Investigating the need for environmental risk assessment of chemical crop protection practices in seaweed

Bas Buddendorf, Mechteld ter Horst, Ivo Roessink

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Seaweed has the potential to deliver more food to an increasing world population. Diseases endanger production security and yield of any farm, seaweed farming is no exception, hence crop protection plans may be developed that include the use of chemical crop protection either directly or indirectly in co-cropping systems. This document reports a first attempt to map the extent to which chemicals are being used in seaweed production, which production systems are used, where potential risks of the use of chemicals resulting from protection of seaweed production (or co-produced products) against diseases can be anticipated, and how this could be taken into account for future work. The investigations concerning open sea production systems indicate that for the control of pests and diseases in the described cultivation systems only prevention, monitoring and mechanical/physical measures are common, at least for Indonesia. In contrast, results from closed pond- or tank-based multi-trophic systems where seaweed can be included for example as feed or filter, or for biomass production, indicate some reasons for concern. Uptake and sorption of veterinary medicinal products and other chemicals can lead to additional input to shrimp and/or fish (via feed) or to the environment (via disposal of filter material). The ERA-AQUA model, originally developed for risk assessment of aquaculture production of fish and shrimp, was identified as possible means to further explore the fate of chemicals used in land-based multi-trophic production systems, for their bioaccumulation and biomagnification potential and possible risk for the environment, the produced goods (fish/shrimp), and finally human health.

Keywords: environmental risk assessment, seaweed, chemical crop protection, multi-trophic system, shrimp, pond aquaculture, ERA-AQUA

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Preface

Ending food shortages is an important aim of the Sustainable Development Goal 2 of the United Nations. It aims to make sufficient and nutritious food available to everyone by 2030. In pursuit of this goal, to date, the world's marine environments are utilised only to a limited extent. The overarching aim of this 'Knowledge Base' (KennisBasis) project is the development of interdisciplinary skills and knowledge to benefit the sustainable production of high-value produce and raw materials from the marine environment, thus contributing to food security globally. Here, aquaculture systems with primary producers like seaweed and micro-algae, potentially as part of multi-trophic systems that include, for example, fish or shrimp will have a prominent role in this project.

This report has been produced with input from colleagues at WENR: Mechteld ter Horst for section 2; Bas Buddendorf for sections 1,3, and 4; Ivo Roessink for contributions to sections 1 and 4 and discussions. Special thanks to Andreas Focks (Osnabrück University, formerly WENR) for vital discussions and inputs at the early stages of this work.

This report focusses strictly on environmental risk related aspects of seaweed aquaculture. Further details about the Aquatic systems project (running from 2019 – 2022) can be found on the project webpage: https://research.wur.nl/en/projects/aquatic-systems-kb-35-004-001, and in Debrot (2020).

Summary

This document reports a first attempt to approach the question in how far chemicals are being used for seaweed production, which production systems are used, where potential risks of the use of chemicals resulting from protection of seaweed production (or co-produced products) against pests and diseases can be anticipated, and how this could be taken into account for future work. Two main cropping systems are investigated. Firstly, open sea seaweed farming is discussed, using seaweed farming in Indonesia, a major seaweed producing country, as an example. Secondly, on-land tank/pond systems are addressed. Pond systems are used for the production of, for example, fish and shrimp, either in mono-culture or in multi-trophic co-cropping systems.

With respect to open sea seaweed cultivation we conclude that for the control of pests and diseases in the described cultivation systems only prevention, monitoring and mechanical/physical measures are common in Indonesia. Risks for the marine environment are not expected from treatments with chemical pest control products or biological pest control agents as there are no signs these kinds of products are authorised and used in seaweed cultivation in open sea. This does not mean that there is no potential for environmental risk to the marine environment but this risk is predominantly a result of large scale commercial seaweed farming (e.g., introduction of alien species, marine pollution).

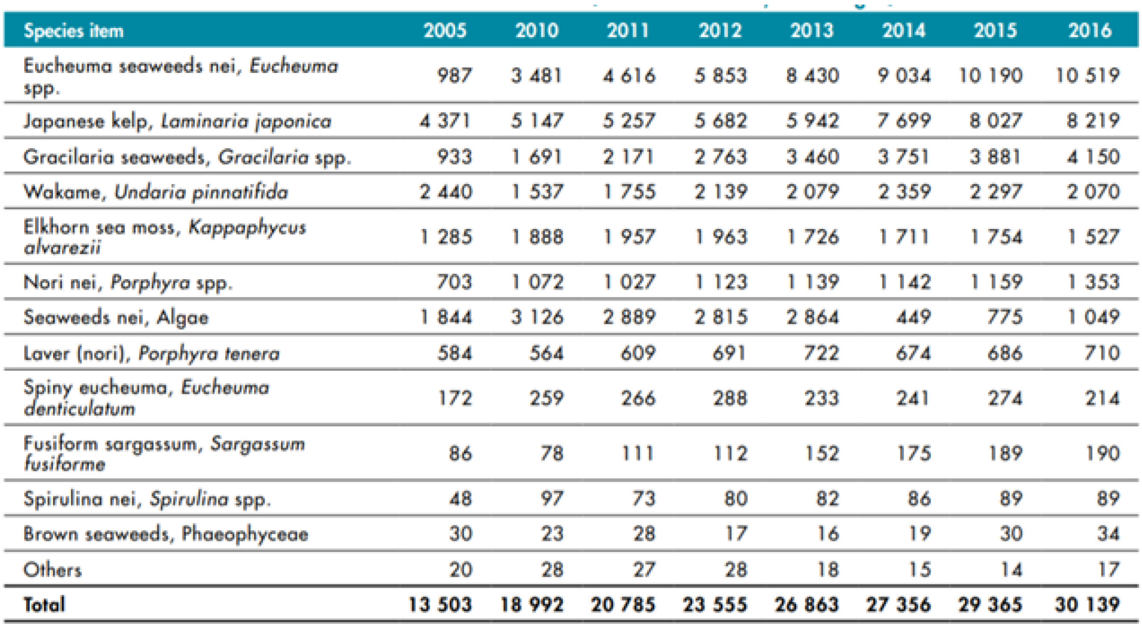
There are expected benefits of using seaweed as part of multi-trophic pond/tank production systems, like increased water quality, diversification of produced goods, and reduced need for feed. However, there remain potential risks to human health and the environment from the use of chemicals (like veterinary medicinal products (VMPs) and/or pesticides) in pond aquaculture. The current available data to assess the hazard of for example pesticides in seaweed is very limited, and monitoring data is not readily available. It remains unclear how integrated multi-trophic systems compare with traditional monoculture pond systems, and adding seaweed to pond systems to act as biofilters may involve a risk of bioaccumulation of pesticides and/or VMPs. An existing model (ERA-AQUA, https://www.era-aqua.wur.nl/) can be used to assess the risk for four endpoints: 1) the targeted produce; 2) aquatic ecosystems receiving aquaculture effluents; 3) consumers; and 4) the trade of harvested aquatic animals. It appears conceptually possible to include a seaweed compartment into the ERA-AQUA model. With such an addition, it can be used in the risk assessment of integrated multi-trophic aquaculture systems. Given the expected increase in the number of these systems, it would seem a good opportunity for development and further research.

