Mapping aquaculture production systems

A systematic literature review

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Abstract

The purpose of this study was to map the production functions of aquaculture production systems, and the methods applied to carry out the functions. Over one hundred articles were systematically analyzed in order to identify the production functions of different systems. The articles were analyzed in terms of the production functions, and the types and intensities of the aquaculture systems covered. The production functions were grouped in these three categories of functions depending on their nature and their role in the map: Input functions, treatment functions and output functions. The map created from this work provides a general overview of the production functions that are applied in aquaculture systems. Furthermore, variations of the map were created to show different applications of the production functions in aquaculture systems of different intensity levels. The analysis of systems of different intensity levels resulted in new definitions of system intensity in terms of the production functions. The map and the variations of the map are tools that can be used by professionals to analyze aquaculture systems in terms of the production functions, and compare them to the maps to look for improvements in the production area. This work gives rise to further studies in this area as it reveals possible gaps in the literature in terms of some of the production functions. Future studies can build on and update the results of this work as new technologies emerge, and more variations of the map can be created in terms of other factors of interest, such as the types of systems or the animals cultured.

Útdráttur

Tilgangur þessa verkefnis var að kortleggja virkni framleiðslukerfa í fiskeldi og þær aðferðir sem notaðar eru til að framkvæma nauðsynlega virkni. Búið er að yfirfara og rýna fleiri en eitt hundrað greinar til að bera kennsl á framleiðsluvirkni í hinum ýmsu tegundum af fiskeldiskerfum. Greinarnar voru flokkaðar út frá framleiðsluvirkni, tegund og framleiðsluumfangi þeirra kerfa sem þær fjalla um. Framleiðsluvirknirnar voru jafnframt flokkaðar í eftirfarandi yfirflokka eftir eðli þeirra og hlutverki: Inntak, meðferð og úttak. Kortið veitir almenna yfirsýn yfir framleiðsluvirkni fiskeldiskerfa en einnig voru kynntar þrjár útgáfur af kortinu sem sýna hvaða virknir eru notaðar í kerfum af mismunandi framleiðsluumfangi. Sú greining leiddi af sér nýjar skilgreiningar á framleiðsluumfangi fiskeldiskerfa í tengslum við framsleiðsluvirkni þeirra. Fagfólk í fiskeldisgeiranum getur notað kortið til að greina fiskeldiskerfi og til að leita umbóta í framleiðsluferlinu. Verkefni þetta leiddi í ljós að mismikið hefur verið fjallað um hinar ýmsu framleiðsluvirknir fiskeldiskerfa sem gefur tilefni til frekari rannsókna á þeim sviðum. Einnig má byggja á og uppfæra þessar niðurstöður í rannsóknum í framtíðinni þegar fiskeldiskerfi þróast og fleiri tækninýjungar líta dagsins ljós. Auk þess mætti kortleggja fiskeldiskerfi og framleiðsluvirkni þeirra út frá öðrum þáttum en hefur verið kannað hér, svo sem í tengslum við tegundir kerfa eða þær tegundir fiska sem framleiddar eru í kerfunum.

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1 Introduction

The word aquaculture stands for the farming of aquatic organisms like fish, molluscs, crustaceans and aquatic plants (FAO, 1997). Aquaculture practices have a long history but aquaculture as a food production sector on a global scale is relatively young. The sector is growing even though increase in production has been slowing down from around 2000. In spite of that, the production of farmed fish for consumption had reached 42.2% of the total production from capture fisheries and aquaculture in 2012. Aquaculture production has constantly increased its share in the total fish production while annual capture fisheries have remained almost the same since the 1990s (FAO, 2014). Fish consumption has been growing and the extra demand has been met by the aquaculture sector.

Various types of aquaculture systems exist and they are located all around the world. The systems differ in size, location, water environments, intensity and species produced. The diversity stems from different needs of different systems and it also allows the production systems to be classified by those factors and others that distinguish between them. The production systems can therefore be viewed from different perspectives depending on the factor of interest.

Numerous articles, books and reports have been published about aquaculture systems but few of them provide an overview of the production systems and their functions. The goal of this study was to create a map of aquaculture production systems based on a systematic literature review. The purpose of the map is to provide an overview of the production functions in aquaculture systems and the methods used to carry them out. The results of the literature review also shed light on the issues that have been studied thoroughly in the literature as well as bringing forward topics that could be studied further. To reach this goal, over one hundred articles have been analyzed in order to identify and define the production functions described in the literature. In the selection of articles the focus was set on input functions, outputs functions and treatment functions that are applied to improve and optimize the production. The map of the production functions will be presented as well as variations of the map that represent the functionalities of aquaculture systems of different intensity levels. Those variations lead to new definitions of the intensity levels of aquaculture systems in terms of the production functions.

