Integrating Hyperspectral Imaging and the Spectral Angle Mapper Algorithm for Sustainable Biofouling Management along the Qatar coast

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Globally, non-indigenous biofouling organisms are recognized as serious threats to biodiversity, economy, and human health. Our recent study confirmed that biofouling organisms associated with marine structures and litter along the Qatar coast pose significant ecological and economic concerns. Effective management of biofouling requires detection and classification methods. In this context, this study integrates hyperspectral imaging (HSI) and spectral angle mapper (SAM) algorithm to address marine biofouling issues sustainably. HSI provides a non-invasive, high-resolution approach to capture the spectral signatures of various biofouling organisms, while the SAM algorithm enables accurate classification by comparing spectral similarities. Sampling of biofouling organisms associated with marine structures and litter along the Qatar coast was conducted during December 2024. The hyperspectral images of the collected samples were captured using a VNIR (400–1000nm) hyperspectral camera. Atmospheric correction, noise reduction, and normalization were applied to account for varying illumination conditions. The SAM algorithm applied to the HSI classified each pixel based on the angle between its spectral vector and reference spectra of known biofouling species. Classification results were validated against ground truth data using metrics such as overall accuracy and confusion matrices. Distinct spectral signatures were identified for major biofouling types, including barnacles, mollusks, and algae. Pre-processing minimized spectral overlap between closely related species. The SAM algorithm achieved an overall accuracy exceeding 90%, with particularly high accuracy for barnacles. Its robustness was demonstrated under varying light conditions. This study highlights the effectiveness of interesting HSI and SAM algorithm for detecting and classifying biofouling monitoring, contributing to sustainable coastal management. Future work will focus on incorporating machine learning classifiers to enhance discrimination between closely related species.

KEYWORDS
~ Biofouling
~ Barnacle
~ Marine litter
~ Hyperspectral imaging
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1. INTRODUCTION

Marine litter is one of the most pervasive environmental pollution challenges facing the oceans today, directly and indirectly affecting all marine ecosystems. In coastal areas, particularly in sand dunes, vegetation plays a crucial role in trapping marine litter. Various organisms utilize different types of marine litter for diverse ecological functions, such as foraging, predator protection, and shelter from competitors. Species attached to marine litter may be transported to new locations by ocean currents and winds using anthropogenic materials such as plastic, anthropogenic wood, and textiles as vectors in a process known as 'rafting' (Rech et al., 2021; Povoa et al., 2025). Organisms associated with marine litter can become harmful when they invade new ecosystems, disrupting the structure and function of native habitats. Biofouling presents significant challenges to the maritime and oil-refining industries in the Arabian Gulf region (Al-Khayat et al., 2021). Biofouling not only introduces non-indigenous species but also impacts multiple sectors, such as shipping, aquaculture, offshore marine energy, renewable ocean energy, ocean-observing systems and marine debris accumulation (Zhang et al., 2019; Povoa et al., 2021; Qian et al., 2022). As a result, biofouling leads to considerable economic costs by increasing expenses related to equipment and instrument use, as well as reducing the output of marketable aquaculture products (GESAMP, 2024). For underwater instruments, biofouling is the primary challenge influencing functionality, upkeep, and data accuracy. Direct costs stem from maintaining, repairing, and replacing equipment, while indirect costs result from compromised decision-making due to unreliable instrument performance either from fouling-induced errors or mitigation efforts that disrupt calibration or operation. These combined costs have spurred significant investments in developing strategies and technologies to control biofouling on stationary instrument-equipped structures (GESAMP, 2024).

Research on biofouling in the Arabian Gulf is essential for developing effective strategies to mitigate its impact on marine infrastructure. Accurate identification of biofouling types and their extent is not only crucial for preventing substantial economic losses but also vital for maintaining ecological balance and biodiversity. However, biofouling identification and management remain major challenges in marine ecosystems with considerable implications for environmental sustainability and industrial operations (Santos et al., 2022; GESAMP, 2024). Identification methods range from conventional techniques such as microscopic inspection, macroscopic photography, molecular biology assays, ecological assessments, community involvement, and chemical analyses (Hong et al., 2024). Yet, these traditional approaches are often time-consuming, expensive, and labor-intensive. As a result, AI-based techniques are emerging as essential tools for the detection, classification, and quantification of biofouling (Mannix et al., 2021). Hyperspectral Imaging (HSI) has recently been suggested for marine monitoring as a more precise and detailed alternative to RGB cameras for taxonomic studies (Kumar et al., 2024; Allentoft-Larsen et al., 2025). Therefore, this study aims to utilize hyperspectral imaging (HSI) and Spectral Angle Mapper (SAM) algorithm to detect and classify biofouling species associated with marine litter along the Qatar coast.

