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# Artificial Reefs in the Arabian Gulf: Benefits, Challenges and Recommendations for Policy-Makers

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***Abstract***

Artificial reef (AR) deployment has increased dramatically in the Arabian Gulf in recent years, and will likely continue as Gulf nations continue to develop their coastlines and expand fisheries. Unfortunately, there is little publicly-available information about AR programs in the Gulf, including information about management goals and program success. ARs can provide economic, social and ecological benefits, but they also have underappreciated risks associated with them. Benefits include increasing short-term catch rates for fisheries, increasing tourism, enhancing and protecting biodiversity and providing ecological services. Risks include exacerbating regional overfishing in the long-term, facilitating the spread of invasive species, altering benthic habitat around the AR, contributing to marine pollution and creating habitats that are "sinks" for larval fish. This paper provides recommendations for managers that are considering whether to initiate AR programs in the Arabian Gulf. Deployment of ARs should not be used as an excuse to allow the destruction or degradation of natural habitat, since ARs are not surrogates of natural habitat. Managers should define clear, explicit management goals in the planning stages of the reef project, and then design and deploy the reef to meet those particular goals. Managers should also set quantifiable objectives for each goal, and implement long-term monitoring programs to determine whether the reef is successful in meeting its goals. Finally, managers should disseminate the results of the monitoring program and share "lessons learned". Implementation of these recommendations will help to guide future sustainable AR programs in the Arabian Gulf and elsewhere.

**Keywords** Artificial reef, Arabian Gulf, Management, Goals, Benefits, Recommendations

## ***1 Introduction***

### *1.1 Pressures on Arabian Gulf Coastal Ecosystems*

A mosaic of highly productive and diverse marine ecosystems border the Arabian Gulf, providing critical goods and services to coastal populations (Vaughan et al. 2019). These ecosystems encompass highly diverse habitats in a region that is typically recognized for its comparatively low-diversity terrestrial deserts (Sheppard et al. 1992, Burt 2014). Mangrove forests, mudflats and sabkha (salt flat) ecosystems support extensive coastal and subtidal food webs (Sheppard et al. 1992, Hegazy 1998, Barth and Böer 2002). Important nearshore subtidal ecosystems include coral reefs, seagrass meadows, algal beds and oyster reefs that cover extensive areas of seafloor (Vaughan et al. 2019). Economically, fisheries are the second-most important economic sector in the Gulf after oil and gas, and these marine habitats are critical for numerous commercially-important species (Siddeek et al. 1999, Van Lavieren et al. 2011, Vaughan et al. 2019). These ecosystems are also important for tourism (Nouri et al. 2008, Ryan et al. 2012, Blignaut et al. 2016), they protect against coastal erosion (Erftemeijer et al. 2020) and they effectively sequester carbon (Campbell et al. 2015, Schile et al. 2017, Rabaoui et al. 2019).

Nations bordering the Arabian Gulf have population growth rates that are almost twice the global average, and most of this growth has occurred in cities bordering coasts (Van Lavieren et al. 2011). This rapid population growth, along with global climate change, has put immense pressure on all coastal ecosystems of the Gulf, and has resulted in widespread habitat degradation and loss (Sale et al. 2011). Threats to Gulf coastal ecosystems include dredging, land reclamation and related development

(Sheppard et al. 2010; Sale et al. 2011; Burt 2014), water pollution and desalination-brine discharge (Freije 2015; Alshahri 2017; Le Quesne et al. 2021) and eutrophication leading to hypoxia (De Verneil et al. 2021; Lachkar et al. 2022), harmful algal blooms and mass die-offs of fishes and other marine organisms (Bauman et al. 2010; Chatziefthimiou et al. 2021). Furthermore, the Gulf fishing industry has expanded rapidly in recent decades to support the growing human populations. The combination of increased fishing pressure and the degradation or loss of critical ecosystems that support fisheries has led to dramatic declines in regional fish stocks (Al-Abdulrazzak 2015; Buchanan et al. 2019; EAD 2021). Unfortunately, fisheries management practices and law enforcement are not adequate to reverse these trends in many parts of the Gulf (Siddeek et al. 1999; Al-Abdulrazzak 2015; Aljasmi 2017).

Global climate change is exacerbating the effects of ecosystem degradation and overfishing in the Gulf, and will continue to have widespread negative impacts in the future (Burt et al. 2021; Lincoln et al. 2021). Some coastal ecosystems in the Gulf are threatened by “coastal squeeze” due to rising sea levels (Melville-Rea et al. 2021). Coral bleaching events associated with elevated sea surface temperatures are increasingly frequent, resulting in reduced coral cover, enhanced risk of regional extinctions and reduced reef complexity (Riegl and Purkis 2015; Riegl et al. 2018; Burt et al. 2019). Reef-associated fish are impacted by this habitat loss (Buchanan et al. 2016, 2019), and global warming may also affect fish size, growth, fecundity and susceptibility to disease (Donelson et al. 2010; Brandl 2020; D’Agostino et al. 2021). Overall, the Gulf represents a highly vulnerable marine environment that is challenged by a wide array of local and global factors that threaten to further degrade the integrity of its coastal ecosystems.

### *1.2 Management Responses to Environmental Change in the Gulf*

Gulf leaders have become increasingly aware of both the importance of coastal ecosystems and the threats to them, and various marine conservation efforts have been instituted in recent years (Khan 2007; Hamza and Munawar 2009; Lamine et al. 2020). Marine environmental management actions have included establishing marine protected areas (Al-Cibahy et al. 2012; Van Lavieren and Klaus 2013), adopting ecosystem-based management approaches (Burt et al. 2017; Mateos-Molina et al. 2021), developing more sustainable fishing practices (Grandcourt 2012), enhancing environmental regulations and strengthening environmental impact assessment processes (Naser 2015). Gulf nations have also adopted various regional and international frameworks to improve sustainable development practices, address climate change, prevent pollution and protect biodiversity, including the Regional Organization for Protection of Marine Environment (ROPME) (Nadim et al. 2008; Lincoln et al. 2021), the United Nations 2030 Sustainable Development Agenda and many others (Al Saidi 2021).

