Are offshore platforms a good candidate to restore functional diversity of reef fish communities in the Arabian Gulf?

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ABSTRACT

Human-made structures are ubiquitous in the marine realm. Complex structures such as oil and gas platforms may constitute a suitable habitat for species in areas where natural reefs have been highly degraded by coastal development. We here explore the suitability of fish assemblages associated to offshore platforms as surrogates for depleted fish stocks from coastal areas. Taxonomic and functional diversity have been used as approaches to test this hypothesis. Beta diversity components (nestedness and turnover) have also been assessed to unveil the magnitude of the differences between fish-associated communities from offshore platforms and natural reefs. The results showed a sharp difference between natural and artificial reef assemblages, suggesting that these artificial structures may not be suitable candidates serving as surrogates of fish assemblages. Natural reefs were characterized by a depletion of species and abundances, typical of overfished sites, together with other factors such as depth and substrate complexity. Reefs at medium depth in the eastern part of oil platforms, i.e. Kharaza, Maydam Mahzam and Fast east-Halul, showed the highest species richness (19–25 taxa) and functional richness. Thus, our results showed that offshore platforms harbor different fish species composition and community structures than natural reefs. Hence, the conservation of natural reefs under pressure, and artificial systems that act as marine protected areas are of utmost importance to preserve the fish biodiversity in the region. From our perspective, an integrative management of both natural and artificial structures is urgently needed, considering the extensive number of installations that will be decommissioned in the study region. The present results have ecological implications of utmost importance that need to be considered in coastal planning of the Arabian Gulf where a substantial portion of natural reefs have been drastically transformed.

1. Introduction

A wide range of offshore facilities such as oil and gas platforms have been installed underwater by humans (Chapman and Khanna, 2000; Ranasinghe and Turner, 2006; Scarfe et al., 2009). These structures provide large and complex habitats for many marine organisms (Claisse et al., 2014), being even considered as an option to mimic or compensate natural reefs (Ponti et al., 2015; Granneman and Steele, 2015; Perkol-Finkel et al., 2006). These benefits have not been previously overlooked by researchers, and a plethora of studies have been conducted focusing on the positive effects of artificial reefs on marine biodiversity (Baine, 2001; Bailey-Brock, 1989), such as the enhancement effects of these structures on the recovery of commercial fish stocks (Grossman et al., 1997; Powers et al., 2003; Bortone, 2006). Although, the use of artificial habitats is still debated due to some differences encountered between those and natural reefs (Feary et al., 2011; Sanabria-Fernández et al., 2018; Paxton et al., 2020) recently demonstrated how artificial reefs supported similar levels of diversity, density, biomass and species richness of fishes as natural reefs. Even so, the potential of associated communities from offshore structures as vectors for restoration of natural reefs remain overlooked in many regions.

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Oil and gas platforms are spatially complex underwater structures, with numerous cross beams and pillars attached to the seabed (Guerin et al., 2007). They support a wide range of organisms (Claisse et al., 2014; Torquato et al., 2017, 2021), that play a pivotal role in ecosystem services (Van Elden et al., 2019). Programs of habitat enhancement and restoration, such as Rigs-to-Reefs, have been extensively discussed despite resistance of stakeholders (Kaiser and Pulsipher, 2005; Macreadie et al., 2012). There are over 12,000 of these installations worldwide (Ars and Rios, 2017) that are primarily located within the Gulf of Mexico, Beaufort Sea, North Sea, southwest Indian Ocean and the Arabian/Persian Gulf. In the last, *ca.* 800 oil and gas platforms are established offshore (Sheppard et al., 2010). These platforms may constitute the only available potential substrate where species can settle and recruit (Prach et al., 2020), because of the low complexity of the Gulf habitats and the heavily disturbed coastal landscapes in the region.

Although, the Gulf countries have developed conservation efforts on environmental management through the increase of marine protected areas (Van Lavieren and Klaus, 2013) and developing coastal sustainable management practices (Burt et al., 2017, 2009; Mateos-Molina et al., 2020), offshore platforms have not previously been considered as a potential reservoir of biodiversity in the region (Burt et al., 2011). In contrast, artificial reefs in other geographic regions have been adopted into ecosystem monitoring and management plans pivotal for fostering ecosystem services (Hylkema et al., 2021).

There is a controversy on the role of artificial substrates as a tool for ecosystem restoration. From one side they are considered substitutes of natural reefs in terms of ecosystem functioning (Hunter and Sayer, 2009; Granneman and Steele, 2015) and on the other side they differ and deviate from their natural counterparts (Perkol-Finkel et al., 2006; Paxton et al., 2020). Many studies have investigated whether artificial reefs effect positive changes on biological communities relative to natural reef ecosystems. These studies are not only based on conventional community descriptors, i.e. species richness, abundance or biomass (Folpp et al., 2020; Schroeter et al., 2015; Paxton et al., 2019), but also other variables focused on high-mobility fauna such as occupancy (Sanabria-Fernández et al., 2018). Other approaches that consider community stability using species compositional turnover, i.e. beta diversity, have been scarcely explored (see Cardoso et al., 2020; Medeiros et al., 2021).

The beta diversity approach can be very useful to provide information regarding the nestedness and spatial turnover of species (Anderson et al., 2011; Baselga, 2012; Erös et al., 2020). The nestedness component describes the variations in composition (or functional traits, or any other type of items used to quantify diversity) due to species loss or gain, causing compositions in species-poor sites to be nested within those of the richer sites. And spatial turnover occurs when the loss of species is compensated by the gain of new ones (Baselga et al., 2007; Baselga, 2010; Villéger et al., 2013). Therefore, beta diversity enable hypothesis testing of mechanisms of community composition changes that drive observed spatial distributions of marine species (Vale et al., 2021), and allows testing hypotheses about the processes that determine the spatial distribution of species (Baselga, 2010; Baselga and Orme, 2012).

