



Case Study: Risk mapping of contamination from fish industry waste in the marine-coastal zone of the Santa Rosa District, Peru, using remote sensing tools

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Abstract: Anthropogenic contamination in marine-coastal ecosystems remains one of the most pressing environmental challenges globally. In Peru, despite the significant presence of fish processing activities, there is a lack of comprehensive assessments regarding the generation and management of solid waste from this sector. This study focuses on the Santa Rosa District in the Lambayeque region, analyzing the risk of contamination caused by fish industry waste discharged into the Pacific Ocean through Drain 4000, covering an area of approximately 16 km². Utilizing 455 Sentinel-2 L2A satellite images from 2018 to 2023 and remote sensing techniques integrated with GIS tools, we developed contamination risk maps that highlight the most vulnerable zones. The combination of these technologies enables a spatially detailed, timely, and cost-effective method for environmental monitoring. Results indicate that the areas surrounding the fish processing facilities in Santa Rosa are at high risk of contamination, posing serious ecological and socio-economic threats. These insights provide a foundation for targeted environmental policies and improved waste management strategies in the region.

Keywords: Marine pollution, fishery waste, monitoring, remote sensing tools.

Resumo: A contaminação antrópica em ecossistemas marinho-costeiros continua sendo um dos desafios ambientais mais urgentes em escala global. No Peru, apesar da forte presença de atividades de processamento de pescado, faltam avaliações abrangentes sobre a geração e o manejo de resíduos sólidos desse setor. Este estudo concentra-se no distrito de Santa Rosa, na região de Lambayeque, analisando o risco de contaminação causado por resíduos da indústria pesqueira lançados no Oceano Pacífico por meio do Dreno 4000, abrangendo uma área de aproximadamente 16 km². Foram utilizadas 455 imagens de satélite Sentinel-2 L2A entre 2018 e 2023 e técnicas de sensoriamento remoto integradas a ferramentas SIG, permitindo desenvolver mapas de risco de contaminação que destacam as zonas mais vulneráveis. A combinação dessas tecnologias possibilita um método de monitoramento ambiental com detalhamento espacial, tempestividade e custo reduzido. Os resultados indicam que as áreas próximas às instalações de processamento de pescado em Santa Rosa apresentam alto risco de contaminação, configurando sérias ameaças ecológicas e socioeconômicas. Esses achados oferecem subsídios para políticas ambientais direcionadas e estratégias aprimoradas de gestão de resíduos na região.

Keywords: Poluição marinha, resíduos pesqueiros, monitoramento, ferramentas de sensoriamento remoto.

1. Introduction

The maritime and coastal regions of Peru are crucial to the nation's economy and ecology [1]. Peru, being a prominent fishing nation, is significantly dependent on its maritime resources. The Peruvian fishing sector generates a significant share of the nation's exports, with anchovies being the primary species for fishmeal production, utilized in animal feed worldwide. The swift growth and industrialization of the fishing industry have resulted in considerable environmental issues [2]. These encompass organic trash, chemical runoff, discarded plastics, and effluents discharged into coastal waterways, which present significant threats to marine ecosystems and people communities dependent on coastal resources [3].

Marine pollution, especially from garbage produced by fishing companies, compromises water quality, devastates habitats, and results in biodiversity decline [4]. Organic waste from fish processing facilities is frequently abundant in nitrogen and phosphorus, nutrients that can induce eutrophication, resulting in harmful algal blooms (HABs) and hypoxic zones where

oxygen levels are insufficient to sustain most marine organisms [5]. Moreover, chemical contaminants, including those utilized in the preservation and processing of fish, can bioaccumulate in marine organisms and infiltrate the food chain, resulting in enduring ecological harm and health hazards [6].

Considering these environmental difficulties, there is an urgent necessity for ongoing surveillance of Peru's marine-coastal regions [7]. Conventional monitoring techniques, such as in-situ water sampling, although successful locally, are labor-intensive, time-consuming, and frequently constrained by accessibility to remote regions. Remote sensing presents a viable option [8]. Satellite imaging and data processing enable the monitoring of extensive environmental changes, identification of pollution sources, and evaluation of the spatial distribution of contamination [9].