### *1.3 Artificial Reefs as a Tool for Marine Management in the Gulf*

Better conservation management, stronger regulations and stricter enforcement will help slow the degradation of marine ecosystems, but there is also a need for habitat restoration and enhancement efforts to compensate for habitat that has been degraded or lost (Burt and Bartholomew 2019; Alghunaim et al. 2020; Erftemeijer et al. 2020). Artificial reefs (ARs) are a management tool that can be deployed for various ecological and economic benefits in the Gulf. To assess the current status of artificial reef use and performance, we performed a systematic literature review to explore patterns and trends in AR-related research in the Arabian Gulf region. We searched Google Scholar for “artificial reef” combined with “Arabian Gulf”, “Persian Gulf’ and the names of each country of the Gulf, and we included “gray literature” sources. Some of the Gulf AR programs are described in detail, and information about these reefs is included in Table 1. In other cases, ARs are only mentioned very briefly. These are listed below by country, but are not included in Table 1. (Kuwait: Maghsoudlou et al. 2008), (Bahrain: Shams 2002), (Qatar: Abdel-Moati et al. 2006; Maghsoudlou et al. 2008; Richer 2008; Rosciszewski-Dodgson and Cirella 2022), (Oman: Alhabsi 2013), (Iran: Ajdari and Ajdari 2016) (United Arab Emirates: Salahuddin 2006; EAD 2016; Gibling 2013; Mateos-Molina et al. 2020). In some cases, one or more management goals were stated for the AR program, and this information was incorporated into Figure 1. In several cases no management goals were explicitly stated. Figure 1 shows that artificial reefs have been deployed in the Gulf for a variety of purposes, including: promoting fisheries (Downing et al. 1985; Harris and Schroder 2001; Ajdari et al. 2011; Azhdari et al. 2012; Ajdari and Ajdari 2016; Loughland and Bass 2016), enhancing biodiversity (Salahuddin 2006; Hopkins 2007; Al-Cibahy et al. 2009; Loughland and Bass 2016), promoting dive tourism (Harris and Schroder 2001; Gibling 2013), providing additional reef habitat to compensate for lost natural hard bottom habitat (EAD 2016; Mohamed 2021), preventing trawling (Shams 2002) and creating hard bottom habitat to transplant corals that would otherwise be destroyed by development (Deb et al. 2014). Most of these are common goals for artificial reef projects worldwide, but the use of artificial reefs to support large-scale coral transplantation efforts in Qatar (Deb et al. 2014; Rosciszewski-Dodgson and Cirella 2022) is unusual.

For many Gulf AR programs there is little publicly-available information available, and no stated management goals. When stated, management goals are often imprecise, and in most cases there is insufficient monitoring after deployment to determine if any stated goals were met. Marine managers also usually do not account for possible negative consequences of the AR program, so no efforts are made to prevent or mitigate these problems (Feary et al. 2011). Without explicitly-stated goals and adequate monitoring, managers may claim their reef projects are successful, when in fact they are not meeting management objectives (Baine 2001). AR programs may even exacerbate some of the existing problems managers are trying to fix, or create new unanticipated problems (Grossman et al. 1997; Bulleri and Airoldi 2005; Morley et al. 2008).

The purposes of this paper are threefold. Firstly, we summarize the various ways in which ARs have been used as tools for marine management globally and in the Gulf, and we discuss possible benefits associated with their use. Secondly, we highlight various risks associated with ARs if they are not properly designed, deployed and managed. Thirdly, we use this information to propose six policy recommendations for managers considering AR programs, in order to minimize risks and maximize benefits of future AR programs in the Gulf.

## *2 Uses and Benefits Associated with ARs*

### *2.1 Economic and Cultural Uses and Benefits*

This section of the paper is summarized in Fig. 2.

ARs have been deployed successfully to promote various economic interests. ARs have been deployed in the Gulf (Table 1; Ajdari and Ajdari 2016) and elsewhere (Delmendo 1990; Zhang et al. 2005) to attract commercially-important species of fish, or to provide them with habitat and refuge spaces (Charbonnel et al. 2002; Leitao et al. 2008a). This can benefit local fisheries in the short term, but there is a long-standing debate about whether ARs "produce" new fish biomass for local fisheries or simply attract existing fish to them (*sensu* "attraction versus production" Bohnsack and Sutherland 1985; Grossman et al. 1997; Roa-Ureta et al. 2019). Efforts to design and create reefs that produce fish have been less successful than reefs that simply attract fish, although there are instances where ARs seem to contribute to increased net production of fish, even with the increased fishing pressure associated with the ARs (Roa-Ureta et al. 2019). ARs can increase fish production by providing refuges from predation, if refuge habitat is limiting (Simon et al. 2011; Roa-Ureta et al. 2019; Folpp et al. 2020), or by providing habitat for planktivorous fish that would not live in an area without the reef (Rilov and Benayahu 2002; Champion et al. 2015; Smith et al. 2016). ARs can also increase production by providing suitable breeding habitat (Pondella et al. 2002; Kim et al. 2011). ARs can increase feeding opportunities, leading to increased growth rates and more fish biomass production (Fabi et al. 2006; Love et al. 2007; Cresson et al. 2014). ARs can also alter water circulation patterns to improve larval recruitment to an area (Cenci et al 2011) or provide suitable recruitment habitat for planktonic fish larvae that would otherwise die because they would be transported to regions lacking hard-bottom habitat (Emery et al. 2006).

Improving the design of ARs may increase the likelihood that they produce fish, rather than just attract fish. Recommendations include creating vertically-oriented reefs (Rilov and Benayahu 2002), and creating reefs with void spaces that are the appropriate size to provide refuge spaces for fish, especially juvenile fish that normally have high mortality rates (Charbonnel et al. 2002; Patranella et al. 2017; Burt and Bartholomew 2019). Placing reefs “downstream” of natural reefs in areas without natural hard-bottom habitat may provide settlement sites for planktonic fish larvae that would otherwise not survive (Carr and Hixon 1997).