Here we compare fish assemblages from offshore platforms and adjacent coastal reefs in Qatari jurisdictional waters as a model study to explore the potential of artificial substrates as a source of restoration of heavily-disturbed reefs. One of the primary factors contributing to the decline of coral reefs in the Arabian Gulf is the rapid pace of coastal development along the shores that has caused extensive disturbances on the coastal realm. Reclamation projects, dredging, and coastal urbanization lead to increased sedimentation and pollution runoff into the marine environment (Sheppard et al., 2010). Climate change is also an important factor to take into consideration since several coral bleaching episodes have been reported in the last decades in this area (Noori et al., 2019). Lastly, overfishing and destructive fishing practices have further compounded the plight of Gulf coral reefs. Unsustainable and destructive fishing methods result in habitat destruction and the loss of keystone species that play crucial roles in maintaining the reef ecosystem (Burt et al., 2017; Bouwmeester et al., 2020).

Torquato et al. (2017) found diverse fish assemblage associated with offshore platforms that may constitute a reservoir, acting as source populations to replenish extensively-altered natural coastal reefs. A few faunas, in particular natural reef fish, were recently studied with both underwater visual census (UVCs) and environmental DNA (eDNA) showing large differences between near shore and offshore natural reefs (Sigsgaard et al., 2020). Our main aim was to assess at the community level by comparing taxonomic and functional diversity and composition patterns of fish assemblages between artificial (offshore platforms) and natural (coastal reefs) substrates.

We hypothesized that offshore platforms were associated with similar fish species assemblages as natural reefs, and additionally, they might be a suitable pool source to replenish and restore fish assemblages in natural reefs. We tested this hypothesis by estimating the degree of nestedness of fish assemblages associated with offshore platforms and coastal natural reefs. Considering that offshore platforms could act as restoring more diverse fish assemblages, the turnover component would indicate replacement of species that occurs when the loss of species is compensated by the gain of new ones.

2. Material and methods

2.1. Study area

In the present study, we compare fish assemblages from coastal natural reefs and offshore platforms. These platforms were located within the Al Shaheen oil field, Block 5, 90 km offshore and within the Northeastern sector of the Qatari exclusive economic zone (EEZ). This site includes platforms scattered across 9 locations (i.e. A-I), with platforms differing according to their height, year of installation and function (see details in Torquato et al., 2021) (Fig. 1). Offshore platforms in Qatar have a 500-m fishing ban area that may potentially play a role for the conservation of fishing resources in the study area. These platforms consist of steel structures rising above the water's surface and are equipped with drilling facilities and equipment. Over time, these platforms have also served as artificial reefs, providing a unique and artificial habitat for marine life, including fish (Albano et al., 2016; Torquato et al., 2017). Data on functional traits from the nine offshore platforms were averaged into a single one, since no significant differences were found (see Torquato et al., 2017 for details).

A total of 10 natural coastal reefs were sampled, with depth rangings from 2 to 19 m (Table 1). Historically, coastal natural reefs in The Gulf have faced significant fishing pressure due to the region's importance as a fishing ground for local communities (Ben-Hasan and Daliri, 2022). Overfishing and destructive fishing practices have led to declines in fish populations and changes in species composition in some areas (Sheppard et al., 2010; Mashjoor et al., 2022).
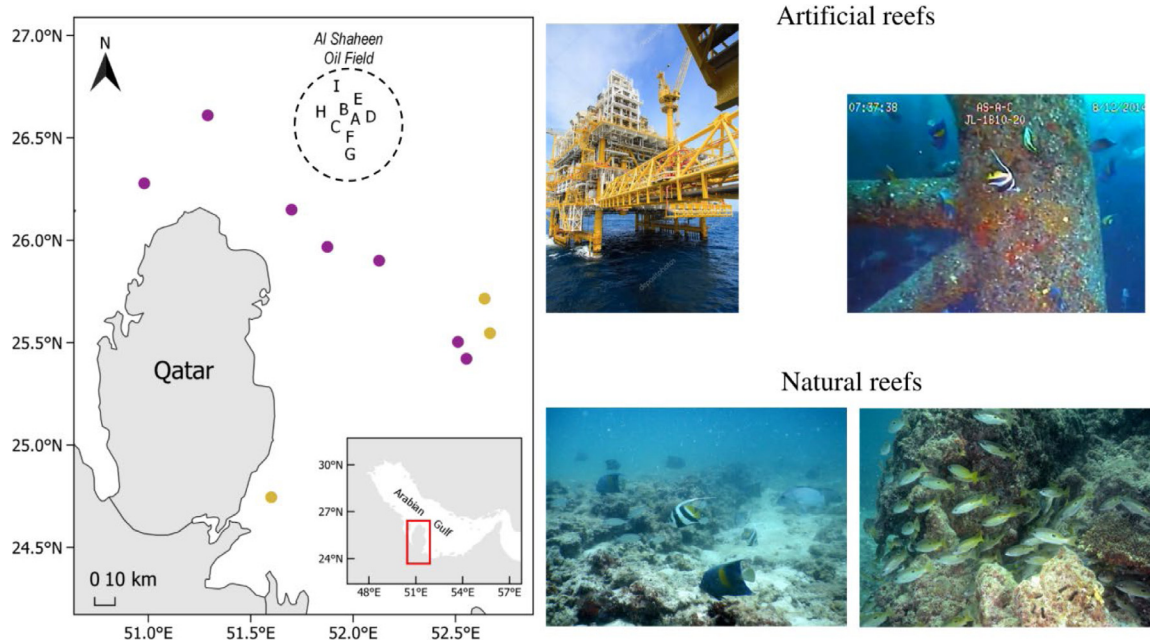
Fig. 1. Map of the study area showing the study locations (purple: cold surveys; yellow: warm surveys). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Sampling locations of natural reefs in the study region.