Remote sensing has effectively been employed globally to observe marine pollution [10]. For instance, the Deepwater Horizon oil disaster in the Gulf of Mexico in 2010 utilized satellite photography extensively to monitor the development

and trajectory of oil slicks [11]. In the Mediterranean, satellite tracking has been employed to identify unlawful rubbish dumping from vessels [12]. In areas such as Southeast Asia, remote sensing has facilitated governmental oversight of aquaculture's effects on coastal ecosystems, particularly with nutrient runoff and sedimentation [13]. These examples illustrate the potential of remote sensing for environmental monitoring and emphasize the importance of employing such approaches in Peru [14].

This study aims to apply remote sensing tools to map contamination risks in the marine-coastal zone of the Santa Rosa District, Lambayeque, focusing on waste generated by local fish processing activities [15]. By integrating satellite imagery with Geographic Information Systems (GIS), the research identifies high-risk zones near Drain 4000 and examines the spatial distribution of pollution in the surrounding marine environment [16]. The findings are expected to support the development of targeted environmental management strategies and promote more sustainable practices within the artisanal fishing industry in Santa Rosa [17]. Moreover, the use of remote sensing in this case study underscores its potential as a long-term monitoring tool for marine and coastal ecosystems [18].

In the broader context, this research contributes to the growing body of literature on the use of remote sensing for environmental conservation [19]. Recent advances in satellite technology, such as higher resolution imagery and more frequent data collection, have made remote sensing an indispensable tool for environmental scientists and policymakers alike [20]. As global concerns over marine pollution rise, especially with respect to plastic debris, oil spills, and nutrient runoff, remote sensing is increasingly seen as a crucial component of integrated environmental monitoring systems [3].

1.1 Study area

The marine-coastal zone of the Santa Rosa District, located along Peru's northern Pacific coastline (Figure 1), is part of a dynamic and ecologically rich region influenced by the Humboldt Current, a cold, nutrient-rich oceanic current that sustains one of the most productive marine ecosystems globally [21]. This area includes important coastal features such as estuarine zones and sandy beaches, which are critical for both biodiversity and economic activities. Santa Rosa, known for its artisanal and small-scale fish processing operations, contributes to Peru's broader fishing industry, particularly in anchovy processing for fishmeal and fish oil-key products in international markets [16]. The ecological significance of this region, combined with intense fishing activity, underscores the need for sustainable environmental management practices [22].

Figure 1. Location of the study area.



Source: Crop-monitoring.

1.2 Regional characteristics

The northern coast of Peru, where the Santa Rosa District is located, features a mix of productive marine and coastal ecosystems that support diverse fishing activities. While it lacks extensive mangrove systems like those found in Piura and Tumbes, the Santa Rosa area plays a vital role in supporting artisanal fisheries and small-scale fish processing industries [16]. These operations contribute to local livelihoods but also pose environmental risks, especially in the absence of proper waste management. The region is highly sensitive to climatic events such as El Niño, which can alter sea surface temperatures, disrupt marine productivity, and exacerbate the impacts of organic runoff and fish waste contamination [23].

Unlike the central coast, where industrial fishing operations dominate near Lima and Callao, the Santa Rosa District is less urbanized but still faces growing environmental challenges. Although it lacks the scale of large ports, localized fish processing activities near Drain 4000 have led to concerns over wastewater discharge and pollution of coastal waters. Without adequate regulation and infrastructure, even small-scale operations can significantly impact marine ecosystems through nutrient loading, habitat alteration, and degradation of water quality [24].

Similarly, while not as industrially intense as southern ports like Chimbote or Pisco, Santa Rosa shares some of the same environmental vulnerabilities. These include the accumulation of organic sediments from fish waste and possible contamination of coastal waters due to inefficient treatment systems. Such conditions can alter the ecological balance of the area, affecting both marine life and the sustainability of the local fishing economy [25].

