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Review

Collating evidence on the restoration efforts of the seagrass *Posidonia oceanica*: current knowledge and gaps

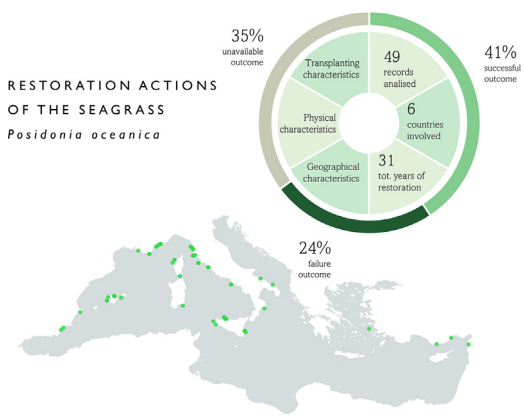
Arianna Pansini [a,*], Mar Bosch-Belmar [b], Manuel Berlino [b], Gianluca Sarà [b], Giulia Ceccherelli [c]

[a] Dipartimento di Architettura, Design, Urbanistica, Università di Sassari, Via Piandanna 4, Sassari 07100, Italy
[b] Dipartimento di Scienze della Terra e del Mare (DISTEM), Università di Palermo, Via Archirafi 22, Palermo 90123, Italy
[c] Dipartimento di Chimica e Farmacia, Università di Sassari, Via Piandanna 4, Sassari 07100, Italy

HIGHLIGHTS

- Past restoration actions of the seagrass *Posidonia oceanica* were reviewed.
- Several practices and conditions were used for *P. oceanica* transplanting actions.
- Poor consistency of available data hides the objectivity of restoration success.
- Identifying the best strategy for *P. oceanica* restoration by stakeholders is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Seagrass meadows are important shallow coastal ecosystems due to their contribution to enhancing biodiversity, nutrient cycling, carbon burial, and sediment stabilisation, but the maintenance of their integrity has been threatened by several anthropogenic disturbances. Active restoration is considered a reliable strategy to enhance recovery of seagrass ecosystems, and decision making for correct seagrass restoration management requires relying on valuable information regarding the effectiveness of past restoration actions and experimental efforts.

Previous experimental efforts and human-mediated active restoration actions of the slow growing seagrass *Posidonia oceanica* have been collated here by combining a literature systematic review and questionnaires consulting seagrass ecology experts. Overall, the poor consistency of the available information on *P. oceanica* restoration may be due to the wide portfolio of practices and methodologies used in different conditions, that supports the need of further field manipulative experiments in various environmental contexts to fill the identified knowledge gaps. The current situation requires an international, collaborative effort from scientists and stakeholders to jointly design the future strategy forward in identifying the best practices that lead to efficient restorations of *P. oceanica* habitat and functioning.

* Corresponding author.
E-mail address: apansini@uniss.it (A. Pansini).

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Contents

1. Introduction

Recovering ecosystem structure and functioning through restoration has become one of the 'grand challenges' in marine ecology (Borja, 2014). Many marine ecosystems are experiencing rapid degradation (Lotze, 2010) therefore restoration strategies to promote large-scale recovery need to be urgently identified (Hobbs, 2007). Such identification would provide the crucial information to protect, manage, but also recover the degraded ecosystems.

Knowledge derived from theory studies on community ecology and ecosystem structure and function recovery through time should build the baseline for a correct application of restoration efforts (Borja et al., 2013). Indeed, evaluating effectiveness of restoration at different scale (habitat, community, or ecosystem level) requires a focus on recovery of ecological processes and functionality (Verdonschot et al., 2013; Borja et al., 2010). In addition, degradation and fragmentation of coastal habitats highlights the need of interdisciplinary approaches to successful science-based restoration of systems (Elliott et al., 2007; Abelson et al., 2016; Possingham et al., 2015; Airoldi et al., 2021). Although the recent advances in developing novel tools for marine ecosystem restoration (e.g., eco-engineering or nature-based solutions; Morris et al., 2019), the implementation of more effective, scalable tools and practical approaches for coastal marine ecosystem restoration has become an urgent request. Such development will have to consider several interrelated methodological problems, that may greatly affect the restoration success (Airoldi et al., 2021; Fraschetti et al., 2021), such as the absence of clear definition of a successful restoration effort, an arduous receiving site selection, inadequate or unsuitable transplanting tool selection, and a lack of unsatisfactory assessment protocols.

In coastal and estuarine systems, foundation species like mangroves, saltmarshes, corals, and seagrasses provide important ecosystem services. Seagrasses are among the most important and productive coastal systems (Costanza et al., 1997) that support nursery areas, habitat types (Heck et al., 2003), carbon production and sequestration (Macreadie et al., 2014), nutrient cycling, sediment retention (Hemminga and Duarte, 2000; Larkum et al., 2006), and protection from erosion (Fonseca and Cahalan, 1992; Fonseca and Koehl, 2006). Nevertheless, because of environmental changes linked to the expansion of coastal human populations, rapid, large-scale seagrass loss over relatively short temporal scales has been reported worldwide (Fourqurean and Robblee, 1999; Marbà et al., 2005; Walker et al., 2006). Physical disturbances as trawling or anchoring, several stressors as sediments and nutrients inputs, invasive species, aquaculture, overgrazing, algal blooms and the synergic effects of global warming are known to be responsible of seagrass declines (Orth et al., 2006; Williams, 2007; Waycott et al., 2009; Bockelmann et al., 2012; Giakoumi et al., 2015). Moreover, the most common factors causing seagrass loss are increased nutrients loading and sedimentation rates (Unsworth et al., 2015; Ceccherelli et al., 2018), with ecological and socio-economics related impacts. Seagrass rehabilitation is a slow process, often taking decades for successful recolonization and meadow establishment (Vaudrey et al., 2010; Greening et al., 2011); facilitating passive recovery through active reintroduction is needed. In fact, worldwide restoration efforts have been performed to compensate or mitigate seagrass loss and to enhance the associated ecosystem services, restoring ecosystem functions (Paling et al., 2009). A comparative quantitative global review on the performance of seagrass restoration has described the general features and the best practice for seagrass restoration (especially for the genus *Zostera*), endorsing the importance of threat removal prior to replanting (van Katwijk et al., 2016). It also evidenced that reduced water quality (mainly due to eutrophication) and habitat modification due to construction activities led to poorer restoration success than, for instance, local direct impacts (such as dredging actions) or natural causes of disturbance (as storms, erosion or wasting diseases). Restoration trial performance was correlated to proximity to and recovery ability of donor beds. Restoration success was also affected by planting techniques and evidence for the requirement of a critical mass for recovery was provided (van Katwijk et al., 2016), contributing to developing the existing seagrass restoration guidelines in general.

