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Review

Sponges as Emerging By-Product of Integrated Multitrophic Aquaculture (IMTA)

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Abstract: The use of marine sponges dates back thousands of years, and interest in these animals is increasing as new applications are discovered. Their potential is extensive, both in their ancient and still popular use as bath sponges for cosmetics and regarding the more recent discovery of bioactive secondary metabolites mainly of interest for the pharmaceutical industry and the less developed aquariology. Despite their proven biofiltration and ecosystem restoration ability and the biomass supply problem for the interested industries, few integrated multi-trophic aquaculture (IMTA) systems incorporate these invertebrates in their facilities. Therefore, in this brief review, the benefits that marine sponges could bring to rapidly growing IMTA systems are summarized, highlighting their suitability for a circular blue economy.

Keywords: Porifera; filtration rate; circular economy; restoration; bioremediation; bioactive compounds; aquariology

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1. Introduction

Marine sponges have been targeted by fishermen for thousands of years, including in the Egyptian civilization, and their presence in our society has been continuous ever since [1]. However, the increasing interest in these animals during the last century has entailed the impossibility of providing the arising sponge market with an adequate amount of natural biomass. In this sense, when diving and collecting techniques improved in the Mediterranean area, different sponge species were collected without any specific legislation to supply a worldwide trade demanding dozens of tons of marine sponges, causing a dramatic reduction of natural stocks [2]. With the development of the pharmaceutical industry in the last decades of the 1900s, for example, and the strong demand for sponge biomass for the industrial production of avarol, e.g., (a powerful anti-inflammatory, anti-tumor, and anti-psoriatic) [3–5], the systematic collection of *Dysidea avara* caused a dramatic depletion of natural stocks, particularly along the eastern Mediterranean coasts, to the point of it being considered endangered [2]. In response to this intensive withdrawal, many demosponge species have been included in the lists of species with high conservation value for which specific protectionist policies are recommended (Annex I of the Berne Convention).

On the other hand, the world's population has tripled in the last seven decades. Contemporaneously, several problems have arisen, one of the most important concerns being food supply [6]. The inability of natural populations to achieve this has accelerated the search for sustainable production alternatives. Fisheries have not been left behind, with aquaculture and its derivative mariculture quadrupling production over the last 3 decades, nearly equalling that of capture fisheries [7]. Still, as in most developing production techniques, there are problems that need to be solved to minimize ecological impact.

Coastal fish farms can have a significant environmental impact due to the release of catabolites by cultured organisms and feed waste, leading to an overall increase in sedimentation, organic matter, and a potentially pathogenic or antibiotic-resistant bacterial load in the water [8]. However, Integrated Multitrophic Aquaculture (IMTA), the practice that combines the cultivation of fed aquaculture species with other organisms able to extract organic and/or inorganic substances from seawater, represents an eco-friendly alternative to monoculture. IMTA allows better water quality and promises high economic return and social suitability, implying an improvement in human welfare and ecosystem services provided by the marine environment.

Among the extractive organisms, economically profitable edible filter-feeders are the most utilized, including the predominant bivalves [9,10]. Nevertheless, Porifera seems to be one of the most promising, although they are still underexploited. Up to now, few sponge species have been tested to assess their rearing suitability and performance, bioactive compound production, or bioremediation capability: on the Mediterranean scale, *Geodia cydonium* [11], *Spongia officinalis* and *Hippospongia communis* [12,13], *Dysidea avara* [14], *Hymeniacidon perlevis* [15], *Chondrosia reniformis* [14,16], *Ircinia variabilis* [17], and *Sarcotragus spinosulus* [18]. In these trials, *G. cydonium* almost doubled its initial weight in six months. *D. avara* and *S. spinosulus* doubled their size in four and twelve months, respectively, and *C. reniformis* achieved a growth rate of 170% in one year, while *S. officinalis* and *H. communis* sponges increased their volume by 100–200% over two years. Additionally, impressive growth exceeding 2000% per year was registered in the Southwestern Pacific Ocean with *Mycale hentscheli* cultured near a mussel farm [19]. Altogether, these impressive results prove the suitability of the rearing system and the species, opening new possibilities in the aquaculture sector.

In this sense, their environmental and economic potential and, thus, the interest in these organisms, is increasing as new sustainable applications arise. This review aims to highlight the suitability and benefits of marine sponges in IMTA systems in a circular blue economy framework by discussing the profitability of these organisms and emphasizing their eco-economic potential. From a literature search conducted in Scopus and Google Scholar databases, the available papers on sponges in IMTA systems were selected to gather current knowledge on this practice, along with relevant literature, providing an informative and comprehensive framework of the status and potential of marine sponges. The results of this bibliographic research are included in the references section of this work.