1.3 Ecological and economic importance

The marine-coastal zone of the Santa Rosa District in northern Peru encompasses ecologically important environments, including estuarine areas and sandy coastal zones. These ecosystems provide essential services such as supporting artisanal fisheries, buffering the coastline against erosion, and serving

as critical habitats for the early life stages of marine species [26]. However, these coastal areas are increasingly threatened by human activities – particularly those linked to local fish processing operations. Waste discharged from these facilities, often rich in organic material, can lead to eutrophication, harmful algal blooms, and oxygen depletion in surrounding waters, all of which negatively impact marine biodiversity [27].

In Santa Rosa, the fishing industry plays a vital socio-economic role, supporting the livelihoods of numerous small-scale artisanal fishers and their families. These communities depend heavily on the health of marine ecosystems for both subsistence and economic stability [17]. However, they are especially vulnerable to the environmental consequences of fish waste pollution, as well as shifts in oceanographic conditions driven by climate variability, such as El Niño Southern Oscillation (ENSO) events. These factors can reduce fish availability, disrupt fishing patterns, and increase ecological stress in coastal waters [27].

1.4 Environmental challenges

Several environmental challenges are present within the Santa Rosa District's coastal zone. One of the primary concerns is organic pollution from artisanal fish processing facilities, which discharge effluents rich in nitrogen and phosphorus. These nutrients stimulate excessive phytoplankton growth, often resulting in harmful algal blooms [28]. As these blooms decompose, they consume large amounts of dissolved oxygen, potentially creating hypoxic “dead zones” that cannot sustain marine life. This process threatens the biodiversity and long-term sustainability of the local marine-coastal ecosystem [29].

Plastic waste is also an emerging issue in the Santa Rosa area, particularly near fishing and processing centers. Items such as discarded fishing nets, plastic containers, and packaging materials accumulate along the coast and in the sea, contributing to the global problem of marine plastic pollution [30]. These pollutants not only endanger marine fauna through entanglement and ingestion but also pose economic risks by affecting tourism and reducing the quality of fishery resources [31].

Additionally, although aquaculture in Santa Rosa is less developed compared to other northern regions, the lack of regulation in surrounding areas has contributed to sedimentation and water quality degradation. The expansion of shrimp farming operations nearby has raised concerns over habitat loss and environmental degradation, particularly in estuarine zones that function as nurseries for marine species [22]. These pressures compound the environmental stress already present due to waste mismanagement and inadequate coastal planning.

1.5 Socio-economic considerations

The marine-coastal zone of the Santa Rosa District plays a vital role in the local and regional economy. The artisanal fishing industry provides employment and sustains the livelihoods of

many families in the community. However, the environmental degradation linked to fish processing activities and poor waste management presents long-term risks to the sustainability of this sector [30]. Artisanal fishers in Santa Rosa are particularly vulnerable, as they rely heavily on nearby marine resources and often lack the financial and technological capacity to adapt to declining environmental conditions. As a result, pollution and overexploitation directly impact their income, food security, and overall well-being [22]. The social consequences of marine ecosystem degradation, including job loss, increased poverty, and reduced access to food, are crucial considerations in the environmental management of this coastal district [32].

Addressing these environmental and socio-economic challenges in Santa Rosa requires a holistic strategy that includes the promotion of sustainable fishing practices, proper treatment and disposal of fish processing waste, and strict enforcement of environmental regulations [16]. In this context, the use of remote sensing tools, as demonstrated in this study, provides an effective means to monitor pollution patterns and identify high-risk areas. These tools offer essential insights that can guide local authorities and policymakers in making informed decisions to protect marine ecosystems and support community resilience.

2. Materials and methods

This study employed an integrated approach using satellite imagery, remote sensing techniques, and Geographic Information Systems (GIS) to assess contamination risk in the marine-coastal zone of the Santa Rosa District, Lambayeque, Peru. A total of 455 Sentinel-2 Level 2A satellite images, acquired between January 1, 2018, and December 31, 2023, were analyzed. Sentinel-2 was selected due to its high spatial resolution (10–20 meters), wide swath coverage, and short revisit time (5 days), which make it particularly suitable for detecting subtle changes in coastal and marine environments over time. The Level 2A product, which provides bottom-of-atmosphere reflectance, enables more accurate analysis of environmental parameters relevant to water quality monitoring.

