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Review

Artificial Reefs around the World: A Review of the State of the Art and a Meta-Analysis of Its Effectiveness for the Restoration of Marine Ecosystems

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Abstract: Over the past decade, there has been increasing interest in marine restoration, requiring a consideration of various approaches for optimal success. Artificial reefs (ARs) have been employed for marine restoration and fisheries management, but their effectiveness in restoring ecosystems lacks well-defined ecological criteria and empirical evidence. A systematic review of the literature on ARs articles between 1990–2020, a meta-analysis of their effectiveness based on the similarity of species composition with reference natural reefs (NRs), as well as bias risk analyses were carried out. Research on ARs primarily focused production of marine communities ($n = 168$). There are important information gaps regarding socioeconomic aspects; design, materials, and disposal in the selected habitats; legal, management, and planning aspects considering long-term monitoring. Regarding effectiveness, few articles ($n = 13$) allowed comparisons between ARs and NRs, highlighting the need to apply proper reference sites in AR implementations. Meta-analysis showed that ARs are not similar to reference NRs ($p = 0.03$, common effect and $p = 0.05$ random effect models). However, a high index of heterogeneity (88%) suggests that this relation may be influenced by factors other than the reef type. Thus, further analysis can disguise variables conditioning this AR–NR similarity as a measure of restoration for degraded marine ecosystems.

Keywords: artificial reefs; active restoration; effectiveness; marine ecosystems; coastal management

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1. Introduction

The loss of biodiversity, complexity, and long-living biomass of organisms has been evidenced in marine systems during the last two decades, but has been stressed at an alarming rate of change especially during the last three-four years [1]. The systematic destruction of complexity due to direct and indirect factors [2] brought entire nations and communities to take seriously the regenerative programs at large scale, such as the targets of the Restoration Decade promoted by the UN to enhance the recovery of biodiversity, blue carbon and associated biomass [3]. As we know, restoration programs are not new, but the upscaling and its feasibility on the long term has become a target that needs a good selection of methods, money, and political commitment [4].

Artificial reefs (ARs) are intentionally placed benthic structures intended to protect, enhance or restore components of marine ecosystems [5], while they can concentrate populations of living marine resources [6]. They have historically been implemented as a strategy to increase the production of species of recreational and commercial interest, receiving more attention since the 1980s [7]. However, ARs may be also considered an active restoration tool for degraded marine ecosystems that have lost habitat heterogeneity, biomass, diversity, richness, and abundance of marine organisms due to various impacts such as mining, oil and gas extraction, trawling, overfishing and pressure for tourism [8,9]. In addition, there are incidental or accidental ARs such as anti-drag tools [10], ARs for coastal erosion protection [11], tourism pressure mitigation on corals [12], etc. Altogether, they can be complementary tools to speed up programs of marine ecosystem restoration [9].

Nevertheless, ARs were often based on structures that were not designed to meet the specific needs of the biota [9]. Therefore, several problems have been associated with AR deployments such as attraction and depletion of species stocks with socioeconomic conflicts [13,14], pollution, and toxicity [15], changes in species composition with the possible introduction and dispersion of exotic species [16], and changes in the hydrodynamics of the site [17].

In this sense, a great conflict about ARs is evident, there are great contrasts between the theory and its application [18], which gives a questionable position to the use of ARs as a restoration measure by some scientific groups [19]. However, it is known that, when implemented correctly, ARs represent a tool that assists in the active restoration of highly degraded reef ecosystems [20]. All this leads us to question ourselves about what causes a successful AR deployment to achieve the necessary restoration of marine ecosystems.

A restoration project aims to re-establish a functioning ecosystem that emulates the reference ecosystem at a comparable ecological age [21]. When a system is restored, it may be applying silviculture methods [22], but the idea is not to completely recover the ancient habitat (which is impossible), but to give enough complexity to the habitat to enhance the biodiversity and biomass lost; thus, restoration must have a very long-term vision [4]. It has to be highlighted, however, that many of the actual plans are not based on an ecosystem engineering approach [23]. A proper assessment of a restoration program should preferably include a BACI (before/after–control/impact) type analysis in which control sites and restored/degraded sites should be compared before and after an impact, in order to verify a change in the intervention site [8]. While it is often unpredictable to know if an impacted site has been monitored and has baseline data that allows for a before-and-after comparison, a comparison of control and impacted sites is more often available when evaluating the success of a restoration program.

Furthermore, studies that have hypothesized the success of ARs based on changes in abundance, biomass, diversity, and species richness [24] could disguise a failed restoration, as their metrics usually identify variations of these metrics but cannot reflect changes in the composition of species, ignoring relevant problems related to ARs such as changes in community structure and invasive species introduction [25]. Thus, we would know that a restoration project is successful if the reef’s ecosystems intervened by ARs achieved a similar state of the reference “healthy” natural reefs (NRs) in terms of species composition, an approach recently applied through meta-analysis in terrestrial ecosystems, known as the species composition–ecosystem function relationship [26,27].

There are also important gaps regarding ARs characteristics and their implementation, which can be filled by reviewing results from published data and analyzing them for an integral evaluation of the social, economic, and environmental aspects [9,18,28].

Although there are some recent systematic reviews on ARs, they focus on the restoration of a limited geographic region [29], or they review qualitative measures of effectiveness based on self-reports and other characteristics of AR implementations [30]. Thus, there is no global statement on the application of ARs, or a measurement of effectivity can be biased, once it was not based on qualitative and verifiable results. The aim of the present study is to address a global measurement of AR restoration success in coastal and marine ecosystems, using quantitative contrasted data on species composition between ARs and their reference NRs. In addition, we have compiled a general historical description of the ARs over the past thirty years around the world.

2. Materials and Methods

2.1. Overview of ARs Deployments around the World

A systematic literature review (SLR) was carried out following the PRISMA Protocol [31] on indexed research articles from 1990 to 2020. The literature search was performed in Scopus® and Web of Science® (WOS) databases using the term "artificial reef" as keywords in the title of the article of any language on 1st March 2020.

We compiled 1265 documents (Figure S1), then studies were selected based on exclusion criteria adapted from [31] (Table 1). For the first exclusion criterion, books, theses, dissertations, technical reports, reviews, and opinion articles were excluded, as information in this type of literature is not granted by per-review validation. Second, duplicate indexed articles were excluded and considered as a single document. Third, articles were excluded if the full document was not available online or, after reading the abstract, if the article did not address the implementation of ARs as its main subject.

Table 1. Inclusion and exclusion criteria taken into account for the systematic literature review.

Inclusion Criteria	Exclusion Criteria
Indexed original articles	Non-indexed articles, reviews, perspective or opinion articles, scientific notes, books, book chapters, dissertations, thesis, conference abstracts, technical reports
Published articles between the years 1990–2020	Articles that were not published between the years 1990–2020
Articles that evaluated the implementation of ARs, which were available online and with DOI	Articles that did not assess the implementation of ARs or that were not available online or without DOI

Information was extracted from each reference including author's name and year of publication; study title; main theme of the study; newspaper name; financing information; country of publication; and the number of times it was cited. In addition, to describe general aspects of ARs around the world, the articles were classified by: (a) type of AR: primary purpose of structure was or was not an AR, such as accidentally sunk vessels, ports, oil platforms, jetties, wharves, breakwaters; (b) purpose of the AR: purpose of creation reported; (c) material used for AR construction; (d) shape of the AR, (e) type of study: observational or experimental; (f) type of ecosystem: marine, freshwater or estuarine ecosystems; (g) type of substrate: environment on which the AR was installed; (h) ecosystem degradation reported; (i) type of impact; (j) active restoration action taken, when reported: coral transplantation, larval resettlement, gardening, etc.; (k) depth of implantation; (l) area of AR system (km^2); (m) AR module area (m^2) and (l) module weight (kg); (n) distance from the coast (km); (o) exploratory variable evaluated; (p) time of AR implantation (years); (q) time of AR monitoring (months); (r) sampling method; (s) involvement of the community: civil, commercial, scientific and/or governmental entity; (t) within a protected area; (u) restricted fishing; (v) control sites: NRs, non-reef sites or the same site prior to implementation; (w) funding; and (x) country of implementation of the AR.