1.1 Classification of aquaculture systems

Aquatic animals have needs that vary between species. Most of them are very captive when it comes to their environment. They are generally poikilothermic which means that their body temperature changes according to temperature changes of the water environment. Different species have different temperature tolerance and for that reason aquatic animals are commonly categorized based on the water temperature in which they can thrive. There are coldwater species that thrive in water environments of temperatures below 20°C. The optimum temperature for coolwater species is around 20°C. Warmwater animals thrive in water environments of temperature around 30°C, and tropical species are those whose optimal temperature is over 30°C. These groups also have different requirements and tolerances related to other characteristics of their water environment, such as dissolved oxygen (DO) requirements, ammonia tolerance and nutrient requirements to name a few (Tidwell, 2012, pp. 52-55). For that reason, numerous types of aquaculture production systems exist and each type is designed to suit the needs of the animals cultured within them.

Aquaculture systems can be classified in terms of various factors. They are commonly categorized by the types of animals cultured and also depending on whether the system is a monoculture system, where only one specie is produced, or a polyculture system where the culture system delivers two or more products (Gomiero, Giampietro, Bukkens, & Paoletti, 1997). Aquaculture farms can also be classified by their location. There are sea farms, tidal zone farms, and land based farms. Land-based farms can be further categorized by the way they are supplied with water. Gravity fed systems are those located below a water source where the water flows by gravity to the farm, and pumped systems use pumps to supply water to the farm. In tidal zone farms water supplying is generally controlled by the tide. Aquaculture systems can also be grouped by the way water supplies are utilized within the farm. We can take flow-through systems as an example. Those systems use water from a source that flows through the system and is only used once. When the water is used several times (where the outlet water is treated and then reused) the system is called a recirculating aquaculture system (Lekang, 2013, p. 2). The systems can also be grouped by the salinity of the water, such as freshwater, brackish water or saltwater systems (Tidwell, 2012, p. 51).

Another common classification is based on production per unit volume (m^3) or unit area (m^2). Extensive aquaculture systems include production systems where the production per unit volume is low. Generally, these systems do not depend on a high level of technology as there is not much human intervention or additional inputs in the system. The cultured species are kept at a relatively low density. On the opposite end there are intensive systems with a higher level of technology, more human intervention is present and additional artificial input is needed. In these systems the production per unit volume is much higher. A semi-intensive aquaculture system is a combination of extensive systems and intensive systems (Lekang, 2013, pp. 1-2). It was noted that the culture systems in the literature analyzed for this study are often classified in terms of intensity.

2 Material and methods

The main focus of this study was to identify the production functions in aquaculture systems where aquatic animals are cultured for human consumption. Two books about aquaculture were used as a starting point for the making of a system map about aquaculture production systems: Aquaculture Engineering by Odd-Ivar Lekang and Aquaculture Production Systems by James H. Tidwell. Those books were read to get a main idea about the functionalities of aquaculture systems. Subsequently, literature searches were carried out using various search terms with the aim to find a set of articles that could describe functions of aquaculture systems. The Web of Science™ citation indexing service online was used to carry out all literature searches for this study.

First some trial searches were carried out to scan the availability of articles related to aquaculture and their production systems. The trial searches verified that numerous articles have been published about issues related to aquaculture. When searching through all the databases of the Web of Science™, the search term ‘aquaculture’ delivered more than 68,000 publications. Limiting the search by using only the Web of Science™ Core Collection and excluding research areas within social sciences, arts and humanities related publications narrowed the search down to almost 19,000 publications. Roughly 1,600 of them belonged to engineering categories, management and operation management science studies. When analyzing those results further by using additional search terms like ‘overview, ‘system map’ and ‘production system’ no publications were found within the set of those 1,600 articles that provided an overview of the most common types of aquaculture production systems and their functionalities. Therefore it was concluded that few publications have focused on providing and overview of the functions of aquaculture production systems.

After several trials, two sets of search results were selected to be further analyzed for this study. Additional articles recommended by the database during those searches were also selected if they could provide a deeper input on certain topics. Backward search was also used to add articles to the selection. Figure 1 explains the search terms and the search results in a more detailed way.