1 Introduction

Seaweed has been harvested globally as direct food source, as staple ingredient in our food and to produce derivative chemicals that can be used for various industrial, pharmaceutical or food products, with carrageenan and agar as the major derivative products. Seaweed production is seen as one particularly interesting method for biomass production, having its anticipated role especially for green energy and for protein from sea programs. As such, seaweed has the potential to deliver more food to an increasing world population. The most widely cultivated seaweed species include *Eucheuma* spp., *Saccharina japonica (*Japanese kelp), *Gracilaria* spp., *Undaria pinnatifida* (wakame) and *Kappaphycus alvarezii* (elkhorn sea moss) (Table 1). Tropical seaweed species, like e.g., *K. alvarezii* and *Eucheuma* spp. are used as raw material for carrageenan extraction. Some species (e.g. *U. pinnatifida*, *Porphyra* spp. and *Caulerpa* spp., produced in East and Southeast Asia) are produced almost exclusively for direct human consumption, although low-grade products and scraps from processing factories are used for other purposes, including feed for abalone culture (FAO, 2018). The red algae *Gracilaria* contributes approximately 66% of the total agar production (Pereira and Yarish, 2008), but is also used for human consumption. *S. japonica* is a temperate cold water species mostly cultivated in the western Pacific (China, Japan, the Republic of Korea and the Democratic People's Republic of Korea) with China being the largest producer by far. *S. japonica* is popular as "kombu" in Japanese cuisine. *Pyropia* and *Porphyra* species is used to make Nori to wrap sushi. Other species like *Spirulina* spp. (cyanobacteria) and the micro-algae *Chlorella* spp. (a freshwater species), *Haematococcus pluvialis,* and *Nannochloropsis* spp. are cultivated in many countries for the production of human nutrition supplements and other uses (FAO, 2018).

After China, Indonesia is the second biggest seaweed producer in the world, contributing to 38% of the global seaweed market. Indonesia is currently the world's largest producer of agar- and carrageenan-bearing seaweeds, accounting for 61 percent of world production in 2010. *Kappaphycus* and *Eucheuma* are the main cultivated species in Indonesia (Valderrama *et al.*, 2013). Almost all of the Indonesian islands are currently planted with different strains or varieties of either *Kappaphycus* and *Eucheuma* using fixed-off bottom, hanging long-line and various raft methods, involving tens of thousands of coastal families (Neish 2013; Hurtado *et al.,* 2014). Indonesia is also a major center for the production of *Gracilaria* (agarophytes) (Hurtado *et al.,* 2014).

Table 1 *World aquaculture production of aquatic plants (thousand tonnes, live weight).*



Species item	2005	2010	2011	2012	2013	2014	2015	2016
Eucheuma seaweeds nei, *Eucheuma* spp.	987	3 481	4 616	5 853	8 430	9 034	10 190	10 519
Japanese kelp, *Laminaria japonica*	4 371	5 147	5 257	5 682	5 942	7 699	8 027	8 219
Gracilaria seaweeds, *Gracilaria* spp.	933	1 691	2 171	2 763	3 460	3 751	3 881	4 150
Wakame, *Undaria pinnatifida*	2 440	1 537	1 755	2 139	2 079	2 359	2 297	2 070
Elkhorn sea moss, *Kappaphycus alvarezii*	1 285	1 888	1 957	1 963	1 726	1 711	1 754	1 527
Nori nei, *Porphyra* spp.	703	1 072	1 027	1 123	1 139	1 142	1 159	1 353
Seaweeds nei, Algae	1 844	3 126	2 889	2 815	2 864	449	775	1 049
Laver (nori), *Porphyra tenera*	584	564	609	691	722	674	686	710
Spiny eucheuma, *Eucheuma denticulatum*	172	259	266	288	233	241	274	214
Fusiform sargassum, *Sargassum fusiforme*	86	78	111	112	152	175	189	190
Spirulina nei, *Spirulina* spp.	48	97	73	80	82	86	89	89
Brown seaweeds, Phaeophyceae	30	23	28	17	16	19	30	34
Others	20	28	27	28	18	15	14	17
Total	**13 503**	**18 992**	**20 785**	**23 555**	**26 863**	**27 356**	**29 365**	**30 139**

Source: FAO (2018). Note that Laminaria japonica, used by the FAO, is an unaccepted synonym for Saccharina japonica.