ARs can also support bivalve fisheries by providing attachment sites and increasing production (Steimle et al. 2002; Macreadie et al. 2011; Lipcius and Burke 2018), and ARs can be designed to support aquaculture for benthic invertebrates (Fabi et al. 1989; Xu et al. 2017). ARs have also been used successfully to promote marine biology education (Seidelin et al. 2018), to create surfing locations (Black and Mead 2001) and to promote dive tourism (Table 1; Salahuddin 2006; Gibling 2013; Belhassen et al. 2017). Dive tourism associated with some ARs, like large shipwrecks, can bring substantial economic benefits to local economies (Broughton 2012).

### *2.2 Ecological Uses and Benefits*

This section of the paper is summarized in Fig. 3.

ARs have also been used to promote various ecological goals. There are examples of large-scale artificial marine structures that have had significant positive ecological effects, including producing fish larvae (Stephens and Pondella 2002), increasing biodiversity (Loughland and Bass 2016), protecting valuable natural habitat from trawling (Charbonnel and Bachet 2010) creating hard-bottom settlement sites for ecological-valuable species like corals and kelp (Burt et al. 2011; Schroeter et al. 2015) and creating transplantation sites for coral that would otherwise be destroyed by development projects (Table 1; Rosciszewski-Dodgson and Cirella 2022). There are also many successful examples of “greening of gray infrastructure”, which refers to ecoengineering coastal infrastructure to enhance its ecological benefits (Firth et al. 2014; Airoldi et al. 2021; O’Shaughnessy et al. 2020). ARs may be used to increase biodiversity as they support various reef-associated fish and invertebrates (Maghsoudlou et al. 2008; Mousavi et al. 2015; EAD 2016). ARs provide attachment sites for habitat-forming species of macroalgae, bivalves, corals, etc. which contribute to increased biodiversity as well (Farinas-Franco and Roberts 2014; Alghunaim et al. 2020; Rosciszewski-Dodgson and Cirella 2022). The organisms associated with ARs can also provide ecological services such as water filtration (Chojnacki and Ceronik 1996; Israel et al. 2017) and carbon sequestration (Hall et al. 2011; Pi-Hai et al. 2014). ARs have also been successfully used to prevent bottom trawling, which protects critical benthic habitat from destruction (Shams 2002; Relini et al. 2007; Ramm et al. 2021), and can help prevent overfishing (Polovina 1990).

ARs are often deployed to provide ecological benefits as a part of mitigation plans for coastal development projects or accidental destruction of natural habitats (Richer 2008; Levrel et al. 2012; Al-Horani and Khalaf 2013). The “mitigation hierarchy” is used by managers to reduce negative impacts of development projects. The first step in the hierarchy is to avoid negative impacts, followed by reducing negative impacts, followed by providing offsets for any remaining unavoidable impacts (Cabrera and Castro 2018). ARs have been repeatedly shown to support diverse and abundant communities of fish and invertebrates. In some cases, diversity and abundances can be the same or higher on ARs compared with natural hard bottom habitat in the Gulf (Al Cibahy et al. 2009; Azhdari et al. 2012, Burt et al. 2013; Ajdari and Ajdari 2016) and elsewhere (Perkol-Finkel and Benayahu 2004; Fowler and Booth 2012; Folpp et al. 2013). With appropriate design, implementation and management, ARs could be deployed as part of the wider actions of the mitigation hierarchy to achieve a “net gain” in biodiversity. Gulf countries do not have adequate management policies for biodiversity offsetting, unfortunately (GIBOP 2019).

It is important to note, however, that ARs typically support very different communities of benthic invertebrates (Burt et al. 2009; Sedano et al. 2019; Hill et al. 2021) and fish (Komyakova et al. 2019; Jones et al. 2020; Mohamed 2021) than surrounding soft-bottom habitats and natural reefs. Paxton et al. (2020a), in contrast, found that artificial reefs generally support similar fish densities and diversities compared with natural reefs. Since ARs often support different communities than natural habitats, using ARs to mitigate destruction of natural habitat can be problematic, because they may be a poor substitutes for the lost biodiversity and ecosystem functions associated with natural habitats (Carvalho et al. 2013; Sanabria-Fernandez et al. 2018; Hill et al. 2021), particularly when the reefs are newly deployed and are in the early stages of colonization and succession (Walker and Schlacher 2014). The creation of ARs should not be used as an excuse to allow the destruction of existing natural habitat through so-called “green-washing” (Firth et al. 2020). Unfortunately, governmental policies may incentivize creation of new habitat, like ARs, for mitigation purposes over preservation of natural habitats (Levrel et al. 2012). At best, small-scale ARs may have limited ecological benefits with significant costs to deploy them. At worst, ARs can have a variety of unintended negative consequences, and have been used as an excuse to allow the destruction of economically valuable and ecologically important natural habitats.

## *3 Unintended Negative Consequences of ARs*

This section of the paper is summarized in Fig. 4.

### *3.1 Opportunity Costs – ARs May Not be the Best Use of Limited Conservation Resources*

Although there are certainly examples of large-scale ARs that have significant positive ecological effects, most AR deployments are small-scale, and may be too small relative to natural-occurring hard bottom habitat to create significant ecological benefits (DeMartini et al. 1989; Pitcher et al. 2002), as the effects of an individual reef may only extend a short distance from the edge of the reef itself (Scott et al. 2015; Smith et al. 2017; Reeds et al. 2018). These AR projects can be costly and time-consuming to create and deploy (Pioch and Doumenge 2010; Levrel et al. 2012; Bayraktarov et al. 2019), and in many cases the time, effort and money spent on ARs would be better spent on alternative conservation projects, such as protecting, restoring or enhancing natural habitat (McCreless and Beck 2016; Morris et al. 2018; Airoldi et al 2021). In the mitigation hierarchy, deploying ARs can be used as an offset with positive impacts. Using offsets is a "last resort", however, and it is preferable to avoid and minimize negative environmental impacts or restore natural habitat instead (Cabrera and Castro 2018).