Posidonia oceanica (L.) Delile is a slow-growing endemic seagrass from the Mediterranean Sea, able to grow both on hard and soft bottoms, exhibiting wide morphological and physiological plasticity (Hemminga and Duarte, 2000). The species forms meadows spanning from the surface to 40 m of depth, stabilizing coastal sediments, attenuating the wave action along the coasts, and sheltering juveniles of commercial fishes and invertebrates (Pergent et al., 1994). *P. oceanica* is highly sensitive to disturbance often associated with highly human-impacted coasts and it is facing an extensive habitat degradation, with an estimated loss area of 124,091 ha, corresponding to 10.1 % of the total known area extent (Telesca et al., 2015). The regression of the seagrass meadows and the following substitution in different habitats (algal turfs or dead matte, defined as the arrangement of root-rhizome portion of a dead *P. oceanica* meadow) is mainly ascribable near urban coastal areas (Montefalcone, 2009; Tamburello et al., 2012). As in the case of other seagrass species, *P. oceanica* meadows are also exposed to several stressors, as increased nutrient and chemical inputs and sedimentation, mechanical damage, coastal armouring and extreme climatic events as storms and floods. Changes in hydrodynamic regime and water quality result in the fragmentation and widespread decline of seagrass meadows (Marbà et al., 2005). Several *P. oceanica* restoration efforts have been used in the last decades as a compensatory measure to reverse meadow regression, carried out without considering site-specific transplantation procedures and not being part of broader integrated coastal zone management projects (Boudouresque et al., 2021). The results in terms of success of the seagrass transplants, based on available data, remain somewhat controversial even because the few collating efforts focused on the description of the single case studies (often detailing new techniques) rather than providing general outcomes (i.e., Bacci et al., 2017; Boudouresque et al., 2021). Therefore, a systematic approach is still needed to derive the best and most fruitful practices for the restoration of this foundation species and, eventually, to identify those approaches that certainly would lead to a failure. This study aimed at identifying and summarising the current knowledge and gaps regarding the main outcomes and most effective methods of *Posidonia oceanica* restoration actions already in place in the Mediterranean Sea by collating information from a systematic review analysis of the literature

and a specific questionnaire consulting experts in the field. Thus, through an evidence-based research technique characterised by a rigorous, transparent, and reproducible methodology, we provide answers to specific research questions following a standardised approach which has minimized eventual biases of the revision process (Moher et al., 2009). The results provide a comprehensive baseline of the effectiveness of *P. oceanica* restoration, assessing the combinations of conditions that may promote successful restoration efforts, and inform future research, along with management plans and strategies.

2. Material and methods

Literature review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009; Hutton et al., 2015). First steps consisted in the formulation of research questions, creation of search strings and protocol settings. Then, research documents were gathered, screened, selected and finally, the collected information was summarized for the current review. The specific research question "What is the effectiveness of *Posidonia oceanica* restoration actions that have taken place in Mediterranean Sea?" was expressed following the Population, Exposure, Comparator, and Outcomes (PECO) formulation guidance (Morgan et al., 2018). The Mediterranean endemic seagrass *Posidonia oceanica* was defined as the target species for Population of subjects (P); the Exposure (E) concerned any human mediated active restoration, transplanting or rehabilitation actions carried out in a receiving site of the Mediterranean Sea; therefore, any plant response as biochemical, survival, growth, and shoot density were considered as proxy of restoration Outcome (O).

Furthermore, in order to obtain any further potentially relevant information or sources, seagrass researchers and stakeholders were invited to participate in a specific survey on *P. oceanica* restoration actions by a message in the mailing list seagrass_forum@lists.murdoch.edu.au. In addition, an overall of 31 technicians, researchers and stakeholders from Spain, France, Belgium, Italy, Croatia, Greece, Cyprus, and Turkey were also personally contacted by email in March 2020 based on their field scientific experience on *P. oceanica* ecology. A Semi-structured questionnaire was sent to each participant to collect information about the drafter affiliation and role within the reported case study, the geographical position, and physical characteristics of the receiving site, transplanting procedures, monitoring duration, plant survival, and outcome of the intervention. Any further potentially relevant information and additional comments could also be given.

2.1. Data extraction

Literature searching process included both electronic and manual searching methods. Academic online databases ISI Web of Science (Web of Science, 2019) and Scopus (Elsevier, 2021) were used to investigate all peer-reviewed literature, conference proceedings and patents published in any language available up to September 2020. A complex search string was defined, involving specific keywords combined with the Boolean operators and wildcards within Title, Abstract and Keywords as follows: ("*Posidonia oceanica*" OR Seagrass) AND Mediterranean AND (restoration OR rehabilitation OR transplant*).

Grey literature has been incorporated in this review since it is an important source for valuable research-relevant information. To this aim, a manual search involved browsing targeted websites of relevant technical institutes, ecology organizations and agencies publishing potentially topic related documents (i.e. handbooks, guidelines and symposium proceedings) as follows: Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA, https://www.isprambiente.gov.it/it/pubblicazioni/manuali-e-linee-guida), Instituto Mediterráneo de Estudios Avanzados (IMEDEA, https://imedea.uib-csic.es/centre.php), Regional Activity Centre for Specially Protected Areas (RAC/SPA, http://www.rac-spa.org/publications), Società Italiana di Ecologia (S.It.E, https://www.ecologia.it/storico-congressi/), and Società Italiana di Biologia Marina (SIBM, https://www.sibm.it/index.php?p=documenti).

Information provided by experts regarding *P. oceanica* restoration actions was screened, extracted, organised, and analysed as literature systematic review data. In case a questionnaire included information already published or present in any other type of considered document, to avoid duplicates, the questionnaire was dismissed from the analysis. Studies with a specific receiving site name in which human-mediated actions were used to enhance recovery of a degraded or changed marine environment, or to create or enhance *P. oceanica* habitat type were selected. In addition, only studies with response variables were expressed as a proxy of transplanting intervention outcome were considered. Furthermore, exclusion criteria (not complementary to the inclusion criteria) rejected any work, assessment and technique descriptions providing insights to manage and protect *P. oceanica* habitat type, without a direct evaluation effect. For systematic review, screening process was managed by a single reviewer, with a second reviewer who worked independently through the title screening on a random subsample of 10 % of references (Pullin and Stewart, 2006) for the check-up of data quality and consistency of the inclusion criteria.