Like with any other form of mass-cultivation, also seaweed production systems are susceptible to diseases and pests. Both endanger production security and yield of any farm, seaweed farming is no exception, hence seaweed producers might develop crop protection plans that may include the use of chemical crop protection either directly or indirectly in co-cropping systems.

Two main cropping systems are investigated. Firstly, open sea seaweed farming is discussed, using seaweed farming in Indonesia, a major seaweed producing country, as an example. Here challenges in pest control are related to the scale of operation of a seaweed farm and to working in an open system where pest species may enter the cropped area unhindered. Secondly, on-land pond systems are addressed. Pond systems are used for the production of, for example, fish and shrimp, either in mono-culture or in multi-trophic co-cropping systems. Here, challenges are related to direct or indirect exposure of seaweed via pest control that may be intended for other species in the system (e.g., against white spot syndrome in shrimp).

2 Environmental risks of chemical crop protection practices in seaweed cultivation in open sea

2.1 Seaweed farming in open sea in Indonesia

Eucheuma and *Kappaphycus,* the most cultivated species in Indonesia, are generally grown within coastal areas, submerged in water near the surface for photosynthesis (although these seaweeds can be placed in deeper waters, as long as water is clear), thriving in fast moving waters, but without too much wave action (Waters et al, 2019).

Eucheuma and *Kappaphycus* seaweeds are generally farmed in two ways in Indonesia: 1) the off-bottom line method, which generally occurs in shallow waters or 2) the floating long-line method, which is suitable for areas where the currents are weak or the ocean is too deep for the off-bottom line method (Figure 1).

With the floating long-line method the lines are anchored in the seabed and seaweed is hung from ropes that are suspended by floaters. The off-bottom line method is constructed as follows: i) wooden stakes are driven into the seabed at a 5 to 10 meter spacing, ii) monofilament nylon or polypropylene ropes are attached and suspended between the stakes. The line sits 20 to 30 centimetres above the seafloor, the water needs to be deep enough to ensure that the seaweeds are not exposed during low tide.

In both methods, small fragments of seaweed, either cuttings from existing lines, a seed nursery, and/or purchased seed, are tied to the lines. Under proper growth and maintenance conditions, the seaweeds reach 10 times their original size after 6 to 8 weeks, through either method of farming (McHugh, 2003).

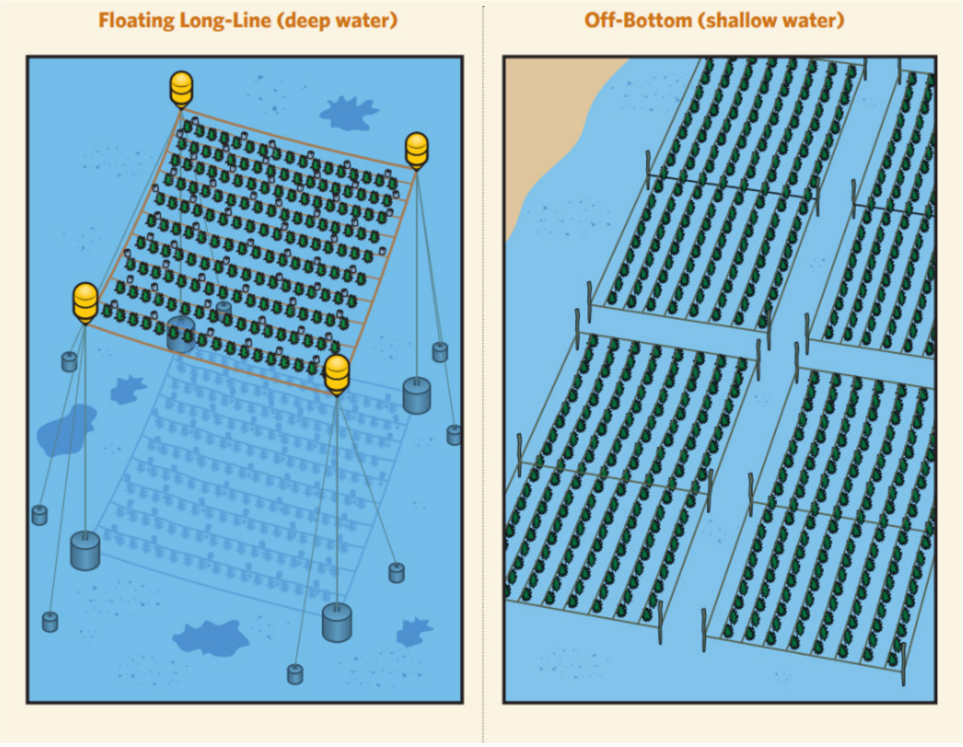


Figure 1 *Floating long-line method (left hand side) and the off-bottom line method (right hand side). Source: Waters et al., (2019).*