*3.2 Attraction of Fish that Exacerbates Overfishing*

The most widely-cited and important negative economic consequence of deploying ARs is that they can contribute to unsustainably high fisheries catch rates, leading to a decline in regional fish stocks and overfishing over the medium- to long-term (Bohnsack 1989; Chou 1997; Grossman et al. 1997). This occurs because ARs often attract more fish from surrounding habitats than they produce themselves, which can contribute to decreased fish abundance in nearby natural habitats (Matthews 1985; Simon et al. 2011). ARs are effective at attracting and concentrating commercially-important species, including highly migratory species (Pears and Williams 2005; Shroepfer and Szedlmayer 2006), and numerous studies around the world have recorded increased short term catch rates and economic gains associated with ARs for both commercial and recreational fishers (Korea: Kim et al. 1994; Taiwan: Lin and Su 1994; Philippines: Chou 1997; Portugal: Santos and Monteiro 1998; Iran: Azhdari et al. 2012; India: Kasim et al. 2013; Australia: Keller et al. 2017). In the long term, these increased catch rates can contribute to regional overfishing, however (see paragraph below). ARs may improve catch rates of certain species but not others, and ARs may not affect overall fisheries catches in a region (Polovina 1989; Polovina and Sakai 1989; Sun et al. 2017). In some cases, ARs may even negatively affect regional fishing income (Islam et al. 2014).

ARs are often deployed to be easily accessible, and the combination of short travel times to known, fixed locations with high densities of commercially-important species means that ARs usually concentrate fishers as well. (McGlennon and Branden 1994; Watanuki and Gonzales 2006; Keller et al. 2016). High concentrations of fish and fishers around an AR can contribute to regional overfishing in the long term (Polovina 1990; Whitmarsh et al. 2008; Simon et al. 2011), particularly in countries with poor fisheries management (Watanuki and Gonzales 2006), unless regulations restricting fishing at ARs are implemented and enforced (Pears and Williams 2005). Concerns about ARs contributing to the decline of vulnerable commercial species has caused the government of South Australia, for example, to discourage any further deployment of ARs (Pears and Williams 2005).

*3.3 ARs as Sink Habitat for Larval Fish*

ARs may intercept fish larvae that would have otherwise settled in superior natural nursery habitats, and thus contribute to lower regional recruitment. ARs, particularly those with high vertical relief, tend to have high densities of large, predatory fish species (Paxton et al. 2020b), which can lead to low juvenile and prey fish survivorship on these reefs (Herrera et al. 2002; Leitao et al. 2008b; Folpp et al. 2011) compared with natural habitats. If this occurs, ARs would be a "sink" habitat that contribute to a decline in the regional abundance of prey species (Carr and Hixon 1997; Levrel et al. 2012).

*3.4 Halos of Altered Benthic Habitat Around ARs*

ARs usually support different faunal communities than the surrounding natural habitats, particularly if they are deployed in soft sediments (Bulleri 2005). ARs may also alter currents and sediment movement. Both the altered currents and the reef-associated fauna contribute to a "halo" of altered benthic habitat surrounding ARs (Herrera et al. 2002). Several studies have noted that the high densities of predatory fish associated with ARs alter the benthic prey community around the reef (Bortone et al. 1998; Herrera et al. 2002; Reeds et al. 2018) and high densities of herbivorous fish may deplete vegetation around ARs (Edelist and Spanier 2009). Alternatively, high densities of fauna on ARs may lead to increased nutrient deposition that spurs the growth of vegetation and alters the vegetation community around the AR (Alevizon 2002; Dewsbury and Fourqurean 2010). ARs can also alter the local hydrology and can cause increased sediment erosion around the reef in high-energy environments (Herrera et al. 2002; Raineault et al. 2013) or increased sediment deposition in other cases (Martin et al. 2005; Cenci et al. 2011). These changes in sedimentation can, in turn, affect the benthic community around the reef (Danovaro et al. 2002; Herrera et al. 2002; Raineault et al. 2013).

### *3.5 Facilitating the Spread of Invasive Species*

ARs may act as stepping stones for the spread of hard-bottom invasive species (Bulleri and Airoldi 2005; Adams et al. 2014; Firth et al. 2016), particularly if the ARs are deployed in soft sediment habitats, such that these invasive species would not become established without the ARs (Sheehy and Vik 2010; Airoldi et al. 2015). ARs can also facilitate the spread of invasives when deployed in hard-bottom habitats, however, particularly if the invasive species are more successful on the artificial structures compared with natural hard-bottom habitats (Dafforn et al. 2012). After invasive species become established on artificial structures, they can then successfully invade nearby natural hard-bottom habitats (Glasby et al. 2007; Broughton 2012; Simkanin et al. 2012). There are several examples where ARs have clearly contributed to the spread of invasive species, including a green algae, ascidians, a coral and a caprellid amphipod in the Mediterranean (Bulleri and Airoldi 2005; Ros et al. 2013; Salomidi et al. 2013; Airoldi et al. 2015), a green algae in Chile (Neill et al. 2006) and a blenny, a coral, mussels and an ascidian in the Gulf of Mexico (Sheehy and Vik 2010). The supplemental material of Clarke et al. (2020) lists more than 30 benthic or demersal invasive species that have been found in the Gulf that could potentially become associated with ARs. These include species of macroalgae, tunicates, barnacles, nudibranchs, bryozoans and demersal fish. There are several design features that can reduce the prevalence of invasive species on ARs, including: using natural rock and shell as substrates while avoiding wood, concrete, rope and other artificial materials, avoiding steep vertical relief, reducing shading on the reef and "seeding" the reef with native fouling species soon after the reef is deployed (Firth et al. 2016; Dafforn 2017).