2. MATERIALS AND METHODS

A marine biofouling survey was conducted along the Qatar coast during December 2024 to collect various types of biofouling organisms associated with marine litter items, including plastics, metals, glass, and wood. The collected biofouling organisms attached to marine litter were examined using the Pika XC2 hyperspectral imaging (HSI) camera in the Remote Sensing Laboratory of Environmental Science Center (ESC) at Qatar University. The HSI system operated within a spectral range of 400 to 1000 nm, capturing 1600 spatial pixels across 447 spectral bands with a spectral resolution of 1.9 nm. The samples were exposed to direct sunlight and imaged using the HSI camera, along with a Spectralon reference panel and an imaging system. Subsequently, the raw hyperspectral data were preprocessed for radiance and reflectance calibration and then subset for image analysis. Considering both the spectral and spatial characteristics of HSI datasets, various data processing techniques were applied to analyze the images. In this study, the Spectral Angle Mapper (SAM) algorithm was employed to discriminate biofouling organisms (especially, barnacles) at the pixel level. This approach allowed for the identification of alteration and mineralization areas using the Spectral Hourglass scheme (Kruse et al., 2003) available in ENVI 6 image processing and analysis software (https://www.nv5geospatialsoftware.com/Products/ENVI). The method begins by reducing abundant information and data dimensionality in the image data using Minimum Noise Fraction (MNF) transform. Subsequently, the Pixel Purity Index (PPI) is applied to determine the purest pixels in the image. The wizard tool allows the extraction of endmembers using the n-Dimensional-Visualizer.

3. RESULTS AND DISCUSSION

3.1. Spectral dimensionality reduction and endmember extraction for biofouling classification

In this study, the 462 VNIR spectral bands of images containing biofouling organisms associated with marine litter were first assessed for their inherent dimensionality using MNF transform (Fig. 1a; Boardman and Kruse, 1994). The interpretation of the MNF-transformed image data revealed an increase in noise from MNF bands 1 to 462. The MNF bands containing relevant information were further processed to identify the most spectrally pure (extreme) pixels representing biofouling organisms. This was achieved using the PPI method with a PPI iteration value of 5000 (Fig. 1b; the maximum), a default threshold value of 2.5 and a SAM angle of 0.10 radians. Fig. 1c shows the group of pure pixels and extracted endmembers (highlighted in colors) using the n-Dimensional visualizer plot. The endmembers show the spectral absorptions near 680 nm (red dotted rectangle) and around 940 to 970 nm (green dotted rectangle). The absorptions in the bands are due to the physical and chemical characters of the barnacles. The obtained pure pixels corresponded to mixing endmembers computed by repeatedly projecting n-D scatter plots on a random unit vector. PPI recorded the extreme pixels in each projection, making those that fell at the ends of the unit vector, and counted the number of times each pixel was identified as extreme before extracting the endmembers. Additionally, a spectral library was developed by extracting endmembers to discriminate the barnacles in the samples. Since the endmembers are directly associated with surface components detectable in the images, this spectral library facilitates the accurate classification and analysis of biofouling organisms.