The key environmental indicators derived from the satellite data and used in the contamination risk assessment included chlorophyll-a concentration, sea surface temperature (SST) anomalies, and suspended particulate matter (SPM). Chlorophyll-a serves as an indirect measure of phytoplankton biomass and acts as a proxy for nutrient enrichment and organic pollution, particularly from fish viscera and wastewater discharges. SST anomalies reflect variations in sea surface temperature that can indicate thermal pollution and environmental stress often associated with effluent discharges or shifts in oceanographic conditions. Elevated levels of SPM suggest sediment runoff or the presence of organic and inorganic waste discharged by fish processing facilities, further contributing to the degradation of water quality in the study area.

These parameters were retrieved and processed using LandViewer, a free, web-based remote sensing, and GIS, platform

developed by EOS Data Analytics. LandViewer enables the visualization and analysis of satellite data through preconfigured spectral indices and band combinations that are well-suited for monitoring aquatic environments. The Chlorophyll-a Index, Normalized Difference Turbidity Index (NDTI) for SPM, and Sea Surface Temperature index (SST) were selected from LandViewer’s analytics toolbox, ensuring consistency and reliability in detecting pollution-related patterns over the six-year study period.

The satellite data was processed using GIS software (such as ArcGIS and QGIS) to generate spatial risk maps. The data was classified into different risk levels based on pollution indicators, and the spatial distribution of high-risk zones was analyzed. The number of fish processed per year from 2018 to 2022, and the amount of effluent generated from the amount of solid waste (viscera) produced were also considered (Tables 1, 2 and 3).

The processed data was used to generate spatial risk maps, classifying the study area into different contamination risk levels based on the environmental indicators derived. The spatial distribution of high-risk zones was then analyzed in relation to key pollution sources, particularly Drain 4000, which receives effluents from the local Centro de Procesamiento Pesquero Artesanal (CEPPAR). Additionally, the annual volume of fish processed in Santa Rosa between 2018 and 2022 was considered, alongside estimations of effluent generated based on the amount of solid waste, mainly fish viscera, produced during processing (see Tables 1, 2 and 3). This combination of remote sensing data and locally sourced production statistics allowed for a more comprehensive assessment of contamination dynamics.

Table 1. Fish processed by month and year, tonnes (t).

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2018	245	231	315	249	34	54	18	41	262	298	126	355
2019	503	606	467	298	159	139	133	136	118	105	79	176
2020	277	284	766	59	68	102	147	177	96	80	98	47
2021	159	296	197	209	187	196	211	138	204	178	266	242
2022	309	313	278	236	158	162	115	142	71	140	157	91
Total	1492	1730	1800	1051	60	653	623	634	750	800	726	912
\bar{X}	298	346	360	210	121	131	125	127	150	160	145	182

Source: CEPPAR (2024)

Table 2. Solid waste (viscera) generated per tonne of fish processed, t.

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2018	44	42	57	45	6	10	3	7	47	54	23	64
2019	91	109	84	54	29	25	24	25	21	19	14	32
2020	50	51	138	10	12	18	26	32	17	14	18	8
2021	29	53	35	37	34	35	38	25	37	32	48	44
2022	55	56	50	42	28	29	21	25	13	25	28	16
Total	269	311	684	189	109	117	112	114	135	144	131	164
\bar{X}	54	62	137	38	22	24	22	23	27	29	26	33

Source: CEPPAR (2024)

Table 3. Water used per tonne of fish processed, cubic metres (m³).

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2018	302	285	388	308	41.7	66	22	50	323	367	156	438
2019	621	748	576	368	196	171	164	168	146	130	97	217
2020	342	351	946	72	84	126	181	219	118	98	121	58
2021	196	365	244	257	231	242	261	171	251	220	328	299
2022	381	386	343	291	195	200	142	175	88	172	194	212
Total	1841	2135	2689	1297	748	805	769	783	926	987	896	1225
\bar{X}	368	427	538	259	150	161	154	157	185	197	179	245

Source: CEPPAR (2024)

2.1 Remote sensing data processing

The satellite imagery was pre-processed to correct atmospheric interference and sensor noise. Standard image correction techniques were applied using software tools such as ENVI and QGIS. For Landsat 8 imagery, atmospheric correction was performed using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS), while Sentinel-2 data were processed using the Sen2Cor processor.