Period	Location	Coordinates X	Coordinates Y	Sampling period	Depth (m)
Cold	Balhambar	25.967454	51.874527	29/03/2017	14
	Binzayan	26.609917	51.290222	21/03/2016	16
	Fasht Al-Dibal	26.277932	50.980532	30/03/2017	3
	Kharaze	25.421569	52.553618	23/03/2017	9
	Maydan Mahzam	25.503842	52.512169	23/03/2017	10
	Umm Al Shaef	26.149223	51.699654	29/03/2017	13
	Ras Dow	25.900429	52.127283	22/03/2017	19
Warm	Bul Hanine	25.54666	52.66863	08/06/2018	11
	Al-Ashat	24.74531	51.60062	18/10/2017	2
	Fasht East Halul	25.71472	52.64228	08/06/2018	11

2.2. Sampling procedures and species

Remotely operated vehicle (ROV) and UVCs were used to compare offshore platforms and natural reefs fish community composition. ROV surveys were the unique viable option to sample fish associated with the studied offshore platforms. For security reasons, we did not have permission to carry out UVC surveys in these platforms. ROVs have demonstrated to be adequate for sampling relatively larger-size commercial fish species of low-mobility, though they underestimate the crypto-benthic and nekto-benthic species and their abundances compared to UVC surveys (Andaloro et al., 2013). In the present study, ROV underwater video recordings were compiled over six years (2007, 2009, 2010, 2011, 2012 and 2014), and we used exclusively those ROV records done during the day and in shallow depths (0–20 m) (see details in Torquato et al., 2017) to compare with UVC surveys. At each natural reef, we ran visual censuses that quantified fish using the Reef Life Survey (RLS) methodology (Edgar and Stuart-Smith, 2014) during surveys conducted in 2016, 2017 and 2018 in ten reefs (Fig. 1, Table 1). We only used data from the visual census of fish through two 50 × 10 m transects in each reef.

To avoid a temporal effect in the composition of fish assemblages, the study was split into two periods: cold (October–March) and warm (April–September). Particular families or genera which include difficult to distinguish species with similar ecology were grouped together and treated as groups of confamilial or congeneric species (Appendix S3). Fish species within each system were recorded as presence-absence data.

2.3. Functional trait selection

Fish species were described based on functional traits focusing on eight elements determining the habitat use, locomotion, feeding, swimming mode and life history (Mouillot et al., 2013; Villéger et al., 2017; Carrington et al., 2021) (Suppl. Mat. 1): body shape (Bdsh), maximum body length (SzCl), home range (Hr), size group (Sg), vertical position (VPos), diet (Diet), trophic level (Trophic) and spawning (Spawn). Values for all traits were obtained from a database reported by Quimbayo et al. (2021) (see Table 2), fish guides for Qatar (Sivasubramaniam and Ibrahim, 1982), and Fishbase (Froese and Pauly, 2020). For data on traits where no information were available from literature, authors' background were used. This study did not consider diverging trait values within taxonomic groups, e.g. family or genus. Categorical trait modalities (Appendix 1) were selected based on methods defining functional features in previous studies (Farré et al., 2013; Riera et al., 2018; Carrington et al., 2021). Fish body shape is a proxy contributing to multiple traits at a higher level such as swimming, searching for food, striking and capturing prey, evading predators, migration, defending territories, spawning, among others (Wainwright, 1994; Walker, 2010). Species were grouped into six body shapes: fusiform, elongated, oblong, oval, symmetrical and asymmetrical flatfish (Farré et al., 2013). Maximum body length (TL) was partitioned into six length-based categories: 0–7, 7.1–15, 15.1–30, 30.1–50, 50.1–80, and > 80 cm of total length. Home range represents the area of activity and was split into three categories: sedentary, mobile (<1 km) and very mobile (>1 km). Gregariousness was defined for aggregation size group as: solitary, pair, small (<10 individuals), medium (10–50 individuals) and large-groups (>50 individuals). Position in the water column was expressed as: bottom, low and high, characterizing the habitat usually used by fish for living and feeding. Diet was assigned in seven trophic categories: herbivorous, macroalgal feeder, sessile invertebrates, mobile benthic invertebrates, planktivorous, omnivorous and piscivorous. The trophic level indicates

Table 2

Functional diversity found in some Qatar's reefs and oil platform during two sampled stations. In bold, the numeric traits with higher values. Traits: Bdsh, body shape; Diet, diet; Hr, home range; Sg, size group; Spawn, spawning; SzCl, maximum body length; VPos, vertical position; Trophic, trophic level. Diversity indices: CWM, community-weighted means; FRic, functional richness; FGR, functional group richness.