To characterise the context of effectiveness of *P. oceanica* restoration actions, information was extracted for each selected record and a case studies matrix was created. When a record contained more than one element or type of information, each one was split into different case studies, with distinct identification code.

For each case study, the following information were extracted (Table 1):

- Year of publication, document type, language and author.
- Geographical characteristics, such as GPS coordinates, donor and receiving site name, political region, and country.
- Physical characteristics of receiving and donor site, such as presence of stressor and its possible mitigation, depth, substrate type, geographical and depth distance from the donor to the receiving site.
- Procedures related to transplanting interventions: reason of the intervention; area of intervention, transplanted plant portion, anchoring technique applied to the transplanted material, monitoring period.
- Information related to the intervention outcome: seagrass explanatory variables measured after the intervention exposure used as a proxy of transplanting outcome and the eventual judgement given by the authors about the outcome, whether successful or unsuccessful.

The full case studies matrix dataset is available through accessing the Dryad data repository (Pansini et al., 2022).

2.2. Data analyses

With the aim of synthesising collected information of the included studies in the review, we performed a qualitative and semi-quantitative description of each categorical variable considered for each case study. For visualisation, data were managed in Microsoft Excel (Microsoft Corporation, 2018) and presented in terms of number and percentage frequency. Geographical distribution of case studies was resumed in a map produced with QGIS 3.16 software (QGIS.org, 2021) and an alluvial plot was used to illustrate different combinations of functionality categorial variables related to the outcome of intervention with R 3.6.3 software (R Development Core Team, 2019).

3. Results

Electronic and manual searching methods initially identified a total of 219 records, which dropped to 160 after the removal of duplicates. Then, the screening process (Fig. 1) excluded 50 records from Title, 25 from Abstract and, consequently, 45 from Full-text screening (Table S1). Inclusion criteria considered a total of 40 records, consisting of 208 case studies (Pansini et al., 2022). Regarding the survey, 5 out of the contacted experts decided to collaborate and completed the questionnaire, giving rise to 23

Table 1
List of categorical variables extracted from each selected record.

Categorical variable	Description	Class unit
Record characteristics		
Document type	Type of document	Journal article Project report Conference paper Technical manual Dissertation Book section Questionnaire
Year	Year in which record was written	1989–2020
Language	Language in which record was written	English French Italian Spanish
Author	Corresponding author, reviewer, or drafter of the record	Open field
Geographical characteristics		
Receiving longitude	Longitude of the receiving study site	−5.40–36.10
Receiving latitude	Latitude of the receiving study site	30.45–45.70
Receiving name	Name of the intervention receiving study site	Open field
Receiving region	Political Region in which receiving study site is located	Open field
Receiving country	Country in which receiving study site is located	Open field
Donor longitude	Longitude of the donor site	−5.40–36.10
Donor latitude	Latitude of the donor site	30.45–45.70
Donor name	Name of the intervention donor site	Open field
Donor region	Political Region in which donor site is located	Open field
Donor country	Country in which receiving donor is located	Open field
Physical characteristics of the study site		
Receiving depth	Depth of the intervention receiving study site	-m
Receiving depth classes	Classes of depth of the intervention receiving study site. Shallow (0–9.9 m); medium (10.0–19.9 m); deep (20.0–40 m)	Shallow Medium Deep
Substrate	Type of substrate in which intervention has occurred. Hard includes unvegetated rock, pebble, artificial reef bottoms; Soft includes unvegetated gravel, sand, silt bottoms. Dead matte includes the remaining arrangement of root-rhizome bed of a dead *P. oceanica* meadow. Meadow is the living *P. oceanica* prairie.	Hard Soft Dead matte Meadow
Receiving stressor	Presence of eventual stressor in the receiving study site. Mechanical damage includes anchoring, dredging, bombing, shipwreck	Aquaculture Chemical pollution Turbidity Mechanical Damage Wave exposure None
Receiving stressor removal	If mentioned, eventual removal of the stressor in the receiving study site	Yes No
Receiving protection	Eventual protection of the location in which intervention has occurred: Marine Protected Area, Marine Reserve, Natural Park, Regional Park, Site of National Interest.	Yes No
Donor – receiving distance	Kms of distance from donor to receiving site	km
Donor – receiving distance classes	Kms of distance in classes from donor to receiving site	0–0.9 km 1–9.9 km >10 km
Donor depth	Depth of the intervention of donor site	-m
Donor depth vs. receiving depth	Donor depth difference respect to the receiving site. Shallower donor consists in a deeper transplanting depth from the original site; same consists in the same transplanting depth; deeper donor consists in a shallower transplanting site	Shallower Same Deeper
Donor stressor	Presence of eventual stressor in the donor study site. Mechanical damage includes anchoring, dredging, bombing, shipwreck	Aquaculture Chemical pollution Turbidity Mechanical damage Wave exposure None
Procedural context of the transplanting intervention		
Reason	Purpose of the transplanting intervention. Experiment (manipulative approach to test the performance of *P. oceanica* to a particular factor, pilot restoration trials) Opera (restoration action to compensate for the loss of *P. oceanica* meadow)	Experiment Opera
Transplanted area	Area of intervention for the case study	m^2
Transplanted area classes	Spatial scale of the area of intervention for the case study: micro (<10 m^2), meso (10–10,000 m^2) macro (>10,000 m^2)	Micro Meso Macro
Transplanted plant portion	Portion of the plant used for the transplanting action	Plagiotropic rhizome Orthotropic rhizome Sod Seedling
Anchoring technique	Technique applied to anchor the transplanted plant portion to the substrate: Modular cumulates metallic, plastic, or biodegradable grid, mesh, mesh pot, wood and cement cross, degradable "star"; Individual cumulates iron peg, cable tie, staple, natural anchoring. Degradable Carpet consists of 25 m^2 of a natural mesh coupled with steel grid structure directly anchored to the substrate. Mat consists of a module covered by natural tissue and filled with sand	Modular Individual Degradable Carpet Mat
Monitoring period	Period from the start of the transplanting intervention to the last monitoring survey	Months (n)
Restoration outcome information		
Response variable	Explanatory variables measured after the intervention exposure: growth indicators include leaf length (cm), number of leaves/shoot, rhizome biomass (gDw), number of shoots with roots; biochemistry includes chlorophyll, carbohydrates, N, P, C, content, density (number of shoots/m^2, number of shoots/plant)	Survival rate (0–1) Establishment rate (0–1) Persistence rate (0–1) Growth Biochemistry Density
Outcome	Outcome of the intervention explicitly stated by the authors	Success Failure NA

records on *P. oceanica* restoration studies, although 14 of them were excluded from the analysis since they reported information already present in the collected literature. Thus, 9 records were produced and treated as 15 case studies. In view of this, an overall of 49 records (10.4 % of the original records), consisting of 208 total case studies were considered in the review. Among the included records, 19 belonged to scientific articles, 4 to conference proceedings, 6 to dissertations, 8 to project reports, 5 to technical manuals, 1 to book section and finally 9 to questionnaires.