After pre-processing, specific remote sensing indices were calculated to detect potential contamination in the marine environment. Key indices used in this study included: (i) Normalized Difference Water Index (NDWI): This index was used to detect water bodies and monitor changes in water quality. (ii) Chlorophyll-a Concentration: Derived from multispectral bands, this indicator is used to detect algal blooms, which can signify organic waste pollution. (iii) Turbidity Index: This index was calculated to identify areas with high levels of suspended sediments, which may be associated with runoff or industrial discharge.

2.2 GIS analysis and risk mapping

Geographic Information Systems (GIS) were used to integrate remote sensing data with other spatial datasets, such as maps of industrial activity, population density, and coastal topography. The GIS platform allowed for the overlay of multiple data layers to identify potential contamination sources and their spatial relationships with sensitive marine habitats. Key steps in the GIS analysis included: (i) Spatial Data Integration: Satellite-derived indices, in-situ data, and industrial activity maps were integrated into a single GIS platform. (ii) Buffer Analysis: Buffers were created around major industrial fishing ports and processing plants to assess the extent of contamination risk. (iii) Weighted Overlay Analysis: A weighted overlay method was applied to combine various risk factors (e.g., organic waste, turbidity, chemical pollutants) and produce a comprehensive risk map. Each factor was assigned a weight based on its relative importance to marine ecosystem health.

2.3 Validation and accuracy assessment

The accuracy of the remote sensing and GIS-based contamination risk map was assessed using both in-situ measurements and historical data. Water quality data from field surveys were compared with satellite-derived indices to validate the accuracy of pollution detection. Additionally, historical records of contamination events, such as harmful algal blooms or fish kills, were used to assess the predictive capability of the risk map.

The final risk map was evaluated using standard statistical methods, including correlation analysis between remote sensing data and field measurements. The accuracy of the contamination risk zones was assessed using a confusion matrix, comparing the model's predictions with actual contamination events observed during the study period. This combined methodology, integrating remote sensing data, GIS analysis, and in-situ validation, provides a robust framework for assessing and mapping contamination risks in Peru's marine-coastal zone.

3. Results

The results of this study focus on the spatial distribution of contamination risk in Peru's marine-coastal zone, with specific emphasis on areas impacted by waste from fishing industries. The contamination risk map developed using remote sensing tools reveals several key patterns of pollution, particularly around major fishing ports.

3.1 Contamination risk zones

High-Risk Areas: The areas around Chimbote, Pisco, and Callao were identified as high-risk zones due to the concentration of industrial fishing activities. These regions exhibited elevated levels of chlorophyll-a, indicating the presence of organic waste in the water. The satellite-derived turbidity index also showed higher values in these areas, pointing to increased levels of suspended sediments.

Moderate-Risk Areas: Moderate contamination risk was observed in coastal regions near Tumbes and Piura. These areas support both artisanal and industrial fisheries but are less industrialized than the southern ports. However, nutrient run-off from aquaculture and agriculture was detected, increasing the potential for eutrophication in coastal waters.

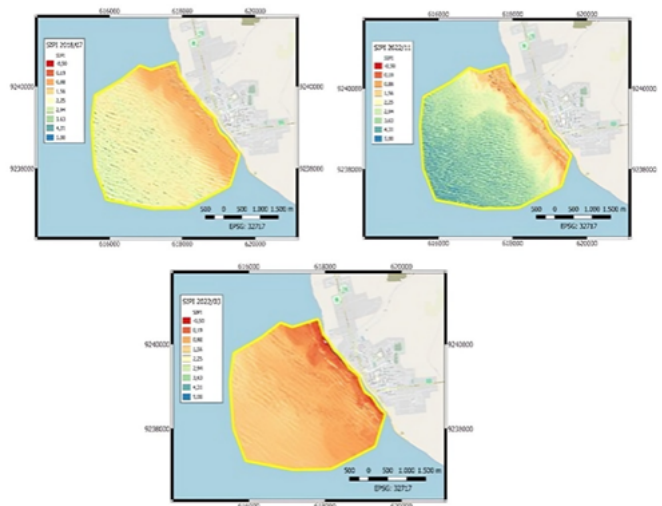
Low-Risk Areas: The northern coast, including mangrove regions, was identified as a low-risk zone, though some pockets of pollution were detected. These were attributed to small-scale artisanal fishing and aquaculture operations.

