Accepted Manuscript

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PII: S0044-8486(17)31157-2
DOI: doi:10.1016/j.aquaculture.2018.02.035
Reference: AQUA 633083

To appear in: *aquaculture*

Received date: 5 June 2017
Revised date: 17 November 2017
Accepted date: 21 February 2018

Please cite this article as: Periklis Kleitou, Demetris Kletou, Jonathan David , Is Europe ready for integrated multi-trophic aquaculture? A survey on the perspectives of European farmers and scientists with IMTA experience. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Aqua(2017), doi:10.1016/j.aquaculture.2018.02.035

Is Europe ready for integrated multi-trophic aquaculture? A survey on the perspectives of European farmers and scientists with IMTA experience

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Abstract

Integrated Multi-Trophic Aquaculture (IMTA) refers to the integrated farming of several species from different trophic levels in close proximity. In IMTA, one species is intended to complement another. The concept has long been in use in Asia and contributes significantly to the sustainability of aquaculture as it can potentially drive ecological efficiency, environmentally acceptability, product-diversity, profitability and benefit society. Although the concept has received increasing academic attention during the last two decades, it has not yet become a commercial reality in European mariculture. The reasons for this were explored, by interviewing farmers and scientists with previous experience on IMTA. The interviewing approach can be effective in identifying important omissions from the available literature and also possible exaggerations of positive results. For the purposes of this study, a qualitative survey was undertaken using a structured questionnaire with open-ended questions. As a result, the opinions of 34 farmers and scientists with substantial experience of IMTA from 12 European countries have been obtained. A broad spectrum of IMTA impediments has been identified. These have been separated into nine major categories; namely Biological, Conflicts, Environmental, Interest, Legislation, Market, Operational, R&D, and Vandalism. The importance of each category was found to vary among different locations and regions of Europe indicating the need for site-specific targeted approaches. Nevertheless, factors from several categories were raised in all countries / IMTA configurations which highlights that for IMTA to be further developed and adopted, the involvement of stakeholders and personnel from several disciplines is necessary (i.e. biologists, economists, engineers, farm managers, modellers, regulators, stakeholders and statisticians). This work identifies many of the challenges that European IMTA is likely to encounter, and proposes areas that are likely to benefit from focused research and development.

Keywords:

Aquaculture

IMTA survey

Farmers and scientists

Integrated Multi-Trophic Aquaculture

Barriers

Challenges

1. Introduction

Integrated Multi-Trophic Aquaculture (IMTA) refers to the associated culture of several species from different trophic levels. IMTA allows uneaten feed and by-product particulate wastes and dissolved nutrients to be recaptured by extractive co-cultivars and converted into energy, feed, or fertilizer (Casalduero, 1999; Neori et al., 2000; Troell et al., 2003; Zhang et al., 2009; Chopin, 2012). For instance, farmers can combine fed-species, like salmon, with seaweeds, suspension feeders, such as scallops and mussels, and/or organic deposit-feeders, such as sea cucumbers, to increase production efficiency and decrease waste.

IMTA has been widely acknowledged to hold a great promise for aquaculture sustainability as it can potentially drive ecological efficiency, environmental acceptability, product-diversity, profitability and social benefits (OECD, 2010; Schmidt et al., 2011; Chopin, 2012). The concept has long been in use, and commercially successful in Asia, particularly in China, Japan and South Korea, with the integrated cultivation of fish from different trophic levels, and/or the use of shellfish and seaweed in lagoons or bays next to fish net pens (Neori et al., 2004; Sorgeloos et al., 2011). Through trial and error, these countries achieved a sequential development of IMTA over the years (Wartenberg et al., 2017); although information is rarely published and the reasons for success might not be understood, even among the farmers' involved (Neori et al., 2004). Western countries, including Europe, have been latecomers to the IMTA concept, and it was not until recently that their interest in IMTA has emerged (Barrington et al., 2009; Chopin et al., 2012). It has been at least 40 years since the potential of IMTA was first discussed in the scientific literature (Ryther et al., 1972; 1975) and yet there has been very little uptake of this technology by the European industry (Lane et al., 2014). Barrington et al. (2009) ascribed this slow progress to a lack of compelling political, social and economic reasoning and lack of motivation towards sustainability, long-term profitability and responsible management of coastal waters. In order to better understand its limited implementation in Europe, it is also important to move beyond the use of IMTA as a purely conceptual framework (Hughes and Black, 2016). It is clear that there might be several factors that do not favour the current commercialisation of IMTA in European marine-based aquaculture. These include the lack of direct financial benefits for the farmer, and the need for more efficient integrated farming systems to reduce complexity and allow processing of all crops, as well as better support from policy and regulatory bodies to enable and incentivise the adoption of IMTA (Hughes and Black, 2016; Alexander and Hughes, 2017).

Published literature can provide significant information about the current state of IMTA in Europe, but this information may be biased by the fact that journals tend to publish research demonstrating positive outcomes (Lee et al., 2013). Report bias might also depend on the funding source and evaluation processes of an experiment, as reported for other industries (Als-Nielsen, 2003). These factors can often lead to an exaggerated effect in later meta-analyses (Ioannidis, 2005; Lee et al., 2013). For example, a recent meta-analysis of IMTA peer-reviewed data concluded that around 80% of studies on macroalgae and 50% on bivalves - cultivated in the vicinity of open-water fish farms - demonstrated strong evidence for increased growth relative to controls. According to the authors these figures may be highly overestimated (Kerrigan and Suckling, 2016).

Contacting the authors of publications directly has been effective in identifying important omissions from reported outcomes and avoiding exaggerations (Chan and Altman, 2005). In order to elucidate potential factors and barriers which currently impede widespread adoption of IMTA, we have interviewed farmers and scientists with substantial experience of IMTA practices in various parts of Europe.

2. Materials and Methods

2.1. Survey

An internet search identified a total of 80 farmers and scientists from 13 European or EU-Associated countries (i.e. participating in Horizon 2020 Research and Innovation programme under the same conditions as EU Member States) (hereafter referred to as European) with IMTA involvement. From this initial sample that was contacted, 6 were later excluded due to inadequate experience or relevance over recent years and 3 declined to participate due to conflict of interest. The interviewees were contacted by email followed by a telephone call, and a qualitative survey was undertaken using a structured questionnaire with open-ended questions designed to extract broader information. The questionnaire is reproduced in the Appendix.

The survey consisted of three sections. The first part aimed to collect personal information about the respondent and the location(s) of their IMTA practices. The second part consisted of questions regarding the IMTA application, such as the species cultivated, reasons for IMTA application, bottlenecks faced and support received (e.g. financial aid and incentives). The third part evaluated the perceptions of farmers / scientists on the IMTA level of development at their experimental site and country, its future potential, the challenges to overcome in their region / country, and IMTA species of future potential. Interviewees were asked to order their issues/challenges/opportunities in a priority sequence (i.e. most important first and least important last). However, it is important to note that the questionnaire was asking only for the major issues/challenges/opportunities to be mentioned, and therefore all answers should be considered as important; even if seldom reported.

2.2. Data analysis

2.2.1. Countries aggregation

In order to allow comparison between regions and different areas of Europe, the countries were separated and also analysed as region and sub-region aggregations. Specifically, countries were aggregated into two regions (i.e. Northern Europe and Southern Europe) and five sub-regions: North Europe (N), North-West Europe (N-W), South Europe (S), South-East Europe (S-E) and South-West Europe (S-W) (Table 1). To our knowledge, no major marine IMTA application has been carried out in North-East Europe so far, and so this region was excluded from the analysis.

2.2.2. Responses' categorization

The responses raised several issues that were very similar or interrelated. For instance, some respondents mentioned environmental conditions as a major obstacle faced during their IMTA application while other mentioned weather/storm. To avoid complexity and enable interpretation of the answers, all issues (i.e. bottlenecks, obstacles, challenges) were categorised into broader subjects. For example, issues such as lack of available seed and lack of general knowledge regarding the IMTA species were placed into the broader category of "Biological" while issues such as weather / storms and general environmental conditions were placed into the broader category of "Environmental".

3. Results

3.1. Survey responses

A total of 34 people from 12 countries participated in the survey (43% of the people initially contacted). Most of the responses were obtained from the United Kingdom (UK) (n=6) followed by Spain (n=5). The two regions were equally covered with 16 and 18 respondents from Northern Europe and Southern Europe respectively. The S-W and N-W sub-regions were the most covered with 10 and 9 respondents respectively, followed by 7 from N, 4 from S and 4 from S-E (Table 1).

The average IMTA experience of the respondents was 74.7 months. Only two respondents had an IMTA experience of less than 12 active months. Respondents from Israel had the longest experience with average of 270 months followed by the respondents of the UK with average of 110 months. However, respondents from the two regions had approximately the same average period of IMTA experience; with 70.1 months reported from Northern Europe respondents and 76.4 months reported from Southern Europe respondents.

Table 1

Aggregation of countries into regions and sub-regions, respondent code's (RC) assigned to each individual for the purposes of analysis, and number of respondent's and average period-experience for each country.

Region	Sub-region	Country	Respondent's code (RC)	Number of Respondent(s)	Average period-experience of IMTA (months)
Northern Europe	N	Denmark	16, 18, 37	3	60
		Norway	13, 14, 65	3	27.3
		Netherlands	75	1	48
	N-W	Ireland	1, 6, 72	3	80
		United Kingdom	8, 56, 57, 64, 67, 78	6	110
Southern Europe	S	Greece	80	1	6
		Italy	49, 73, 74	3	24
	S-E	Cyprus	30, 31	2	31.5
		Israel	39, 69	2	270
	S-W	France	35, 43	2	33
		Portugal	2, 3, 20	3	88.7
		Spain	33, 34, 52, 55, 56	5	68.4

3.2. Species cultivated in IMTA systems

The experience of respondents in IMTA involved a large variety of exogenously fed species (Table 2) and a broad range of inorganic extractive species, organic suspension feeders, and organic deposit feeders cultivated using various techniques either in land-based or marine-based systems (Table 3). Of the "extractive" species, only the brown algae *Alaria esculenta* appears to have been attempted in a particular region (Northern Europe), and together with *Saccharina latissima*, *Mytilus edulis* and *Aequipecten opercularis* they constitute the only IMTA species cultured at a commercial level.