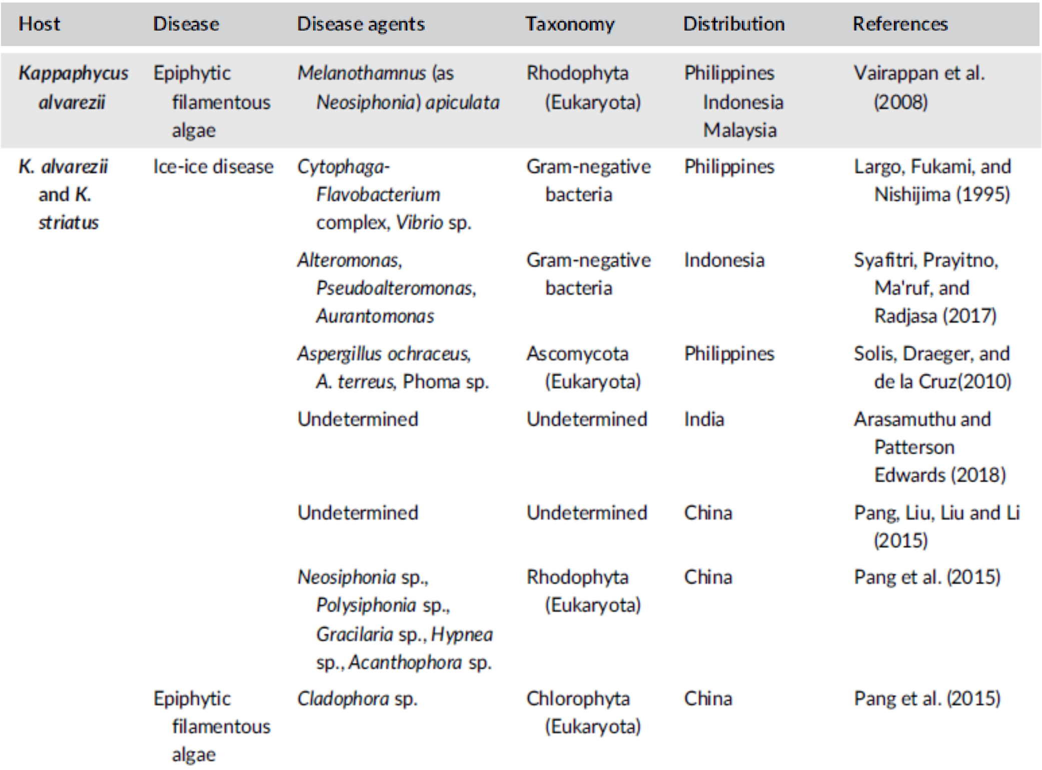
2.2 Pests/ diseases and corresponding control measures

Occurrence of pests and diseases are observed internationally in seaweed aquaculture (Watkiss *et al.,* 2012; Hurtado *et al.,* 2017; Quiaoit *et al.,* 2018). Ward *et al.,* (2019) provide a review of diseases that have been reported in the scientific literature for species of red (e.g. *Eucheuma*, *Gracilaria, Kappaphycus*) and brown seaweeds (e.g. Japanese kelp), focusing on the major seaweed crops grown in Asia. Table 2 shows the most common diseases and disease agents of *Kappaphycus* in Asia. Most relevant disease affecting *Kappaphycus* and *Eucheuma* spp. is ice-ice disease. It is characterized by a whitening of the thallus in response to environmental stress and the action of opportunistic pathogenic bacteria (Ward *et al.*,2019). Table 2 shows that several bacterial species and complexes have been linked to ice–ice disease, but also marine fungi (*Aspergillus* spp. and *Phoma* spp.) may induce ice–ice symptoms (demonstrated in both *Kappaphycus alvarezii* and *K. striatum* under laboratory conditions by Solis *et al.*, 2010).

Another major problem affecting the yields and quality of commercial cultivated seaweed is epiphytism. Marine epiphytes may, for example, be other unwanted algal species, bacteria, and fungi. Almost all marine epiphytes attract many grazers that feed on them and on the host leading to additional yield reduction (Ingle *et al.*, 2018). Different environmental conditions like the temperature, salinity, and current of seawater and intensity of light and nutrient availability may be important contributors to epiphytism.

One of the main problems of commercially cultivated *Kappaphycus* and *Eucheuma* spp. in Southeast Asia are epiphytic filamentous algae which are responsible for a significant decrease in both the production of biomass and carrageenan quality (Ward *et al.*,2019). Heavy infections with epiphytic algae have also shown to weaken *Kappaphycu*s and *Eucheuma*, making it susceptible to bacterial attack (Vairappan *et al.*, 2008).

Table 2 *Diseases and disease agents of Kappaphycus in Asia. Source: Table 2 in Ward et al., 2019.*



Host	Disease	Disease agents	Taxonomy	Distribution	References
Kappaphycus alvarezii	Epiphytic filamentous algae	*Melanothamnus* (as *Neosiphonia*) *apiculata*	Rhodophyta (Eukaryota)	Philippines Indonesia Malaysia	Vairappan et al. (2008)
K. alvarezii* and *K. striatus	Ice-ice disease	*Cytophaga-Flavobacterium* complex, *Vibrio* sp.	Gram-negative bacteria	Philippines	Largo, Fukami, and Nishijima (1995)
		Alteromonas, Pseudoalteromonas, Aurantomonas	Gram-negative bacteria	Indonesia	Syafitri, Prayitno, Ma'ruf, and Radjasa (2017)
		Aspergillus ochraceus, A. terreus, Phoma sp.	Ascomycota (Eukaryota)	Philippines	Solis, Draeger, and de la Cruz(2010)
		Undetermined	Undetermined	India	Arasamuthu and Patterson Edwards (2018)
		Undetermined	Undetermined	China	Pang, Liu, Liu and Li (2015)
		Neosiphonia sp., *Polysiphonia* sp., *Gracilaria* sp., *Hypnea* sp., *Acanthophora* sp.	Rhodophyta (Eukaryota)	China	Pang et al. (2015)
	Epiphytic filamentous algae	*Cladophora* sp.	Chlorophyta (Eukaryota)	China	Pang et al. (2015)

Several control and mitigation measures have been used to put an end to, or mitigate the impact and spread of disease and pest outbreaks on commercially cultivated seaweed. Lately, analogous to

Integrated Pest Management (IPM) in terrestrial agriculture, Marine Integrated Pest Management has been advocated (MIPM; Ingle *et al.*, 2018). Basically, pest management is done along the lines and in the order of prevention, monitoring in order to make decisions on control and direct measures. Direct measures can be mechanistically/physically or biologically, with chemical control as a last resort.