2.2. Restoration Effectiveness in ARs Deployments

Articles that were included for the description of global AR deployment were examined by applying additional exclusion criteria: Articles where AR sites were not compared with reference healthy NRs as appropriate control or reference sites, as well as articles that did not report data by species for ARs and NRs sites separately, and those that did not have an appropriate number of replicates of ARs and NRs sites, were excluded (Table 2).

Table 2. Inclusion and exclusion criteria taken into account for the meta-analysis.

Inclusion Criteria	Exclusion Criteria
Original articles that allow quantitative comparisons between ARs and more than two NRs or spatial replicas of NR sites	Articles that do not allow quantitative comparisons between ARs and more than two NRs or spatial replicas of NR sites
Articles with adequate reference NRs regarding the characteristics of the ARs implementation site	Articles without adequate reference NRs regarding the characteristics of the ARs implementation site
Articles that report data on complete species composition, by taxonomic groups or functional groups in absolute or relative abundance for each AR and NR separately	Articles that do not report data on integral species composition, by taxonomic groups or functional groups in absolute or relative abundance for each AR and NR separately

In addition, due to the low number of articles that fulfill our criteria, we ran a new SLR following the PRISMA protocol for SLR and a meta-analysis, and population, intervention, control, and outcome (PICO) strategy was performed. We applied the PICO strategy using the string search in the Scopus database on May 2023 as follows: (TITLE (reef) OR TITLE (reefs) AND TITLE (natural) AND TITLE (artificial) AND TITLE-ABS-KEY (species)). The search resulted in 53 articles (Figure S2), to which the same exclusion criteria were applied for screening (Table 2).

Metrics for species composition used to calculate the Bray–Curtis similarity index were absolute or relative density, absolute or relative abundance, and proportional frequency of occurrence, among others [32]. Afterward, species composition lists were transcribed for AR and NR sites from studies that met the conditions (Table 2). We used the Bray–Curtis index to compare reported species composition similarity between ARs and NRs, due to it having several numerical qualities that make it suitable for comparing species or functional groups composition across ecological communities [32].

The similarity indices were calculated by making all possible comparisons between all NRs sites within a study as a control. Comparisons between each AR site and NRs were also calculated for each study as intervened. The mean and standard deviation of the similarity indices were calculated for control (similarity between NRs) and for intervened sites (similarity between RNs and ARs). Meta-analysis and bias analysis as funnel plot and Egger's test were performed in order to ensure the robustness of the meta-analysis using the RStudio software with the "meta" package.

Effect measure values (mean differences) around zero were desired as a successful outcome of the restoration, that is, ARs species compositions achieved were to be similar to those of reference NRs. Negative values should mean that ARs did not achieve the same species composition of reference NRs. Positive values should mean that ARs hold more species than reference NRs, which is probably associated with invasive species presence [26,27].

3. Results

3.1. Research on ARs between 1990–2020

From 502 articles screened, 281 articles showed that there was interest in ARs worldwide during the period 1990–2020 around the world, with a particular spike in 1994 and two increases in the years of 1998 and 2002 (Figure S3). Among the pioneer countries, Japan shows up in the implementation of ARs, along with the United States and Italy. In general, the country that led the studies on ARs in the world between 1990–2020 was the United States (*n* = 78), followed by Australia (*n* = 23), Italy (*n* = 24), Israel (*n* = 18), and China (*n* = 17) (Figure 1). While the number of surveys is not an identical reflection of the number of AR installations in the world, it does represent the interest of countries in evaluating ARs.

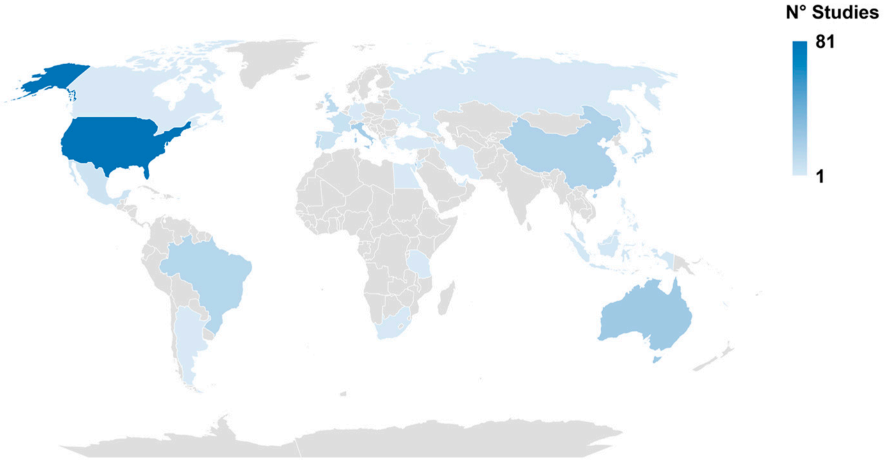


Figure 1. Distribution of AR surveys around the world included in the SLR between 1990–2020.

Most of the research (60%, n = 168) on ARs included in this review was focused on biomass production (Figure S4), including the association of biological and ecological aspects of species of commercial and food interest with ARs, such as changes in biomass, abundance, richness, species diversity, the effect of ARs on patterns of use, occupation, and the behavior of fish populations and communities, as well as topics related with aquaculture and the attraction–production dilemma. The production topic was followed by the topics of mitigation/restoration, including transplantation of corals and other invertebrates, larval resettlement of fish and corals, mitigation of habitat loss, by invasive species, by pollution of materials and mining; and effectivity/management with 12%, respectively (n = 33). Next, topics of monitoring and impacts represented 4.6% and 5%, respectively (n = 13 and 14, Figure S4). Additionally, the type of research that predominated was experimental, particularly during the period of 1990–2010, giving way in the last decade to observational research (Figure S5). The latter was often the report of continued long-term monitoring of implementations cited in previous years within the same period 1990–2020.

Research on ARs over the years 1990–2020 has focused on assessments of marine population and community structure. During the 1990s–2000s, 65% of the studies focused on production in terms of abundance, biomass, and richness of commercial species increases, while 10.6% of the studies evaluated impacts, 8.2% focused on themes of restoration and mitigation, and 7% of the articles evaluated effectiveness and management (Figure 2). In the following period 2001–2010, interest in production decreased to 60.8%, leading to more interest in studies of mitigation/restoration (12.4%) and effectivity and management (10.3%). During the 2001–2010 period, studies about impacts decreased to 4%, and a new topic related to the disposition and orientation of ARs was studied. More recently, 2011–2020 period, interest in production-focused studies dropped slightly (54.5%), while interest in effectiveness and management studies grew by 17.2%, as did efforts to restore and mitigation of marine ecosystems (14.1%). There has also been an increase in studies related to the development of monitoring methods; however, it is noteworthy a drop in studies in which ARs are related to environmental impacts, as well the low numbers of studies focused on socioeconomic aspects, abiotic changes, the development of new material technologies.