Table 2

Exogenously fed species used by the respondents.

Exogenously fed species	Country	Land-based / Sea-based farming	RC
Argyrosomus regius	Spain	Sea-based	34,55
Dicentrarchus labrax	Cyprus, France, Greece, Italy, Portugal, Spain, United Kingdom	Land-based & Sea-based	3,20,30,31, 34,35,49,52, 55,73,74,78,80
Diplodus puntazzo	Spain	Sea-based	34
Gadus morhua	United Kingdom	Land-based	78
Hippoglossus hippoglossus	United Kingdom	Land-based	8
Labrus bergylta	United Kingdom	Land-based	78
Mugil cephalus	Greece, Israel	Land-based & Sea-based	39,80
Mytilus galloprovincialis	Spain	Sea-based	28
Oncorhynchus mykiss	Denmark	Sea-based	36,48,96
Salmo salar	Ireland, Norway, United Kingdom	Sea-based	1,6,13,14,56, 57,64,65,72
Scophthalmus maximus	United Kingdom	Land-based	78
Sparus aurata	Cyprus, Denmark, Greece, Israel, Italy, Portugal, Spain	Land-based & Sea-based	2,3,30,31,34,37,49,52, 55,69,73,74,80

Table 3

Extractive IMTA species used by the respondents.

Feeding mode	Species group	Species	Country	Technique	Land-based / Sea basedfarming	Commercial / Experimental	RC
Algae	Brown algae	*Alaria esculenta*	Ireland, Norway, United Kingdom	Hanging rope & Horizontal rope (Long-line)	Sea-based	Commercial & Experimental	1,6,56,57, 64, 65,72
		Saccharina latissima	Denmark, Ireland, Norway, Portugal, Spain, United Kingdom	Hanging rope & Horizontal rope (Long-line)	Sea-based	Commercial & Experimental	1,13,14,16, 20,28,37,56,57, 64,65
	Green algae	*Ulva lactuca*	Israel, United Kingdom	Tanks	Land-based & Sea-based	Experimental	69,78
		Ulva rigida	Portugal	Tanks	Land-based	Experimental	3, 55
		Ulva rotundata	Portugal	Tanks	Land-based	Experimental	3
		Ulva sp.	France, United Kingdom	Tanks	Land-based	Experimental	8,35
	Plankton	n/a[1]	France	High-rate algal ponds	Land-based	Experimental	35
	Red algae	*Asparagopsis armata*	Portugal	Tanks	Land-based	Experimental	2,3
		Hydropuntia cornea	Spain	n/a	n/a	Experimental	55
		Palmaria palmate	Ireland, United Kingdom	Tanks & Horizontal rope (Long-line)	Land-based & Sea-based	Experimental	6,8
Suspension feeders	Abalone	*Haliotis tuberculata*	Cyprus, Spain	Ortac baskets	Sea-based	Experimental	30,31,55
	Clam	*Ruditapes decussatus*	Israel, Spain	n/a	n/a	Experimental	33,39
		Ruditapes philippinarum	Spain	n/a	n/a	Experimental	33
	Mussel	*Mytilus edulis*	Norway, Spain, United Kingdom	Cages, Long-line, Smart farm system	Sea-based	Commercial & Experimental	13,14,16,18,37, 56,57,64
		Mytilus galloprovincialis	Cyprus, Denmark, Italy, Spain	Longline	Sea-based	Experimental	30,31,34,49
	Oyster	*Cassostrea gigas*	Israel, Italy, Portugal, United Kingdom	Lantern nets & SEAPA baskets	Sea-based	Experimental	20,39,56,57,74, 75
		Ostrea Edulis	Cyprus, Italy, Spain	Lantern nets & Ortac baskets & Stacked boxes (40 x 40 x 10 cm)	Sea-based	Experimental	30,31,33,52,73, 74
	Scallop	*Aequipecten opercularis*	United Kingdom	Collectors & pearl & lantern nets	Sea-based	Commercial & Experimental	56,57,64
		Mymachlamys varia	Spain	n/a	Sea-based	Experimental	34
		Pecten maximum	Norway	Cages	Sea-based	Experimental	13,14
	Sponges	*Spongia sp.*	Cyprus	Mesh quadrats	Sea-based	Experimental	30,31,86

Feeding mode	Species group	Species	Country	Technique	Land-based / Sea basedfarming	Commercial / Experimental	RC
Deposit feeders	Crab	*Callinectes Sapidus*	Cyprus, Greece	SEAPA baskets & Tanks	Land-based & Sea-based	Experimental	30,31,80
	Fish	*Mugil cephalus*	Greece, Israel	Cages	Land-based & Sea-based	Experimental	69,80
	Polychaete	*Alitta virens*	United Kingdom	Tanks	Land-based	Experimental	35
		Hediste diversicolor	France	Tanks	Land-based	Experimental	78
	Sea cucumber	*Holothuria forskali*	Spain	n/a	Sea-based	Experimental	34
	Sea urchin	*Paracentrotus lividus*	Cyprus, Israel	Bottom cages & Ortac baskets & Oyster baskets & Pots	Land-based & Sea-based	Experimental	30,31,39,69
		Psamechinus miliaris	United Kingdom	n/a	Sea-based	Experimental	74
	Shrimp	*Lysmata seticaudata*	Spain	n/a	Sea-based	Experimental	34

n/a - not applicable - information not provided by respondents

3.3. Major drivers of IMTA application

The major drivers of the IMTA projects based on the survey responses were mitigation / nitrogen removal (n=19), research for species suitability (n=17), enhanced production (n=16), general R&D of sustainable mariculture (n=8), examination of IMTA suitability (n=6), diversification (n=3), public image improvement (n=1), and legislation; particularly to allow to increase production in Danish waters (n=1) (Fig. 1). The drivers varied among individuals within the same country, with an exception for species suitability research which was reported as the primary reason by all the Italian respondents (n=3) and mitigation, which was reported as the primary or secondary reason by all the Norwegian respondents (n=3).

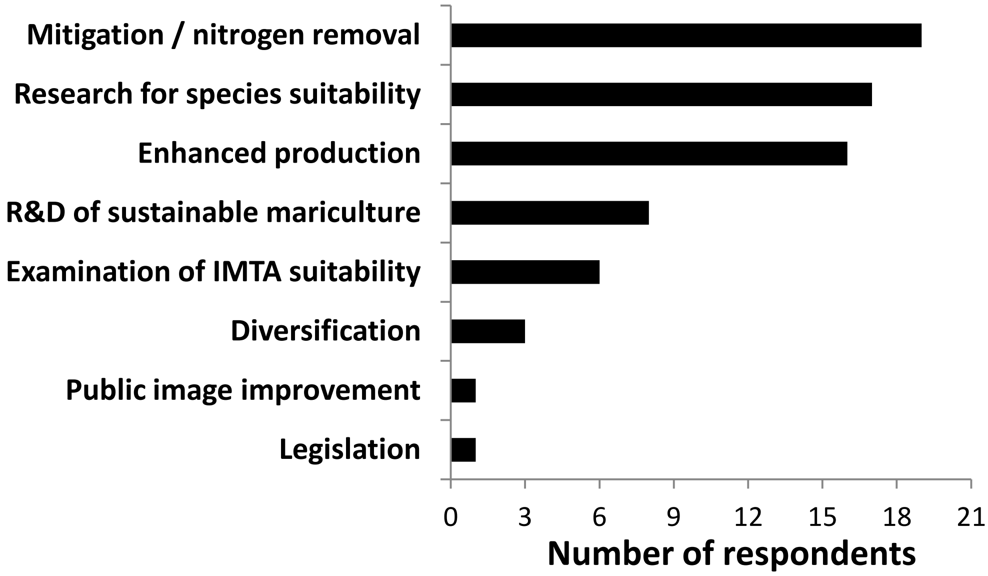

Fig. 1. Major reasons for IMTA application per number of respondents.

3.4. Financial / support of IMTA application

For the implementation of the IMTA experiments and practices, 19 respondents (55%) received financial support from at least one funding scheme / instrument of the EU (e.g. The Seventh Framework Programme – FP7), 16 (47%) of respondents received aid from at least one National scheme / instrument (e.g. Spanish National Plans for Aquaculture – JACUMAR) and 4 (11%) received aid from at least one Regional scheme / instrument (e.g. INTERREG IIIC programme). It is noteworthy that all respondents from Denmark (n=3), Norway (n=3) and Spain (n=5) received national financial support for IMTA on at least one occasion, indicating support for IMTA implementation by the governments of these countries.

Respondents were also asked if they received other incentives to develop IMTA, such as sustainability certificates, and all the answers were negative.

3.5. Major bottlenecks / obstacles faced during IMTA

During the implementation of IMTA, several major bottlenecks / obstacles were faced by the respondents and these are displayed in Table 4. For each bottleneck / obstacle category, the proportion (r/r = number of records / number of respondents) of each type of system (i.e. land-based vs sea-based) was found. Since one respondent could report more than one bottleneck /

obstacle from the same category, the proportion could exceed the value of 1. Biological issues were the most reported, followed by operational and market issues for both respondents that worked with land-based and sea-based systems (Fig. 2). Legislation and environmental bottlenecks / obstacles faced during IMTA application were more commonly recorded by farmers / researchers that worked with sea-based compared to land-based systems, while issues of interest, conflict, vandalism were mentioned only from the respondents that worked with sea-based systems (Table 4). On the other hand, R&D issues were mentioned more often by respondents that worked with land-based systems.

Although different bottlenecks / obstacles were raised by individuals of the same country, key findings included the fact that three out of the four records of multi-operation complexity came from respondents of the UK, while four out of the six UK respondents raised market issues. Market issues were also raised by two out of three respondents from Denmark and Portugal. In addition, two out of three respondents from Portugal raised issues of sustainable production over long periods.

Table 4

Major bottlenecks / obstacles faced by the respondents during the IMTA application.