### *3.6 Waste Dumping and Destruction of Natural Habitat*

Some "AR projects" may be little more than glorified trash dumping (with lower disposal costs) in which cars, boats, airplanes, tires, construction waste, decommissioned oil rigs, etc. are sunk to the bottom as "habitat" for marine life (Chou 1997; Firth et al. 2020). Decommissioning oil rigs may cost several million dollars, for example, and oil companies can reduce their disposal costs with "rigs-to-reefs" programs (Broughton 2012). ARs made from haphazardly deployed "scrap" material support lower fish abundance and diversity compared with purpose-built ARs that are carefully deployed (Brock and Norris 1989). These scrap materials are generally not built to withstand strong waves and currents, and they may break apart and be transported surprisingly long distances by storms. Hurricanes have transported relatively low-density AR materials, like concrete pipes, steel cubes, automobiles, tires and recycled plastic 1 – 2 km, or further, away from their original location (Bell and Hall 1994; Turpin and Bortone 2002; Morley et al. 2008). Even materials like sections of steel radio towers and vessels can be moved several hundred meters in a hurricane (Bell and Hall 1994; Blair et al. 1994; Turpin and Bortone

2002). In some cases, scrap transported from ARs may end up damaging nearby natural habitat. An AR in Florida was created using millions of tires that moved several kilometers in some cases, and damaged nearby natural coral habitat. This necessitated costly cleanup efforts to remove some of the tires (Morley et al. 2008). Low-density materials, like automobiles, tires and shipping containers, should not be used as ARs where there is a possibility of strong storms, and the state of Florida, for example, has outlawed the use of these materials (Broughton 2012). Even relatively stable scrap artificial structures, like vessels, should be placed at least several hundred meters away from natural hard bottom habitats in regions susceptible to strong storms.

### *3.7 Pollution Released from ARs*

ARs associated with waste materials may also release various pollutants associated with fuels, lubricants, batteries, metals, asbestos and paints, including toxic antifouling paints, unless they are thoroughly decontaminated before deployment. Examples of pollutants associated with ARs include polychlorinated biphenyls (PCBs) associated with vessels (Dodrill et al. 2011), heavy metals associated with paint (Broughton 2012; Gaylarde et al. 2021), heavy metals from tires (Collins et al. 2002) and toxic antifouling paint associated with vessels. This antifouling paint can reduce the densities of sessile invertebrates as well as the fish that would normally feed on them (Wendt et al. 1989; Walker et al. 2007; Szedlmayer and Miller 2018). Concrete associated with construction waste has a high pH (~13), and may be a poor substrate for recruitment of sessile organisms (Sella and Perkol-Finkel 2015).

## ***4 Recommendations for Improved AR Policy in the Arabian Gulf***

This section is summarized in Fig. 5

Gulf countries have developed ultra-modern, cosmopolitan cities, and Gulf leaders have clear visions for the future of their nations. Gulf countries are increasingly focusing on sustainability and effective environmental management as a part of their visions (Burt and Bartholomew 2019). Below we provide general recommendations that decision makers and managers should adopt in order to enhance the effectiveness of future AR programs in the Gulf.

### *4.1 Avoid 'greenwashing' with ARs*

ARs provide additional hard-bottom habitat that can support diverse communities of fish and invertebrates. The communities that develop on artificial reefs are usually distinct from natural communities, however, so ARs should not be considered replacement surrogates for natural habitats that are degraded or destroyed by coastal development projects (Firth et al. 2020; Watchorn et al. 2022). Deployment of artificial reefs should not be used as an excuse to allow the destruction of natural habitat. Coastal management policies should promote the preservation, restoration and enhancement of natural ecosystems whenever possible. These policies will often be less costly than ARs and more successful in supporting sustainability-related management objectives.

### *4.2 List explicit goals for the AR program*

The management goals for any AR project should be clearly defined at the earliest planning stage of the project, as these goals underpin all subsequent work on the AR (Spieler et al. 2001; Seaman 2007). ARs can be used to fulfill a variety management goals, and different goals would be supported by different AR materials, designs, deployment patterns and site locations. Reef programs with multiple goals should list and assess each goal independently, and some goals may be incompatible to an extent (fishing and dive tourism, for example).

### *4.3 Define quantifiable criteria for assessing the AR's performance in meeting each goal*

AR projects should have specific, quantifiable benchmarks associated with each goal, so that managers can judge AR performance and determine whether the AR project can be considered successful or not (Spieler et al. 2001; Becker et al. 2018). It is insufficient to say that the reef should simply increase fish density or coral percent coverage, for example. Multiple variables can be measured to determine if some goals are being met. For example, if a goal is enhancing dive tourism, managers could measure AR fish abundances, number of visitors to the reef, increased dive shop revenues, etc. These measurable objectives should be devised early on in any AR program, and should be re-evaluated after engaging relevant stakeholders, before moving on to later phases of the project (Pears and Williams 2005).

### *4.4 Design and deploy the ARs to meet the intended goals*

ARs have been constructed using many different materials, they come in a wide variety of shapes and sizes, they may have different surface features and attachments and they have been deployed in a variety of configurations in many different locations and habitats around the world (Tickell et al. 2019). Only a subset of these will support the intended goals of the project, however, and managers should read published accounts of regional AR programs to determine what design features and deployment techniques have worked in the past to achieve similar goals. There are government-issued guidelines available for artificial reef planning, materials, construction and deployment that are available (Lukens and Selberg. 2004; Lindberg and Seaman 2011; Fabi et al. 2015). Decision makers should also consult with regional stakeholders during the planning stages and afterwards, so that these stakeholders can input their knowledge and they feel included, both of which would contribute to the success of the AR program (Clarke et al. 2002; Sayer and Wilding 2002).

### *4.5 Develop a robust monitoring program to assess criteria in meeting goals*

It is critical to implement a scientific monitoring program after deployment, to determine the impacts of the reef and whether the goals of the AR program are met (Ramm et al. 2021). The monitoring program should ideally be implemented by professional marine ecologists associated with independent, non-commercial organizations. Factors such as the sampling design (e.g. Before-After, Control-Impact), amount of replication, the extent of sampling in space and time, the appropriate methods for sampling different species and data analyses need to be considered in-depth. Monitoring should be long-term and systematic, because the communities associated with ARs will change rapidly soon after deployment, but can continue to change for decades (or longer) (Perkol-Finkel and Benayahu 2005; Nicoletti et al. 2007). ARs are often expensive and time-consuming to deploy, and monitoring requires relatively little cost and effort by comparison, but unfortunately long-term monitoring is rare (Ramm et al. 2021). Monitoring data will be a "good return on investment" because it can help guide decision makers about whether and how to deploy more ARs in the future.