While production was the most popular topic, this was mainly evaluated using ichthyofauna as the explanatory variable (60%) (Figure 3). Studies of ichthyofauna (n = 101) were followed by studies that evaluated the fauna in general (n = 52), including studies that evaluated infauna, epifauna, and endofauna, as well as microfauna, meiofauna, and macrofauna (Figure 3). Twenty-one studies evaluated cnidarians, where corals were the main explanatory variable. Other variables less studied in association with ARs were changes of abiotic factors, socioeconomic aspects, aspects of the ARs, impact indicators such as microplastic and heavy metals, and biotic variables such as aquatic flora, crustaceans, malacofauna, ascidians, plankton, bryozoans, echinoderms, and fungus (Figure 3). This highlights the need to diversify research and integrate key aspects in the assessment and management of ARs for restoration programs.

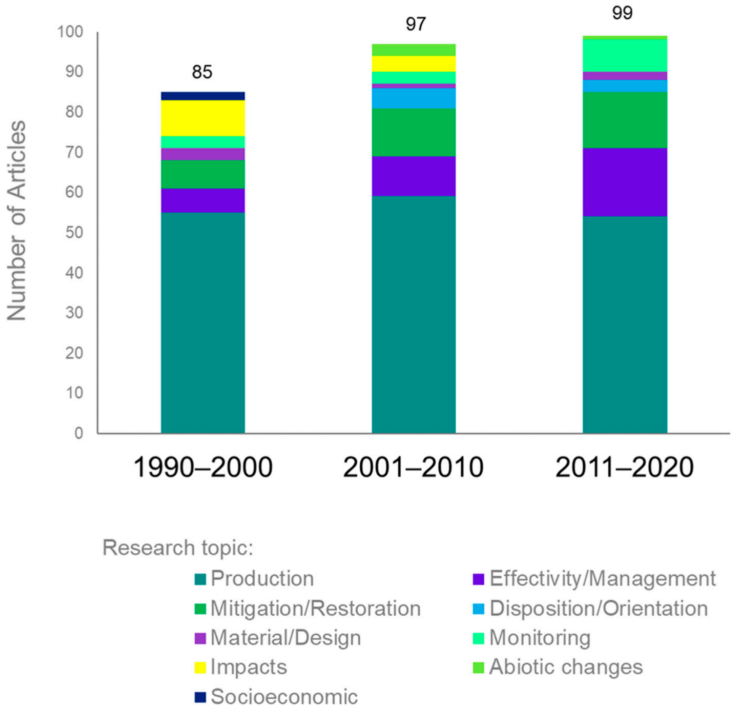


Figure 2. Main research topics found in studies of artificial reefs during the last three decades.

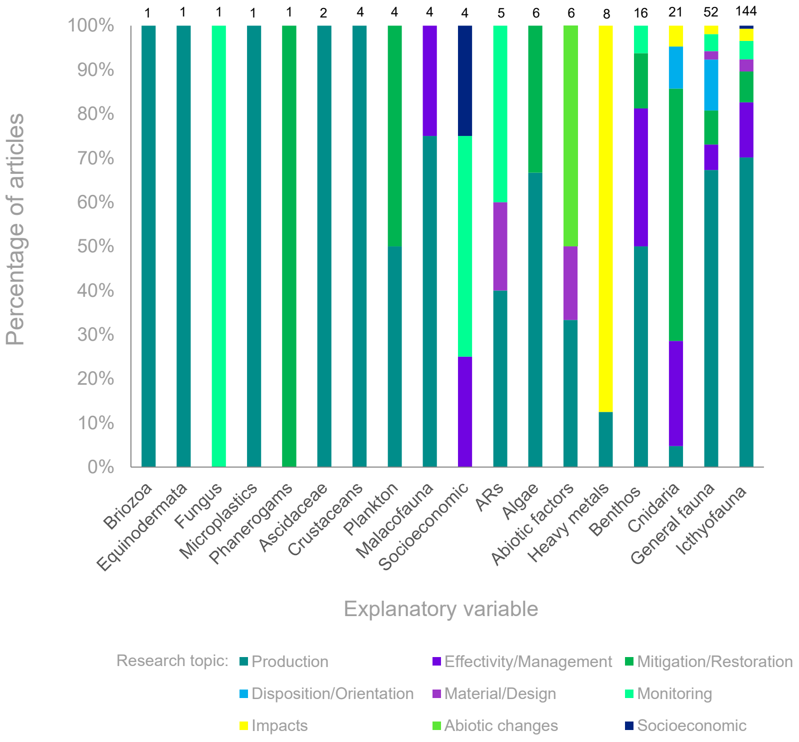


Figure 3. Exploratory variables used in studies regarding artificial reefs between 1990–2020.

On the other hand, if ARs will be installed as a restoration measure, it should be declared first which type of previous impact the ARs will restore in the deployment area. However, there is a high number of studies that did not report a previous impact in the deployment area (84%, n = 236). Between the 16% of articles describing the impact of the site (n = 45), most were related to the fishing sector (17.8%), mentioning trawling, crops, overfishing, and the urban and economic development sector (17.8%). Heavy metals were reported as pollutants from the construction materials of ARs (13.3%), as well as articles evaluating the risk of trophic imbalance, including the introduction of invasive species (9%). Noteworthy is the low frequency of reports of other impacts, no less important for the conservation of reef ecosystems, such as climate change, oil spills, coral mining, plastic pollution, and accidental/incidental sinking of vessels (Figure 4).

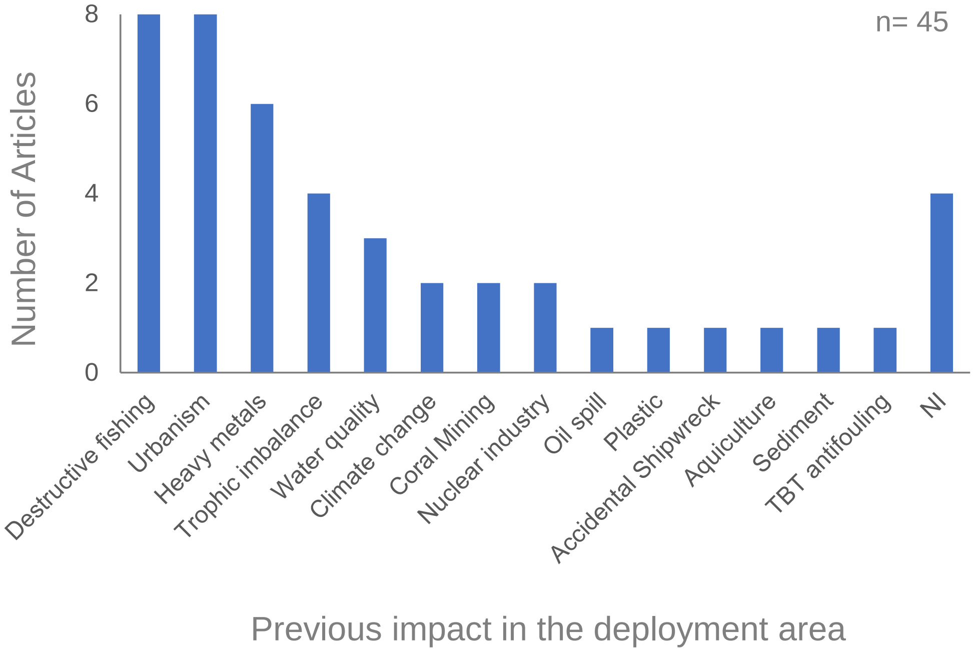


Figure 4. Reported impacts in studies related to ARs during the period of 1990–2020. NI = Studies that declared the site as impacted, but did not specify the impact type or cause of impact.