Prevention measures like optimal sites in terms of physical, geographic, and pollution parameters for seaweed farming, selection of suitable seaweed species and using healthy seedlings are common practice. The current technique for decreasing the impact of pest epiphytes is to monitor cultivated populations and remove the pests by hand as quickly as possible before they can reproduce and spread (Ward *et al.*,2019). The following quote on current practices for the control of ice-ice disease is taken from Ward *et al.,* (2019): "The development of ice–ice symptoms in *Kappaphycus* and *Eucheuma* is thought to be the result of stress to the host from abiotic conditions, such as temperature and salinity (Vairappan *et al.*, 2008) and light intensity and water movement (Hurtado & Critchley, 2006) in combination with the action of opportunistic bacteria (Largo *et al.*, 1995; Uyenco *et al.*, 1981). The triggers behind disease onset and progression are not well understood, and as a result, no effective management protocols that are cost effective have been developed to date."

No findings on the use of biological pest control agents or chemical pest control in seaweed cultivation in open sea, other than the use of organic acids or acid ionic(electrolysed) water were found in literature. This is in line with Ingle *et al.,* (2018) who state that there is a lack of commercially available pesticides that can be used in the seaweed cultivation, particularly in the near shore or offshore environments. In the Republic of Korea there are no authorizations for the use of chemical pesticides in seaweed cultivation (personal communication Jina Oh, NAS-RDA). Use of such products in seaweed cultivation is therefore forbidden. Illegal uses can however not be excluded. In the Republic of Korea, there was a case in which the use of pesticides for laver (*Porphyra* spp.) farming was discovered (personal communication Jina Oh NAS-RDA).

Ingle *et al.,* (2018) also state that, at low levels, some chemicals such as copper can be applied for the onshore cultivation or nursery level for control of certain epiphytes.

As mentioned before disinfection with acids baths occurs commonly. The washing of *Pyropia* blades in acid solutions is a widespread practice in the Republic of Korea and is often used in an attempt to control all diseases, albeit ineffective for some diseases like *Olpidiopsis* (Kim *et al.*, 2014). A common method used to disinfect seaweed cultivated in open sea is to pull the seaweed nets onto a box-shaped ship carrying containers that store a disinfectant solution, such as acid solution, and then immersing the seaweed adhering to the net in the disinfectant solution in the container. It is not clear whether this disinfection method is used in cultivation of *Kappaphycus* and *Eucheuma* in Indonesia.

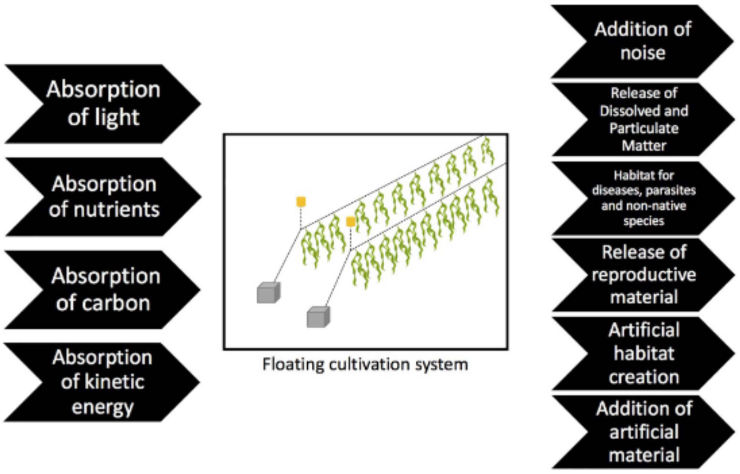


Figure 2 *Drivers for environmental change in relation to seaweed farming. Source: Campbell et al., 2019.*

Compared to other types of aquaculture, seaweed farming has a generally low impact on the environment. Nonetheless, there are potential direct or indirect negative effects of especially large-scale seaweed farming, such as introduction of alien species and changes in local environmental conditions (Eggertsen and Halling, 2020). Other risks stemming from non-chemical sources are inherently associated with large scale commercial seaweed farming. Campbell *et al.,* (2019) provide a systematic review of the ecosystem changes likely to be associated with large scale commercial seaweed farming. Although focusing on cultivation of kelp in Europe, many lessons are drawn from Asia. Campbell *et al.,* (2019) identified the key drivers for environmental change (Figure 2).

According to Campbell *et al.,* (2019) the three major environmental changes of greatest concern are:
- facilitation of disease,
- alteration of population genetics,
- wider alterations to the local physiochemical environment.

Yet, they also remark that the true extent of some environmental changes are surrounded by high levels of uncertainty.

Pest control strategies in marine fish/shell fish aquaculture might contribute to deterioration of the marine environment. The use of chemical pest control products in marine fish/shellfish aquaculture, especially disinfectants and antibiotics, causes effects in the marine environment. It is not clear whether pest control strategies in large-scale seaweed farming have similar impacts on the environment.

For now we conclude that for the control of pests and diseases in the described cultivation systems only prevention, monitoring and mechanical/physical measures are common in Indonesia. Risks for the marine environment are not expected from treatments with chemical pest control products or biological pest control agents as there are no signs these kind of products are authorised and used in seaweed cultivation in open sea. This does not mean that there is no potential for risk to the marine environment but this risk is predominantly a result of large scale commercial seaweed farming.

3 Seaweed cultivation in multi-trophic pond/tank based systems

In mariculture there are good examples of integrated systems with seaweed and salmon. These are generally open water net pen systems (Petrell and Alie 1996, Chopin *et al.,* 1999) and there are expected beneficial effects of integrating these systems that result in increased seaweed production and improved water quality (Troell *et al.,* 1997, Chopin *et al.,* 1999). The majority of salmon production is sea-based with an annual global export valued of more than 25 billion USD (FAO Globefish 2020). Yet the industry is increasingly facing issues linked to sea-lice infestation, environmental pollution, escaped animals, and a high carbon footprint (Liu *et al.,* 2016). Consequently, the commercial farming of salmon using land-based pond or tank production systems could increase in the future (Bjørndal and Tusvik 2019). Whereas the majority of research on integrated multi-trophic has been based on seaweed and fish, the shrimp aquaculture industry has grown substantially since the 1990s (Copertino *et al.,* 2009), and continues to grow to this day (FAO 2020a, FAO 2020b). There is an increase in both demand and production losses (FAO 2020b), which means more sustainable solutions have to be incorporated.