Category	Bottlenecks / obstacles faced	Number of records		Country	RC
		Land-based	Sea		
Biological	Lack of available seed	2	3	Cyprus, France, Israel, Spain	30,31,34,35, 69
	Lack of general knowledge regarding the IMTA species (biology, production cycles, net balance of nutrients at the end of the system)	1	2	Cyprus, France, United Kingdom	31,43 ,78
	Biofouling impedes culturing processes	0	3	Denmark, United Kingdom	16,56,64
	Sustainable production for large periods (e.g. >1 year / not seasonal) is questionable	2	1	Norway Portugal	2,3,13
	Low nutrient uptake / growing performances	0	2	Israel, Norway	13,49
	Predation (i.e. birds, settling starfish and turtles)	0	2	Cyprus, Denmark	16,31
	Lack of complementary diet (e.g. seaweeds for abalone)	0	1	Cyprus	30
	Pests / diseases	1	0	United Kingdom	78
Environmental	Weather / Storms	0	2	Ireland, Spain	1,52
	General environmental conditions	0	2	Cyprus, Norway	13,30
	Deep waters unsuitable / unsafe	0	1	Cyprus	31
	Oligotrophic ecosystem	0	1	Italy	74
	Low light / temperature during periods	1	0	United Kingdom	78
Interest	Lack of private investment	0	1	Italy	49
	Lack of awareness / interest	0	1	Norway	14
Legislation	Licencing / regulations	1	9	Cyprus, Denmark, Ireland, Norway, Spain, Italy	6,14,18,28,31, 33,55,72,73,7 4
Market	Uncertain profitable market	4	9	Denmark, Israel, Portugal, Norway, Spain, Italy, United Kingdom	2,3,13,16,18, 28,33,34,56, 64,69,74,78
	Undeveloped market	0	2	United Kingdom	57,78
Operational	Inadequate technology & lack of infrastructure to harvest / process / cleanse extractive species	1	6	Cyprus, Denmark, Greece, Ireland, Israel, Norway, Spain	1,28,31, 37,55,65,69, 80
	Inadequate expertise	1	3	France, Greece, Norway, Spain	28,33,35,65, 80
	Multi-operation complexity (space, facilities, equipment)	1	3	Norway, United Kingdom	13,56,64,78
	Logistical constraints	0	1	United Kingdom	57
Vandalism	Vandalism	0	1	Spain	52
R&D	Time to progress / develop IMTA	2	1	Denmark, Portugal, United Kingdom	8,20,37
Conflicts	Public opposition - low acceptance	0	2	Ireland, Norway	14,72

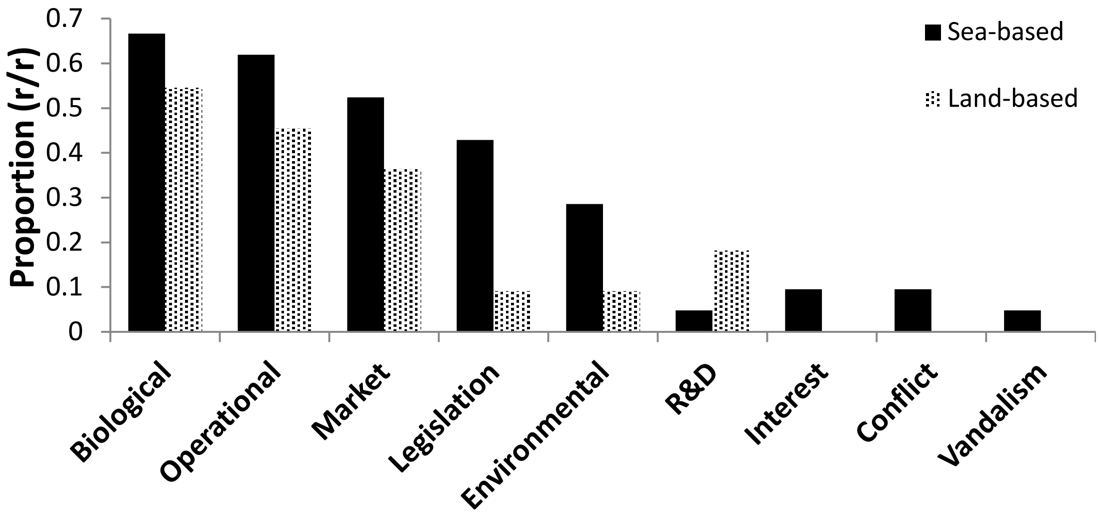

Fig. 2. Major categories of bottlenecks / obstacles faced during sea-based and land-based IMTA based on proportions..

The issues raised by the respondents of each sub-region are shown in Fig. 3. Remarkable differences among sub-region proportions can be found in the records of biological issues which are one of the top categories for all regions but their proportion is substantially higher for the sea-based systems of S-E Europe (r/r = 2). It is noteworthy that all 5 records of lack of seed as a major obstacle come from the Mediterranean Sea and particularly 3 out of 5 come from the three respondents that worked with sea-based systems in the S-E Europe (2/2 from Cyprus, 1/2 from Israel). Environmental bottlenecks / obstacles were reported by the respondents of all sub-regions apart from N. Market issues were reported by the respondents of all sub-regions but they were more commonly recorded in the N, N-W and S-W Europe (for both land-based and sea-based systems). Public acceptance was reported only as an obstacle in the sub-region of N Europe. Operational issues were raised by the respondents of all sub-regions but comparatively more often by the respondents that worked with land-based IMTA in S Europe. Finally, legislation issues were recorded more often by the respondents that worked in sea-based systems in the S and SW Europe sub-region.

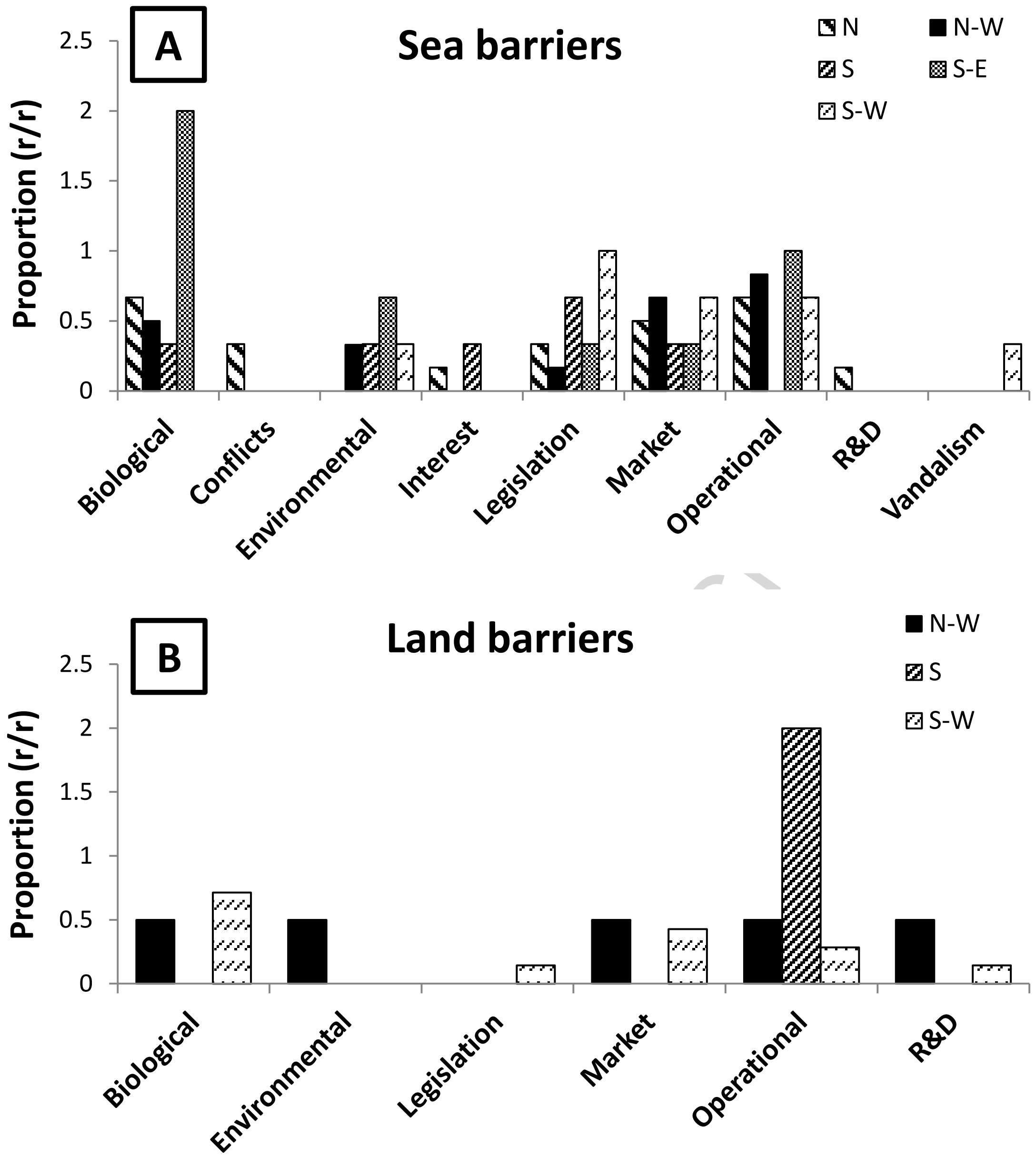

Fig. 3. Major bottlenecks / obstacles faced during IMTA based on proportions per sub-region and area (A: sea-based application; B: Land-based application).

3.6. IMTA potential in Europe

Despite the several bottlenecks / obstacles faced, the majority of respondents believed that there is a high potential for IMTA in Europe. This was supported by 26 individuals (76%) compared to 7 who believed that there is no potential (21%), and 1 being neutral (3%). All the negative answers came from different countries with an exception of two that came from Danish respondents.