About two-thirds (67 %) of the total sources were written in English, while 22 % were in Italian, 8 % in French, and 2 % in Spanish. The number of records on *P. oceanica* restoration has increased from the 1989 (the year of the first documented study) to the 2020, reaching the maximum value in 2019 (13 works, Fig. 2): in detail, only 7 (22 %) records were produced before 2005, with an average of 0.9 ± 0.2 (±SE) works per year, while more than a half (27, 55 %) were produced from 2014 to 2020, with an average of 3.4 ± 1.7 (±SE) works per year. Mediterranean countries have contributed in varying degrees to the production of *P. oceanica* restoration works. France focused its efforts in the very first decades, but eventually stopped participating actively after 2007; meanwhile Spain markedly increased its contribution in the last 5 years, passing from 2 to 9 works in 2020, and Italy emerged in terms of total number of works produced (n = 24).

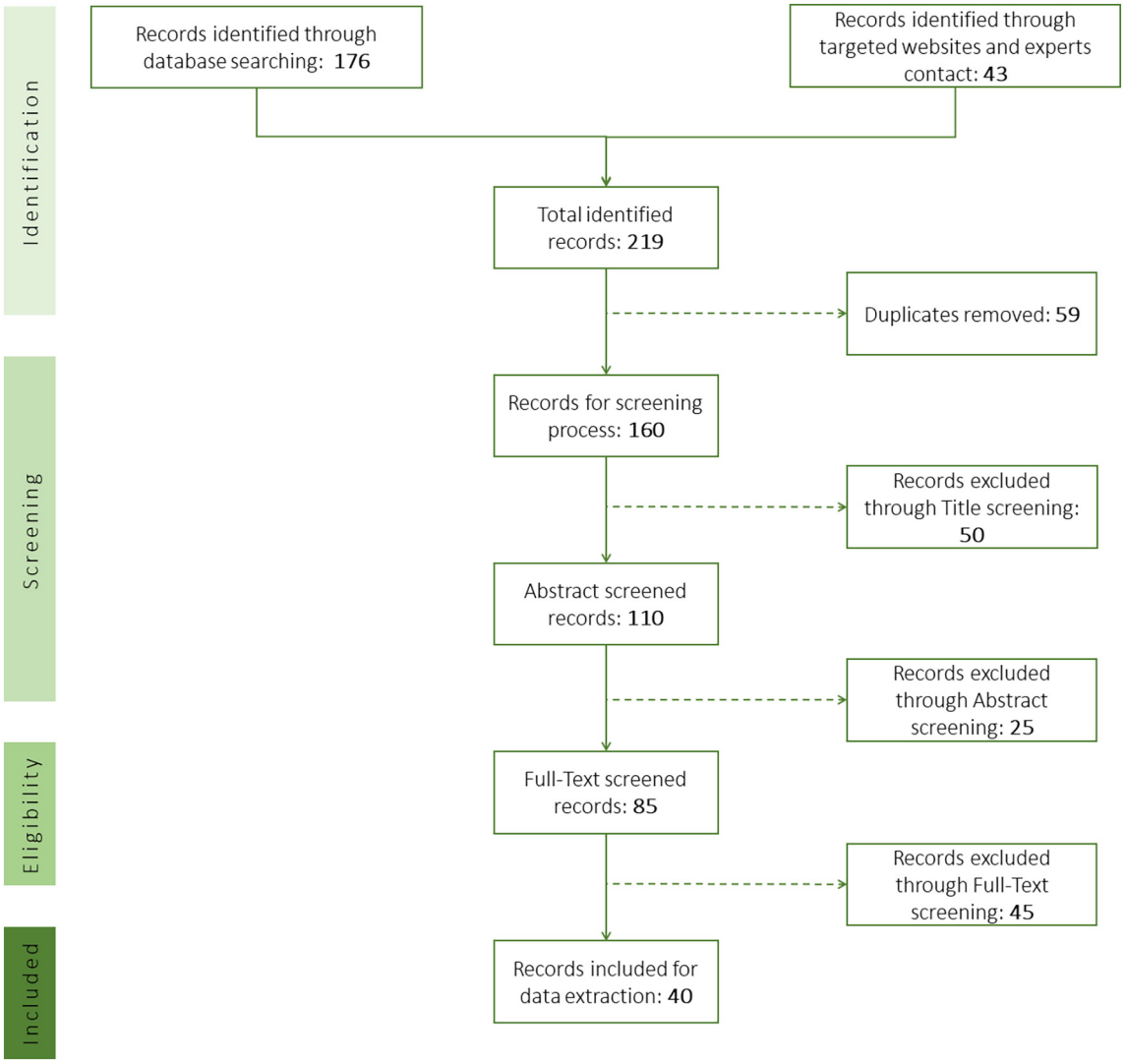

Fig. 1. PRISMA study flow diagram representing the selection process of the literature systematic review, based on Moher et al., 2009. In each box, the number of records screened is reported.

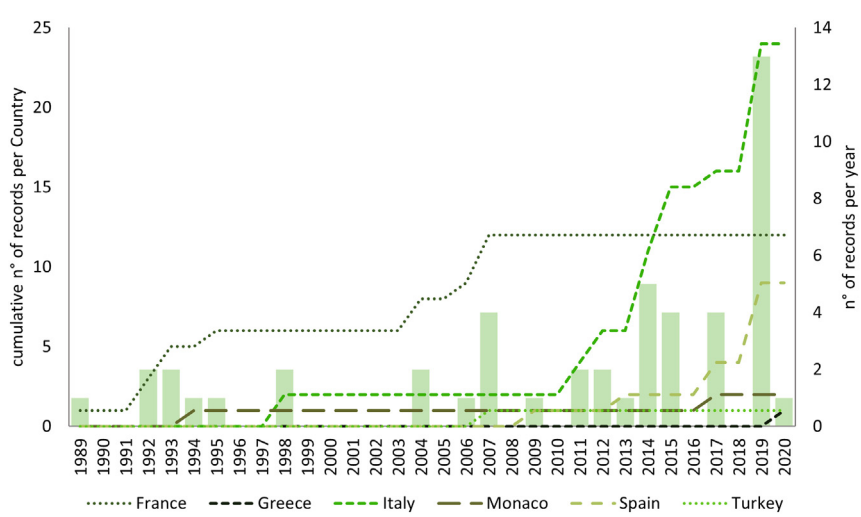

Fig. 2. Temporal trend of included records on *P. oceanica* restoration actions from 1989 to 2020. Lines represent the cumulative number of records per years and country.