In 2018, 62.5% of farmed fish is produced by inland aquaculture (i.e., in pond/tank systems), of which 91.5% are finfish (FAO 2020a). Although multi-trophic production using filter feeding animals and/or seaweed is a common practice in Asia, Central and Eastern Europe and Latin America, farmed larger carnivorous fish and shrimp are of higher economic value to the grower (FAO 2020a). Their production systems tend to be monocultures (Neori 2009). Typical for monocultures, they have a relatively high demand for artificial feed, antibiotics, disinfectants, and chemical pest control. Moreover, with increased production demands this could lead to unacceptable levels of excess nutrients and chemicals being released into the environment via effluent water and issues with long-term viability and sustainability of the food production chain.

The application of integrated multi-trophic systems in monoculture systems could help to reduce or alleviate some of the issues. There are indications such systems can increase water quality (e.g., Evans and Langdon 2000, Viera *et al.,* 2005, Paul and de Nys 2008, Copertino *et al.,* 2009). In turn, increasing water quality may reduce the risk of disease and thus the need for antibiotics, disinfectants, and chemical pest control. There are indications that product quality can increase while the need for artificial feed is decreased (Cruz-Suárez *et al.,* 2010, Rosales *et al.,* 2019). Additionally, seaweed can be used as an extra crop for the producer allowing for a further diversification of production systems (Neori 2009).

Despite the reported benefits of multi-trophic systems, there are potential risks to human health and the environment from the use of veterinary medicinal products (VMPs) in pond aquaculture (Rico *et al.,* 2013). The current available data to assess the hazard of for example pesticides in seaweed is very limited, and monitoring data is not readily available (Banach *et al.,* 2020). It is unclear how integrated multi-trophic systems compare with traditional monoculture pond systems, and adding seaweed to pond systems to act as biofilters may involve a risk of bioaccumulation of pesticides and/or VMPs. Rico *et al.,* (2013) have developed a model (called ERA-AQUA) that can be used to assess the risk from VMPs used in aquaculture in pond systems. The ERA-AQUA model in its current form considers four endpoints: 1) the targeted produce; 2) aquatic ecosystems receiving aquaculture effluents; 3) consumers; and 4) the trade of harvested aquatic animals (Rico *et al.,* 2013).

Pond or tank-based systems can have different set-ups with a varying degree of connection to open surface waters. Pond systems are often directly connected to a canal, stream, river or directly to the sea via their irrigation systems and may even experience flooding with tidal cycles. In such cases they are likely similar to near shore, open sea farming in terms of potential environmental impacts. For tank aquaculture systems there are open, semi open and recirculation aquaculture systems (RAS). Open systems, like ponds, generally have a flow-through of water, semi-open systems make use of tanks that are refilled and flushed (i.e., are “connected” at intervals), and RAS systems are completely closed off and should have no open connection to surface water. In the following section, we will first look at the function of seaweed in pond/tank production systems and what sources of potential risks to human health there are, next we will link seaweed to the ERA-AQUA model and discuss the adaptions that would be required to incorporate a seaweed-component to the ERA-AQUA model.

3.1 Seaweed as part of pond/tank based integrated multi-trophic systems

A beneficial use of seaweed is as feed for animals integrated in the multi-trophic system. This can reduce the need of artificial feed greatly. For example, Cruz-Suárez *et al.,* (2010) show the inclusion of *Ulva clathrata* as a food resource for the shrimp *Litopenaeus vannamei* can reduce the need for artificial feed while leading to increased growth rates, reduce lipid content and increase carotenoid content. However, not all seaweed species will be equally nutritious of beneficial, for example Viera *et al.,* (2005) showed differing feed intake rates, feed conversion ratios and protein efficiency ratios for three red algae (*Hynea spinella*, *H. musciformis*, and *Gracilaria cornea*), which could have implications for the optimal choice of seaweed species in a multi-trophic set-up.

Another widely reported reason to include seaweed in integrated multi-trophic systems is the role they can play as biofilter. Complex multi-tank semi-recirculation systems using seaweed as biofilter of effluent water showed an improved pH balance, a reduced water use, a reduced nutrient load in the environment and improved water quality conditions for the system’s fish pond (Schuenhoff *et al.,* 2003). Others have also demonstrated that seaweed can be highly efficient at removing nutrients from effluent waste-water with substantial nutrient (N and P) reductions of 30-82% (Neori *et al.,* 1998, Copertino *et al.,* 2009). Not all seaweed species are equally suited to be incorporated in both pond and tank systems. For example, Paul and De Nys (2008) show culturing of *Caulerpa* species is not straightforward, but might work well in tank-based systems or can be used to treat effluent of ponds.

Besides the effectiveness of seaweed in filtering out nutrients, and forming an additional source of food and/or feed, there are important aspects related to the risk assessment to take into account. These are mainly related to uptake, sorption, and degradation rates of e.g., VMPs, heavy metals, and other chemicals. Owing to their hydrophobicity seaweeds can easily associate with pesticides (García-Rodríguez *et al.,* 2012, Lorenzo *et al.,* 2012), which has applications in phycoremediation: for example *Liminaria digitata* was shown to be effective at reducing levels of diflubenzuron, lindane, copper, and cadmium (Anacleto *et al., 2017*). Yet, it obviously also poses a risk to human health through potential bioaccumulation and subsequent exposure to contaminated food. Pesticides have even been found in wild seaweed (Pavoni *et al.,* 2003, Moreno *et al.,* 2007, García-Rodríguez *et al.,* 2012, Lorenzo *et al.,* 2012), this seems more likely to happen with seaweed in closed (semi-circulated) pond/tank systems that may, in turn, be part of a larger system of interconnected ponds. Yet, monitoring data is scarce and thus currently the risk to human health is difficult to assess (Banach *et al.,* 2020).