3.7. IMTA development in regions / Europe

On a scale of 1-5, where 1 means not developed and 5 means very well-developed, respondents were asked how well-developed their IMTA system is compared to other IMTA production systems / sites. A total of 11 respondents ranked land-based IMTA systems while 20 respondents ranked sea-based IMTA systems. Only Israel, Spain and UK had respondents that mentioned both sea & land-based systems. Cyprus, Denmark, Ireland, Italy and Norway respondents mentioned only sea-based systems while respondents from France, Greece and Portugal only land-based systems.

For the sea-based systems, the highest average record was obtained from the UK, while the lowest average record was obtained from the eastern Mediterranean countries (i.e. Cyprus and Israel) (Fig. 4). Israel, followed by UK and Portugal, obtained the highest average record for the land-based systems.

Differences were observed in the records of farmers / scientists from the same country (e.g. Norway and Denmark) (Fig. 4) which indicates possible differences in IMTA development even between IMTA systems of the same country and depending on site and species cultured.

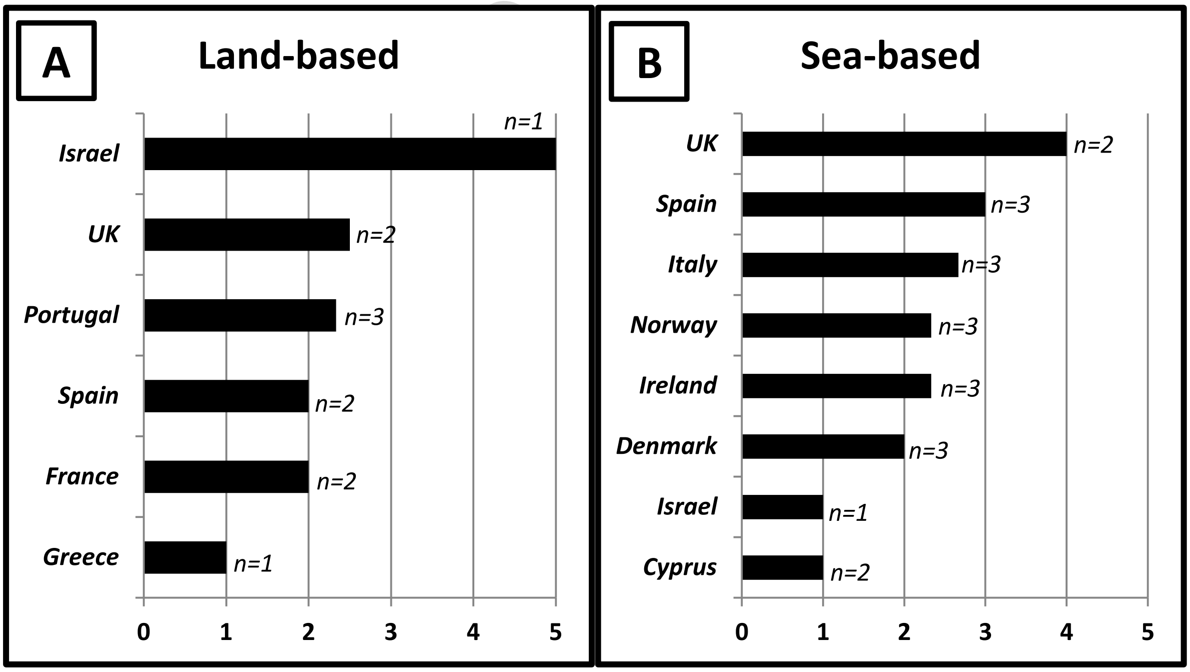

Fig. 4. Respondent scores by country on the development status of their IMTA system (A: sea-based application; B: Land-based application) compared to other systems in Europe, where 1 = not developed and 5 = highly developed. The number of respondents per country is also shown.

Using the same scale (1-5), respondents were asked how well developed is IMTA in Europe compared to other regions. The average value reported was 2.12, with a maximum of 3.

3.8. Major challenges to overcome

Respondents identified several challenges that need to be overcome for IMTA to be widely adopted in their country / region; these showed some correlation with the obstacles faced during their IMTA application. The most-often reported challenges were related to economic and legislation issues (see Table 5; Fig. 5).

Three respondents reported that IMTA (at sea) is not possible in their region (Respondents 13 - Norway, 52 - Spain, and 67 – UK). For example, Respondent 52 (Spain) mentioned that "*all farms in the western Mediterranean are offshore and under these conditions dilution and dispersion of wastes does not allow their exploitation*".

Table 5

Challenges to overcome for IMTA to be widely adopted in the respondent's country.

Category	Challenges to overcome	Number of records	Country	RC
Biological	Identification of efficient species	3	Cyprus, United Kingdom	30,31,78
	Predation	2	Cyprus, Denmark	16, 31
Conflicts	Social acceptance to aquaculture	5	Denmark, France, Ireland, United Kingdom	1,16,35,72,78
	Conflicts with other producers	1	Spain	28
Interest	Funding agencies (funders & investors)	8	Greece, Ireland, Israel, Italy, Spain, United Kingdom	33,39,49,64, 69,72,74,80
	Promotion from industry	3	Portugal, Spain, United Kingdom	20,28,56
	Promotion from governments	2	France, United Kingdom	35,56
Legislation	Legislation & regulation bottlenecks	9	Cyprus, Denmark, France, Ireland, Netherlands, Spain	6,18,28,31,34, 35,49,55,75
	Lengthy and difficult procedures	2	Ireland, Italy	1,73
	IMTA should become compulsory	1	Israel	69
	Lack of labels	1	Italy	74
	Lack of polluter-pay policy	1	Portugal	3
Market	Market development	5	Greece, Netherlands, Norway, Portugal, United Kingdom	2,20,57,65,75
	Profitability	5	Cyprus, Denmark, France, United Kingdom	8,18,30,37,43
	Valorisation of products - processing / refining industry	3	France, Netherlands, Norway	43, 65,75
	Stability of yields	1	France	43
Operational	Technological feasibility (Infrastructure and labour)	4	Cyprus, Ireland, Portugal, United Kingdom	1,2,31,64
	Multi-disciplinary collaboration (e.g. shellfish & seaweed industry)	2	Cyprus, United Kingdom	30,56
	Expertise	2	Ireland, Spain	1,33
	Practicability	2	Portugal, United Kingdom	8,20
	Spatial configuration - new farming areas	1	Italy	49
R&D	General lack of scientific knowledge incl. economics	6	Denmark, Norway, Portugal, Spain, United Kingdom	2,16,55,56, 64,65

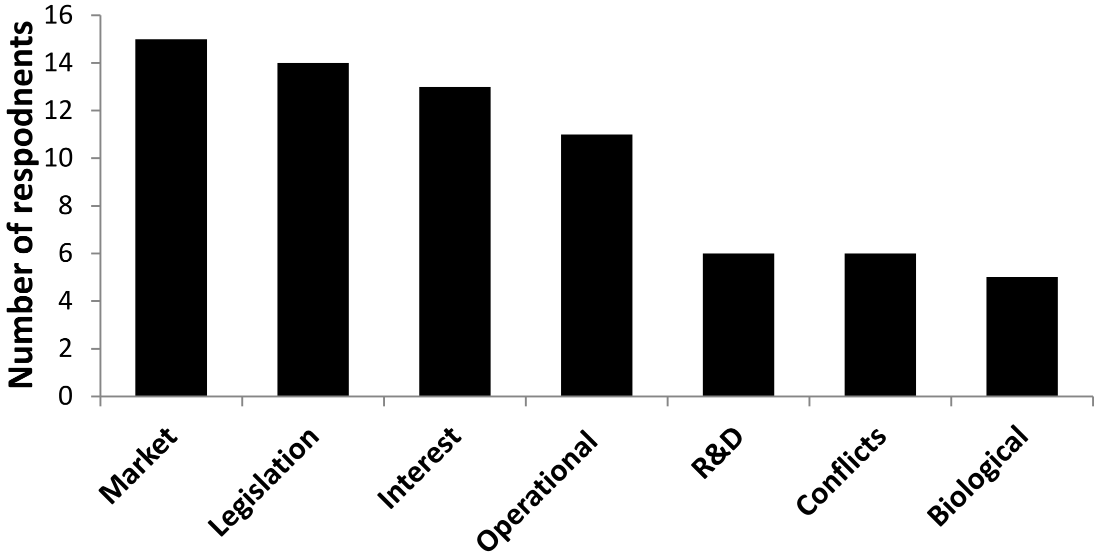

Fig. 5. Categories of challenges to overcome for IMTA to be widely adopted in the respondent's country.

The challenges that need to be surpassed in order for IMTA to be widely adopted have also been separated per sub-region and proportion. As with obstacles faced during sea-based IMTA operations, records of biological issues were the most prevalent in S-E Europe. In addition, lack of interest from the industry, government and funders / investors was more common in S and S-E Europe. The proportion of economic challenges was higher in the N and S-W Europe, and together with legislation, they were the only categories that were raised from the respondents of all five sub-regions (Fig.6).

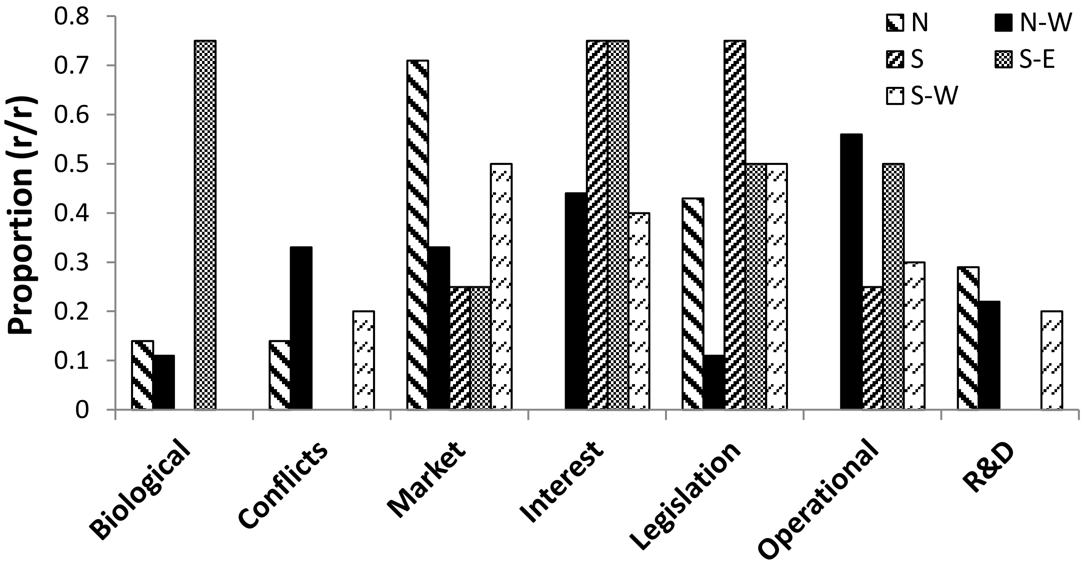

Fig. 6. Challenges to overcome (per sub-region) for IMTA to be widely adopted based on proportions.