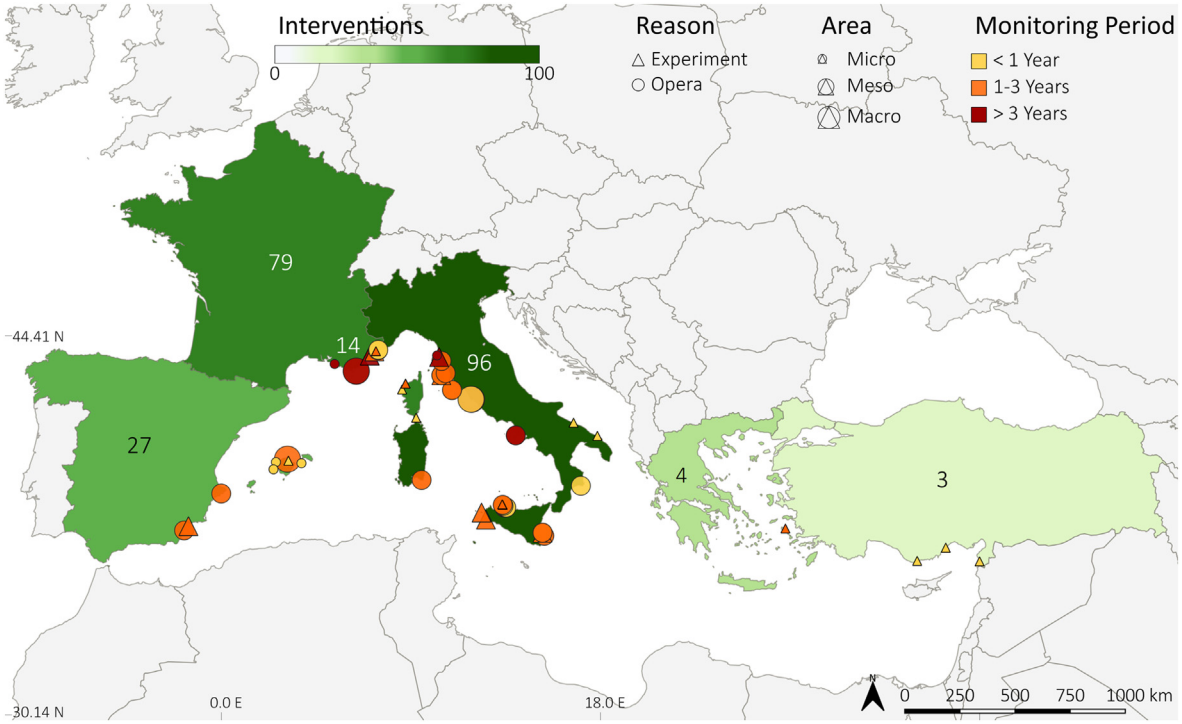

Fig. 3. Geographical distribution of case studies and related reason of intervention, area scale: micro (<10 m^2), *meso* (10–10,000 m^2) macro (>10,000 m^2), and monitoring period (in years) of interventions.

Principality of Monaco, Greece, and Turkey have contributed at a lesser extent, with only 8 % of the restoration interventions.

Overall, almost all the transplanting interventions (89 %) was derived from the Western Mediterranean Sea, as just a small part is ascribable to the oriental side (Fig. 3). None of the reviewed studies reported transplanting sites at Southern Mediterranean Sea. For almost two-thirds (68 %) of the selected studies, the intervention had an experimental purpose aimed at testing the performance of transplanted *P. oceanica* to a particular factor, or the performance of techniques from pilot restoration studies; the other 32 % of the interventions fell within restoration opera to compensate for the loss of habitat in a specific receiving or donor site. Transplanting area of intervention sites ranged from 1 m^2 up to 2 ha, as observed in Balearic Island (Spain). Micro (<10 m^2) and *meso* (10–10,000 m^2) scales were more represented than the macro (>10,000 m^2) scale (44 %, 45 % and 11 %, respectively) for the overall case studies. Specifically, while the micro scale was almost exclusively associated to the experimental case studies (89 %), meso and macro scales were similarly related to either the experimental and opera reason, being the meso 52 % and 48 % and the macro 54 % and 46 %, respectively. Most of the interventions (66 %) were monitored for more than one year, 28 months on average, reaching a maximum of 18 years of surveying in the Marine Protected Area of Port-Cors, France. The 26 % of transplanting actions were performed inside a Protected Area as Marine Protected Areas or 'Other effective area-based conservation measures' (OECMs).

The reviewed transplanting interventions were mainly performed between 10 and 19.9 m of depth (59 %, Fig. 4a); shallower depths were also selected in 32 % of cases. The clear majority (90 %) of receiving sites were affected by a local anthropogenic stressor, as chemical inputs (31 %) or mechanical damages (34 %; Fig. 4b), and almost 50 % (specifically the 44 %) of those were unmitigated before the transplant intervention. Regarding the donor sites, almost two thirds of them (63 %) were not affected by anthropogenic stressors (Fig. 4c). In the majority (58 %) of the cases, the *P. oceanica* material was collected very close to the receiving transplanting site, while the 19 % and 23 % of donor sites were 1–9.9 km and >10 km distant, respectively (Fig. 4d). About the half (55 %) of the donor sites were located on a shallower meadow respect to the receiving sites, the 37 % was at the same depth, while in only the 8 % the material was collected from a deeper meadow (Fig. 4e). Specifically, the highest percent of success was found in actions within the same depth (69 %), independently of the presence of a donor stressor (41 % and 40 % with and without stressor, respectively). Increasing the distance of the donor site positively affected the outcome of the transplanting actions (43 %, 15 % and 10 % of failures at 0–0.9, 1–9.9 and >10 km, respectively). In terms of type of substrate (Fig. 4f), receiving sites were characterised by unvegetated soft bottoms (46 %) and dead matte (39 %), while unvegetated hard substates and meadows have gained less interventions (10 % and 5 %, respectively). Almost the total actions was made by transplanting cuttings (the rest used seedlings), comparably distributed in orthotropic (erect shoots, 34 %) and plagiotropic rhizomes (creeping shoots, 41 %; Fig. 4g), fixed to the substrate using a wide range of anchoring techniques. Individual anchoring techniques involved hooks, pegs, staples, cable ties, while modular anchoring techniques required the use of grids, meshes, pots, arms, or artificial reefs (Fig. 4h). The survival rate was the most widely *P. oceanica* response variable measured (44 %, Fig. 4i), followed by variables linked to plant growth (31 %), as the number of leaves per shoot, leaf, and root length. The 41 % of interventions were reported as successful, but for the 35 % of the studies it was not possible to deduce the real outcome of transplanting intervention given by the authors (Fig. 4j). Particularly, survival rate reported a success outcome for 44 % of case studies and a low rate of unsuccess (21 %). Response variables that reported a higher rate of success were establishment (80 %) and growth (46 %).