3.2 Integration with ERA-AQUA

Integrated multi-trophic systems can have varying levels of complexity (Figure 3), but given that they are modular by design (e.g., Shpigel and Neori 1996, Schuenhoff *et al.,* 2003), the transfer of mass between compartments should in principle be quantifiable.

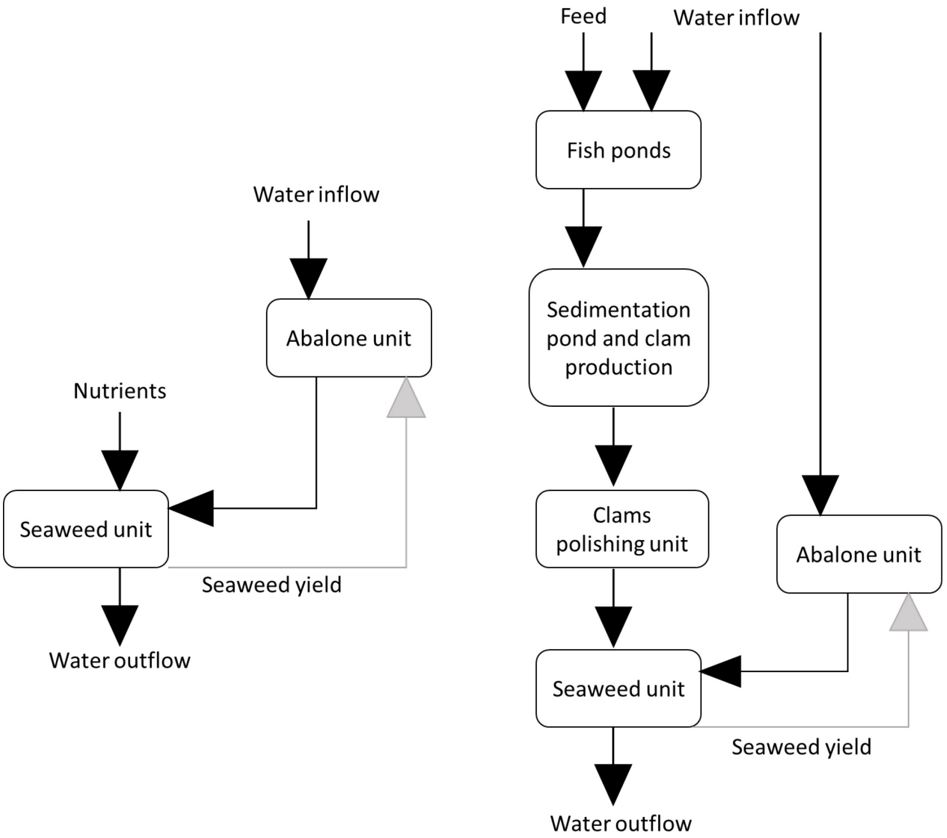


Figure 3 *Two examples of integrated multi-trophic systems of differing complexity. On the left is a two-species system, on the right a four-species unit with processing units. Reproduced from: Shpigel and Neori (1996).*

The ERA-AQUA has a similar modular set-up (Figure 4), which means an in-line seaweed unit can be integrated in the model. In the current version of the model the risk of exceeding a threshold value by a risk quotient (RQ) is already incorporated for micro-algae. This RQ is based on the ratio between maximum Predicted Environmental Concentration (PEC) and the so-called Predicted No Effect Concentration (PNEC). Here the PEC is based on the total water concentration from dissolved and sorbed fractions and the PNEC is based on a 50% effect concentration divided by safety factors of 100 and 10 for acute and chronic risk, respectively (Rico *et al.,* 2013). The RQ is used a measure for how far removed the concentrations are from any negative effects on a target species. This is usually done for both for acute and chronic toxicity, where different assessment factors are applied. If an RQ is below 1, the risk is deemed low; between 1 – 10 there is an exceedance of acceptable risk; for RQs > 10 there is a large exceedance of acceptable risk. However, the current model does not have a compartment that explicitly models the changes in mass fluxes when multiple compartments and/or seaweeds are taken into account.