3.9. Promising IMTA species per region

Respondents were asked to mention the most promising species in their region for future IMTA based on their own perspective. The species identified for each country, sub-region and the reasons for selection are displayed in Table 6.

Table 6

Species with the highest potential based on the responses.

Sub-region	Country	Species group	Species	Reason	RC
N	Denmark	Seaweeds	n/a[1]	Raw material for high end-products	16
		Mussels	*Mytilus edulis*	Grows quickly, available seed, good production techniques	16,18
	Norway	Algae	Macro & Micro	n/a	13
		Seaweeds	n/a	Large biomass	65
		Deposit feeders	n/a	Mitigation	13,65
N-W	Ireland	Native seaweeds	n/a	Under-utilised resource, multi-functional, seeded string are carried out on-site in Ireland	72
		Brown algae	*Alaria esculenta, Saccharina latissima*	Good environmental conditions, growing market	1,6
		Red algae	*Palmaria palmata*	n/a	6
		Mussels	*Mytilus edulis*	Popular, expertise already in place	1,6,72
		Oysters	n/a	Popular, high-valued	1
		Sea urchins	n/a	n/a	6
	United Kingdom	Seaweeds	n/a	Low production costs, increasing demand, easy and fast grow, various species / products, food for sea urchins	56,79,64,78
		Seaweeds	*Ulva* sp.	Fast growing, easy, multiple uses	8
		Shellfish	n/a	Showing continued demand and is a key 'healthy' food	56
		Oysters	*Crassostrea gigas*	Producers existence, and high commercial value	78
		Scallops	*Aequipecten opercularis*	Plentiful wild supply, great market potential	57,64
		Deposit feeders	n/a	Mitigation, highest potential	67
		Polychaetes	n/a	Some species high value, easy and fast to grow	78
		Sea urchins	n/a	Plentiful wild supply	64
S	Greece	Mussels	n/a	Market and expertise already in place	80
		Fish	*Mugil cephalus*	Feed on benthos, mitigation	80
	Italy	Seaweeds	n/a	High biomass - good biomitigation	49
		Bivalves	n/a	High biomass - biomitigation, expertise already in place	49,73
		Oysters	*Crassostrea gigas*	Evidence have shown they can reach market size in two years, high-valued	74
S-E	Cyprus	Abalone	*Haliotis tuberculata**	High market value, high survival in experiments	30

Sub-region	Country	Species group	Species	Reason	RC
		Clams	*Pinna nobilis*	Grow naturally in the area, large bivalve, high filtration rates	31
		Scallops	n/a	Grow naturally in the area	31
		Sea cucumbers	n/a	Grow well in muddy substrates	31
		Sea urchins	*Paracentrotus lividus**	High market value, high survival in experiments	30
	Israel	Green algae	*Ulva* sp.	Some previous success	39,69
		Clams	n/a	n/a	39
		Oysters	n/a	n/a	39
		Sea cucumbers	n/a	n/a	39
		Fish	*Mugil cephalus*	Feed on benthos, mitigation	69
S-W	France	Seaweeds	n/a	High potential, easy to cultivate and harvest	35
		Seaweeds	*Ulva* sp.	Rapid growth	43
		Oysters	n/a	n/a	43
		Sea cucumbers	n/a	n/a	43
	Portugal	Seaweeds	n/a	Cosmetic & biotechnology potential	3
		Seaweeds	*Laminaria ochroleuca*	Controlled cultivation methods, commercial value	20
	Spain	Red and green algae	n/a	n/a	55
		Seaweeds	*Saccharina latissima*	Useful and malleable species with medium-high commercial value, developed culturing technology, high growth - especially in Galicia	28,34
		Abalone	n/a	n/a	55
		Mussels	n/a	Good expertise north and south of Spain, very marketable	33,34,52
		Oysters	n/a	n/a	33
		Sea urchins	n/a	n/a	55

n/a - not applicable - information not provided by respondents

4. Discussion

4.1. Survey overview

This study aimed to gather information from people with known contribution in European IMTA research. The number of these people in Europe is limited. For the purposes of this survey (i.e. identify major impediments of European IMTA), the aim was to receive feedback only from those people with substantial experience and practical understanding on IMTA; thus increasing the reliability and validity of the responses. It is noteworthy that 32/34 of the respondents had at least one year of active involvement in the IMTA R&D. The respondents' list included pioneers with major contribution to the development of the European IMTA so far; such as people with leading roles/coordinators of important IMTA projects (e.g. IDREEM, GENESIS, SEABIOPLAS, IMTA-Effect etc.).

Although European IMTA is still in its infancy, it is believed to offer a great potential for the sustainability of the aquaculture industry (Granada et al., 2015) and this belief appears to be shared by the majority of our survey respondents. Respondents also mentioned several species that could be promising for IMTA in their region due to reasons such as high potential market value, high growth and survival observed in experimental studies, plentiful wild supply/available seed, expertise availability, and high mitigation capacity.

Nevertheless, IMTA uptake currently faces inherent bottlenecks which need to be tackled. Respondent 13 recorded: "*The concept of IMTA looks good on the paper, but it still has a lot (everything) to prove, especially in open cage aquaculture systems!*" It is interesting that a considerably high proportion of the respondents (21%) answered that there is no potential for IMTA in Europe. From those, one individual added that IMTA will not work in open waters (Respondent 67) while four other (Respondents 2, 18, 37 and 69) raised issues of economic feasibility, legislation and governmental support. Respondent 2 mentioned: *"Even though I think IMTA is the appropriate thing to do, I am not sure that the industry will ever be interested on it unless it becomes mandatory. And we are very far from that possibility."*

A large array of IMTA challenges / obstacle issues were mentioned which were categorised into a total of 9 broader subjects; namely i) Biological, ii) Environmental, iii) Interest, iv) Legislation, v) Market, vi) Operational, vii) R&D, viii) Conflicts, and ix) Vandalism. The issues varied among countries and sub-regions of Europe. For instance, market limitations were more prevalent in the N, N-W and S-W sub-regions, perhaps reflecting the prevailing yet infant seaweed industry or the generally more advanced level of IMTA in Northern and Western Europe. This is supported by the fact that commercial production IMTA extractive species was reported only in the aforementioned sub-regions.

On the contrary, S and S-E sub-regions still face basic production challenges (e.g. lack of available seed or unfavourable environmental conditions for potential IMTA species) which currently do not allow empirical IMTA market exploitation. Thus, market limitations could become an issue at a later time when successful control over the production processes is achieved. With the exception of Italy and a land-based closed system (Israel), all the respondents from the S and SE sub-regions (Cyprus, Greece, and Israel) reported the lowest level of development (1 out of 5) for their IMTA facilities compared to other regions. Moreover, respondents from S Europe, and mainly Italy, were found to be more concerned about the legislation bottlenecks that currently exist and particularly the lengthy and difficult procedures necessary to acquire permits for IMTA application.

The different levels of IMTA development recorded among the farmers / scientists from different sites and the different levels of impediments identified, imply that Europe should differentiate its IMTA strategies among different countries and regions based on the characteristics of each site.

4.2. Control over the production processes

A key driver for the expansion of aquaculture production is the ability to have control over the production processes since this allows the application of systematic research and development leading to innovations (Kumar and Engle, 2016; Asche, 2017). The responses raised several production issues that need to be overcome for IMTA to be implemented at a larger scale in Europe. These included issues such as lack of available species, inadequate infrastructure, configuration design and technology, and insufficient knowledge on species production and rearing processes

Lack of available seed was reported as a major obstacle from the respondents of the Mediterranean Sea, especially in the SE sub-region. This was also identified by the project REPROSEED (European FP7 programme), which in 2012 found that shellfish hatcheries existed only in nine European countries, all of which are located in North and Western Europe. Lack of available seed of promising local species can obscure the potential of IMTA in some areas, especially in the oligotrophic waters of the Mediterranean where it is inevitably challenging.

Operational issues adverted to the need for higher technology and better infrastructures were raised by many respondents of different regions. Specifically, the needs for development of more mechanised systems of production, which are less labour intensive, and viable systems for benthic IMTA species, which will ameliorate the seabed impacts of the fin-fish cultivation were emphasised. A respondent from Cyprus (RC 31) elaborated to the experiments with abalone (*H. tuberculata*) and sea urchins (*P. lividus*) that were growing in Ortac Oyster baskets and highlighted that biofouling maintenance and supplementary diet provision were very labour-demanding which questioned the sustainability of their system. Many other respondents raised issues of predation by turtles and marine mammals, or unfavourable weather conditions that lead to disaster indicating the need for a better system design that will eliminate the loses due to ecosystem interactions.

A respondent from UK (RC 67) mentioned that the IMTA development relies on deposit feeding organisms since "*dilution of relevant by-products (in the sea) means no growth enhancement apart from direct bottom coupling*". Currently there are no suitable systems for deposit feeders. For example, a recent study (Tolon et al., 2017) demonstrated that sea cucumbers (*H. tubulosa*) can successfully grow below finfish cages (*D. labrax* and *S. aurata*) and provide an additional income for the farmers. However, the authors mentioned that harvesting of the specimens in open net farms (as the system they used), requires excessive labour via scuba diving and handpicking of sea cucumbers at such depths, crops are subject to predators attacks, while they can also escape by climbing up or crumbling under the net walls. Nonetheless, Robinson et al., (2011) suggested that two dimensional bottom structures for co-cultured species are unlikely to be sufficient and three dimensional structures are necessary to provide additional space, improve food availability from settling particulate material and to increase available biomass. Thus, for IMTA to be efficient and successful, robust systems that can resist extreme weather conditions, allow easy maintenance, harvesting, provision of supplemented diets (if required), protection from predators, and utilization of three dimensional space should be developed.