In addition, the time of deployment of ARs or "AR age", as well as the duration of the monitoring in the studies are important aspects as they can help to understand the evolution of the ecosystems where the ARs are implanted. Most studies had monitoring for up to 2 years, with an important number of articles where ARs were monitored between 1 and 12 months. Monitoring intervals of up to 4 years, 8 years, or more, were less frequent (Figure 5). In addition, 22 articles did not inform the monitoring time. Furthermore, most of the studies did not report the ARs age (n = 78). The age of the ARs varied between new structures of 1 month and old structures of more than 100 years, and the latter were mainly shipwrecks (Figure 5). There was a considerable number of ARs up to 42 years old; however, older ARs were less frequent in this review.

In addition, the preferred sampling method for monitoring ARs was the visual census (34.5%), followed by manual collection (17.4%), and photos or videos (8%, Figure S6). Methods with more advanced technologies were less frequent, but present from the late 1990s onwards, such as telemetry using ecosonar (n = 16, 5.7%) and remotely operated vehicles (ROV) or baited remote underwater video (BRUV) (n = 15, 5.3%). The collection through gillnet fishing was equally frequent with 14 articles. It is worth mentioning that few articles applied more than one sampling method, and there were 10 articles that omitted information about the data collection method (Figure S6).

Regarding monitoring of ARs, there was also a low consideration of control sites as a reference in the evaluation of ARs (23.5%), that is, almost 80% of the articles (n = 213) did not apply at least one control or reference site when monitoring the ARs progress (Figure 6). Of those articles that used control sites, 31 used non-reef ecosystems as reference sites, 26 articles applied RNs as reference sites, and 6 used NR and other non-reef ecosystems as reference sites. Another way to assess a change in an ecosystem is to obtain a record prior to the intervention of AR as a control, which was the case of a few articles ($n = 7$). Most articles applied a single reference site ($n = 34$), and fewer articles used 2 ($n = 13$) or more than 3 reference sites ($n = 21$, Figure 6). In addition, only 16 articles reported to study ARs within protected areas, and 6 articles signaled the restriction of fishing in ARs, while 13 evaluated ARs with use for fishing and 268 did not inform the fishing status.

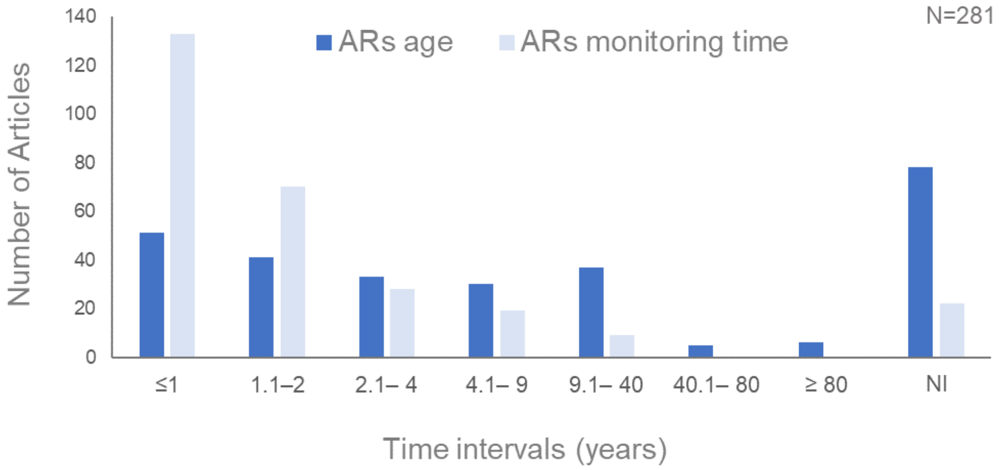


Figure 5. Time of deployment and monitoring of ARs in studies between 1990–2020.

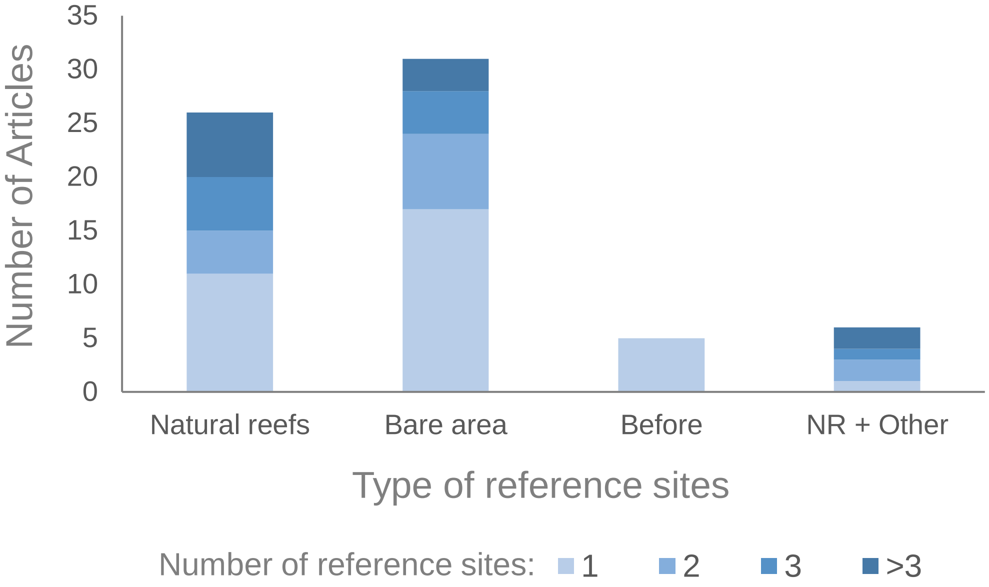


Figure 6. Types and number of reference sites taken into account in studies of ARs between 1990–2020.

Apart from the authors of the articles evaluated, other members of different communities were involved in the work effort for the development of most of the studies (74.3%) in which was recognized the participation of one or more personalities. In addition, there were few reports of implementations in which the civil community was involved (0.5%), with few exceptions of articles that assessed socioeconomic aspects through interviews with fishermen or administrators of ARs. On the other hand, in addition to the scientific community, commerce/industry and government agencies were among the most involved (9 and 3%, respectively). Other partnerships involving two or more societies represented 32.4% of studies, thus, demonstrating the need for interdisciplinary and logistical support in this type of enterprise (Figure S7).

Likewise, a large number of funded articles (79%), compared to research that did not report funding (21%), demonstrates the almost mandatory requirement for financial support where one or more governmental, scientific, and commercial agencies have invested in research on ARs (Figure S8).

3.2. Characteristics of ARs in the World

Structures purposely built for the enhancement of marine ecosystems, here called ARs, were most cited ($n = 209$). The largest proportion of these types of ARs was constructed of concrete, rocks, metal, and concrete with metal, and a combination of various materials, although a considerable number did not specify the material used for the ARs studied ($n = 17$). Few articles reported the use of biogenic materials ($n = 5$), such as shells, corals, among others. Structures not intentionally constructed for marine ecosystems enhancement were metallic or wooden vessels sunk deliberately or accidentally, as well as ports, jetties, piers, oil platforms, cars, breakwaters, and dams, which were less frequently reported and whose materials were not always defined ($n = 13$, Figure 7).