### *4.6 Publicize the results of the AR program*

The final stage in any AR program should be to evaluate its effectiveness, and share the results and 'lessons learned' publicly. Managers should report information about the reef itself (Ramm et al. 2021), management goals and the data from the long-term monitoring program. Ideally, information about the costs and work hours associated with the AR program should be presented, so managers can assess whether the outcomes created by the AR are worth the money and effort. All this information will help decision makers to determine whether to deploy additional ARs, and how to improve them if more are deployed. By sharing this information publicly, marine managers can demonstrate their commitment to promoting environmental sustainability and help other managers develop successful AR programs in the future (Ramm et al. 2021).

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**Table**

Table 1. A summary of AR programs in the Arabian Gulf that are adequately described in the publicly-available literature, including information about the reef, the stated management goals and the reported results.

| Country / reference(s) | Reef Information | Management Goals | Results of the AR Program |
|---|---|---|---|
| Kuwait / Downing et al. 1985 | - 3 car tire reefs<br>- 25 $m^2$ x 0.8 m or 2.4 m high | Test if reefs attract fish | - ARs quickly attracted commercially important species.<br>- 2.4 m reef attracted more fish biomass |
| Saudi Arabia / Loughland and Bass 2016 | - Multiple 1 $m^3$ cubical concrete modules at 24 sites.<br>- 1 "mega site" with central and peripheral modules connected by limestone basket spokes | Create habitat to enhance fisheries and biodiversity | Reefs became "thriving new ecosystems" with a variety of fish and other reef organisms. |
| Qatar / Deb et al. 2014 | Almost 2800 coral colonies were transplanted to 550 limestone boulders and 213 low-relief concrete modules | Transplant corals away from pipeline sites | Initial transplant monitoring indicated:<br>- 5% coral mortality, and similar health to reference corals<br>- Corals support reef fauna<br>- Coral recruitment |
| Qatar / Mohamed 2021 | Concrete orb-shaped reef modules deployed in clusters | Compensate for lost natural reefs | ARs had lower fish species richness but higher fish densities than a natural reef. |
| Iran / Ajdari et al. 2011 Azhdari et al. 2012 | - 1.5 x 1.2 domed concrete modules, 1.5 x 1.4 pyramid concrete modules and concrete construction waste deployed in different combinations<br>-Each reef type combination replicated 3 times<br>- Each replicate had 16 pieces of artificial reef material | Test if reefs increase fish catch | Reefs with all 3 materials performed best:<br>- They had higher catches than 2 other reef types in Ajdari et al. 2011.<br>- They had higher catches than other reef types and natural habitat in Azhdari et al. 2012.<br>-Other reef types did not have higher catches than natural habitat |
| United Arab Emirates / Hopkins 2007 | - 3 reefs deployed, each with:<br>- A central concrete cylinder 1.4 m diameter x 2.5 m tall<br>- 14 rows of plastic pipes with 11 pipes in each row radiating from the cylinder | Test if reefs enhance biodiversity | After two years, the reefs were covered by fouling organisms, including corals, and attracted a variety of fish. |

| | | | |
|---|---|---|---|
| United Arab Emirates / Al-Cibahy et al. 2009 | 144 ceramic branching modules deployed in 4 reefs | Test if reefs enhance biodiversity | In less than 1 year, artificial reefs had:<br>- Higher fish biomass and slightly higher fish species richness<br>- Higher coral % coverage<br>compared with natural reference sites |
| United Arab Emirates / Harris and Schroder 2001 | Various vessels sunk by fishers, private companies or the government to create ARs | Attract fish | - These wrecks attract a variety of fish, including commercially-important species.<br>- They are used by recreational divers |
| United Arab Emirates / Harris and Schroder 2001 | 3000 1m$^3$ concrete construction blocks deployed in a 30 x 100 m area. | Create an AR for dive tourism | - Supports a variety of sessile invertebrates, including corals, and abundant fish. |

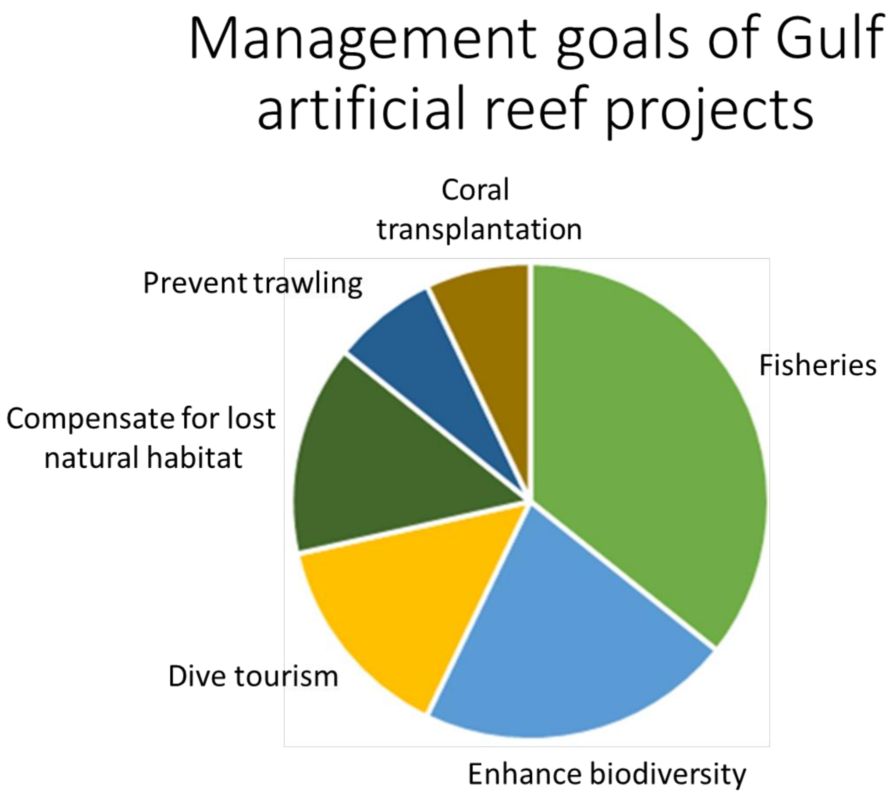


Fig. 1 Management goals of 13 Arabian Gulf AR projects with publicly-available stated goals. One project had more than one goal, and both are included in this chart. *Note to editors: this figure should be in color for online readers, but grayscale for print publication.*