2. Past and Present Concerns

The trade of sea sponges dates back thousands of years to when they were collected mainly for cosmetic use and known as "bath sponges". In the last century, sponges could be purchased for USD 30 per individual, and the annual value of imports is estimated to be millions of USD. However, in a span of 50 years, sponge production declined by more than 80% due to unregulated overexploitation, catastrophic diseases, and the introduction of synthetic sponges into the market [20]. Even so, today in the Mediterranean basin, countries such as Italy (e.g., Spugnificio Incorvaia, Gela; Bellini Let's BE natural, Cogozzo di Viadana; Spugnificio Rosenfeld, Muggia), Greece (e.g., Cipreo J.-Kypreos Natural Sea Sponges, Kalymnos; Gerakios traders of natural sponges, Peristeri; Bioesti, Agios Nikolaos), Croatia (e.g., Spuga2, Kapranj), Cyprus (e.g., Old Port Sea Sponges, Limassol), and Tunisia (e.g., Éponge, Kraten) still maintain this economic sector based on traditional harvesting.

Although attempts to culture sponges have been documented since the late 18th century [21], the lack of knowledge and the failure of experiments made harvesting individuals from natural populations the most efficient and profitable methodology [22]. Still, the aforementioned negative events during the 20th century prompted the search for new business strategies. Thus, by the early 1970s, organized and successful mariculture trials with bathing sponges had already been conducted. The number of attempts has only increased over the years, becoming the second market interest for the culture of these animals [23,24]. In the search for sustainable and profitable production, as reviewed in [25], many studies have tried to define the best rearing system for bath sponges and have concluded it to be strongly dependent upon species and environmental conditions.

In recent years, marine natural products have gained popularity and the demand for sponges, though they are more expensive than those of synthetic origin, is high. However, despite the research effort and promising growth rates of cultured bath sponges (doubling or tripling in size annually) [26–30], few countries currently cultivate them for commercial purposes, where they are mostly sold in the local markets, e.g., Micronesia [31] and Zanzibar [32]. Additionally, few studies have been carried out concerning bath sponges within an IMTA system [12,13], but everything remains in the theoretical framework since, to date, there is no such production method at a commercial level. Incorporating bath sponges in these environments where bacterial load is high involves zero cost of consumables like food, while the material for their cultivation would barely reach a few hundred USD [30]. Since their maintenance is based on monthly growth monitoring, bath sponges rearing seems an ideal candidate for promising high economic profitability when looking for a blue circular economy in IMTA systems.

3. Bioremediation, a Way of Life

One of the main advantages of filter-feeding organisms such as Porifera is that their energy source is obtained by the highly efficient filtration of organic particles between 0.1–50 μm, such as dissolved and particulate organic particles, heterotrophic bacteria and eukaryotes, phytoplankton, and even viruses [33–35], so that their mere growth leads to bioremediation of the surrounding environment. Therefore, they are considered a possible solution to reduce eutrophication and bacterial load.

In this sense, numerous works have tried to calculate this potential by employing experiments on the filtration and retention capacity of sponges. When it comes to those performed ex situ, controlled conditions reduce the variability of factors, such as temperature, salinity, nutrients, or microorganisms used, which, together with visualization techniques and cell counting (such as spectrometry or cytometry), have served to prove that this capacity differs significantly depending on the species and size of the sponge explant or the size and even the motility of the microorganism used (Figure 1).

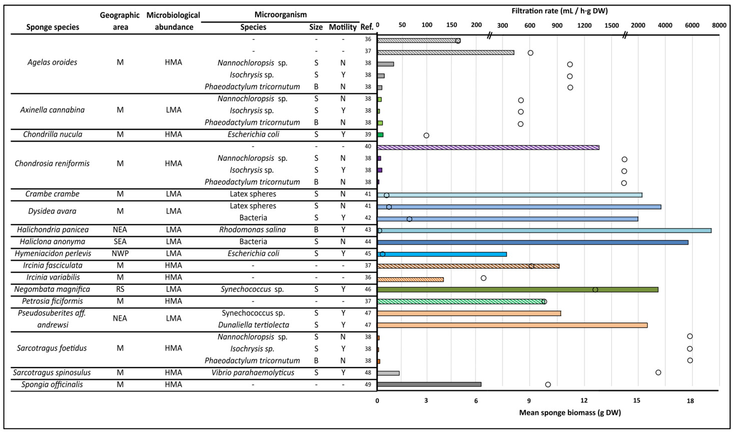

Figure 1. Comparison of sponge filtration rates (bars) according to species, explant biomass (circles), and microorganism characteristics. The cited bibliographic references are shown in the ref column [36–49]. Rayed bars represent in situ studies where no specific microorganism was used. When standardizing explant size and filtration rates, volume-to-weight and weight-to-weight conversions were made based on [50,51], respectively. Microbiological abundance classification was that described in [52]. M (Mediterranean), NEA (North-eastern Atlantic), SEA (South-eastern Atlantic), NWP (North-western Pacific), and RS (Red Sea) for the geographic area; HMA (High Microbiological Abundance) and LMA (Low Microbiological Abundance) for microbiological abundance and S (Small, <15 μm), B (Big, >15 μm), Y (motile), and N (non-motile) for microorganism description are the abbreviations used.