In addition, several biological issues and concerns were raised by the respondents which should be improved in order for IMTA to become sustainable. Many responses indicate the need for R&D at a species individual level, in order to better understand their biology, nutrient uptakes, life cycles, and disease resistance and vulnerability. Overall, uncertainties about IMTA production exist among some farmers / scientists which are limiting IMTA adoption at larger scales. Respondent 37 commented that "*there is generally insufficient understanding of viable IMTA concepts in most people's mind-set (very few researchers & farmers have sufficient knowledge on how hydrodynamic conditions influence 'coupling / uncoupling' of trophic groups; and knowledge on basic requirements of seaweed / mussels".*

In line with issues raised in the literature (Chopin et al., 2012; Handå et al., 2013; Skjermo et al., 2014; Hughes et al., 2016) respondents also highlighted biological challenges that obscure the sustainability of

IMTA such as the need for expansion into a broader range of extractive species, development of mass hatchery productions, and optimization of IMTA extractive crop production throughout the year.

4.3. IMTA complexity and the need for a cross-industry contact

Despite the production issues that have been discussed, the fact that there is adequate knowledge to allow monoculture production of some "extractive" species in Europe, especially of bivalves, indicates that IMTA is also impeded by factors beyond availability of species, and sufficient available knowledge on species production / rearing and design processes. It is interesting that such factors (e.g. lack of species knowledge, expertise, and technology) were some of the most common issues raised by the farmers / scientists highlighting the additional layers of complexity of IMTA incorporation into the core business of a fish farm and the difficulty in meeting these new requirements. Many of the respondents mentioned issues of multi-operation complexity, or even that aquaculture farms cannot meet the labour requirements to successfully implement IMTA at a commercial scale or do not have adequate facilities or technologies for harvesting low-value products such as mussels and seaweeds. Similar limitations were observed in recent interviews conducted among seven SME partners of the IDREEM project (funded under the European FP7) in which experimental IMTA was implemented across six European countries (Cyprus, Ireland, Italy, Israel, Norway, and UK) (Alexander and Hughes, 2017). Limitations, such as the lack of processing and packing infrastructure within the company, and the lack of drying facilities for those who were dealing with algae production, were reported as major issues in IMTA experiments (Alexander and Hughes, 2017).

Drying of algae is considered to be one of the main bottlenecks in algae culture, and is used to decrease water content that retards microbial growth, and helps to conserve quality and reduce storage volume (Aziz et al., 2013; Alexander and Hughes, 2017). In other locations, post-harvest treatments such as seawater storage (Paull and Chen, 2008), cold storage (Liot et al., 1993) silage (Herrmann et al., 2015) and freezing (Choi et al., 2012) have been tried with satisfactory results, but such practices need to be further investigated. Respondent 2 from this study mentioned that "*harvesting seaweeds at a regular base was difficult as the boat with a crane was used very frequently for salmon farming purposes*". In order for the IMTA system to be efficient, it is important that it does not interfere with the production of other species in the system and that it is able to act independently. Therefore, the idea that boat equipment is already present on fish farms, thus lowering the IMTA start-up costs (Kerrigan and Suckling, 2016) might not always be true, at least for the species that require harvesting boats and mechanical tools, such as *L. digitata, L. hyperborea* and *S. latissima.* This is also the case for other equipment, such as moorings, buoys, rope lines, and baskets, which might have to be added, especially in cases where the extractive species need to be placed at some distance from the fish farm facilities.

All types of aquaculture (e.g. finfish, shellfish and seaweeds) are highly technical and skilled professions, and it is very challenging for small companies to encompass skills for all species (Alexander and Hughes, 2017). Buying expertise from another industry could be an option for larger enterprises, but for smaller or family operations such an approach might not be feasible. If knowledge for all species is not adequate, then IMTA applications will lead to learning by trial-and-error, similar to the approach followed in Asia, Canada and most experiments in the IDREEM project (Neori et al., 2004; Reid et al., 2011; Alexander and Hughes, 2017). However, such a learning approach can be very slow and site-specific. Some respondents from the survey mentioned that there should be a cross-industry contact between finfish and invertebrates cultivation (RCs 30 and 56). A similar strategy has been initiated in Canada with the development of a strategic network in 2010, named the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN), which aims to provide interdisciplinary research and development and highly qualified personnel training to more than 100 individuals in the areas of (1) ecological design, ecosystem interactions, and biomitigative efficiency; (2) system innovation and engineering; (3) economic viability and societal acceptance; and (4) regulatory science (Chopin et al., 2013). A network like this could also be promoted in Europe, in order to encourage the collaboration of farmers, scientists and stakeholders from multi-disciplinary backgrounds, to share and develop knowledge effectively, while at the same time acquire assistance when needed.

4.4. Economic feasibility

Limitations in IMTA practicality and system design, together with high labour requirements, can lead to decreased profitability (Yu et al., 2017). This is more the case for highly advanced industries, such as in Europe, where production is achieved with less human labour and thus less flexibility to deal with complexity (Hughes and Black, 2016). Moreover, in many European countries it is also very difficult to make a business case for lower value species production due to the high labour costs (Ferreira and Bricker, 2016). Europe still lacks a comprehensive economic analysis of IMTA based on empirical evidence and there is a need for a greater body of evidence on the financial benefits involved to make valid business plans that ensure IMTA profitability and compel individual farmers to adopt them.

Indeed, uncertainty about its profitability coupled with the lack of niche markets and supply chains were some of the most common IMTA challenges reported in this survey. Profitability is not only diminished by the high requirements in terms of labour and infrastructure of the system, but also by the lack of profitable species. In contrast to Asia, Europe produces only a limited number of extractive species and with less relative value compared to fin-fish value thus making the application of IMTA business case less attractive (FAO, 2012; Hughes and Black, 2016).

In addition, there is currently a lack of available markets for some promising extractive species. For example, seaweed and sea cucumber consumption is marginal in the European countries, while some species, such as sea cucumbers native to the Mediterranean, are not considered prime products for the Asian market which drives the global sea cucumber sales (Sicuro and Levine, 2011; Stévant et al., 2017). It is important for Europe to develop such niche food markets based on consumer insights, given that reliability and normalisation of production processes, as well as regulatory health safety frameworks (considering the tendency of extractive species to accumulate undesired compounds) are first established.

Production of some extractive species, such as seaweeds, faces heavy competition from Asian countries, although the latter was often criticized for its adverse environmental impacts (Van den Burg et al., 2013; Groenendijk et al., 2016). IMTA also faces competition with wild production and the production by European monoculture systems. For example, Respondent 74 from Italy reported that "*one of the major obstacles faced was the difficulty to produce a competitive product: oysters grew to a commercial size, although their weight was slightly lower than those produced in monoculture near France and there is a need for a strong marketing strategy to create a niche market for the product*". This highlights the general belief that IMTA products should be differentiated through traceability and ecolabelling / sustainability certificates that will provide an advantage to products derived from IMTA configurations (Chopin et al., 2012; Chopin, 2015), similar to the case of the niche market created for organic food items. Respondent 3 mentioned that "*without a polluter-pay policy it will be hard to justify the inherent cost with IMTA".*

There are a number of other areas which can contribute to economic feasibility, but improvements are still needed. These include: i) an integrated, sequential biorefinery approach, focusing on more sophisticated bio-based high valued products and complete utilization of biomass–with lower-value commodities, such as bioenergy compounds (Mazarrasa et al.,2014; Sarkar et al., 2017; Tabassum et al., 2017), (ii) selective breeding of crops to improve yields, general performance and quality, and increased environmental tolerance, to enable extension of the growth season and mariculture expansion of profitable species into new coastal regions (Ask and Azanza, 2002; Zhang et al., 2007; Stévant et al., 2017), and (iii) use of exotic profitable species under strict controlled conditions, ensuring that genetic swamping and biological pollution is avoided.

4.5. Legislation

Although production and market development are important for the successful uptake of IMTA technology, the regulatory system is equally important, and often receives less attention (Asche, 2017; Osmundsen et al., 2017). Issues related to the regulatory system and legislation were among the most-common IMTA challenges identified by the survey. The survey responses confirm some of the legislation barriers that have been discussed in-depth in the literature (Alexander et al., 2015; Freitas et al., 2016), and particularly the lack of licencing arrangements and dedicated aquaculture policy for IMTA, the exhausting bureaucracy that exists, with lengthy procedures for licencing the co-cultivation of multiple species in close proximity. For example, Respondent 73 (Italy) mentions that "*laws and bureaucrats are very confusing on the necessary steps to take and at least one year was required to start the accreditation process for the seawater classification, necessary to sell filter feeders*". Legislation which is too tight can prevent an industry from being competitive and economically sustainable (Abate et al., 2016) and in the case of IMTA, governments in Europe need to proceed to substantial regulatory reforms, especially on aspects relating to the transfer of disease, fish health, and food safety in order to foster and allow commercial expansion of IMTA (Alexander et al., 2015).

4.6. Financial support, public perception and interest from the industry

Other important obstacles to the wider adoption of IMTA identified by the survey were the lack of awareness, interest and investment by the aquaculture industry, lack of external financial support and a negative public perception on aquaculture.

Lack of financial support exists despite the fact that the majority of the respondents received funding for IMTA projects, while lack of interest and investment from the industry comes as no surprise, especially for small enterprises, given the high risk and complexity of IMTA. The lack of financial, governmental and industry support was reported as a major challenge to be overcome by a high number of respondents (12/34) (35%) which signifies a general consensus that although IMTA holds a great potential for

European aquaculture, its concept has not received adequate attention yet. Respondent 55 (Spain) mentioned that "*the situation is the contrary and scientists have to demonstrate the interest and disseminate the information to governments and funding institutions*".