The alluvial plot explored the relationships between restoration functionality categorical variables with respect to the reviewed studies whose outcome was specified (as success or failure) by the authors (65 % of all case studies) (Fig. 5). The trend showed a generic higher success in terms of flow of frequencies of the diagram, evidencing that 100 interventions were successful and 65 failed. Specifically, results with higher success rates were associated to the shallow depth (70 %), hard substrate and dead matte (100 % and 80 %, respectively), transplanting plagiotropic rhizomes or seedlings (both >90 % of success rate), and to the use of individual anchoring techniques or dead matte (78 % and 100 % respectively). Conversely, most of the interventions that occurred on soft substrates (73 %)

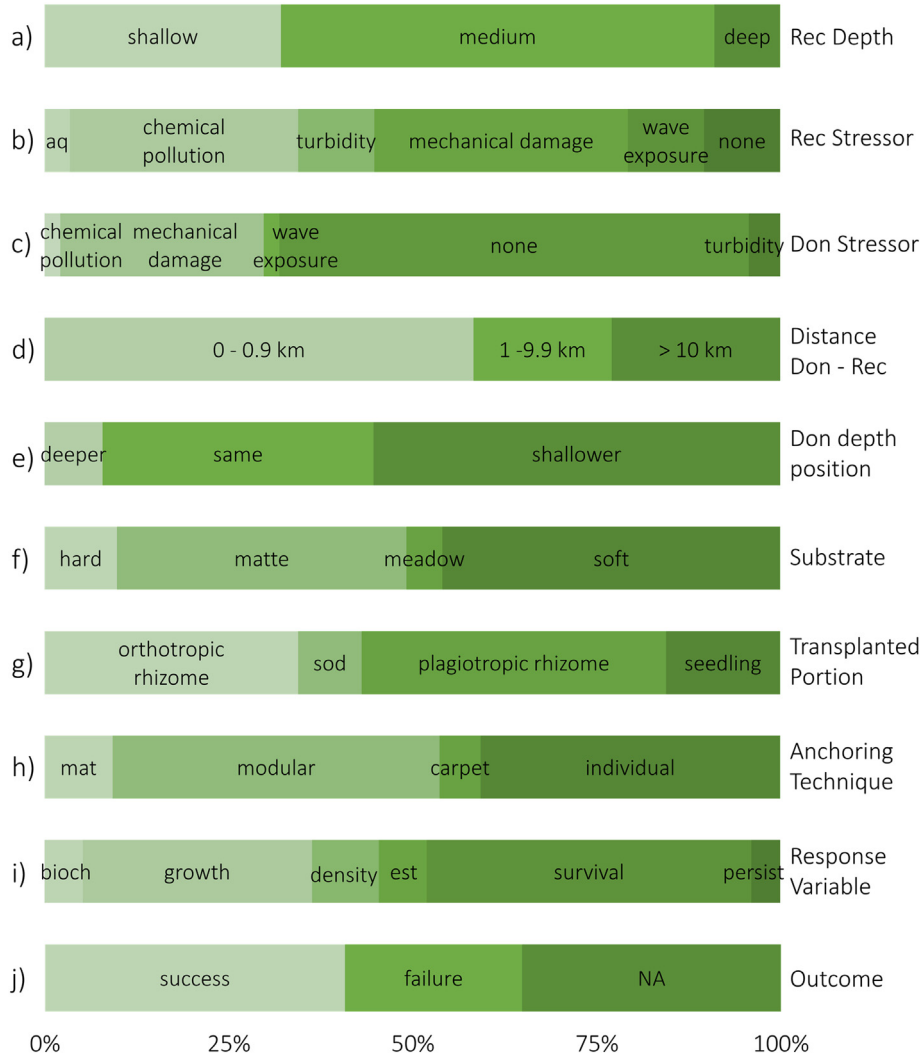

Fig. 4. Percentage frequency of categorical variables describing physical characteristics of the receiving sites and donor sites (a, b, c, d, e and f), procedures related to transplanting interventions (g and h) and information related to the interventions outcome (i and j). Rec = receiving site; Don = donor site; aq = aquaculture; bioch = biochemical variables; est. = establishment; persist = persistence; NA = not available.

or that used degradable carpets as anchoring technique (86 %) failed, as well the totality of actions that transplanted sods. None of the interventions in mitigated receiving sites reported a failure.

4. Discussion

This review was driven by the need of providing an evidence-based knowledge of the effectiveness of the seagrass *Posidonia oceanica* restoration to promote profitable actions, enhancing stakeholder cooperation to contrast the trend of meadow regression.

Information extracted from the review came from diversified types of documents, whether peer-reviewed literature or not. Indeed, almost one restoration action out of five, 18 % of total information of this review, came from questionnaires which provided unpublished material. This conspicuous contribution to the review could be likely enlarged if further knowledge was accessible through a capillary involvement of practitioners in seagrass restoration. When the aim is to plan a large scale management of biodiversity in the Mediterranean Sea, it is necessary to consider its biogeographical and geopolitical complexity: the basin supports the livelihood of millions of people, connecting three continents and surrounded by 21 countries, with huge differences in socioeconomic status, political regimes, languages, governance, and cultures that have raised obstacles to cooperation for marine conservation efforts (Mazor et al., 2014; Katsanevakis et al., 2015). Therefore, there is the need to encourage knowledge sharing between stakeholders and scientists for a profitable collaboration, at least in those countries in which restoration policy has been embedded into regulatory framework and incorporated adequately into government, approvals, and guidance (e.g., Marine Strategy Framework Directive, 2008/56/EC, MSFD). In addition, among the selected records, almost one-third of them (32 %) were not written in English, emphasizing the need of including any type of language in eligibility criteria of the systematic review, not to neglect important information to the evidence-based knowledge. As a result, a significant part of the overall information is not promptly making it available to scientific communities, causing an overlook of evidence by researchers and stakeholders during restoration decision making. On the other hand, the English language may hinder its use by field practitioners and policy makers for local issues (Amano et al., 2016). In any case, it shows the need for a cross-border approach between the different countries of the Mediterranean basin.