However, the logistics and maintenance of conditions involve an expense that does not exist in IMTA systems, being the natural environment of the sponges. In addition, variables such as season, currents, or depth are excluded in ex situ experiments, despite being proven to affect the growth, survival, morphology, composition, and pumping activity of some sponges [39,40,53–56]. Although the remediation and conversion of organic carbon have been studied (references already reviewed in [57]), little work has focused on in situ filtration capacity (e.g., [36,37,40]) and even less on IMTA systems, where knowledge is very limited [58,59]. Despite that, it has been shown that carbon uptake in these animals may exceed that of commercial species, such as bivalves, whose market is well established and generates large economic benefits while that of sponges is still under development [60].

Similarly, being filter-feeding organisms, they are constantly exposed to contamination of the water column. More specifically, since the last century, numerous experiments have been carried out to test the accumulation capacity and levels of pollutants, such as heavy metals (HM, related to diseases such as autism, Alzheimer, or diabetes mellitus) [61] from mercury or copper to heavier metals such as uranium, americium, or rare earth elements, which in some cases have been seen to be higher than in mussels [62–83]. As with filtration, it has been shown that this ability depends on the sponge species and the contaminant tested, including the morphology of the individual, and that, although spicules represent the main component of the biomass, they accumulate mainly in the organic tissue [84,85]. Additionally, they could potentially consume contaminated bacteria and incorporate their HMs [86] and are being proposed as a source of biomagnification of these compounds in higher trophic levels [87]. However, subjecting sponges to elevated HM concentrations has been found to negatively affect growth, survival, fecundity, and filtering ability and to cause DNA damage, ROS production increase, alterations in macromolecule composition, or even apoptosis, suggesting them as bioremediators of environments partially exposed to these contaminants [64,67–69,88–92].

The same is true for organic pollutants (OP), whose accumulation in sponges and biomagnification has also been demonstrated, including natural compounds that have been classified as such due to their possible toxic effects [93–98]. In this regard, there is a diversity of results according to contaminants and sponge species. While some results state that the accumulation of some polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) is higher than in some commercial oysters and mussels, others have found similar levels [72,76,94,99]. However, as expected with pollutant compounds, also OPs induce stress, DNA damage, and cell apoptosis in sponges [93,100,101].

On the other hand, microplastics (MP) represent a threat that has been gaining importance for the past decade, despite having been found in sponge samples dated more than 20 years ago [102,103]. Therefore, work and knowledge on the accumulation of these contaminants and their derivatives in these animals are scarce [104–108]. As might be expected, a higher concentration of MPs has been seen in filter feeders (similar between sponges and mussels) than in other feeding strategies, and in the case of sponges, a possible preference for very small fibers and particles as well [102,104]. While no negative effect has also been reported [106,109], a more recent study demonstrates that the uptake of some of these contaminants reduces filtration and respiration rates [110]. However, being that the levels of MPs in the surrounding water are higher than in their tissues, these studies agree and suggest a possible resistance or ejection mechanism that allows them to thrive in contaminated waters [106,110].

When talking about remediation, and considering the concept of the sponge as a holobiont, the capacity of the associated microbiota to resist, accumulate, and degrade contaminants cannot be disregarded. In this sense, recent works have demonstrated the HM accumulation capacity of some symbionts and identified genes that grant resistance to them, which could have been transmitted via plasmids [111–117]. However, not all these microorganisms appear to possess them, and, although no differences have also been reported [118,119], the accumulation of HMs in the host has been shown to negatively affect symbiont communities [79,120]. The usefulness of these microorganisms does not stop there. They have also been proposed to biotransform and can produce biosurfactants for the bioremediation of these metals [121–126], for the degradation of MPs [127], and of many OPs, such as pyrenes, brominated phenols, steroids, crude oil, dyes used in the textile industry, or even alkylbenzene sulfonates present in detergents [96,128–136], which increases the interest in and confirms sponges as a hot-spot for the search of new green alternatives in this field.

All in all, the works cited above define marine sponges as good biofilters and bioindicators of pollution caused by increased bacterial load and organic and inorganic contaminants due to their ability to filter and accumulate them. In search of new remediation technologies, these animals have even inspired the creation of synthetic sponges to treat water [137–139]. Therefore, incorporating them into the production systems of species for human consumption, such as IMTAs, implies the possibility of monitoring and improving water quality and, thanks to the demonstrated ability to reduce the pathogen bacterial load, a possible reduction in antibiotic costs.