Periods	Reef	Number species	FRic	FGR	CWM								
					Bdsh	SzCl	Hr	Sg	Vpos	Diet	Trophic	Spawn	Swimming
Cold	Balhambar	13	0.06952	6	Fusiform	s4	mob	School	Low	im	3.36	Pelagic	Sub-carangiform
	Binzayan	15	0.06890	6	Fusiform	s4	mob	School	Low	im	3.25	Pelagic	Sub-carangiform
	Fasht Al-Dibal	9	0.02913	5	Fusiform	s2	mob	School	Low	im	3.33	Pelagic	Sub-carangiform
	Kharaze	**19**	0.14129	7	Compressed	s4	mob	School	Low	im	3.19	Pelagic	Sub-carangiform
	Maydan Mahzam	**19**	**0.37147**	**8**	Fusiform	s2	mob	School	Low	im	3.44	Pelagic	Sub-carangiform
	Umm Al Shaef	7	0.00001	4	Elongated	s2	mob	School	Low	im	3.43	Pelagic	diodontiform
	Ras Dow	9	0.01162	6	Compressed	s5	mob	School	Low	fc	3.39	Pelagic	Sub-carangiform
	Oil Platform	10	0.01494	5	Compressed	**s6**	mob	School	Low	fc	**3.70**	Pelagic	Sub-carangiform
Warm	Bul Hanine	15	0.00789	6	Fusiform	s2	mob	School	Low	im	3.38	Pelagic	Sub-carangiform
	Al-Ashat	12	0.00002	**7**	Fusiform	**s6**	mob	School	Low	im	3.44	Pelagic	Sub-carangiform
	Fasht East Halul	**25**	**0.19585**	**7**	Fusiform	s2	mob	School	Low	im	3.37	Pelagic	Sub-carangiform
	Oil Platform	10	0.00001	5	Compressed	**s6**	mob	School	Low	im	**3.61**	Pelagic	Sub-carangiform

the species position in the food web. Spawning denotes the preference of species for depositing eggs in water: live, attach or oral. Swimming mode reflects the body-shape and swimming factor commonly used to describe locomotive performances of fish. Eight categories were used: amiiform, anguilliform, balistiform, carangiform, diodontiform, labriform, ostraciform and sub-carangiform.

2.4. Data analysis

The alpha taxonomic diversity – defined as the within-sample diversity – was assessed as the species richness at each reef or platform per season. Prior to estimating the functional diversity, pairwise distances among functional traits were computed using Gower's distance (Torquato et al., 2017; de Bello et al., 2021), which allows different types of variables to be mixed while giving them equal weights (Gower, 1971) using *FD* package (Laliberté et al., 2014) in R (Team, 2021). Principal coordinates analysis (PCoA) was then performed on the basis of this trait matrix applying a Cailliez correction to correct any potential generated negative eigenvalues (Cailliez, 1983). A multidimensional functional space for the localization of species was built using principal axes. The R^2-like ratio indicated the quality of the reduced spatial representation, as a measure of goodness of fit for model selection, which was 0.459 with six axes for cold stations and 0.634 for nine axes for warm period. Functional richness (FRic) was standardized within the dbFD function in the *FD* package, which calculates the FRic for each reef relative to the Convex hull volume filled by all species. Functional group richness (FGR), which represents the number of functional units found in each assemblage, was obtained by a functional dendrogram. A subjective similarity threshold of 0.3 was used for FGR based on a functional dendrogram using the Ward method (Murtagh and Legendre, 2014). Additionally, community-weighted means (CWM) calculated for all categorical traits were used to represent changes in trait composition among fish assemblages (McLean et al., 2019).

To further explore taxonomic and functional overlap between assemblages we analyzed the beta diversity using Jaccard dissimilarity index. The functional beta dissimilarities integrated two additive components: the turnover component (replacement of species or functional space not shared by communities) and the nestedness-resultant component (difference in species or functional space filled by communities) (Baselga, 2010; Villéger et al., 2013). The turnover (β TURN) and nestedness (βNES) components were quantified as beta diversity partitioning (Baselga, 2010; Villéger et al., 2013). β TURN integrated into the Simpson index describes the spatial turnover without influence of gradients of species richness, whilst βNES describes the variation

in composition due to species loss or gain, occurring when the sites with smaller numbers of species are subsets of the richer sites (Wright and Reeves, 1992; Ulrich and J. Gotelli, 2007). This may reflect a non-random process of species loss that underpins the ecological collapse through the disintegration of assemblages (Gaston and Blackburn, 2000). Both components of beta diversity were calculated using the *betapart* package (Baselga and Orme, 2012). They range from 0 to 1, where higher values indicate greater dissimilarities among fish assemblages. Following a trade-off between information quality and interpretability, these indices of functional beta diversity were computed using the first four PCoA axes (Zhang et al., 2021). Clusters per locality were constructed using the 'average' clustering algorithm. In addition, tanglegrams were constructed using the untangle function (algorithm step1side) using the *dendextend* package (Galili, 2015) to illustrate the fit in clustering outcomes achieved using the taxonomic and functional diversities (i.e., β TURN-taxonomy *vs* β TURN-functional; βNES-taxonomy *vs* βNES-functional; and βeta-taxonomy *vs* βeta-functional).

2.5. Ethical statement

Ethical statement is not applicable since specimens were not collected nor manipulated. Only underwater visual censuses and ROV video footages were carried out in the present study.

3. Results

A total of 42 (cold period) and 36 (warm period) fish species were observed at the natural reefs and oil platforms. Of these, *ca.* 50% (cold) and 32% (warm) were found at one site due to mobility of species and the high spatial variability of fish composition (Table 2). The alpha-taxonomic diversity associated with oil platforms was low for both seasons (10 species, which 50% were exclusive of each season) considering the maximum alpha-taxonomic diversity for natural reefs: 19 species in Kharaze and Maydan Mahzam reefs (cold) and 25 species in Fasht East Halul (warm) (Table 2).