A general increase in number of records written and published per year on *P. oceanica* transplanting actions was found and this could be mainly ascribable to the emerging environmental management and conservation attention. Particularly, ecological restoration became an increasingly important tool in adapting to and mitigating global environmental change (Baker and Eckerberg, 2013) and the technical task has been implemented into international agreements to compensate for the species or habitat

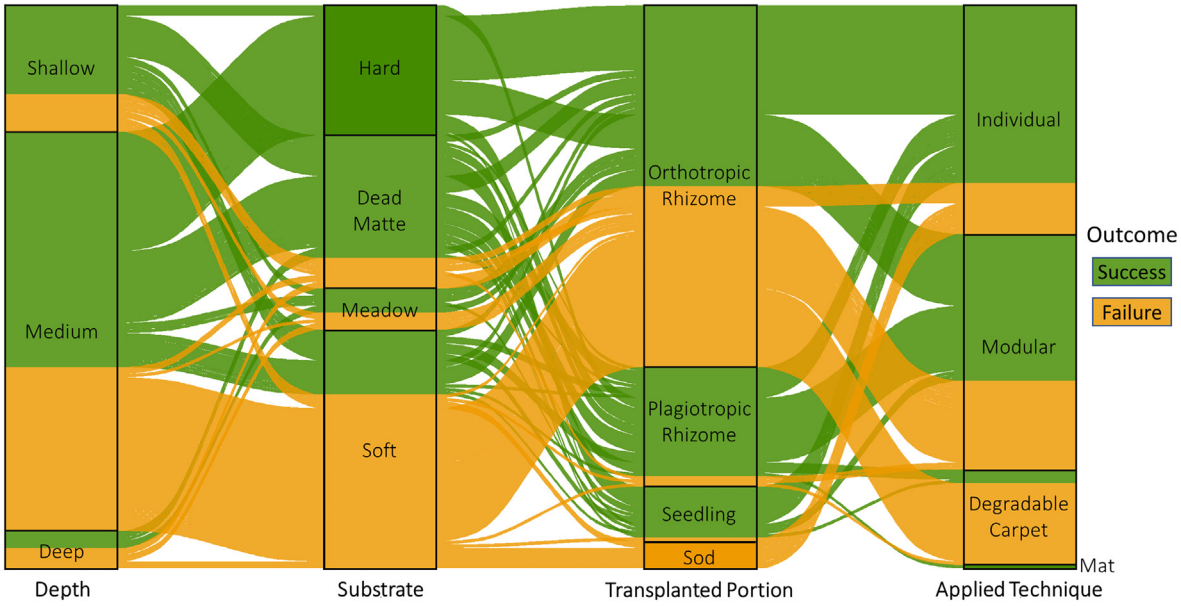

Fig. 5. Percentage frequency of the association between restoration functionality categorical variables (transplanting depth, type of substrate, transplanted plant portion and anchoring applied technique) to the specified outcome of the intervention (success vs failure).

regression (e.g., A New Deal for Nature, UNEP, 2019; Convention on Biological Diversity, UNEP, 2021; UN Decade on Ecological Restoration 2021–2030, United Nations Environment Agency, 2019). Specifically, France emerged as the pioneer country in addressing restoration efforts, starting in 1989 with Loques et al. (Table S1 and Pansini et al., 2022) and developing the actions during the 1990s and the beginning of the 2000s. Nevertheless, considering the amount of restoration efforts, Italy has stood out as the country with most numerous restoration trials, contributing 24/49 records and 96/208 case studies produced.

Distribution of study sites differed greatly through the Mediterranean Sea, with a lack of locations in the Southern and Eastern Mediterranean basin, as opposed to the Western side owning almost the totality of interventions. This pattern can only be partially explained by the seagrass distribution: to date, evaluations of *P. oceanica* meadows coverage along the Mediterranean coastline are not fully completed, especially in the southern and eastern coasts where information about the presence of the seagrass remains largely unknown (Telesca et al., 2015). Therefore, mapping *P. oceanica* meadows extent with continuous monitoring programs, even relying on new techniques (Rende et al., 2022; Ventura et al., 2022), would be required to identify the presence, possibly before patterns of regression were noticed, otherwise the description of the meadows would be concurrent to restoration actions planning. At this aim, a great contribution is given by the European Marine Observation and Data Network (EMODnet) Seabed Habitats website which is in continuous development (https://www.emodnet-seabedhabitats.eu/) and provides a portal for accessing, or uploading as well, *P. oceanica* habitat distribution data.

Results from this review reported a higher number of interventions linked to experimental purpose rather than to restoration opera, with a small local (micro and *meso*) scale of interventions, using a large variety of techniques, types of substrates and transplanting depths. This is not surprising, since seagrass restoration ecology is a developing discipline (Wood et al., 2019) and there has been the obvious need of building the current knowledge, filling the gaps on *P. oceanica* restoration actions. After all, restoration efforts in marine habitats deal with a hardly accessible environment, rather than on land, which often leads to difficulties in management (Hawkins et al., 2002; Abelson et al., 2016), for the consequent high expenses due to high labour costs (Bayraktarov et al., 2016). Moreover, for difficulties deriving from *P. oceanica* ecology due to the high vulnerability and low resilience (Procaccini et al., 1996), its restoration management may not be closely related to efforts done for all other seagrasses (van Katwijk et al., 2016).