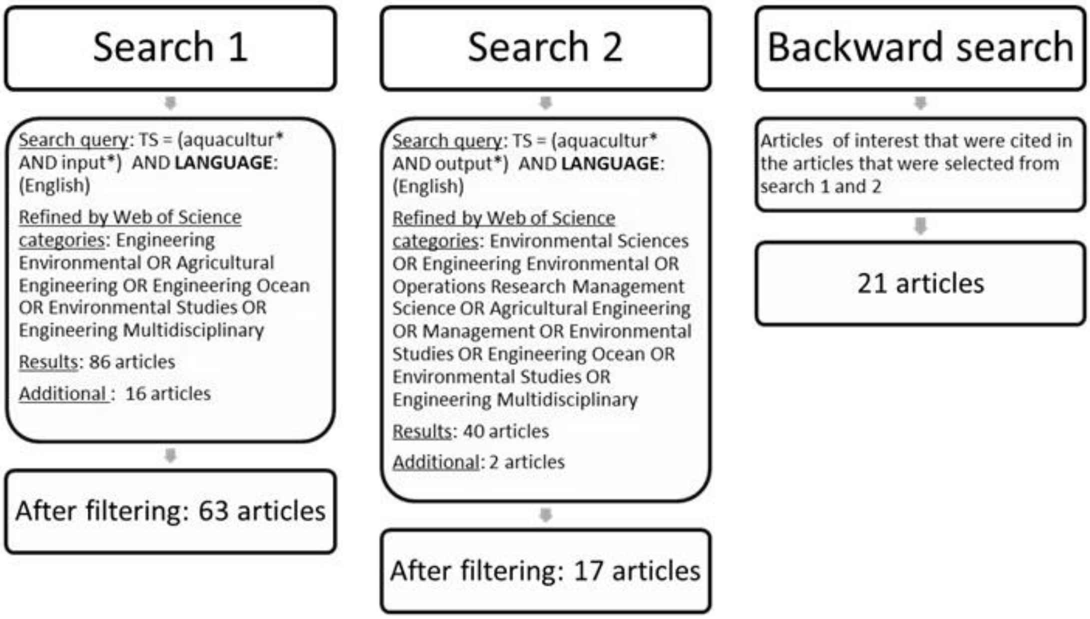


Figure 1: The search and selection process.

The searches were carried out in September 2014 using the Science Citation Index Expanded category in the Web of Science™ Core collection database. The search results were refined by selecting categories of research areas that were considered relevant for this subject. It was decided to include all categories of engineering sciences as well as the categories of management, operation research management and environmental studies. The articles resulting from searches 1 and 2 did not fall into the exact same categories of research areas. That is the reason why there is a difference between how the two searches were refined in terms of research areas.

The articles were then analyzed in two phases in order to filter out articles that would not contribute to the system map. The following subjects were considered out of scope for this study:

- Articles not dealing with issues related to production systems in aquaculture
- Articles dealing only with production of aquatic plants or aquatic animals not intended for human consumption (such as culturing of ornamental fish)
- Articles dealing with structural issues of aquaculture systems: Layout of farms, land use, site selection or highly detailed/technical machinery or equipment issues
- Articles dealing with laws, rules and regulations related to aquaculture systems
- Articles dealing with economic issues of aquaculture systems
- Articles dealing with aquacultural models, tools and methods that do not clearly relate to any production functions or issues
- Articles dealing with the processing of aquatic animals after they have been harvested

In the first filtering phase, abstracts of the articles were read to decide whether the articles should be included or excluded. In the second filtering phase the included articles were analyzed more thoroughly to find out whether any of the articles where out of scope for any of the above mentioned reasons. All the articles that were included in the selection were collected and listed in a table where their coverage was documented and categorized. Initially, the table was supposed to only include the functions of production systems. But as the analysis progressed it was decided to add more factors to the table to be able to identify what drives the need of applying some of the functions. The category of water quality parameters was added to the table as it became clear that a large part of the functions described in the literature are related to treatments applied to control and adjust the characteristics of the water. The category of types of systems was added in order to understand what types of systems apply the functions identified. In table 1, all the keywords that were used to document the coverage of the articles have been listed and categorized.

Table 1: The expanded list of keywords describing inputs, treatments, water quality parameters, outputs, types of systems and types of environments.