Considering the offshore platforms and natural reefs, FRic was similar between periods, 8 (cold) and 7 (warm) (Fig. 2). This slight difference was due to the lack of species with a high mobility, large size and solitary behavior (Functional group 1, *FGR-1*) (e.g., *Acanthopagrus latus* and *Rhabdosargus sarba*) during the warm period. The cluster with the highest species richness was the *FGR-5* in the cold period (Fig. 2a) and *FGR-6* in the warm period (Fig. 2b). Both groups were mainly represented by species with fusiform shape and schooling behavior (e.g., *Caesio varilineata* and *Siganus canaliculatus*), which were not frequent
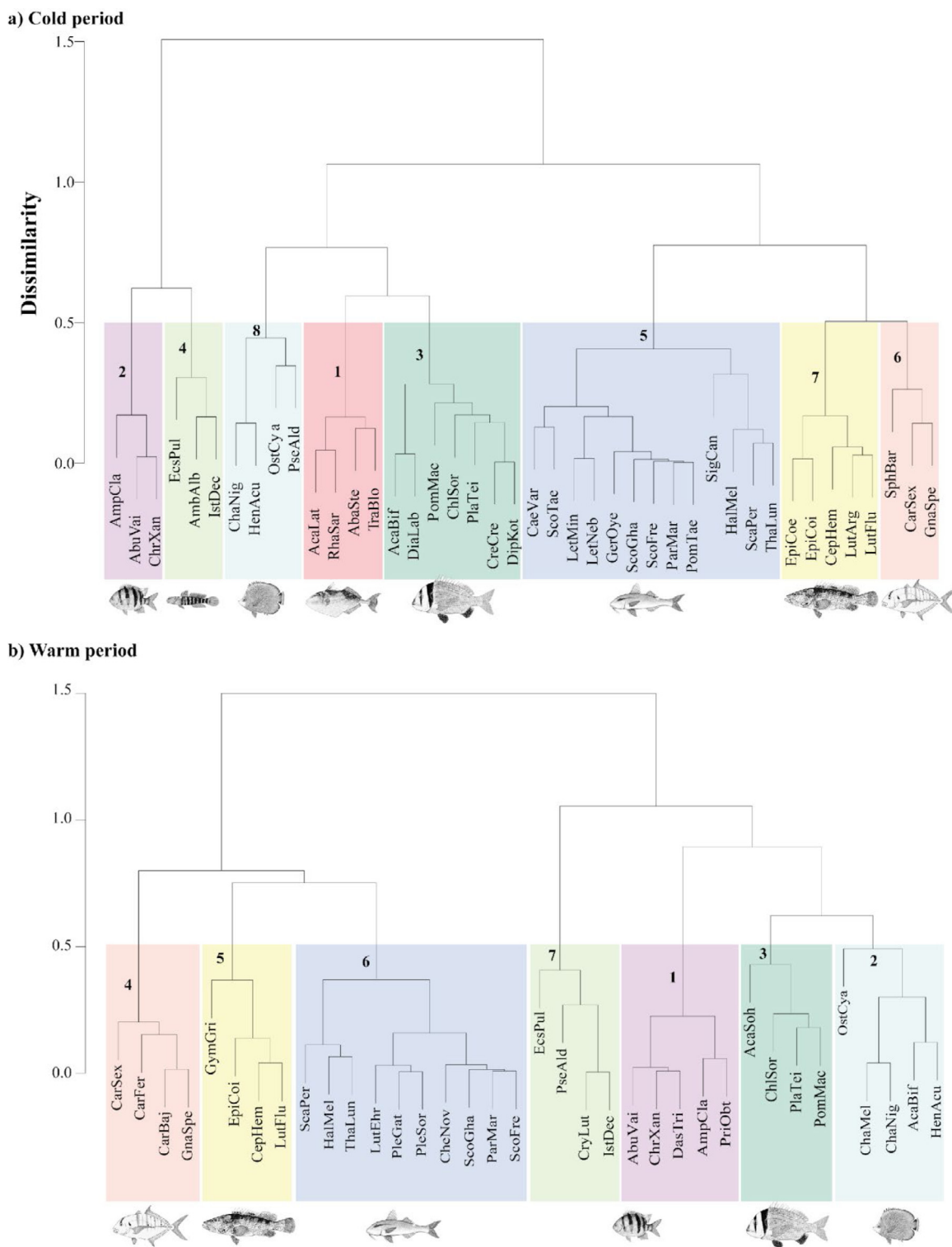
Fig. 2. Functional groups of fish during (a) cold and (b) warm periods. Numbers represent Functional Group Richness.

in offshore platforms (Table S1). These species showed a high similarity in the functional space during the cold period (Fig. 3). By contrast, fish associated with oil platforms were formed by species with a higher trophic level and compressed body shape in both seasons (e.g., *Scolopsis taeniatus* and *Lethrinus nebulosus*) (Table S1; Fig. 3). In general, the functional spaces clearly organize species depending on the size (X-axis) and the body shape (Y-axis) (Fig. 3). The functional richness obtained was very low in oil platforms (0.0001 and 0.01494) due to low representativity

of functional group richness; even so, a strong relation between functional richness and the species richness was detected (Table 2). The higher values of functional richness were obtained in offshore mid-reefs (10–16 m), far from oil platforms (Tables 1 and 2).