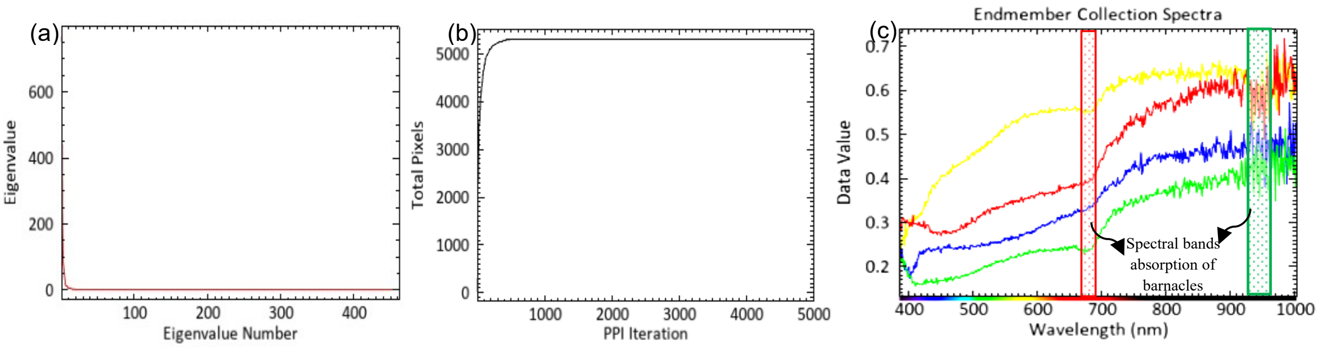

Figure 1. Showing the results of (a) minimum noise reduction (MNF, data dimensionality), (b) pixel purity index (PPI), and (c) the endmember of biofouling barnacles

3.2. SAM algorithm and discrimination of barnacles

The representative barnacles attached on the marine litter deposited along the Qatar coast are illustrated in Fig. 2, including RGB, MNF, MNF Rule images, and the classified results of SAM. The RGB image of sample exhibits the presence of barnacles in light grey with round to elliptical shape. The study of barnacles in hand specimens showed that the barnacles are developed a salt-mixed carbonate crusted structure. The portion of marine litter sample (metal tin) appears in white, and the weathered section appears light yellowish-brown to dark brown. The interpretation of MNF bands (R: Band 1; G: Band 2; B: Band 3) showed the presence of barnacles in dark green to light green with barnacle structures. The metal tin appeared in pale bluish-pink to pinkish-red. The MNF image results of dimensionality reduction showed the improved pixels that have barnacle information, which can be well compared and interpreted with the MNF rule image. The classified image of SAM algorithm successfully discriminated the barnacles in red, green, blue, and yellow based on the chosen endmembers that represent different parts of the barnacles. The discrimination and classification of barnacles were achieved by hyperspectral imaging of such features by the SAM method using endmembers on the 462 bands.

Figure 3 shows the endmember spectra extracted from other samples collected along the Qatar coast. All the spectra exhibit similar spectral bands absorptions around 680 nm and 950 nm (green and red dotted rectangles, respectively), which significantly represent the presence of barnacles as shown in Figure 1c.