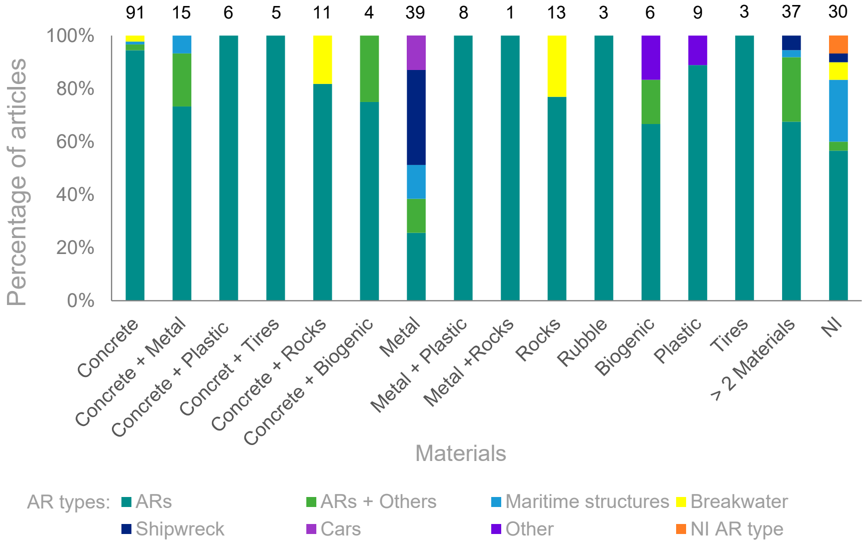


Figure 7. Types and materials of ARs used in studies during the period of 1990–2020.

Although many articles did not directly or indirectly report the purpose for which the AR was created, studies related to ecological or fishery research, evaluating the effect of ARs in promoting, increasing or changing the abundance, diversity or richness of species associated with structures, predominated ($n = 168$, Figure 8). These were classified as ARs for production purposes (60%), followed by ARs for restoration or conservation (7.5%), and by ARs for mitigation or compensation (5.3%, Figure 8).

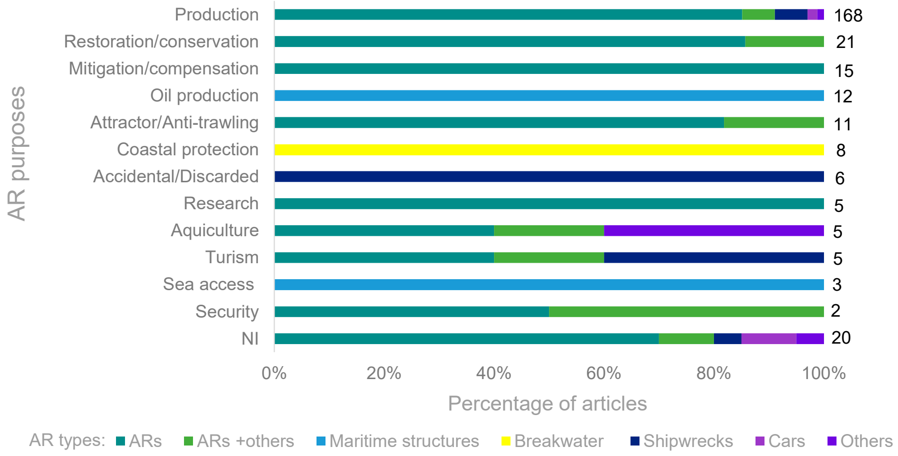


Figure 8. Purposes for which ARs were constructed during the period of 1990–2020.

There are some types of ARs that have not been initially created for it. For example, certain structures such as oil platforms, jetties, ports, piers, breakwaters, etc., despite their creation purpose, inevitably excerpt as incidental ARs, as they provide a new immerse surface that serves for marine fauna and flora to colonize. There were also other types of structures, such as vessels whose purpose of creation was transport, however purposely or accidentally sunken, in which the increase in biomass and diversity was sought for commercial, food, or recreational purposes. Thus, structures whose creation was accidental, or for coastal protection, maritime uses, cultivation of organisms, security, conservation, and scientific research, were less frequent (Figure 8).

Among the studies that had declared the ARs purpose of restoration and mitigation, some applied supplementary techniques for active restoration such as transplantation of coral, algae, and other taxa, larval and juvenile resettlement, among others (7.8%, *n* = 22, Figure 9).

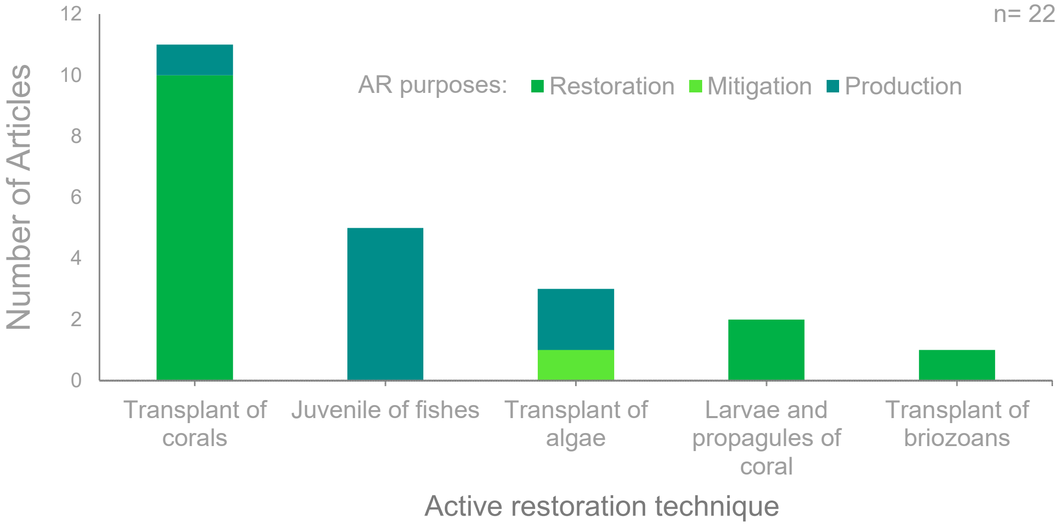


Figure 9. Active restore support actions during the period of 1990–2020.

The marine environment was almost exclusive in the use of ARs (*n* = 241); however, there were a few studies citing deployments in estuaries (*n* = 13) and rivers (*n* = 3), and 2 studies as laboratory experiments. The type of bottom, where the structures were installed, was predominantly sand (*n* = 62), muddy sand (*n* = 29), phanerogams (*n* = 13), reef (*n* = 11), or rocky (*n* = 10, Table S1).

Furthermore, most articles that reported distance from the coast (43%, *n* = 121) show that most structures were located no more than 5 km offshore (*n* = 77), followed by articles whose ARs were between 5 and 10 km (*n* = 19), by those between 11–50 km (*n* = 17), and those located more than 50 km offshore (*n* = 8). However, there were 160 articles in which this information was not provided. Likewise, the implementation depths also varied between the first 10 m (*n* = 79), as far as 20 m (*n* = 95), 30 m (*n* = 48), 40 m (*n* = 13), and deeper depths up to the 130 m (*n* = 7), and 39 articles did not report the depth where ARs were deployed.

In addition, the size of AR systems, as well as the size of each module, varied and depended on the purpose of their use. Large-scale AR systems were infrequent and usually consisted of various types of ARs including those built with primary and secondary purposes (systems with ARs of various materials, vessels, bridge debris, and cars) as disposal material and/or with a special purpose to promote the production of marine organisms. Medium-scale ARs were also used for production, usually built primarily for that. However, small-scale ARs were mostly used for restoration, mitigation, or scientific purposes.

Thus, most AR systems did not exceed the square kilometer, and most modules did not exceed the square meter. However, there were important gaps in this information as many studies did not report it (40%). On the other hand, the shapes of these ARs varied, counting domes (Reefballs), pyramids, tetrahedrons, cubes, blocks, boxes, cones, cylinders, columns, walls, meshes, and panels or plates, with pyramidal and cubic configurations being the most popular between the studies reviewed (Table 3).