The low taxonomic and functional similarity of offshore platforms related to natural reefs indicated a high β TURN-diversity in the species composition, regardless of the natural site, and a lack of βNES-diversity (Fig. 4). This difference was mainly
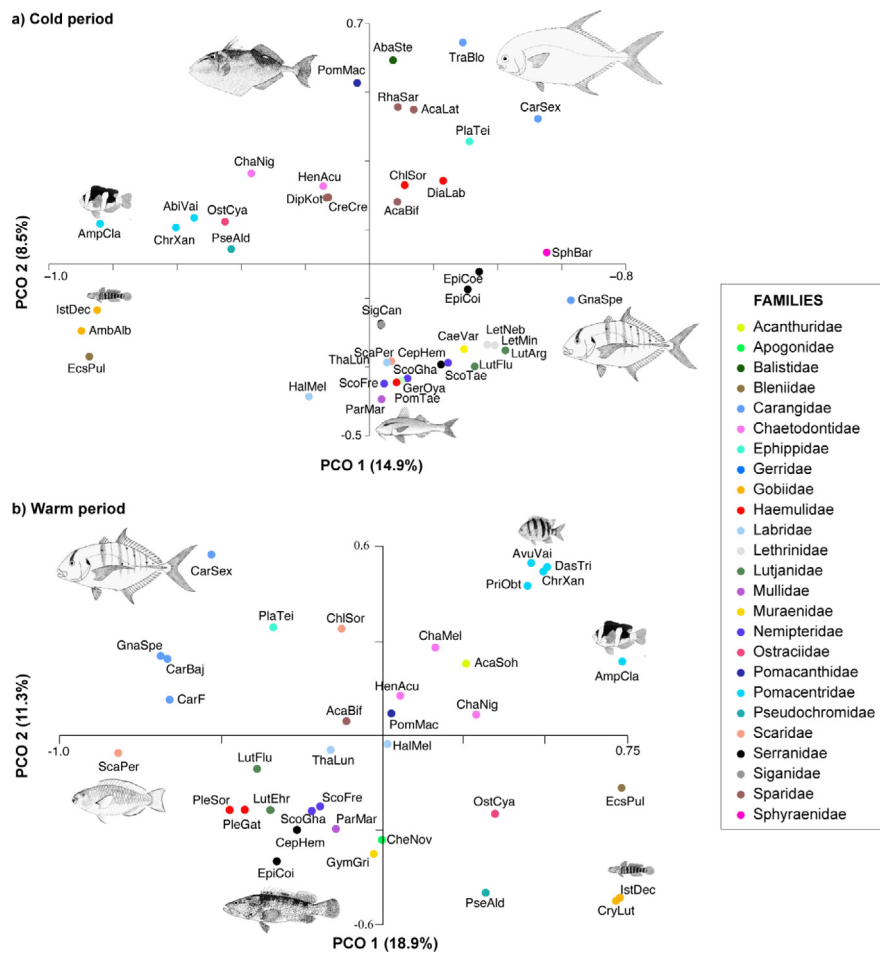
Fig. 3. Species distribution in the functional space. (a) cold and (b) warm waters. Colors indicate the fish families. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

due to the presence of mid-large predators such as, *Carangoides ferdau*, *Caranx sexfasciatus*, *Platax teira* and *Trachinotus blochii* in offshore platforms. However, the remaining species were common in natural reefs increasing the similarity of taxonomic and functional βNES-diversity. In general, the natural reefs exhibited a lower (<50%) β TURN-diversity and a high (>80% of similarity) βNES-diversity, except for Maydam Mahzam and Umm Al Shaef, and Al-Ashat and Fasht East-Halul with a low β TURN-diversity (Fig. 4). The reefs of Maydan Mahzan and Kharaze, close to the offshore platforms, showed a great variability in functional richness due to the lack of functional group richness-6 (three species) in Kharaze. This fact affected the βNES diversity, but the total β-diversity grouped the two former reefs since the dissimilarity between the remaining reefs was higher (Fig. 4). Only, the fish assemblages of Binzayan and Ras Dow showed a low β TURN and a low βNES dissimilarity (Fig. 4) despite their geographical distance.

4. Discussion

Using functional diversity in the studied coastal fish communities can address the challenges posed by different sampling periods (Years: 2016, 2017 and 2018; Periods: Warm and Cold), sampling methods (Underwater Visual Censuses in natural reefs and ROV footages in offshore platforms), and different natural reefs, with depths ranging from 2 to 16 m, sampled in cold (7 reefs) and warm (3 reefs) periods. Functional diversity harbour a series of advantages to overcome sampling unbiases and limitations such as, (i) Overcoming temporal variability, mitigating the

impact of different sampling periods by focusing on the functional roles and traits of species, which tend to be more stable over time compared to species composition; (ii) Standardizing comparisons despite different sampling methods: Functional diversity allows to identify patterns and differences in ecological functions and behaviors, which are less influenced by sampling techniques; (iii) Understanding ecosystem response to environmental variability: When comparing different natural reefs in both warm and cold periods, functional diversity allows us to analyze how the functional structure of fish communities responds to environmental variations; (iv) Identifying key functional players: Species or functional groups that play vital roles in ecosystem functioning can be identified, even if they are not consistently present across sites or sampling periods; (v) Exploring ecological complementarity: Functional diversity allows for an assessment of how different natural and artificial reefs complement each other in terms of functional roles and traits.