4. A Marine Bioactive Compound Factory

The first drugs of marine origin reaching clinical trials were extracted from a Caribbean sponge around seven decades ago [140]; since then, the number of these compounds has only increased, and, together with cnidarians, they are the most prominent organisms discovered [141]. By November 2022, nearly 12,000 compounds were reported from the phylum Porifera (exceeding a quarter of the total of marine origin), more than 200 of which were described this year (Figure 2). These are synthesized not only by sponges but also by their symbiont microorganisms. The value of the approved and artificially synthesized ones can reach from hundreds to thousands of USD [142,143], demonstrating the potential of profitable natural production carried out by these organisms.

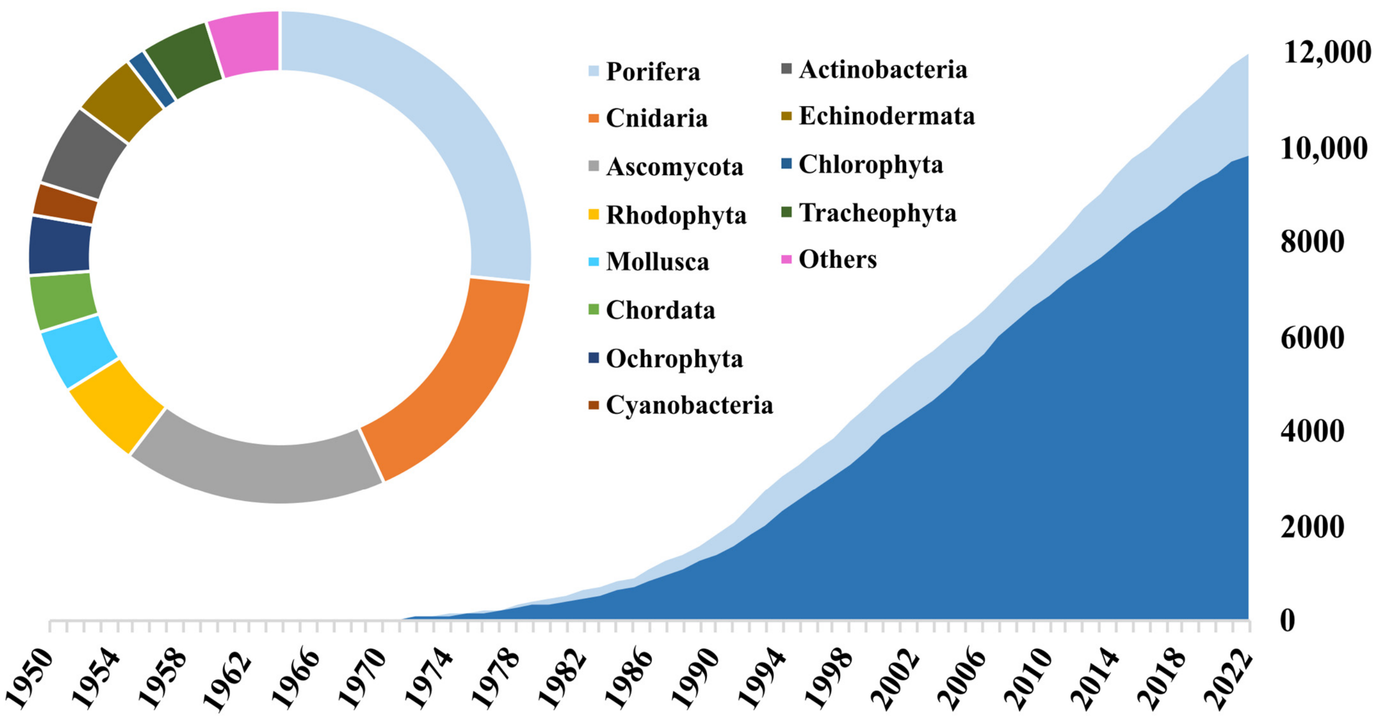

Figure 2. Cumulative number of compound discoveries (light) and publications (dark) on marine sponges over the last seven decades. The proportion of marine natural products of poriferan origin regarding the total number of described molecules is shown in the pie chart. Row data from https://marinlit.rsc.org (accessed on 14 November 2022).

The different sponge species and their micro inhabitants open the possibility to search for and characterize a great number of biomolecules, with different structures and activities that review works have already tried to collect and synthesize, e.g., [141,143–146]. In a very generalized way and without detailing, they have a wide range of applications: from anti-tumour, antiviral, and antimicrobials in human medicine to antimicrobial and antifouling activities in the aquaculture industry or biomaterial production in different sectors. However, obtaining the needed biomass involves a considerable challenge, as natural populations cannot supply this market sustainably.

Therefore, as with bath sponges, attempts to culture them for this purpose have increased in recent years to become the main commercial target of these activities [24]. However, few attempts have been carried out in IMTA systems, and some of these are cultures close to other fisheries facilities [11,14,16,18,19,147–149]. Considering the importance of symbionts in the synthesis of bioactive compounds, the conditions to ensure their production should be optimal not only for the sponge but also for their inhabitants, which ex situ can be costly and difficult to maintain. Therefore, co-culture strategies such as IMTA appear to be possible and economically profitable solutions, as from reared sponge biomass, as well as others for the pharmaceutical industry, antifouling and antibiotic compounds could be obtained that would reduce the annual losses of billions for fisheries [150], fostering a circular economy of the sector.