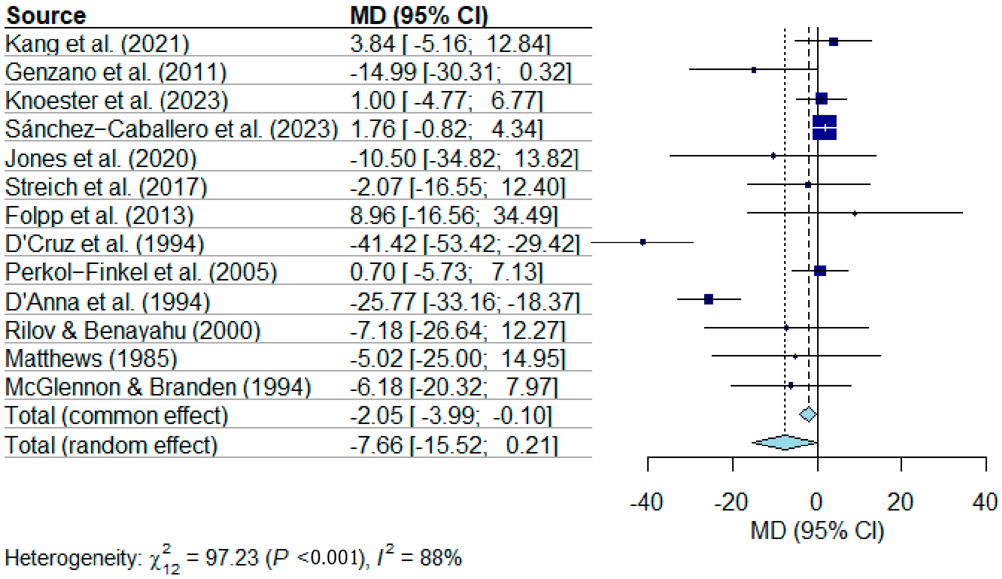
Table 3. Physical characteristics of ARs in studies during the period of 1990–2020.

AR Type	ARs	ARs + Other	Car	Maritime Structures	Shipwreck	Breakwater
Total area (km^2)						
0–1	58	8	1	4	1	1
1.1–5	9					1
5.1–10	3					
10.1–20	4					
20.1–50	2					
50.1–200	6			1		
200.1–500	2					
500.1–1000						
1000.1–5000	1		1			
5000.1–10,000						
10,000.1–20,000	1					
NI	123	12	3	10		7
Module area (m^2)						
0–1	34	1				
1.1–5	24	1				1
5.1–10	9	1		1		
10.1–30	8	1				
30.1–50	2		1			
50.1–100	4	1			1	
100.1–300	7	1				
300.1–500	2				1	
500.1–1000	1	1			2	
1000.1–5000	1				3	
5000.1–10,000	3					
> 10,000	3					
NI	111	13	4	14	10	8
Weight (kg)						
0–100	2					
101–500	5					
501–1000	3	1				
1001–5000	5					
5001–10,000	4					
10,001–50,000	5					
50,001–100,000	1					
100,001–500,000	1					
>500,000	4	1				
NI	176	18	5	15	17	9
Shape						
Conical/triangular/pyramidal	32	3				
Cubical/tetrahedron/block	47	1		1		3
Cylindrical/tubular	9			2		
Panel/plates	11	1				
Dome (Reefballs)	16	0				
Wall/mesh/column	4	0		1		1
Irregular	12	2	5	6	17	
ARs systems with several shapes	27	8				
NI	47	5		5		5

NI = Not informed.

3.3. Effectiveness of ARs Based on Similarity with RNs

Artificial reefs did not achieve the state of NRs, along the 13 studies that fulfilled the inclusion criteria. The species similarity values between ARs and NRs sites were significantly lower than similarity values between reference NRs sites (Figure 10).



Source	MD (95% CI)
Kang et al. (2021)	3.84 [-5.16; 12.84]
Genzano et al. (2011)	-14.99 [-30.31; 0.32]
Knoester et al. (2023)	1.00 [-4.77; 6.77]
Sánchez−Caballero et al. (2023)	1.76 [-0.82; 4.34]
Jones et al. (2020)	-10.50 [-34.82; 13.82]
Streich et al. (2017)	-2.07 [-16.55; 12.40]
Folpp et al. (2013)	8.96 [-16.56; 34.49]
D'Cruz et al. (1994)	-41.42 [-53.42; -29.42]
Perkol−Finkel et al. (2005)	0.70 [-5.73; 7.13]
D'Anna et al. (1994)	-25.77 [-33.16; -18.37]
Rilov & Benayahu (2000)	-7.18 [-26.64; 12.27]
Matthews (1985)	-5.02 [-25.00; 14.95]
McGlennon & Branden (1994)	-6.18 [-20.32; 7.97]
Total (common effect)	-2.05 [-3.99; -0.10]
Total (random effect)	-7.66 [-15.52; 0.21]

Heterogeneity: $\chi^2_{12} = 97.23$ ($P < 0.001$), $I^2 = 88\%$

Figure 10. Forest plot of effect size (mean difference) for species similarity between ARs and NRs. Effect sizes and their 95% confidence intervals are provided for each study. Dark blue square sizes represent the weight of the effect size of each study, and the line width of squares corresponds to the 95% confidence interval limits for the effect size. Light blue diamond's represent the total effect size for species composition for the common effect model (smaller) and random effect model (bigger). Positive effect sizes indicate that species composition is higher on natural than artificial reefs, and a negative value means the opposite. Confidence intervals that overlap the zero line indicate that species composition is not significantly different on ARs vs. NRs. Kang et al. (2021) [33], Genzano et al. (2011) [34], Knoester et al. (2023) [35], Sánchez-Caballero et al. (2023) [36], Jones et al. (2020) [37], Streich et al. (2017) [38], Folpp et al. (2013) [39], D'Cruz et al. (1994) [40], Perkol-Finkel et al. (2005) [41], D'Anna et al. (1994) [42], Rilov & Benayahu (2000) [43], Matthews (1985) [44], McGlennon & Branden (1994) [45].

Despite the total effect measure almost reaching the null effect line (light blue diamonds, Figure 10), as few articles supported similar metrics describing species composition between artificial and natural reefs with a considerable weight ([35,36,41], both common and random effect models showed significant differences (total common effect $p = 0.03$, total random effect $p = 0.05$).

This result has proven to be robust enough as the funnel plot shows a consistency in values between articles (Figure S9). Furthermore, aside from detecting a significant heterogeneity ($p < 0.001$, $I^2 = 88\%$), the Egger test confirmed the robustness of the analysis ($p = 0.149$).

Characteristics of ARs in studies included for the meta-analysis also varied in features, as well as deployment characteristics and situations (Table 4).

Table 4. Conditions of AR deployments in studies included for the meta-analysis on restoration effectiveness.