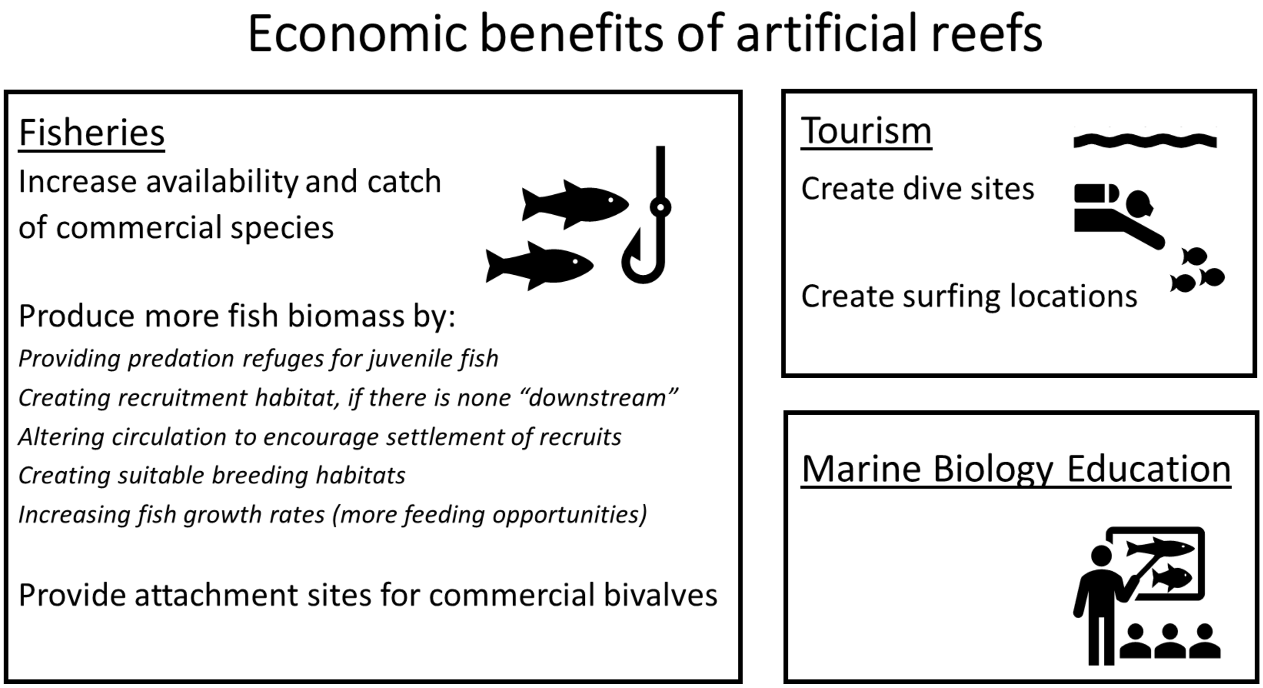


Fig. 2 Infographic depicting possible economic benefits of artificial reefs.

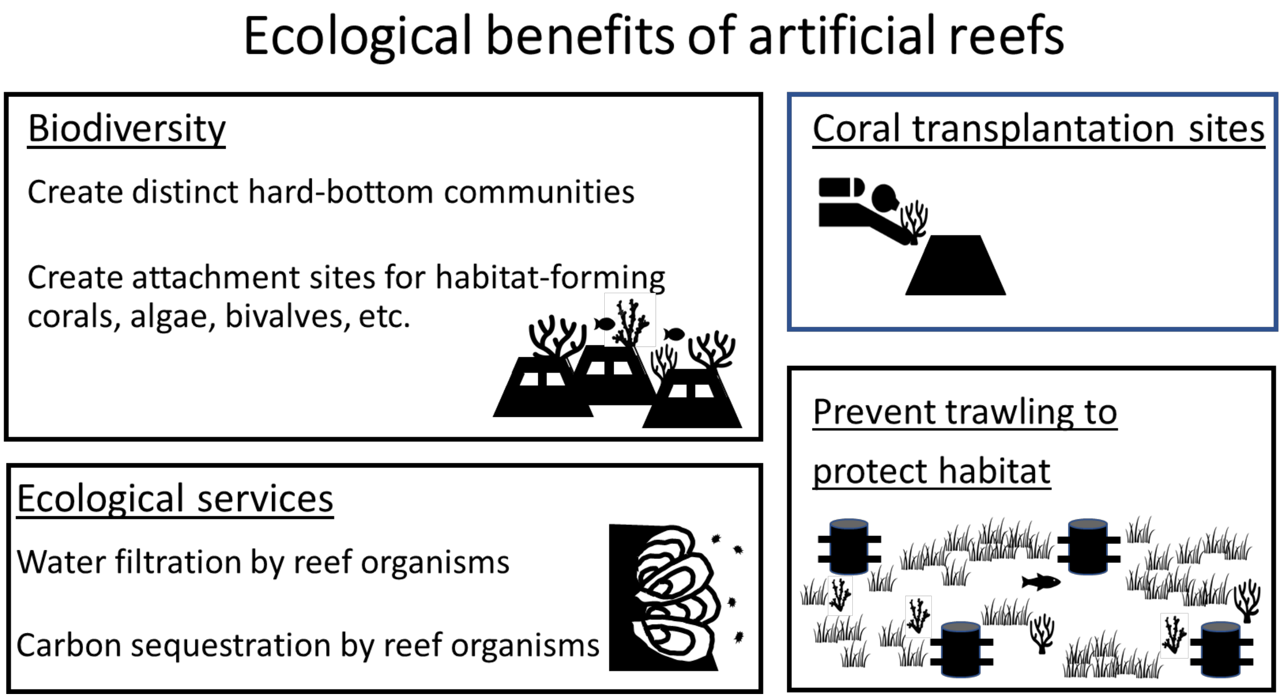


Fig. 3 Infographic depicting possible ecological benefits of artificial reefs.