Fish assemblages in offshore platforms were clearly differentiated from those inhabiting natural coastal reefs, and both taxonomic and functional turnover diversity were responsible for this dissimilarity. Natural reefs harbored a greater fish biodiversity, especially in mid-depth (>15 m) sites but fish composition was represented by mostly small-sized and with no commercial species. Offshore platforms showed a low biodiversity, mostly due to the data selected here since only species recorded in the 0–20 m range (i.e., *ca.* 45–65 m above the sea floor) were included. Diel vertical migration was previously observed only for *Acanthopagrus bifasciatus*, concentrated at shallow depths during
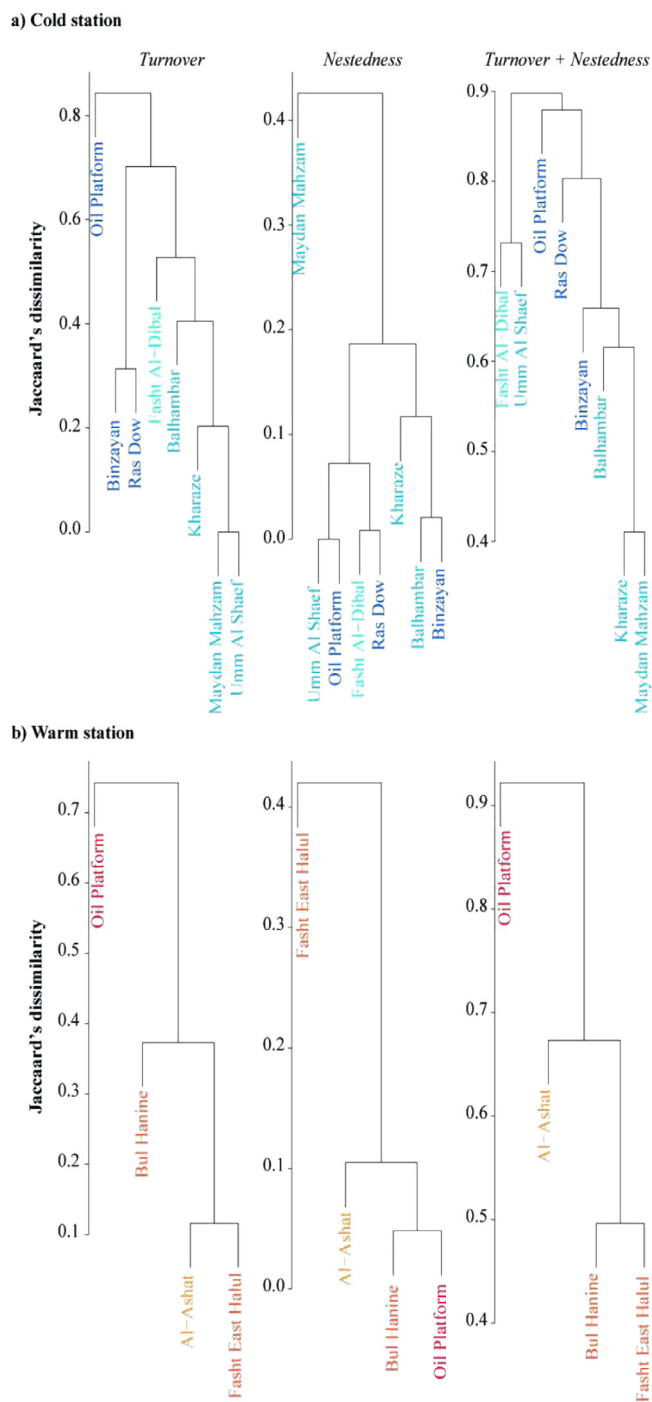
Fig. 4. Beta-diversity components of fish assemblages during cold (a) and warm (b) periods.

the day, and at deeper layers at night (Torquato et al., 2017). Although Torquato et al. (2017) found a greater diversity when it was analyzed the overall depth of platform (0–65 m), even considering the 0–20 m depth range they observed a high variability in species composition and range and dominance of functional traits in the fish assemblage relative to natural reefs. These differences might be explained by several factors, i.e. spatial variability, environmental variables and human-induced perturbations such as, fishing. Moreover, strong seasonal fluctuations in fish species richness and abundance have been previously found in the Arabian Gulf (e.g. Burt et al., 2009; Bouwmeester et al.,

2020), with the lowest values during summer months. However, contrasting patterns have also been observed in shallow waters, with an increase of fish abundance during the warmest months (Grandcourt, 2012; Vaughan et al., 2021).

In the present study, only two periods (warm and cold) were sampled due to logistic constraints. No clear trends were found between natural and artificial reefs due to differences in sampling procedures, i.e. underwater visual census in natural reefs, and ROV video footage in offshore platforms, and different natural reefs were sampled in cold and warm periods. Previous studies have compared various fish census sampling techniques, such as ROV (Remotely Operated Vehicle) and BRUV (Baited Remote Underwater Video), among others (Murphy and Jenkins, 2010). ROVs have demonstrated the ability to provide comprehensive descriptions of fish assemblages associated with offshore platforms (e.g. Francour et al., 1999; Andaloro et al., 2013). Despite logistical constraints and stringent security measures in these offshore areas, ROVs have become a commonly employed method for fish counting around these structures due to their suitability. BRUVs have also been used as a complement to underwater visual censuses, although they may have certain limitations in counting cryptic fish species. Nevertheless, BRUVs have proven to be effective in recording fish species associated with artificial reefs (e.g. Lowry et al., 2012). These findings highlight the valuable contribution of both ROV and BRUV methods in studying fish communities in distinct marine environments, offering essential insights into the diversity and distribution of fish populations around offshore platforms and artificial reefs.