Authors	AR Type	AR Purpose	Material	Shape	Size Module (m^2)	Depth (m)	Age (Months)	Variable
Knoester et al. (2023) [35]	AR	Restoration *	Concrete, glass, metal, plastic	Bottle, cage, cake	16	8	24	Benthos-ichthyofauna
Kang et al. (2021) [33]	AR	Production	Concrete	Cubic	16.7	21	588	Benthos, ichthyofauna MO
Folpp et al. (2013) [39]	AR	Production-tourism	Concrete	Dome (reef balls)	0.35	7	18	Ichthyofauna
D'Anna et al. (1994) [42]	AR	Production	Concrete	Pyramid of blocks	4	18	48	Ichthyofauna

Table 4. *Cont.*

Authors	AR Type	AR Purpose	Material	Shape	Size Module (m^2)	Depth (m)	Age (Months)	Variable
Matthews (1985) [44]	AR	Production	Concrete	Cylindrical	1.5	13.7		Ichthyofauna
McGlennon & Branden (1994) [45]	AR-sunken vessels	Production	Concrete and tires	Tetrahedron	3		72	Ichthyofauna
Sánchez–Caballero et al. (2023) [36]	Shipwreck	Production-restoration-tourism	Ni	Irregular	500	20	516	Benthos
Genzano et al. (2011) [34]	Shipwreck	Accidental	Ni	Irregular	Ni	23		Benthos and ichthyofauna
Perkol–Finkel et al. (2005) [41]	Shipwreck	Ni	Metal	Irregular	1170	15	1572	Coral
Jones et al. (2020) [37]	Vessel, caisson and debris	Ni	Ni	Irregular		130	132	Ichthyofauna
Rilov & Benayahu (2000) [43]	Jetty	Sea access	Metal	Cylindrical column	250	20	264	Ichthyofauna
Streich et al. (2017) [38]	Oil platform	Several	Ni	Irregular	3	58	Ni	Ichthyofauna
D'Cruz et al. (1994) [40]	Ni	Production	Ni	Ni	Ni	Ni		Ichthyofauna

* Coral transplantation implemented.

4. Discussion

4.1. Research on ARs in the World in the Last Thirty Years

Artificial reefs have received global attention, particularly with the purpose of increasing the hard surface to be colonized and the associated to the reef biomass of a marine ecosystem, regardless of their conservation status [18]. However, geographic regions, such as the equatorial and tropical zone, which have been most affected by the effects of climate change with coral bleaching [46], showed lower development of this kind of studies.

There was an explosion of ARs especially during the 1990s, where many formats, distributions and materials were tested [47]. The idea during these decades was that ARs may be promoters of hard bottom spaces, and that vagile fauna was especially attracted by such structures [48]. However, it was not clear at all if these structures were only attractors or if the vagile organisms could close part or the entire life cycle in the surrounding areas, and the sessile biomass, algae, and especially mega zoobenthos were not clear targets then [47,49].

Although recent advances have been made in studies of ARs, there are still gaps regarding more elaborate techniques, important to cover the full purpose of ARs [18]. It is necessary to develop studies that evaluate the socioeconomic sector, the reef design, materials and disposition, legislation, and planning aspects to consider the management and mitigation of impacts related to ARs, active restoration techniques with long-term monitoring of functional groups and to apply mathematical models that allow the evaluation of ecological, economic and social aspects for ecosystem restoration [9,18,48].

Recently the focus on artificial reefs has been driven to enhance the blue carbon and facilitate habitat restoration [50]. It is clear that ARs per se are not enough, as we need to design not only the morphology, texture, and material of the structures, but also their real functionality in terms of population connectivity, species growth enhancement, or complexity as a true marine forest [4,9].

Examples of proper AR assessments are infrequent compared to the level of reef development, because monitoring is often an afterthought in AR projects; thus, most reports are not very accurate in terms of evaluating these ARs [51]. Only 50% of ARs are successful, and the rest have no, little, or limited success [47]. Monitoring ARs to quantify the effects of their implementation is essential to assess their effectiveness, or to adjust them to achieve their objectives. Quantitative monitoring of biological, socioeconomic, and ecological aspects has already been shown to benefit other types of approaches such as aquaculture-based fisheries [48]. Such information is lacking in most of the analyzed studies.

To measure the success of ARs there must be an estimate that serves as a reference to prove the change caused by the AR in the habitat to restore. For example, control or reference sites are necessary taking into account the situation before and after the intervention. Thus, a BACI (before–after/control–impact) approach would be preferable for ecological monitoring to perceive ecological changes [8]. Furthermore, effective ARs should be similar to natural reference reefs in functional diversity and ecological processes (i.e., recruitment, species-habitat interactions, trophic interactions), which must also be researched through experimental approaches in order to advance these goals [52].

The lack of reference data highlights a need for consensus in the application of valid methods to demonstrate the effectiveness and evolution of ARs. Management of ARs must include adequate planning on the use and configuration of materials, site selection, and regulatory control of fisheries. Without long-term planning and management, ARs fail and represent yet another impact that contributes to the further degradation of marine environments [8,53]. In addition, sessile organisms, such as gorgonians, corals, algae, bryozoans, etc., which are easier to follow, were not considered in such monitoring programs, although they have an essential role as three-dimensional alive structures that enhance biodiversity and associated biomass [54].

Furthermore, in the attraction–production dilemma, bigger ARs concentrate biomass leading to an increase in the catchability of stocks. Therefore, trawling, overfishing, and crops were mostly identified as impacts associated with ARs. Local fishermen know this fact, and in many interventions, they were pro-positive (Bracho et al. submitted). Few articles reported the regulation of fisheries at ARs and there is a clear lack of information regarding the real impact on local fisheries. In this sense, fisheries must be regulated at different scales, including semi-industrial and industrial fisheries, particularly in relation to herbivorous species, whose presence directly impacts other trophic levels [49,55].

The implementation of ARs comes with a wide range of logistical, political, and social issues as it can incur high costs and is logistically challenging [55]. Joint decision-making, considering economic, cultural aspects, and preferences is essential for the success of these projects. Interdisciplinary programs can contribute to the simplification of logistics, permits, inspection, financing and administration, monitoring, education, and professional training, promoting an identity and sense of belonging to people around [8,56].

4.2. Structural Characteristics of Ars

Among the most important characteristics to be considered in the construction of Ars in tropical coral reef systems are related to the spatial orientation, complexity, and shape of the substrate [57]. Few studies considered testing depths [58], vertical or horizontal orientations [59], floating or fixed dispositions [60], or distances between NRs and ARs [61] on faunal colonization, aspects that could determine the first stages of settlement, colonization, and successional processes in the ARs. Controlling the above-mentioned aspects combined with a site selection for installation must mitigate the problem of species introduction. Non-native species are commonly associated with ports and oil platforms, as their dispersal mechanisms can be through the fouling attached to ships, ballast water, and fouling on oil platforms [62]. Therefore, the disposal of the ARs must avoid the sea currents that come from this type of installation, since they probably come loaded with larvae of foreign species, and the presence of the AR would facilitate this type of environmental impact.

Moreover, ARs can be made from waste materials to specific structures since, originally, almost any hard substrate that had been submerged in the sea could be called an AR [52]. Consequently, much of the accumulated knowledge about ARs has been empirically constructed, with materials that may not currently be considered the best option in environmental terms [9], such as tires, leftover material from civil construction, remains of vessels, entire ships, and oil platforms, decommissioned and sunk without proper maintenance, etc.

Some programs such as “rigs-to-reefs” gained value in some countries, due to the reef communities that were established over time when these accidental or incidental structures were submerged, which originally were oil platforms, discarded ships, etc. Potential negative impacts of this program include physical damage to existing benthic habitats within the "fall zone", unwanted changes in marine food webs, facilitation of species invasions, and release of contaminants as platforms erode [63]. Thus, a great concern arises among scientists about an undiscriminating way of using ARs implementations. As well as us, some scientists emphasize the study and deepening of the knowledge of the ARs already installed and the development of technologies that allow for marine ecosystems to be restored, avoiding new impacts, before continuing to implement non-functional and even more impacting ARs [25,55].

Artificial reefs do not represent the only solution for damage to marine and coastal ecosystems. They are one of several management tools available, which, when properly managed, promote the improvement of habitats and biological productivity [20,53]. The use of concrete ARs in coral transplants [64] and plastic sheets in the resettlement of coral larvae [65], are a clear example of the use of these structures as active restoration tools. In places of great recreational activity, ARs appear as an alternative to diminishing human pressure in natural environments where visitation, sport fishing, and diving cause potential damage to RNs [9,66]. It is clear that the paradigm of these structures has to change to be much more efficient and in line with the real habitat needs in the zones where they may be implemented.