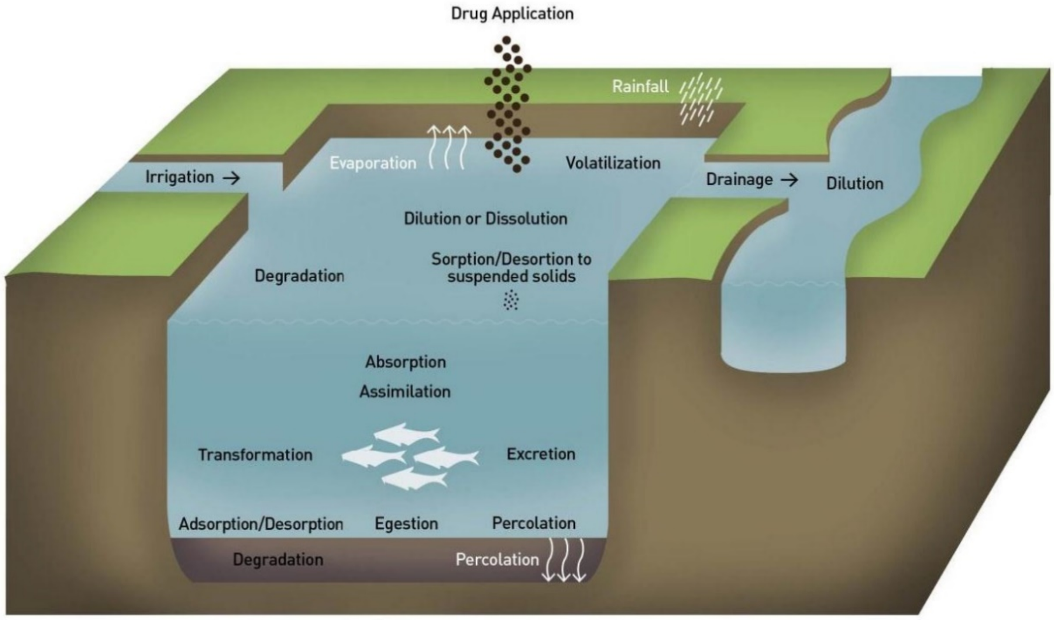


Figure 4 *Processes describing drug transfer and dissipation included in the ERA-AQUA model. Source: Rico et al., (2013).*

Looking at Figure 3, the ERA-AQUA model can in theory be applied to each of the compartments within an integrated system. For each pond and species, one would set up the pond characteristics, cultured species characteristics, planned stocking and harvest times, and feed administration regimes (which includes a feed conversion rate that could be altered by including seaweed as feed). For the water exchange management the water inflow and water outflow from the separate compartments can form inputs for irrigation and drainage in ERA-AQUA. Thus each compartment can be modelled as 'stand-alone' unit that receives inputs/outputs at each timestep. Depending on the characteristics of the compartment, e.g., some compartments might be earthen ponds, others can be tanks, the parameters describing the processes related to substance mass balance can be adjusted accordingly.

In the simplest form a multi-compartment system is linear, i.e., there is no recirculation of water and transfer of biomass between them. In such a scenario the only role seaweed would have is as bioremediation of effluent water, and the risk would simply be the risk of the cultured species and the risk of contaminated effluent water re-entering the environment.

In more complex systems, part of the seaweed yield may be used as feed and/or food. This requires a growth model for seaweed, potential reductions in growth/photosynthesis following exposure. Additionally, the frequency and amount of harvest needs to be known as well as the additional inputs of chemicals (e.g., VMPs and anti-fouling agents) adsorbed to or bioaccumulated in seaweed that is moved into the receiving compartments. Additionally, if the system has some form of recirculation, the additional inputs of VMPs from the recirculated water need to be taken into account for the receiving compartment. These extensions are not currently available in the ERA-AQUA, but could have potential in the environmental risk assessment of integrated multi-trophic aquaculture.

A major caveat is a general lack of information in the literature with respect to seaweed and chemical risk assessment, with implications for food safety (Banach *et al.,* 2020). Indeed, there is evidence that seaweed can take up pesticides and other compounds very efficiently (Lorenzo *et al.,* 2012, Cheney *et al.,* 2014, Anacleto *et al.,* 2017), but there is a lack of uptake, bioaccumulation, and effects studies under laboratory conditions for seaweed species.

A quick search in Web of Science yielded only five results when using the search:
- ALL=(seaweed bioaccumulation chemical effect)

Of these five, only one dealt with herbicides (Ojemaye *et al.,* 2020) and the remaining four look at metal concentrations (Villares *et al.,* 2005, El-Said 2013, Rangabhashiyam *et al.,* 2016), or C-14 bioaccumulation (Begg *et al.,* 1992). Others have detected pesticides in seaweed from samples taken from the field (e.g., Pavoni *et al.,* 2003, Polat *et al.,* 2018, Sundhar *et al.,* 2020, Contarini and Dromard 2021), whereas only few have studied uptake and bioaccumulation in a laboratory setting (Sikka *et al.,* 1976). Such studies, with commonly used pesticides and/or VMPs would be useful for parameterisation of a seaweed compartment. Notwithstanding the scarcity of studies looking at uptake, bioaccumulation, and effects of chemicals for seaweed species, it appears conceptually possible to include a seaweed compartment into the ERA-AQUA model. With such an addition, it can be used in the risk assessment of integrated multi-trophic aquaculture systems. Given the expected increase in the number of these systems, it would seem a good opportunity for development and further research.

4 Summary and conclusions

This document provides a first approach to evaluate the needs and possibilities for an environmental risk assessment for chemicals used in seaweed (co-)productions systems. The investigations concerning open sea production systems indicate that for the control of pests and diseases in the described cultivation systems only prevention, monitoring and mechanical/physical measures are common in Indonesia. However, practices may be different in other major seaweed producing countries like China and Chili. Notwithstanding the apparent low risk for the environment resulting from the use of chemicals, other environmental risks are associated with large scale commercial seaweed farming. Campbell *et al.,* (2019) identified three key drivers for environmental change: facilitation of disease, alteration of population genetics, and wider alterations to the local physiochemical environment. Risk analyses for these aspects are possible, but not within the field of ERA for chemicals.

In contrast to the findings from open sea cultivation methods, results from closed, pond- or tank-based multi-trophic systems where seaweed can be included for example as feed or filter, or for biomass production, indicate some reasons for concern. Uptake and sorption of veterinary medicinal products (VMPs) and other chemicals can lead to additional input to shrimp and/or fish (via feed) or to the environment (via disposal of filter material). Owing to their hydrophobicity pesticides can easily associate with seaweeds. This obviously also poses a risk to human health through potential bioaccumulation and subsequent exposure to contaminated food. The ERA-AQUA model, originally developed for risk assessment of aquaculture production of fish and shrimp, was identified as possible means to further explore the fate of chemicals used in land-based multi-trophic production systems, for their bioaccumulation and biomagnification potential and possible risk for the environment, the produced goods (fish/shrimp), and finally human health.

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