Functional differences found between natural reefs and offshore platforms were mainly explained by the variability in the functional traits such as the presence of fusiform species forming schools in natural reefs, and compressed-shaped and high trophic species in platforms. Size and body shape were the most important functional traits in structuring the studied fish communities. Mid-large predators (e.g. *Carangoides ferdau, Caranx sexfasciatus, Platax teira* and *Trachinotus blochii*) were well represented at offshore platforms whilst the remaining small-sized fish are shared with natural reefs. The most abundant species in offshore platforms was the pennant coralfish (*Heniochus acuminatus*), as previously observed by Torquato et al. (2017). This fish seems to respond positively to artificial reefs, as shown in the South China Sea (Chang, 1985). This species is rare in natural reefs in Qatar (Sigsgaard et al., 2020), though it has been reported elsewhere in the Arabian Gulf (Bouwmeester et al., 2020). By contrast, fish assemblages from natural reefs were characterized by small-sized species, with no commercial value for artisanal fishermen except the Twobar seabream (*A. bifasciatus*). Commercial species were also recorded in natural reefs but they were not frequent such as the groupers *Epinephelus* (*E. coeruleopunctatus* and *E. coioides*), the orange-spotted trevally (*Carangoides bajad*) and the emperors *Lethrinus* spp. In this sense, a high spatial variability was also detected between fish assemblages from the studied natural reefs, most likely due to differences in environmental factors such as habitat complexity and depth (Dupont, 2008; Feary et al., 2013). The latter seems to be pivotal in the study region due to the extreme conditions during summer seasons in shallow seabeds (<10 m) (Noori et al., 2019), even reaching over 35 °C in shallow water bodies (Bouwmeester et al., 2020). Although a higher functional diversity in artificial reefs have been previously observed in fish assemblages from the NW Mediterranean compared to natural counterparts (Koeck et al., 2014), this pattern is not generalized in all studies (e.g. Santos and Monteiro, 2007). Artificial reefs increase environmental heterogeneity and hence the increase of β-diversity among habitats, which is an adequate tool that provides an accurate picture of community changes (Vale et al., 2021). This diversity is partitioned in two components

that may define the variations of diversity between samples or environmental gradients (Whittaker, 1960). Both components of β-diversity, nestedness and turnover (Baselga, 2010), are pivotal to elucidate the mechanisms responsible for among-site variation (Anderson et al., 2011), i.e. offshore platforms and natural reefs in the present study. However, the turnover component, differences in species from site to site (Gaston and Blackburn, 2000), played a minor role. Nestedness appears to be pivotal in the present study, since both substrates mainly differ due to replacement of species; natural reefs did not apparently harbor a subset of species that are recorded in offshore platforms. Therefore, differences in fish assemblages from natural reefs and offshore platforms were largely explained by species replacement rather than by a difference in species richness (Friedlander et al., 2014; Nunes et al., 2016; Torquato et al., 2017). The lowest levels of turnover and nestedness were found in Binzayan and Ras Dow, two mid-depth reefs that are the closest ones to the sampled offshore platforms. In the remaining reefs, a high spatial variability was also observed within the same locality. This dissimilarity was a pivotal factor affecting fish assemblages, with a low overlap in the functional space. The main factors structuring fish assemblages in coastal natural reefs in the study region are habitat heterogeneity, i.e. coral cover and substrate anfractuosity, and other environmental factors such as, depth (Feary et al., 2013; Vaughan et al., 2019). They underpin a shift in species composition, especially in commercial fish in natural and full-access reefs. On the other side, offshore platforms have a 500-m fishing ban area, with strict surveillance that clearly contributes to the establishment of large-sized exploited fish. The platforms create a complex 3-D structure underwater that harbor rich fish assemblages, as it has been shown all over the globe, i.e. Southern California (Claisse et al., 2014), Gulf of Mexico (Stanley and Wilson, 2000), North Sea (Todd et al., 2018), Gulf of Thailand (Harvey et al., 2021) or Western Australia (McLean et al., 2019). Nevertheless, the high fishing pressure in natural reefs underpin a biotic homogenization through an impoverishment and a high similarity of fish assemblages, as it has been previously observed in habitat-degraded areas (see Cardoso et al., 2020). Thus, fishing activities are also a key stressor of Qatari waters, as observed by previous studies (e.g. (El Sayed, 1996)). Overfishing is pervasive in Qatari waters, as shown by direct, i.e. derelict fish traps (ghost fishing), and remains of traps, and indirect evidences, i.e. dominance of fast-growing fish species, small size of commercial species, low fish abundance and coral fragmentation (Burt et al., 2017; Fanning et al., 2021).

Our findings provide further insight on biodiversity patterns (taxonomic and functional facets) of fish fauna that might be an asset for future conservation and coastal management of Qatari reefs and offshore platforms. Specifically, fish conservation priorities or identification of biodiversity hotspots could be developed or identified based on the components of beta-diversity, i.e. turnover and nestedness. The present results need to be taken with caution due to data limitations, mostly related to the disparity of sampling techniques, i.e. ROV surveys and visual censuses in offshore platforms, and natural reefs, respectively. Moreover, differences in depth range, distance from the coast, heterogeneity of platform ages, etc. need to be considered since they are potentially confounding factors that may affect the results of this study. Fish associated to offshore platforms from Qatar have been previously characterized as diverse and complex (Torquato et al., 2017). The results showed that fish associated to offshore platforms greatly differ from those inhabiting natural reefs. This suggests that offshore platforms from Qatar may not constitute an alternative pool of fish assemblages to natural reefs, nonetheless these provide certainly refuge and may support recruitment of fish at natural reefs

5. Conclusions

In our study area, we have identified significant differences in fish assemblages between coastal reefs and offshore oil platforms. It is crucial to conduct further research to fully understand the potential of these offshore artificial structures as potential reservoirs for coastal fish species that inhabit natural reefs. The contrasting dissimilarities in fish communities between both habitats, i.e., natural reefs and offshore platforms, pose a significant challenge when considering the possibility of using platforms as a means to replenish disturbed coastal reefs. Therefore, additional investigations are essential to gain deeper insights into the ecological dynamics and implications of utilizing offshore platforms for fish conservation and reef restoration efforts along the coast of the Arabian Gulf.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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