To facilitate the success of a restoration project, a strategic prioritization of costs and efforts should always be supported. A preliminary understanding of the local environmental conditions of a potential receiving site, such as previous existence of the species, removal of an anthropogenic stressor, depth of transplanting, and type of substrate is required (van Katwijk et al., 2016). As a matter of fact, none of the reviewed receiving sites in which a previous presence of an anthropogenic stressor was mitigated reported a failure of interventions. Therefore, the need of removing the anthropogenic stressor or disturbance seems required not to fail the intervention, corroborating the hypothesis that a careful site selection before investing efforts is a key step into restoration projects (Fraschetti et al., 2021). Conversely, our results do not show the same need for the donor site since the success of the reviewed interventions seems not to depend on the stressor of the donor meadow. Commonly, restoration actions used local material (0–0.9 km of distance), however, the higher is the distance of the donor site, higher is the success of the restoration actions, probably due to the selection of genetically distant populations as donor source (Reynolds et al., 2013; Tan et al., 2020). Moreover, successful outcomes were more frequent when donor and receiving sites were at the same depth, likely due to more rapid acclimation responses to environmental conditions (Dattolo et al., 2013). Finally, extending the spatial scale and the monitoring period of restored meadows is needed to understand the development of seagrass reimplants, the possible causes of eventual losses, and the real intervention outcome (Tan et al., 2020). The results gathered only 11 % and 13.3 % of interventions extended for >10,000 m^2 and monitored for >3 years, respectively. It seems noteworthy that the most enduring monitoring survey in time, 18 years, only involved an experimental case study (Port-Cors Marine Protected Area, France) and not a restoration opera. Furthermore, since *P. oceanica* is a long-living and slow-growing seagrass, expectations in restoration actions should carefully consider the low regenerative potential and recovery rate (Ceccherelli et al., 2007) to accurately define the transplanted surface and plant arrangement, as well as monitoring duration. Indeed, short term monitoring results might feed in stakeholders the expectancy effect of a high restoration effectiveness and provide misleading outcomes.

Furthermore, survival rate (percent of surviving individuals from the initial plantings) has been the most used response variable to determine

restoration success, although several other descriptors of the plant performance (such as morphological, physiological, and biochemical variables) are commonly measured during monitoring surveys. However, the survival outcome could be considered as a misleading benchmark to evaluate the effectiveness of a restoration: being a binomial variable (alive or dead), it overshadows any change in health conditions of the transplanted plants. Likely, changes in morphology, physiology, and biochemistry of the plant should be implemented as descriptors and predictors of seagrass performance (Ceccherelli et al., 2018), despite implying longer monitoring periods and higher labour costs.

This review reported an overall higher success outcome rate than failure of the analysed restoration actions, even though more than one third of information did not yield a real outcome. It is widely recognised that a publication bias in favour of successful restoration outcomes exists because optimistic results may be more likely to be published than the failed ones (Miller et al., 2014; Zedler, 2007). However, outcomes collected by questionnaires reported a half (53 %) of failures so that the success rate is unlikely to have been skewed by the type of source.

Although the poor consistency of the available information, this review findings evidenced a higher failure outcome when using sods (regardless the other transplanting characteristics) and degradable carpets, even if this latter technique has only been used very recently (since 2017, Piazzi et al., 2021). Weak success was also obtained on soft bottoms, especially with orthotropic rhizomes. Conversely, restoring on hard bottoms and dead matte seem to be the best options, especially if using plagiotropic rhizomes and seedlings, with individual anchoring techniques. Specific habitat requirements of *P. oceanica* could play a crucial role in its settlement: the transplanted material is often lacking in a fully developed root system, and establishment could be difficult on unconsolidated substrates with sediment instability (Badalamenti et al., 2011; Alagna et al., 2015), while hard substrates allow a well-developed anchoring root system (Alagna et al., 2019). Contrary to the results of van Katwijk et al. (2016), this study showed the success of restorations performed with seedlings. The use of seedlings has been first described by Balestri et al. (1998, Table S1) and became well established since 2013 (Pansini et al., 2022); although *P. oceanica* seed release is seasonally restricted, global warming could increase the frequency of flowering events (Ruiz et al., 2018) and thus the availability of this source material for restorations. It is also important to consider seedlings as an alternative valuable source of transplantation, since the material can be generated from collected beach-cast fruits and seeds, minimizing the impact on donor meadows (Terrados et al., 2013).

In addition, the critical evaluation of a restoration action is often too inaccurate by the authors to draw conclusions for categorising it as a success or a failure. This gap highlights the need of defining accurate hypotheses about expectations of a successful *P. oceanica* restoration, based on past experimental trials, using a quantitative approach. In fact, despite some guidelines for transplanting *P. oceanica* have been provided (Boudouresque et al., 2021), proxies of restoration outcomes still need to be defined and implemented by evidence that identify the plant material more suited to the future climate scenarios (Pansini et al., 2021; Pazzaglia et al., 2021; Stipcich et al., 2022). Incorrect estimates of success rates and failure provided by the authors could be probably due to the intent of attracting stakeholders to enhance their restoration techniques rather than others. Consequently, inappropriate conclusions about the best practices to adopt for good restoration efforts and, overall, about the intrinsic value of restoration as a management tool in adapting and mitigating global environmental change could be driven (Miller et al., 2014). Despite it all, unsuccessful restoration or unexpected outcomes that commonly go unpublished can still be informative and better knowledge sharing would seriously help in spreading information among seagrass researchers, managers, and practitioners.

5. Conclusions

This collated evidence review (combining information from literature and experts questionnaires) was a helpful tool to synthesise existing information on *P. oceanica* restoration, as well as identifying previously unknown evidence. It formally highlighted knowledge gaps that should be filled with international planning, monitoring, and management plans. Overall, the current work identified an overall lack of consistency of the available information about *P. oceanica* restoration, probably due to the very wide portfolio of practices and methodologies used in different environmental conditions. It clearly clamours for an international effort from scientists and stakeholders to jointly design the forward strategy in identifying the best practices that lead to effective restorations of *P. oceanica* habitat and functioning in the current and future changing scenarios. Although it is not claimed finding only one solution to be extended to every combination of conditions, standardizing the efforts in a quantitative manner through a meta-analytical approach could certainly provide an increase of solution robustness and thus define the best practices toward effective restoration programs. Nevertheless, the high inconsistency among past restoration efforts and the heterogeneity of results obtained so far support the urgent need of testing different anchoring techniques, type of substrates and transplanted plant materials in field crossed experiments to be developed in various environmental contexts to fill the gaps identified in this study and properly assist future *P. oceanica* restoration reviews and actions.

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CRediT authorship contribution statement

Arianna Pansini: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Validation, Writing – original draft, Writing – review and editing; Mar Bosch-Belmar: Methodology, Investigation, Formal analysis, Visualization, Validation; Manuel Berlino: Methodology, Formal analysis; Gianluca Sarà: Supervision, Project administration, Funding acquisition; Giulia Ceccherelli: Conceptualization, Writing – review and editing, Validation, Supervision, Project administration, Funding acquisition. All authors reviewed and accepted the submitted version of the manuscript.

Data availability

Dataset containing information extracted for each selected record is available at https://doi.org/10.5061/dryad.m905qfv41

Declaration of competing interest

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

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