New studies are now bringing other potential textures, materials, and morphologies that emulate natural substrates [9], enhancing the settlement of vagile or sessile organisms depending on the silviculture paths that want to be promoted [67]. There were some attempts to improve materials for impact mitigation, testing different mixtures of materials for concrete, either in cost reduction [68,69], and mitigation of heavy metals when waste materials reused [70].

Some techniques manage to reproduce the specific material the properties of reef ecosystems from low voltage mineral deposition technology (LVMD) [71]. Although applying it at a large scale may be more difficult than other methods [23], the need for techniques to mitigate the effects of climate change, such as sea level rise coastal protection, increasing carbon sequestration capacity, etc. [9,50], are needs becoming more evident in today's world. ARs could act as facilitators of organisms that work as carbon immobilization species, as the sessile fauna that grows on their structures (sponges, corals, macroalgae, among others) sequester part of the CO_2 to build their hard three-dimensional organic or calcium carbonate ($CaCO_3$) structures, making them key ecosystems for mitigating the effects of climate change [9,54,72].

Some more specific conditions that ARs should fulfill include imitating the natural outcrop of rocky bottoms present in the target areas, having structural characteristics focused on the settlement of corals, gorgonians, and sponges, having cavities of different sizes and shapes to increase the presence of motile species (i.e., fish, mollusks and crustaceans), as well as being designed to capture CO_2, through the surface porosity of their own concrete structures, during the process known as carbonation [9].

Other approaches have been applied in the restoration of coral reef ecosystems, such as transplantation or repopulation by fragmenting corals or nubbins [73]; positive interactions between species [72]; floating reefs [60]; acoustic enrichment [74], integrated multitrophic aquaculture [75,76], among others.

All this suggests that the combination of active restoration methods including ARs can be the way to recover reef ecosystems that come to resemble conserved natural reefs, which can be called symbiotic artificial reefs (SAR). The implementation of artificial reefs to restore marine ecosystems can be well done, investing resources in studies specifically aimed at determining the appropriate characteristics of ARs for each location [77]. ARs should be considered strategically based on scientific assessments of specific location and resource needs to maximize the benefits of improving these habitats [20], with an emphasis on their use in the restoration of marine and coastal ecosystems [9].

4.3. Effectiveness of Artificial Reefs

Several authors have observed similarities between RNs and ARs in terms of abundance, biomass, and species richness, with some inconsistencies at geographical levels [20,78]. Nevertheless, as mentioned before, the species composition index would be preferable to avoid biased conclusions on effectivity. Assessments of the effect of installing ARs for restoration with veridically comparable and adequate reference sites are limited. Few studies have applied ARs for the restoration of highly degraded-declared ecosystems, while monitored by compared with NRs or equivalents (i.e., rocky ecosystems), in a good state of conservation, so that they serve as a comparison with the implementation site/restoration. However, most ARs deployments had little or limited ecological data available, which difficult for an integrated stock assessment [49].

Although there is a great lack of data availability, we tested that ARs harbor fewer species than NRs. On one hand, ARs did not resemble the reference NRs, that is, they did not achieve the restoration state, although studies included in the meta-analysis had a mean age of 30 years since deployment (n = 9), so it would be expected that ARs had reached a steady state at that point. On the other hand, ARs had fewer species than NRs of reference means less probability of the presence of invasive species, as they are globally related to AR structures [25,62], which represents a relevant problem in order to avoid trophic imbalance in already degraded ecosystems.

Among the studies that contributed in a greater measure to a null effect size or restoration state [35,36,41], two of them evaluated shipwrecks ARs of 500 and 1170 m^2 of area, at 20 and 15 m of depth in substrates with rock or reef with sand. They were also two of the older ARs with 43 and 131 years of deployment at the study execution time, and 10 and 1 month of monitoring, being the taxa analyzed benthos and coral species. Additionally, these studies reported impacts in the deployment area related with climate change effects and anthropogenic impacts, mostly related with trawling fishing and other destructive fishing methods, and with trophic imbalance. Furthermore, the study with more weight regarding replicates and sampling effort [79] compared ARs and NRs regarding coral species, thus species composition similarity is more achievable comparing species of a unique taxon than several (i.e., benthos).

However, in [35], ARs sites achieved restoration success in a shorter time, compared to their reference NRs (mean difference near the line of null effect, MD = 1, Figure 10). Using ARs intentionally made of concrete, with a combination of other materials such as glass, metal, and plastic, and applying an additional active restoration technique, such as coral transplantation [35], this study made a big difference in terms of the state of restoration of the ecosystem and the speed of it, comparing to those studies that did not apply it, since it achieved the reference NRs state at two years of monitoring [35]. Thus, the development of intentionally made ARs that achieve a restoration state comparable with natural reefs of reference in a few years is desirable for restoration program implementations, instead of accidental or incidental ARs that make it in several decades.

Furthermore, the restoration success of degraded ecosystems will have local needs related to the ecosystem itself, the impact type and cause of the impact, potential key species available to restore the degraded ecosystem, conflicts of use, etc., this is, ARs deployments must be site specific for each case. In addition, a high index of heterogeneity (88%) suggests that this relation may be influenced by factors other than the reef type. Thus, we suggest further analysis to investigate variables conditioning this AR–NR similarity as a measure of restoration for degraded marine ecosystems. Moreover, further studies must evaluate ecosystems' responses to ARs deployment from a restoration perspective, while concealing social and economic frameworks.

We call the attention of researchers in this area to carry out adequate experimental studies and allow the accessibility of data to evaluate and improve the efficiency of ARs in the restoration of degraded marine and coastal ecosystems. This is important as marine ecosystems harbor an immense diversity of habitats and life forms, as well as they are responsible for providing resources and environmental and economic services essential to human survival, such as food and habitat supply, especially for coastal communities [80]. Efforts to conserve these ecosystems are insufficient measures that must be complemented with an understanding of ecological processes to carry out actions of restoration, given the extent and rapid rate of human impacts [9]. For example, ARs serve as corridors for marine organisms moving poleward and deep ward due to global warming effects in a possible tropicalization process across marine-coastal ecosystems while they can enhance local abundance and biomass of species at range edges [81].

Restoration of marine ecosystems, including active methods, is foolproof to promote the natural recruitment and survival of species of interest, the return of ecosystem structure and function, and the improvement of abiotic processes that shape the community, given the high degree of current degradation, especially in reef ecosystems as a result of climate change [21]. The application of new methods of ARs implementation in coastal and offshore areas may be as well the key to fostering habitat restoration, but it has to be made with an articulate, realistic, and upscaled plan that individuates strengths and weaknesses of such protocols, making an accurate study of local regeneration needs and limitations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments10070121/s1, Figure S1: Flow diagram of the systematic literature review on artificial reefs; Figure S2: Flow diagram of the systematic literature review on artificial reefs effectivity; Figure S3: Number of studies on ARs during the period 1990–2020; Figure S4: Main research topics found in studies of artificial reefs by type of research; Figure S5: Number of experimental and observational surveys during the period 1990–2020; Figure S6: Sampling methods used in studies related to ARs during the period of 1990–2020; Figure S7: Society members involved in studies around Ars; Figure S8: Studies of ARs regarding their financing support; Figure S9: Funnel plot on meta-analysis of ARs effectiveness for marine ecosystem restoration. Table S1: Ecosystem type and substrate in which ARs were deployed.

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