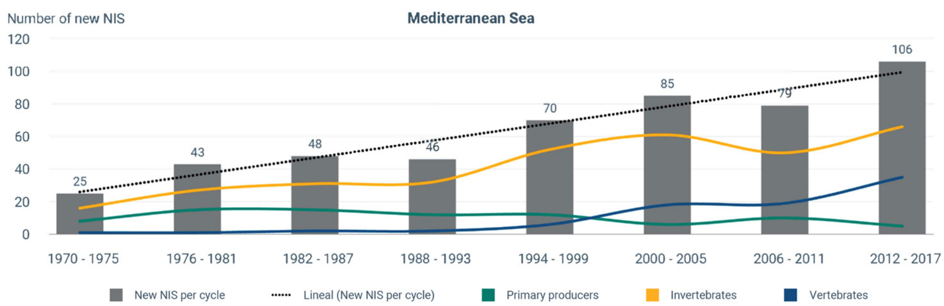

Figure 8. Non-indigenous species spread in the Mediterranean Sea (source www.europa.eu (accessed on 18 December 2024)).

Superyacht marinas, particularly those located near sensitive coastal ecosystems, have a direct impact on marine habitats. Yacht anchoring and mooring activities often damage seagrass meadows, which are critical for carbon sequestration and serve as nurseries for fish and invertebrates [11]. The physical destruction of these habitats not only reduces biodiversity but also contributes to coastal erosion and the loss of ecosystem services that support local economies.

Similar impacts occur to coral reefs and other sensitive habitats. The construction and expansion of marinas often result in habitat fragmentation, while increased yacht traffic disrupts local wildlife. For instance, a superyacht's noise pollution can disrupt the communication and breeding behaviours of marine species, thereby posing a further threat to biodiversity [2]. Studies on marine protected areas near marinas show that carefully managed mooring systems and no-anchor zones can help mitigate habitat damage [10]. Eco-friendly mooring systems, which minimise seabed disturbances, have been particularly effective in preserving seagrass meadows and coral reefs. However, where these technologies are absent, biodiversity continues to decline due to habitat degradation and pollution.

Invasive species also pose a significant threat to marine biodiversity. Ballast water discharge and hull fouling from yachts introduce non-native species, which often outcompete native organisms, leading to shifts in community structures and ecosystem functions [33]. Strengthening ballast water management practises and enforcing anti-fouling measures are essential for preventing further biodiversity loss. The introduction of non-native species via ballast water and hull fouling is one of the most pressing ecological risks associated with superyacht marinas. Invasive species, such as the algae Caulerpa taxifolia, have spread throughout the Mediterranean, outcompeting native seagrasses and disrupting local ecosystems [34]. These species often arrive through ballast water discharge, where yachts unknowingly transport organisms across regions.

Despite the Ballast Water Management Convention, the enforcement of ballast water treatment in Mediterranean marinas remains weak, particularly in smaller marinas that lack the resources for regular inspections [2]. Hull fouling, which occurs when yachts accumulate organisms on their hulls and then release them into new environments, further exacerbates the spread of invasive species. Marinas that enforce strict ballast water management and use advanced anti-fouling technologies have been successful in reducing the introduction of invasive species by up to 50% [10]. However, to achieve broader success, regional cooperation and a more rigorous enforcement of ballast water regulations are required across the Mediterranean. Without these measures, invasive species will continue to degrade biodiversity and ecosystem services critical to the region's environmental health and economy. The inconsistency in regulatory standards across EU member states also exacerbates these issues. Effective enforcement mechanisms, coupled with industry-led best practises, are essential to mitigate these threats.

The findings of this study align with the existing literature on sustainable marina management, particularly with regard to the disproportionate impact of specific activities on environmental footprints. For instance, this study corroborates previous research emphasising the importance of targeting high-impact activities, such as energy-intensive operations and wastewater management, to achieve significant ecological benefits. By integrating the Pareto principle into Green P-Mapping, this research offers a novel approach to prioritising sustainability interventions. The identification of high-impact pollution sources and their operational contexts fills a critical gap in the existing literature. Managers and policymakers can apply these insights to develop targeted strategies that maximise environmental benefits while optimising operational efficiency.

To conclude, this study contributes to both academic discourse and practical marina management by demonstrating the tangible benefits of sustainability-oriented strategies. The findings reinforce the importance of regulatory enforcement, technological innovation, and economic incentives in promoting environmentally responsible marina operations. Moving forward, a multi-stakeholder approach—incorporating policymakers, marina operators, yacht owners, and environmental organisations—will be essential to achieving long-term ecological resilience in the Mediterranean yachting sector. This research provides an analysis of pollution sources and their operational contexts, filling a critical gap in the literature as highlighted by an earlier study [35].

5. Conclusions

This comparative analysis of Marina A and Marina B highlights the critical role of sustainable management practises in mitigating the environmental impacts of superyacht marinas. Marina A, characterised by outdated infrastructure and insufficient regulatory oversight, highlights the ecological risks posed by unmanaged marina operations, including heightened emissions, suboptimal wastewater treatment, and significant biodiversity loss. Conversely, Marina B demonstrates the transformative potential of integrating advanced technologies and proactive environmental policies to minimise ecological footprints while maintaining operational efficiency.

The findings stress the efficacy of green technologies in achieving measurable environmental benefits, including a 50% reduction in NO_x and SO_x emissions and a 25% decrease in CO_2 emissions. Furthermore, biodiversity conservation efforts, such as no-anchor zones and eco-friendly mooring systems, have proven helpful in protecting sensitive marine habitats, with Marina B achieving a 30% improvement in biodiversity indices compared to Marina A.

This study accentuates the need for sustainable technologies and operational models to reduce emissions and conserve biodiversity in high-traffic marinas. Comprehensive environmental management plans (EMPs) with robust monitoring systems are critical to achieving compliance with sustainability objectives. Harmonised regulatory frameworks across Mediterranean countries are essential for addressing transboundary pollution and standardising practises, while inclusive collaboration among policymakers, marina operators, yacht owners, and environmental organisations is vital for fostering long-term ecological stewardship.

As the superyacht industry continues its rapid growth, the findings demonstrate the urgency of aligning economic development with environmental sustainability. By prioritising innovation, regulatory compliance, and ecosystem preservation, Mediterranean marinas can serve as global exemplars of sustainable coastal management. Future research should focus on scaling these practises and integrating them into a unified strategy to ensure the resilience of marine ecosystems amid rising anthropogenic pressures.

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