5. From the Sea to the Tank

With hundreds of aquariums worldwide and millions of recreational ones, another economic potential of marine sponges is their sale for this activity, as due to their diverse colors and shapes they are particularly attractive (Figure 3). There are companies dedicated to their trade (mainly in the US), and their prices vary from tens to hundreds of USD per individual, depending on species and size (e.g., Marine World Aquatics Ltd., Bradford, UK; RUSALTY, St Okeechobee, FL, USA; Aquarium Creations Online, Lauderdale Lakes, FL, USA).

Figure 3. The bright orange and stylized sponge *Axinella cannabina* as an ornamental aquarium species.

In addition, there are fish families such as angelfish (*Pomacanthidae*), filefish (*Monacanthidae*), boxfish (*Ostraciidae*), or pufferfish (*Tetraodontidae*) that graze on different sponge species and can contribute to over 70% of their diet [151–153]. As it is used as an aquarium species, sponge-based food supplies have already been developed (e.g., Mega-Marine Angel, Hikari; Sponge Professional Softgran, EBO; Angel Formula, Ocean Nutrition).

Considering that some of the sponges consumed by these fish have already been the target of in situ culture attempts (albeit if for a different purpose, such as *Agelas* sp., *Callyspongia* spp., *Chondrilla* sp., *Chondrosia* sp., *Geodia* sp., *Haliclona* sp., *Ircinia* spp., *Mycale* spp., *Spongia* spp., or *Xestospongia* sp.) [11,13,14,16,26,27,30,36,53,147–149,154–160], incorporating them into IMTA systems would be a viable option for the production of aquarium feed supplements. On the other hand, physical traits such as color, shape, or size are vital when selecting ornamental aquarium sponges. Depending on the geographic position, these facilities could provide a suitable environment for the correct growth and sustainable production of local ornamental aquarium species.

6. The Challenge in Marine Sponges' Restoration

As many sponge species are considered endangered, efforts to recover natural populations are increasing (Annex I of the Berne Convention). From artificial reefs to vertical collectors, ideas are emerging for different restoration structures to increase biodiversity and create a biotope for these species [161]. Transplanting sponges to areas where they had been almost eradicated has been seen as a viable option to recover the populations of these animals, with 100% survival rates and maintaining fertile individuals to favor the natural recruitment of juveniles and other organisms, such as corals, would improve ecological succession [162,163].

In this sense, wisely planned IMTA systems could be reasonably proposed for environmental restoration and conservation purposes. Such facilities combine bioremediation with biodiversity increase thanks to the fouling attached to artificial substrates and reared specimens (Figure 4). In the case of sponges, the biomass obtained can be valorized for transplantation or restocking of threatened or vulnerable species up to benthic habitat restoration. In addition to the environmental value, the creation of these ecosystems and the indirect recruitment of other species could represent a benchmark of underwater tourism that, at zero cost, would bring income to the local community [161].