3.2 Temporal variability

Seasonal analysis of satellite data revealed temporal variability in contamination levels. During the warmer months, especially under the influence of the El Niño Southern Oscillation

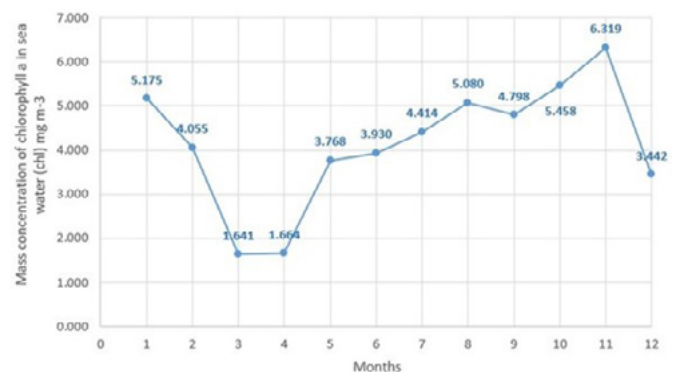
(ENSO), there was a marked increase in sea surface temperatures, which correlated with higher chlorophyll-a concentrations and algal bloom activity. The risk of contamination increased during these periods, suggesting that climate variability plays a significant role in modulating pollution levels (Figure 2). This pattern is corroborated by the satellite-derived fields of chlorophyll-a mass concentration, which exhibit pronounced seasonal peaks and ENSO-linked anomalies in mg m^{-3} , reinforcing the link between thermal forcing and bloom intensity (Figure 3, Mass concentration of chlorophyll a in seawater).

Figure 2. Risk maps.



Source: Crop-monitoring.

Figure 3. Mass concentration of chlorophyll-a in sea water (chl) mg m^{-3} .



Source: Crop-monitoring.

4. Discussion

The analysis revealed that pollution along the Peruvian coast is a high risk due to waste from the fishing industries, with the northern coastal marine strip showing a strong impact generated by artisanal fishing operations, as high levels of chlorophyll-a were found with values of 5,175 and 6,319 mg m^{-3} (figure 3), especially in the months of greatest production (November -

February), which indicates contamination by nutrients from organic waste. As corroborated by Ortiz Alvarez et al. [15] who, in a study carried out in the fishing areas of the Peruvian coast, estimated that artisanal fisheries deposit more than 10,000 kg of solid waste directly into the sea every year. The risk is greater, as most of the solid waste generated by artisanal fishing is dumped directly into the sea, directly affecting the marine ecosystem [33].

Ma et al. [10] report that rapid industrial development has intensified marine pollution, leading to the degradation of coastal bays, marine resources, and the wider environment [34]. The most serious situation is the high organic load that is dumped, favouring the increase of eutrophication processes in seawater, becoming a serious threat to marine biodiversity [35]. Likewise, anthropogenic waste rich in organic matter, as well as wastewater discharges from fishing industries, have led to the eutrophication of coastal waters, with the consequent deoxygenation of estuaries [2].

In the northern region, the proximity of artisanal fisheries to coastal ecosystems such as mangroves and wetlands increases the vulnerability of these habitats to pollution. The use of remote sensing made it possible to detect localised pollution that would be difficult to identify by conventional means. Similarly, in the southern region, industrial fishing contributes to significant pollution, including chemical pollutants and organic waste. [20] report that remote sensing tools have been playing a crucial role in marine monitoring, allowing us to map large areas of coastline, and to measure chlorophyll-a concentrations, suspended sediment concentration, seawater temperature in offshore areas, etc.