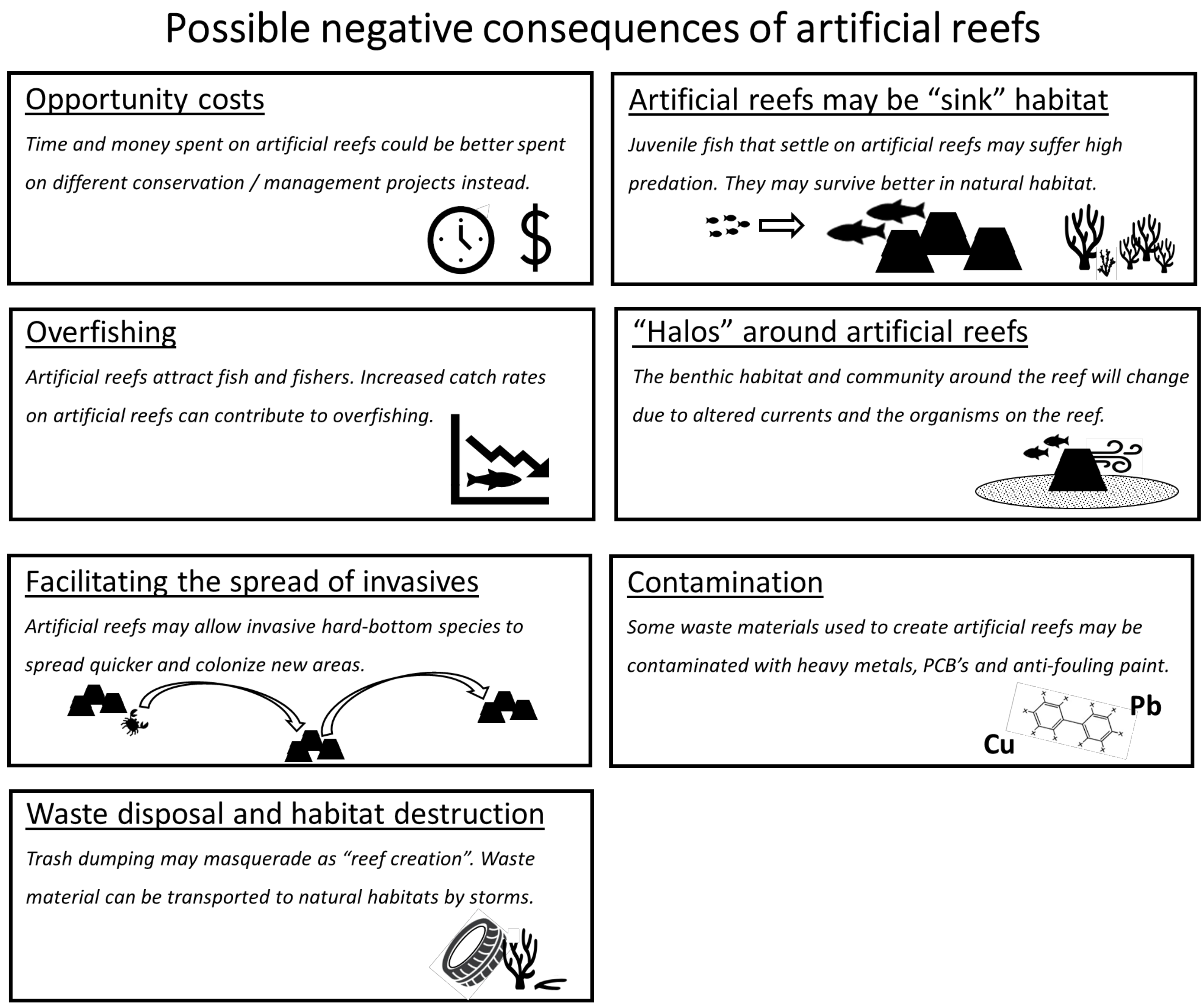


Fig. 4 Infographic depicting possible negative consequences of artificial reefs.

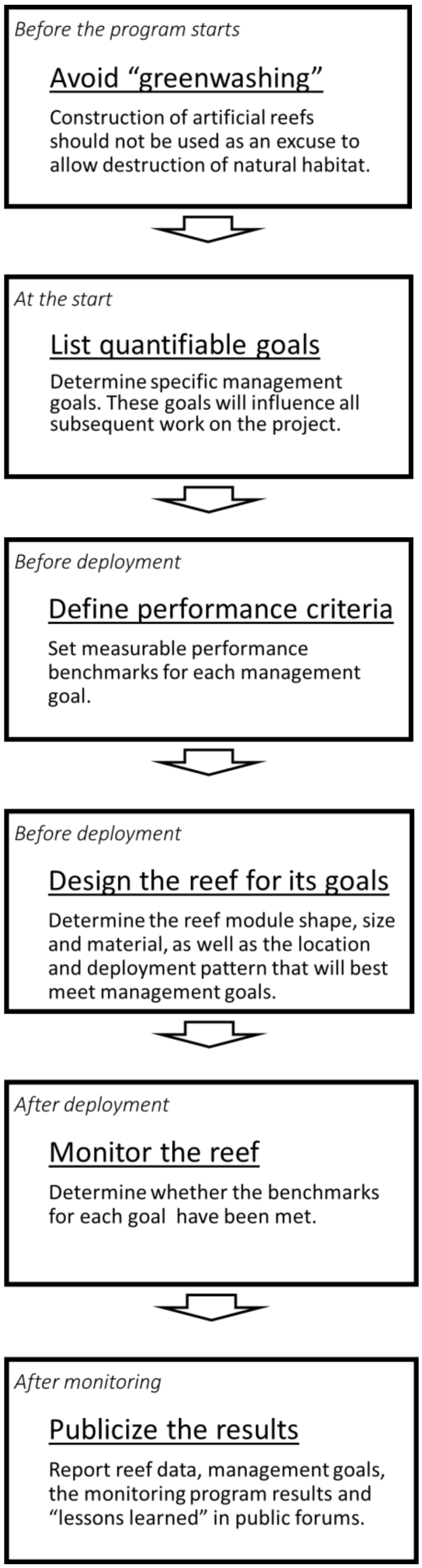


Fig. 5 Flowchart illustrating the policy recommendations in this paper for Gulf AR projects.

Declaration of competing interest

None of the authors has any competing interests to declare.

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