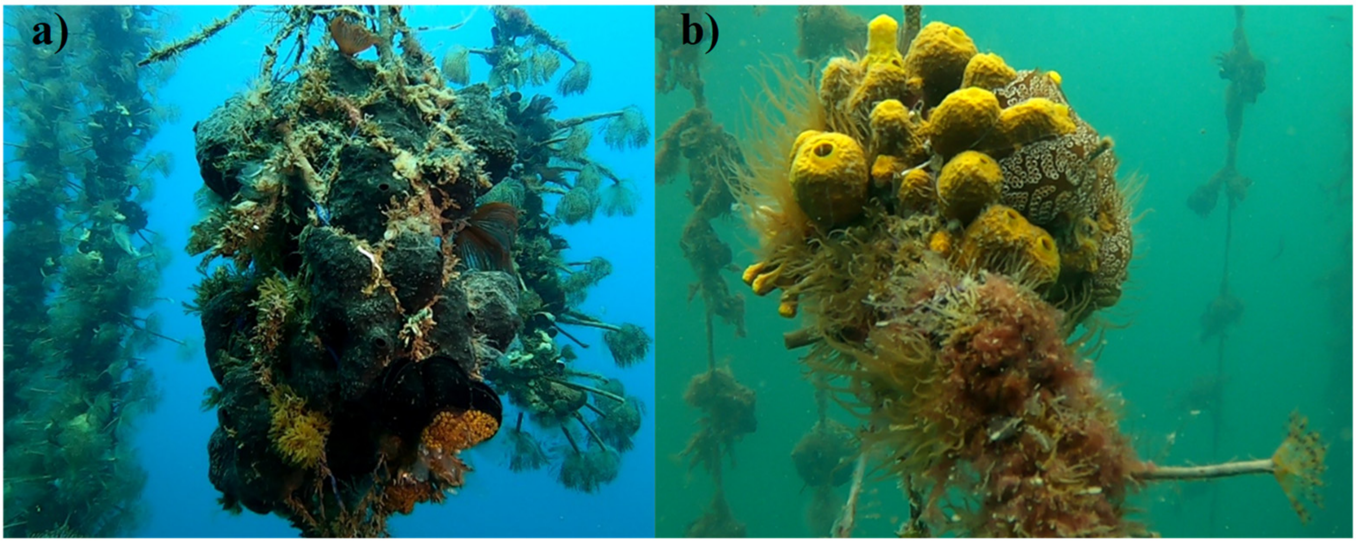

Figure 4. Algae, ascidians, polychaetes, and sea anemones growing on *Sarcotragus spinosulus* (**a**) and *Aplysina aerophoba* (**b**) reared in the Remedia Life IMTA system.

7. Deciding the Methodological Approach

Planning any sponge farm (including those in an IMTA system) requires in-depth preliminary studies to first evaluate the consistency of the natural stocks which will act as "donors". Once the distribution and abundance of the sponge donor beds have been characterized, it is necessary to study thoroughly the biological and ecological characteristics of the potentially selected species. Among the features that must be considered in the species selection, expertise in reproduction, growth performance, resistance to survival in critical conditions, and resistance to manipulation are fundamental.

Going into more detail on the methodology and practical aspects of sponge culture, the design of the systems and the survival and growth rates of the explants used vary according to the sponge species, their skeletal consistency, and the aim of production. Thus, for secondary metabolite production, the shape and appearance of the individual are taken less into consideration, whereas maturity or symbiotic composition are. At the same time, the opposite would be true if the cultured individuals were to be destined for an aquarium.

In this sense, sponge farming systems could be performed vertically in the water column or horizontally on the seabed using different materials and tools. Mobile structures suspended in the water column allow the rearing of many sponge explants around the fish farming cages. In such systems, different tools have been tested, such as ropes, tubular nets, mesh panels, lantern nets, and SEAPA cages where the sponge explants have been inserted (Figure 5). [24] reviews the methodology of studies that have cultured sponges in situ and concludes that artificial substrates are the predominant choice, followed by rope and mesh systems, all with similar percentages (between 25% and 30% of the studies reviewed for each). However, when the search is narrowed down to IMTA systems (present study), those with thread lines running through explants and mesh systems become the most studied (encompassing almost all the studies), while artificial substrates are hardly used [16]. For *Dysidea avara*, for example, Ref. [164] concludes that in pristine natural waters a cage system promotes a higher growth rate when compared with rope and mesh systems, while [14] and the Porifarma company described in [25], being fish-farming associated sponge rearing systems, utilize nylon rope systems with promising results. This change in the choice of methodology could be mainly because, in IMTA systems, the organic load in the water column coming from fish production is high and increases sedimentation [8], which has been shown to negatively affect sponge culture structures with large exposed or semi-enclosed surfaces, such as artificial substrates or cages [14]. Therefore, designs in which more of the sponge surface area is in contact with the water column and less is available for sedimentation and fouling colonization seem to be the most suitable for explant rearing, such as the rope and mesh system variants.

However, when choosing the type of culture system, other factors must also be considered, which in some cases determine the biomass production yield or its usefulness for the established objective. Depth, for example, is a determining factor for collagen production in *Chondrosia reniformis* (higher content in shallow waters) [40]. Consequently, culture structures should be located a few meters from the surface. Heat stress, on the other hand, induces the loss of symbionts [165], which can be crucial to produce secondary metabolites; thus, in areas where the water surface temperature rises above 30 °C, the culture should be placed at greater depths. All in all, the selection of the cultivation method for marine sponge explants is the result of different factors, such as environmental factors, species, or production objectives, that will determine the type of system, material, and placement of the structures.