The risk map generated from this study provides valuable information on the spatial distribution of pollution risks along the Peruvian coast. The results can be used to prioritize areas for environmental clean-up efforts and inform policy makers of the need for stricter regulations on waste management in the fishing industry. As mentioned by [10] and [36], marine environmental monitoring is of great importance both from a theoretical and practical point of view, and is a crucial step to maintain the quality of the marine environment and ensure its ecology, and to achieve sustainable development of the marine ecosystem. On the other hand, the management of marine-coastal zones requires constant monitoring to assess the multiple threats and environmental problems; however, there are still technological gaps in many countries around the world to obtain the necessary data for good decision-making [14].

The results underline the importance of industrial activity as the main risk factor for pollution in Peru's marine-coastal zone. High-risk areas such as Chimbote, Pisco and Callao, where fishmeal production and fishing operations are concentrated, face significant pollution pressures. Organic waste discharged into the water not only causes eutrophication, but also depletes oxygen levels, which can lead to fish kills and loss of biodiversity.

Productive activities close to coastal areas, nutrient and carbon cycling and changing environmental conditions, generated by climate change, affect the oxygen content in the ocean, greatly impacting marine life [37]. On the other hand, Peru has a large artisanal fishing fleet on which many coastal communities depend for food and livelihoods. However, no studies have yet been conducted on the production and management of solid waste from artisanal fisheries and its impact on associated communities [15].

The study confirms that regions with intensive fish processing are particularly vulnerable to organic pollution. High levels of chlorophyll-a in these areas indicate nutrient enrichment from organic waste, which favors the growth of harmful algal blooms. These blooms can have cascading effects on the marine ecosystem, such as oxygen depletion and the creation of hypoxic zones, or 'dead zones', where marine life cannot survive. Furthermore, [38] found that there is a strong relationship between significant differences between sufficient and low oxygen saturation for fish growth.

This problem has a direct impact on the economy of coastal areas, as this change has strong economic implications for the fisheries sector, including catch and closure periods, as well as the cost of effort and the commercial value of fish [39]. As such, areas with declining oxygen levels that support large-scale fisheries are expected to be economically affected (e.g. sardines and anchovies in the waters off Peru and California), where a large oxygen minimum zone has developed, are particularly vulnerable to changes in oxygen content [29].

5. Challenges and limitations

While remote sensing is a powerful tool for environmental monitoring, there are certain limitations to its application. One of the main challenges in this study was the lack of ground-based data to validate the satellite-derived contamination indicators. Future studies should incorporate fieldwork to verify the accuracy of remote sensing data and provide a more comprehensive assessment of contamination risks.

5.1 Data availability and quality

One of the primary challenges in this study was the availability and quality of data. Remote sensing relies heavily on satellite imagery, and while platforms such as Landsat and Sentinel provide extensive data coverage, there are limitations. Cloud covers, particularly in coastal areas, often affect the quality of the images, making it difficult to capture consistent, high-quality data. This is particularly problematic during the rainy season when cloud interference is more frequent.

Additionally, the spatial and temporal resolution of satellite imagery can pose a challenge. While high-resolution data is ideal, it is not always available for specific times or areas of interest. Some regions might have data gaps due to limited satellite overpasses, leading to less frequent updates on pollution levels. The lack of

high-frequency data in some remote or under-monitored regions can impact the accuracy of the risk map, especially when trying to monitor rapidly changing environmental conditions.

5.2 In-situ data limitations

In-situ measurements were used to validate remote sensing data, but the coverage of these measurements was limited to specific points along the coast, primarily near major fishing ports. This presents a challenge for creating a comprehensive risk map because contamination levels may vary significantly over short distances, especially in dynamic coastal environments influenced by tides, currents, and human activity. The lack of extensive field data, especially in more remote areas, limits the robustness of the model and can introduce errors or biases in the final risk map.

5.3 Complexity of marine ecosystems

Marine ecosystems are inherently complex and are influenced by a multitude of factors, both natural and anthropogenic. The study focuses on the contamination caused by fishing industry waste, but other sources of pollution, such as agricultural runoff, urban wastewater, and industrial discharges, also contribute to the overall pollution load in the coastal zone. Separating the impact of fishing industry waste from these other factors is challenging, particularly when dealing with limited field data.

Additionally, marine ecosystems are influenced by seasonal and inter-annual variability, such as those induced by the El Niño Southern Oscillation (ENSO). This variability can affect water temperature, circulation patterns, and nutrient availability, all which influence pollution dispersion and the occurrence of algal blooms. Incorporating these dynamic factors into a risk model adds another layer of complexity, and the current study may not fully account for such variations.