Studies into the awareness and opinions of stakeholders are limited in Europe, where a recent study in six European countries indicated that more stakeholders were aware of IMTA than unaware, and that although stakeholders generally felt that IMTA could improve the image of the industry, many issues remain unexplored and unclarified (Alexander et al., 2016a). However, discrepancies can be found across European countries and this is indicated by Perdikaris et al., (2016) who surveyed 57 farms in Greece, and found that 70% of the producers were unfamiliar with the concept of IMTA.

With an exception of a report from France, public acceptance to aquaculture was reported as a major challenge to overcome from four respondents of Northern Europe (Denmark, Ireland and UK), perhaps reflecting the increased environmental sensitivity of the public in Northern and Western European countries compared to other European regions (Vanhonacker et al., 2013). Public acceptance issues raised among the respondents were related to the fact that the general public cannot differentiate monoculture from IMTA, and they usually associate IMTA with the negative perceptions surrounding carnivorous fin-fish production. For instance, although authorities in Denmark gave permission to increase fish mariculture production if the same amount of nutrients could be removed by harvesting mussels and seaweed, Respondent 16 mentions that *"the concept of compensating for an increase in fish production by producing and harvesting N and P in the form of mussels and seaweed has been accepted as a legitimate form of compensation, but there are several grass root and local organisations that make it difficult to get permission in the local areas".* Inevitably, perceptions can influence acceptance, investigation and implementation of aquaculture (Froehlich et al., 2017). A recent study on public perceptions using 2,520 web-based survey questionnaires across five European countries has shown that the majority of the general public were unware of IMTA, and once the concept was explained to the respondents, most were positive about the capacity of IMTA to improve overall sustainability (Alexander et al., 2016b). Therefore, it is imperative that strategies are developed in order to engage the general public, stakeholders and producers in the sustainability potential of the IMTA technology.

5. Conclusion

This study has assessed the current status of European marine-based IMTA and the major impediments to wider IMTA adoption by describing for the first time at such a large spatial coverage, the opinions of farmers and scientists with experience on IMTA. The findings of this study could help to focus future research and development of IMTA on tackling bottlenecks and exploring opportunities. It is well-recognised that IMTA provides an opportunity for the European aquaculture to increase economic and ecological sustainability, food security and resilience, and social acceptance. However, IMTA production faces inherent difficulties which reasonably limit its wider adoption across Europe. A high number of respondents believe that IMTA has not received adequate support from the governments, industry and funding agencies. For the European industry to embrace IMTA, substantial development in several topics is required. Limitations were found to vary among different areas and thus site-specific targeted approaches are necessary. IMTA in S and S-E Europe appear to be less developed while still facing basic production impediments such as the lack of available seed of promising local species. On the other hand, Northern and Western European countries have been able to commercially exploit a few IMTA species but with a questionable profitability. Valorisation and differentiation of IMTA products through traceability and ecolabelling could ensure the feasibility of IMTA and compel farmers towards its adoption. In general however, respondents believe that uptake of European IMTA is currently impeded by numerous other obstacles and challenges including *inter alia* legislation bottlenecks, general lack of R&D knowledge, IMTA complexity, biological issues such as the biofouling and seasonal production, lack of interest by the industry and funding agencies, negative public perceptions, and lack of cost-effective infrastructures and designs that can allow the successful incorporation of deposit feeding organisms into IMTA configurations. Therefore, the collaboration of people and stakeholders with multi-disciplinary backgrounds (i.e. biologists, economists, engineers, farm managers, modellers, regulators, stakeholders and statisticians) and the formation of cross-industry networks between producers of different species groups should be encouraged and promoted.

Acknowledgements

This work was undertaken as part of an MSc thesis in Sustainable Aquaculture at the University of St. Andrews. The authors are particularly grateful to Mr Jonah van Beijnen and the three anonymous reviewers for their constructive comments during the manuscript preparation. Also, the authors would like to express their deep appreciation to all the anonymous farmers and scientists who contributed and provided their valuable comments in this survey. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abate, T.G., Nielsen, R., et al., 2016. Stringency of environmental regulation and aquaculture growth: A cross-country analysis. Aquaculture Economics & Management, 20 (2), 201-221.

Alexander, K.A., Potts, T.P., et al., 2015. The implications of aquaculture policy and regulation for the development of integrated multi-trophic aquaculture in Europe. Aquaculture, 443, 16-23.

Alexander, K.A., Angel, D., et al., 2016a. Improving sustainability of aquaculture in Europe: stakeholder dialogues on Integrated Multi-trophic Aquaculture (IMTA). Environmental Science & Policy, 55, 96-106.

Alexander, K.A., Freeman, S., et al., 2016b. Navigating uncertain waters: European public perceptions of integrated multi trophic aquaculture (IMTA). Environmental Science & Policy, 61, 230-237.

Alexander, K.A., Hughes, A.D., 2017. A problem shared: Technology transfer and development in European integrated multi-trophic aquaculture (IMTA). Aquaculture, 473, 13-19.

Als-Nielsen, B., Chen, W., et al., 2003. Association of funding and conclusions in randomized drug trials: a reflection of treatment effect or adverse events?. Jama, 290 (7), 921-928.

Asche, F., 2017. New markets, new technologies and new opportunities in aquaculture. Aquaculture Economics & Management, 21 (1), 1-8.

Ask, E.I., and Azanza, R.V., 2002. Advances in cultivation technology of commercial eucheumatoid species: a review with suggestions for future research. Aquaculture, 206 (3), 257-277.

Aziz, M., Oda, T., et al., 2013. Enhanced high energy efficient steam drying of algae. Applied energy, 109, 163-170.

Barrington, K., Chopin, T., et al., 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In: Soto, D.(Ed.), Integrated Mariculture: A Global Review. FAO Fisheries and Aquaculture Technical Paper 529, Rome, pp. 7-46.

Byggeth, S., Hochschorner, E., 2006. Handling trade-offs in ecodesign tools for sustainable product development and procurement. Journal of Cleaner Production, 14 (15), 1420-1430.

Casalduero, F.G., 1999. Integrated systems: "Environmentally clean" aquaculture. In: Environmental impact assessment of Mediterranean aquaculture farms (eds. A. Uriarte and B. Basurco). CIHEAM, Zaragoza, pp. 139-145.

Chan, A.W., Altman, D.G., 2005. Identifying outcome reporting bias in randomised trials on PubMed: review of publications and survey of authors. bmj, 330 (7494), 753.

Choi, J.S., Lee, B.B., et al., 2012. Simple freezing and thawing protocol for long-term storage of harvested fresh *Undaria pinnatifida*. Fisheries science, 78 (5), 1117-1123.

Chopin, T., 2012. Aquaculture Aquaculture, Integrated Multi-trophic (IMTA) aquaculture integrated multi-trophic (IMTA). In Encyclopedia of Sustainability Science and Technology (pp. 542-564). Springer New York.

Chopin, T., Cooper, J.A., et al., 2012. Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Reviews in Aquaculture, 4 (4), 209-220.

Chopin, T., MacDonald, B., et al., 2013. The Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN)—a network for a new ERA of ecosystem responsible aquaculture. Fisheries, 38 (7), 297-308.

Chopin, T. (2015). Marine aquaculture in Canada: well-established monocultures of finfish and shellfish and an emerging Integrated Multi-Trophic Aquaculture (IMTA) approach including seaweeds, other invertebrates, and microbial communities. Fisheries, 40 (1), 28-31.

Da Silveira, G., Slack, N., 2001. Exploring the trade-off concept. International Journal of Operations & Production Management, 21 (7), 949-964.

FAO (2012). The State of World Fisheries and Aquaculture. Food and Agriculture Organization of the United Nations, Rome. 209 pp.

Ferreira, J.G., Bricker, S.B., 2016. Goods and services of extensive aquaculture: shellfish culture and nutrient trading. Aquaculture International, 24 (3), 803-825.

Frei, F.X., 2006. Breaking the trade-off between efficiency and service. Harvard business review, 84 (11), pp. 92.

Freitas Jr, J.R., Morrondo, J.M.S., et al., 2016. *Saccharina latissima* (Laminariales, Ochrophyta) farming in an industrial IMTA system in Galicia (Spain). Journal of applied phycology, 28 (1), 377-385.

Froehlich, H.E., Gentry, R.R., et al., 2017. Public Perceptions of Aquaculture: Evaluating Spatiotemporal Patterns of Sentiment around the World. PloS one, 12 (1), e0169281.

Granada, L., Sousa, N., et al., 2015. Is integrated multitrophic aquaculture the solution to the sectors' major challenges?–a review. Reviews in Aquaculture. 6, 1-18.

Groenendijk, F. C., Bikker, P., et al., 2016. North-Sea-Weed-Chain: sustainable seaweed from the North Sea; an exploration of the value chain (No. C055/16). IMARES.

Handå, A., Forbord, S., et al., 2013. Seasonal-and depth-dependent growth of cultivated kelp (*Saccharina latissima*) in close proximity to salmon (Salmo salar) aquaculture in Norway. Aquaculture, 414, 191-201.

Herrmann, C., FitzGerald, J., et al., 2015. Ensiling of seaweed for a seaweed biofuel industry. Bioresource technology, 196, 301-313.

Hughes, A.D., Black, K.D., 2016. Going beyond the search for solutions: understanding trade-offs in European integrated multi-trophic aquaculture development. Aquaculture Environment Interactions, 8, 191-199.

Hughes, A.D., Corner, R.A., et al., 2016. IDREEM Final Report. Beyond Fish Monoculture. Developing Integrated Multi-trophic Aquaculture in Europe. *IDREEM project - EU Seventh Framework Programme.* http://www.idreem.eu/cms/wp-content/uploads/2016/09/IDREEM_FINALREPORT_2109.pdf (accessed 18.05.2017)

Ioannidis, J.P., 2005. Why most published research findings are false. PLos med, 2 (8), e124.

Kerrigan, D., Suckling, C.C., 2016. A meta-analysis of integrated multitrophic aquaculture: extractive species growth is most successful within close proximity to open-water fish farms. Reviews in Aquaculture. doi:10.1111/raq.12186.