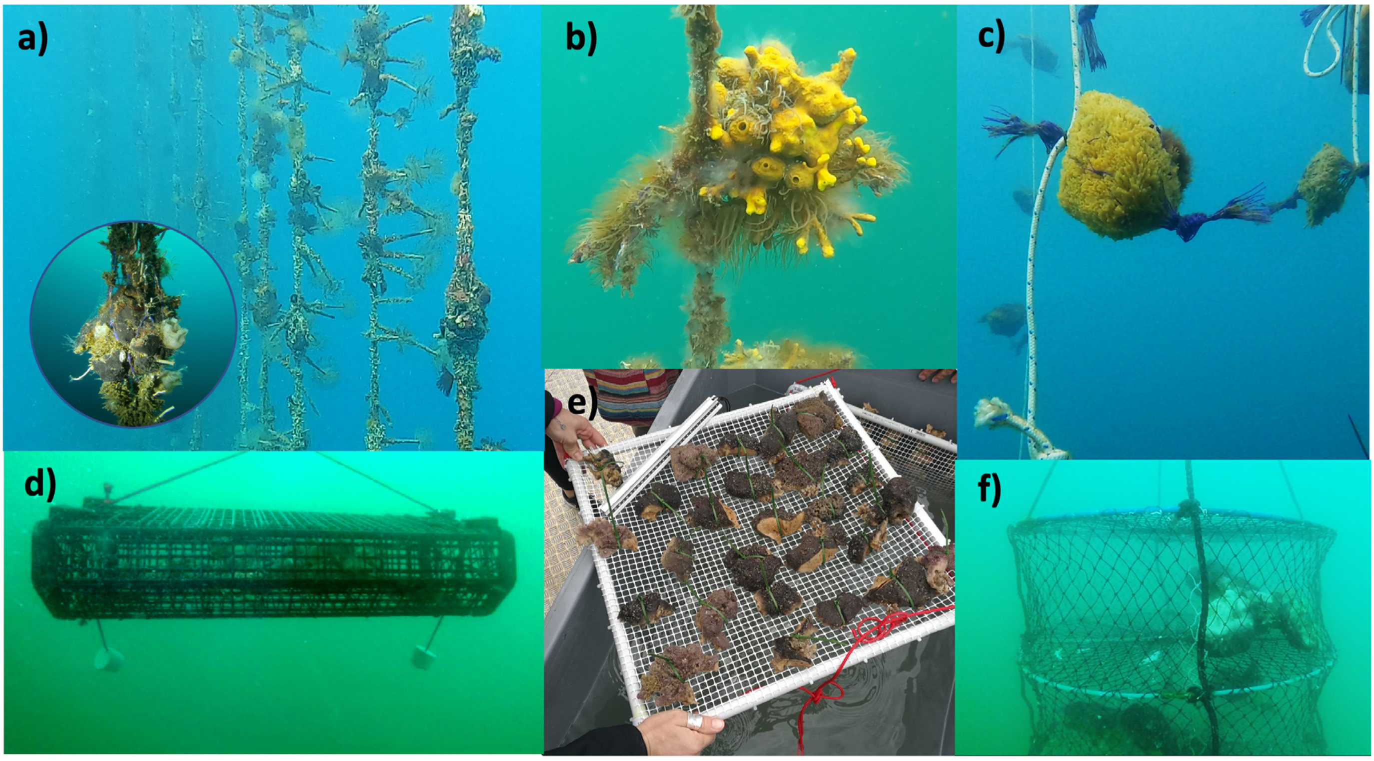

Figure 5. Main rearing methods in Remedia Life (upper) and ASMAR (lower) IMTA systems. *Sarcotragus spinosulus* reared in tubular nets (**a**), *Aplysina aerophoba* (**b**), and *Hymeniacydon perlevis* (**c**) reared in rope systems with net bags in the Maricoltura del Mar Grande fish farm (Mar Grande of Taranto, northern Ionian Sea); *S. spinosulus* in SEAPA nets (**d**), mesh panels (**e**) and lantern nets (**f**) close to Gargano fish farm (Gulf of Manfredonia, south-eastern Adriatic Sea). ASMAR project: Assessment of Sponge Mariculture Potential in Polyculture System in the Manfredonia Gulf–Interreg Adrion Blue Boost 2019–2020.

8. Fitting Strategic and Sustainable Development Goals

The European Union, in the amended 2022 "New strategic guidelines for aquaculture", improved the "Strategic Guidelines for a more sustainable and competitive European aquaculture for the period from 2021 to 2030" with a shared vision for further development of aquaculture in the EU. The goal is to build a sustainable, resilient, and competitive aquaculture (marine and freshwater). Particular attention is paid to the need to put science into practice through applied research and innovation, nationally and internationally. Among the strategic points that member states must consider to achieve the proposed goal by 2030 are supporting the development of new aquaculture methods, in particular those with low environmental impact (e.g., IMTA), and promoting diversified production to expand the supply of aquaculture products, using promising new species in the EU, including marine invertebrates.

From a global point of view and with a focus on future feasible socio-economic development, the use of marine sponges in IMTA systems fits perfectly with the Sustainable Development Goals for 2030 described by the United Nations [166], which detail objectives, such as reducing biodiversity loss and poverty, making sustainable use of marine resources, and promoting environmentally sustainable economic development, among others. Although the inclusion of sponges in IMTA is still underutilized, keeping avoiding the over-exploitation of natural sponge populations in mind, the spreading of such practices can combine environmental needs and sustainable development [24,25,57].

As mentioned above, sponge mariculture has been known for a long time but with only a few large-scale applications, mainly related to "bath sponges" [24,25,57]. Currently, a positive impact has been reported in regions such as Zanzibar and Micronesia, where in situ marine sponge culture systems enhance the recruitment of other species and provide a source of income for the local population [31,32]. Thus, despite being underexploited species in IMTA systems, the environmental and economic potentials of marine sponges are important in the pursuit of the fixed goals of the aquaculture sector and sustainable societal development.