5.4 Remote sensing constraints

While remote sensing is a powerful tool for monitoring large areas, it has its limitations. Detecting pollution in coastal waters, particularly organic waste, can be challenging because the signatures of pollution (such as increased turbidity or chlorophyll-a levels) may not always be directly attributable to human activities. Natural processes like sediment resuspension, algal growth, and tidal mixing can produce similar signals, leading to potential misinterpretations. Furthermore, remote sensing may struggle to detect certain types of pollution, such as chemical contaminants or microplastics, which require more specialized monitoring techniques.

5.5 Accuracy of risk mapping and weighting

The development of a risk map relies on assigning appropriate weights to different pollution factors, such as turbidity, chlorophyll-a concentrations, and proximity to fishing ports. However, determining the correct weighting for each factor is not always straightforward, and it introduces a degree of subjectivity.

Different weighting schemes may produce different risk maps, and there is no universally accepted method for selecting these weights. This limitation is compounded by the lack of comprehensive field data to inform and validate the weighting process.

5.6 Policy and management implications

While the risk map provides valuable insights into potential contamination hotspots, translating these findings into actionable policies remains a challenge. Coastal management in Peru involves multiple stakeholders, including government agencies, fishing industries, local communities, and environmental organizations, each with their own priorities and concerns. The implementation of stricter waste management regulations or enforcement of pollution control measures may face resistance from stakeholders concerned about the economic impacts on the fishing industry. Balancing environmental protection with the economic needs of local communities is a delicate issue that may hinder the practical application of the study's findings.

6. Conclusion

This research successfully demonstrated the use of remote sensing tools to assess the risk of contamination from fishing industries in Peru's marine-coastal zone. The risk map generated in this study provides valuable insights into the spatial distribution of contamination and highlights areas where mitigation efforts are most needed. The findings underscore the importance of remote sensing in environmental monitoring and offer recommendations for future research and policy development.

The development of a risk map for contamination caused by fishing industry waste in Peru's marine-coastal zones provides a crucial step toward understanding and mitigating the environmental impacts of one of the country's most significant economic sectors. Through the use of remote sensing technologies, this study was able to highlight areas that are most vulnerable to pollution, identifying critical hotspots near major fishing ports and industrial centers. The findings suggest that while fishing waste is a significant source of pollution, it must be understood within the broader context of other anthropogenic activities and natural processes that contribute to coastal contamination.

Remote sensing tools, such as Landsat and Sentinel satellites, proved to be invaluable for monitoring large and remote areas, providing an efficient means of assessing water quality indicators like turbidity and chlorophyll-a concentrations. However, the limitations of satellite data—such as low temporal and spatial resolution in certain regions—emphasize the need for continued innovation in both remote sensing technology and in-situ data collection. To ensure that these risk maps can be reliably used for environmental management and policy development, future efforts must focus on integrating higher-resolution data and incorporating other pollution sources beyond fishing waste.

The complexity of marine ecosystems further underscores the importance of interdisciplinary approaches. Involving stakeholders such as government agencies, local communities, and the private sector in coastal management will be essential for translating scientific insights into practical solutions. The role of remote sensing in these collaborative efforts cannot be overstated, as it provides an objective, large-scale view that can guide more targeted interventions on the ground.

This study also highlights the importance of adaptive management strategies, especially in the context of climate change. As Peru's coastal environments continue to face threats from rising sea levels, increased temperatures, and shifting oceanic conditions, pollution risks may also evolve. Continued research is necessary to model future contamination risks under various climate scenarios and to develop proactive solutions that protect both the environment and the economic livelihoods tied to marine resources.

In conclusion, the integration of remote sensing tools into coastal pollution management represents a forward-thinking approach to preserving the health of Peru's marine ecosystems. By identifying contamination hotspots and understanding the multifaceted drivers behind pollution, stakeholders can implement more effective regulations and conservation measures. The success of these efforts, however, will depend on a commitment to ongoing research, technological advancement, and strong collaboration among all parties involved.

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