Kumar, G., Engle, C.R., 2016. Technological advances that led to growth of shrimp, salmon, and tilapia farming. Reviews in Fisheries Science & Aquaculture, 24 (2), 136-152.

Lane, A., Hough, C., et al., 2014. The long-term economic and ecologic impact of larger sustainable aquaculture. Study for the European Parliament, Directorate General for Internal Policies, Policy Department B, Structural and Cohesion Policies—Fisheries. http://www.europarl.europa.eu/RegData/etudes/STUD/2014/529084/IPOL_STU(2014)529084_EN.pdf (accessed 13.05.17).

Lee, C.J., Sugimoto, C.R., et al., 2013. Bias in peer review. Journal of the American Society for Information Science and Technology, 64 (1), 2-17.

Liot, F., Colin, A., et al., 1993. Microbiology and storage life of fresh edible seaweeds. Journal of applied phycology, 5 (2), 243-247.

Mazarrasa, I., Olsen, Y.S., et al., 2014. Global unbalance in seaweed production, research effort and biotechnology markets. Biotechnology advances, 32 (5), 1028-1036.

Neori, A., Shpigel, M., et al., 2000. A sustainable integrated system for culture of fish, seaweed and abalone. Aquaculture, 186(3-4), 279-291.

Neori, A., Chopin, T., et al., 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture, 231 (1), 361-391.

OECD, 2010. Proceedings of the workshop on advancing the aquaculture agenda: policies to ensure a sustainable aquaculture sector. OECD Conference, Paris, 15–16 April 2010. OECD Publishing, Paris.

Osmundsen, T.C., Almklov, P., et al., 2017. Fish farmers and regulators coping with the wickedness of aquaculture. Aquaculture Economics & Management, 1-21.

Paull, R.E., Chen, N.J., et al., 2008. Postharvest handling and storage of the edible red seaweed Gracilaria. Postharvest biology and technology, 48 (2), 302-308.

Perdikaris, C., Chrysafi, A., et al., 2016. Environmentally Friendly Practices and Perceptions in Aquaculture: A Sectoral Case-study from a Mediterranean-based Industry. Reviews in Fisheries Science & Aquaculture, 24 (2), 113-125.

Reid, G.K., Haigh, S., et al., 2011. Hydrodynamic Considerations for Spatial Modelling of Integrated Multi-Trophic Aquaculture (IMTA). Bull. Aquacul. Assoc. Canada, 109 (2), pp. 31.

Robinson, S. M. C., Martin, J. D., et al., 2011. The role of three dimensional habitats in the establishment of integrated multi-trophic aquaculture (IMTA) systems. Bulletin of the Aquaculture Association of Canada, 109 (2), 23-29.

Ryther, J.H., Dunstan, W.M., et al., 1972. Controlled eutrophication—increasing food production from the sea by recycling human wastes. Bioscience, 22 (3), 144-152.

Ryther, J. H., Goldman, J. C., et al., 1975. Physical models of integrated waste recycling-marine polyculture systems. Aquaculture, 5 (2), 163-177.

Sarkar, M. S. I., Kamal, M., et al., 2017. Manufacture of different value added seaweed products and their acceptance to consumers. Asian Journal of Medical and Biological Research, 2 (4), 639-645.

Schmidt, G., Espinos, F., et al., 2011. Diversification in Aquaculture: A Tool for Sustainability. Madrid: Spanish Ministry of Environmental, Rural and Marine Affairs, Publications Centre. http://www.mapama.gob.es/app/jacumar/recursos_informacion/Documentos/Publicaciones/270_guia_diversificacion_en.pdf (accessed 13/05/17).

Sicuro, B., Levine, J., et al., 2011. Sea cucumber in the Mediterranean: a potential species for aquaculture in the Mediterranean. Reviews in Fisheries Science, 19 (3), 299-304.

Skjermo, J., Aasen, I.M., et al., 2014. A new Norwegian bioeconomy based on cultivation and processing of seaweeds: Opportunities and R&D needs. SINTEF Fisheries and Aquaculture. Report No SINTEF A25981. ISBN 978-82-14-05712-6.

Sorgeloos, P., Olsen, Y., et al., 2011. Integrated Multi-Trophic Aquaculture In Coastal Bays In China: A Potential Model For Application In European Seas?. Proceedings of the European Aquaculture Society, Rhodes, Greece, 18-21 October 2011, 2011-10-18/2011-10-21.

Stévant, P., Rebours, C., et al., 2017. Seaweed aquaculture in Norway: recent industrial developments and future perspectives. Aquaculture International, 1-18. doi:10.1007/s10499-017-0120-7.

Tabassum, M.R., Xia, A., et al., 2017. Potential of seaweed as a feedstock for renewable gaseous fuel production in Ireland. Renewable and Sustainable Energy Reviews, 68, 136-146.

Tolon, M. T., Emiroglu, D., et al., 2017. Sea cucumber (*Holothuria tubulosa* Gmelin, 1790) culture under marine fish net cages for potential use in integrated multi-trophic aquaculture (IMTA). Indian Journal of Geo Marine Sciences, 46 (4), 749-756.

Troell, M., Halling, C., et al., 2003. Integrated mariculture: asking the right questions. Aquaculture, 226 (1-4), 69-90.

Van den Burg, S.W.K., Stuiver, M., et al., 2013. A Triple P review of the feasibility of sustainable offshore seaweed production in the North Sea (No. 13-077). Wageningen UR.

Vanhonacker, F., Pieniak, Z., et al., 2013. European consumer image of farmed fish, wild fish, seabass and seabream. Aquaculture international, 21(5), 1017-1033.

Wartenberg, R., Feng, L., et al., 2017. The impacts of suspended mariculture on coastal zones in China and the scope for Integrated Multi-Trophic Aquaculture. Ecosystem Health and Sustainability, 3 (6), 1340268.

Yu, L.Q.J., Mu, Y., et al., 2017. Economic challenges to the generalization of integrated multi-trophic aquaculture: An empirical comparative study on kelp monoculture and kelp-mollusk polyculture in Weihai, China. Aquaculture, 471, 130-139.

Zhang, Q.S., Tang, X.X., et al., 2007. Breeding of an elite *Laminaria* variety 90-1 through inter-specific gametophyte crossing. Journal of Applied Phycology, 19 (4), 303-311.

Zhang, J., Hansen, P.K., et al., 2009. Assessment of the local environmental impact of intensive marine shellfish and seaweed farming—Application of the MOM system in the Sungo Bay, China. Aquaculture, 287(3-4), 304-310.*2*

Appendix 1: Short questionnaire for IMTA UNITS

Part 1. Personal information

1) **Name of the respondent**:
2) **Company of the respondent & IMTA facilities**:
3) **Location (city and country or latitude/longitude)**:
4) **Role in the IMTA experiments/farming (e.g. system design, farming, bioremediation assessment, species research, modelling, literature review, etc.):**
5) **Number of months/years of involvement in IMTA experiments/farming:**

Part 2. Production

1. Which were the exogenously fed species of the IMTA system? e.g. (i) 500 tons/year *Dicentrarchus labrax,* (ii) 500 tons/year *Sparus aurata*

(i)
(ii)
(iii)

2. Which were the secondary-extractive species that were co-cultured and using what technique? Please state if experimentally or commercially.

If commercially please specify the annual quantity produced and year of first commercial production. (e.g. (i) *Paracentrotus lividus* in land-based tanks – experimentally*, (ii) Mytilus galloprovincialis* in longlines, commercially 50 tonnes/year, 2013).

(i)
(ii)
(iii)

3. What were the main reasons of your IMTA practices (e.g. experiment for species selection, suitability, mitigation, enhanced production etc.)? Please list your points in a priority sequence – most important first and least important last.

(i)
(ii)
(iii)

4. Did you receive any financial aid from funding schemes / instruments for your IMTA experiments/efforts (e.g. EU Research and Innovation Programme FP7, Horizon 2020 etc.). If so, please specify which instrument and if it partially or fully-funded your efforts. If not, please leave empty.

(i) **(ii)**

5. What are the major bottlenecks/obstacles you faced in your experience with IMTA? e.g. Inadequate technology, expertise, lack of available seeds, native species, profitability, legislation barriers etc. Please list your points in a priority sequence – most important bottleneck/obstacle first and least important last.

(i) **(ii)** **(iii)**

6. Do you receive or are there any other incentives that promote IMTA aquaculture production in your country? e.g. sustainability certificates. – If so, please name them. If not please leave empty.

(i) **(ii)** **(iii)**

Part 3. Perceptions

1. Do you think IMTA practice holds a great position to the future of European sustainable aquaculture? (Please tick the box next to the chose answer)

Yes ☐ **No ☐**

2. How well-developed do you think is your IMTA system compared to other IMTA production systems/sites (Please use a scale from 1 to 5 where 1 means not developed and 5 means very well-developed)?

☐1 ☐2 ☐3 ☐4 ☐5

3. How well-developed do you think is IMTA in Europe compared to other regions (Please use a scale from 1 to 5 where 1 means not developed and 5 means very well-developed)?

☐1 ☐2 ☐3 ☐4 ☐5

4. In your opinion, what are the major challenges that need to be overcome for IMTA to be widely adopted in your country/region?

(i) **(ii)** **(iii)**

5. Which species do you think has the highest potential for the marine IMTA in your country/region? Please briefly support your choices.

(i) **(ii)** **(iii)**

6. In your opinion, what are the major factors influencing the success of the IMTA at a site (species availability, market, biosecurity, legislation bottleneck, expertise etc.) - Please list your points in a priority sequence

(i) **(ii)** **(iii)**

Highlights

1. The main European IMTA challenges based on the experiences and perspectives of scientists and farmers are described for the first time over such a large spatial coverage.

2. This study is valuable to European researchers, producers and policy makers as the current status of European IMTA is elaborated and new IMTA issues across different countries and seas of Europe are identified.

3. This survey can inform and recommend areas of future research and development to facilitate the uptake of IMTA by the European aquaculture industry.