9. Conclusions

The production of biomass from non-edible species in properly designed IMTAs, such as marine sponges with important profitable applications, implies using new resources that promote a blue circular economy (Figure 6). In this sense, these systems represent an eco-friendly sponge biomass supply not only for economic interests, such as the bath sponge market, green extraction of bioactive molecules, and aquariology (ornamental species or food for fishes) but also for environmental welfare as bioremediation or restoration purposes that increase ecosystem biodiversity. The IMTA systems not only fit perfectly with the general Sustainable Development Goals proposed by the United Nations but, at the same time, lowering the use of antibiotics would reduce costs and economic losses in the pursuit of the aquaculture sector's environmentally friendly progress.

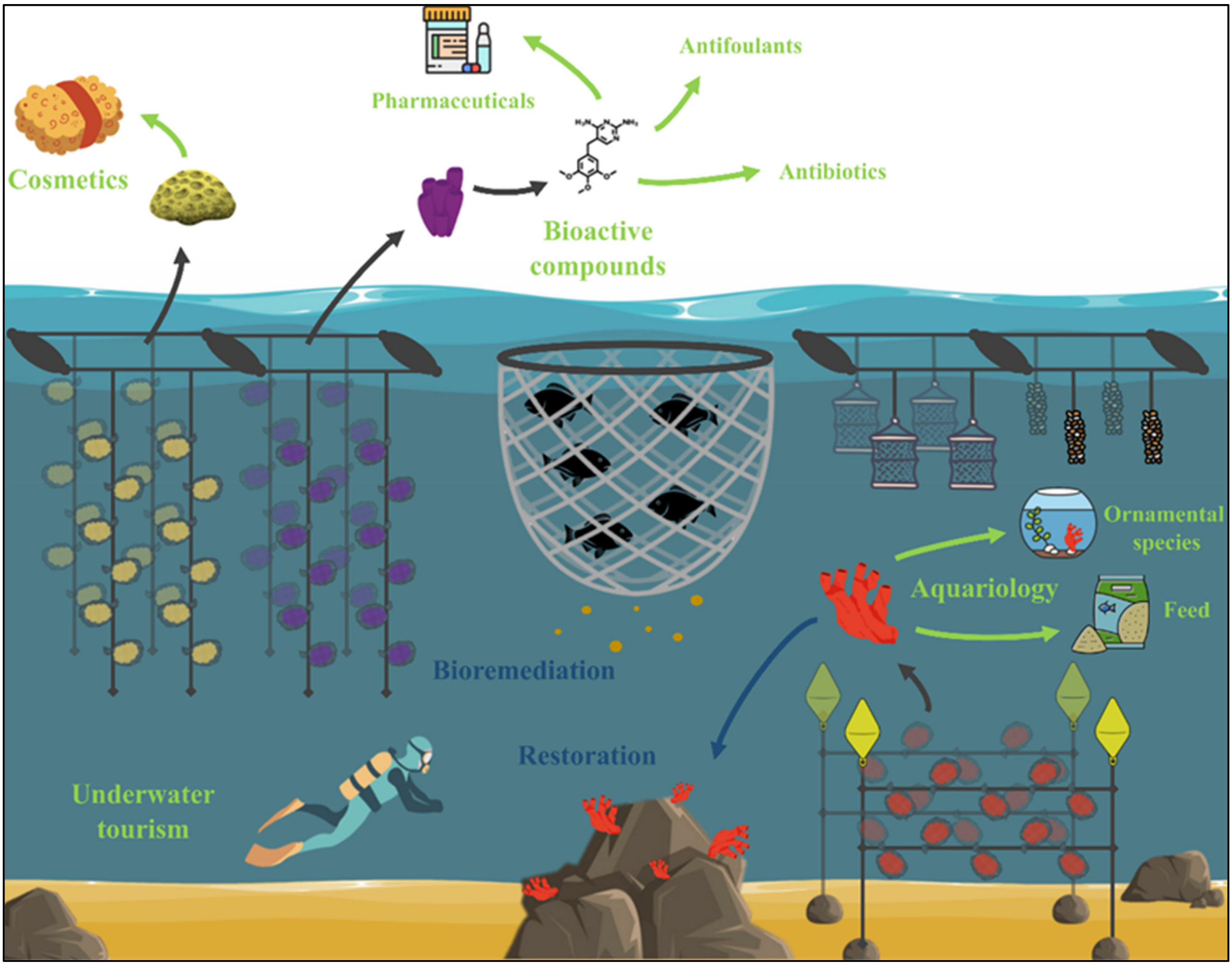

Figure 6. Sponges as a by-product of an IMTA system. Environmental and economic benefits are represented in blue and green, respectively.

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