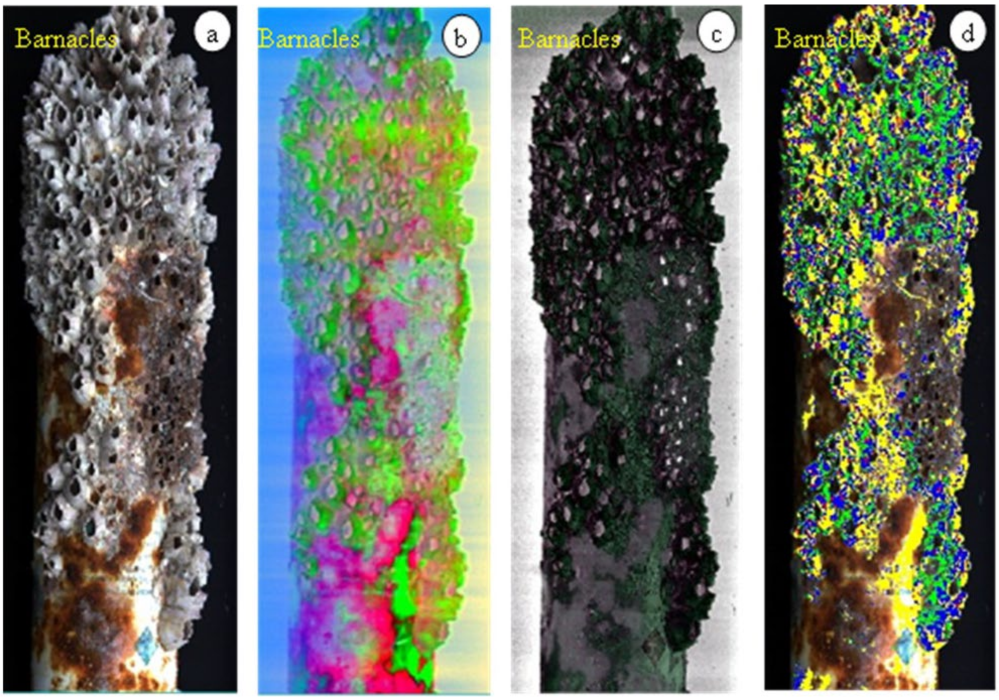

Figure 2. Representative barnacles' assemblage on marine litter (a) RGB, (b) MNF, (c) MNF Rule images, and (d) the classified results of SAM

The results of SAM method applied to all collected samples discriminated the presence of barnacles and their spatial distribution. All samples exhibited barnacles with the typical round to oval-shaped structure that developed from salt-mixed carbonate material. The SAM algorithm discriminated well the barnacles attached to different types of marine litter items (plastic, metal, glass, and wood). This study demonstrates the potential use of hyperspectral imaging and the capacity of SAM algorithm in the discrimination of barnacles associated with marine litter.

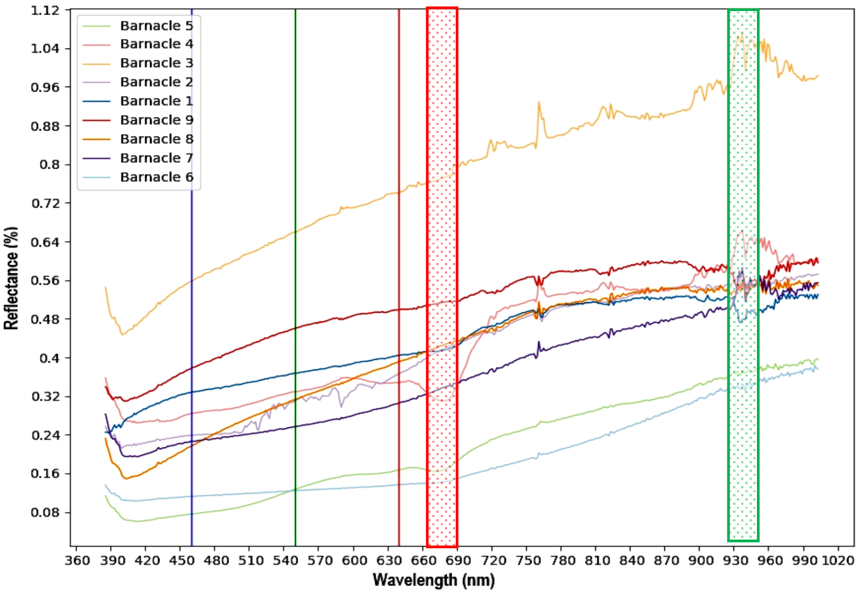

Figure 3. Reflectance spectra of beach barnacles showing the spectral absorption in 400 to 1000 nm

4. CONCLUSION

This study demonstrates the successful integration of HSI and SAM algorithm for the sustainable management of biofouling along the Qatar coast. The combination of HSI's high resolution, non-invasive imaging capabilities with the SAM algorithm's ability to accurately classify biofouling organisms based on spectral similarities proves to be an effective tool for detecting and mapping biofouling in marine environments. The application of these methods enabled the identification of distinct spectral signatures for key biofouling organisms, such as barnacles, mollusks, and algae, and facilitated the accurate classification of these organisms even under varying environmental conditions. The achieved overall accuracy of over 90%, particularly in the detection of barnacles, highlights the robustness and potential of this approach for environmental monitoring. This study underscores the importance of integrating advanced remote sensing techniques with machine learning algorithms in addressing the challenges of biofouling management. Future research will focus on further enhancing species discrimination, particularly for closely related biofouling types, through the incorporation of more sophisticated machine learning models. Ultimately, the integration of HSI and SAM offers a promising and sustainable solution for biofouling monitoring, contributing to more effective and environmentally responsible coastal management strategies.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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