Inputs	Treatments	Water quality parameters	Outputs	Types of systems
Water	Disinfecting functions	Suspended solids	**Fish**	Recirculating systems (RAS)
Feed	Filtration/solids removal	Salinity	Harvested fish	Ponds
Fertilizers	Biofiltration	Conductivity	Escaped fish	Raceway systems
Fingerlings	Treatment ponds	Hardness	Sick fish	Flow-through systems
Light	Liming treatment	Alkalinity	Dead fish	Cages or Net pens
	UV treatment	pH	**Other outputs**	Partial reuse systems (PAS)
	Ozone treatment	Phosphorus	Solid waste	Hydroponics/Aquaponics
	Ammonia removal	Dissolved ions/metals concentration	Effluent water	Mixed systems
	Phosphorus removal	Dissolved oxygen	Seepage	
	pH adjustments	Dissolved carbon dioxide	Greenhouse gasses	
	Temperature adjusments	Dissolved nutrients	Side products	
	Oxygenation or aeration	Dissolved organic matter		
	Bio-treatments	Temperature		
	Ecological ditch			
	Wetlands			
	Disease treatments			
	Other treatments			

The next step was to list down the functions of production systems using the contents of table 1. Inputs and output functions were defined by analysing further the articles that were connected to those categories. A third group of treatment functions was defined by analysing the list of treatments and the purpose of applying them. These groups of functions were the foundation of the map of aquaculture production systems. The resulting analysis of the production functions was mainly based on the contents of the selected articles, but some technical reports and books about aquaculture were used during this work to gain a better understanding of some methods and issues.

3 The production functions of aquaculture systems

The systematic review of articles generated a table where all the selected articles were listed and connected to relevant categories (see table 1). The original table was used to define the production functions that can be found in table 2 on next page. Table 2 includes the list of selected articles and the production functions that have been grouped in three categories: Input functions, treatment functions and output functions. The articles are also classified by the types of systems and intensity of systems. In the next subchapters the functions will be explained in more details before introducing the complete system map that displays all the functions.

Table 2: The selected articles classified in terms of the production functions, types of systems and intensity levels.

	Inputs					Treatments										Outputs				Types of systems								Intensity			
Authors	Supplying water	Stocking	Feeding	Fertilizing	Providing light	Controlling dissolved gas	Controlling the pH, hardness and alkalinity	Removing or controlling solids accumulation	Removing, transforming or controlling N compounds	Removing or controlling organic matter accumulation	Removing or controlling P compounds	Controlling temperature	Controlling metal concentrations	Preventing diseases	Controlling disease outbreaks	Harvesting	Controlling GHG	Processing effluent water	Processing solid waste	Pond	Closed production units	Flow-through system	Recirculating aquaculture system (RAS)	Raceway system	Mixed/Integrated system	Marine/Cages or net pen	Partitioned aquaculture system (PAS)	Extensive	Semi-extensive	Semi-intensive	Intensive
Adhikari, Sahu, Mahapatra, & Dey, 2014			x	x					x	x	x							x	x	x											
Ali et al., 2005			x						x	x	x							x													x
Asmala & Saikku, 2010			x						x		x							x	x							x					
Avnimelech, 2006						x			x	x	x							x					x								x
Beitinger, Bennet, & McCauley, 2000												x																			
Bender & Phillips, 2004			x		x				x	x	x		x							x											
Berg, Michélsen, Troell, Folke, & Kautsky, 1996			x			x														x						x				x	x
Bergero et al., 2001									x									x						x							x
Bjørndal, Lane, & Weintraub, 2004		x	x													x															
Boeuf & Le Bail, 1999					x																										
Braaten & Flaherty, 2000	x																	x		x											x
Bulc, Istenic, & Klemencic, 2011	x													x				x		x			x								
Bunting, 2007	x								x		x							x		x											
Chan, 1993										x								x	x						x						
Chen & Malone, 1994								x										x					x								x
Chen, Chang & Shieh, 2003	x					x	x		x	x								x													
Colt, 2006						x		x	x				x										x								x
Colt, Watten, & Rust., 2009						x	x		x									x					x	x							x
Costa-Pierce, 1998			x		x	x			x		x							x		x					x						
Crab, Avnimelech, Defoirdt, Bossier, & Verstraete, 2007			x						x	x								x					x								x
Cripps & Bergheim, 2000			x					x	x	x	x							x				x	x								x
Dasgupta, Pandey, Sarangi, & Mukhopadhyay, 2008	x		x	x																								x			
Draganovic et al., 2013			x							x	x																				
Drapcho & Brune, 2000				x	x	x																					x				
Eding, Kamstra, Verreth, Huisman, & Klapwijk, 2006								x	x	x								x					x								x
Farnworth & Petrell, 2005	x																			x											
Forsberg, 1996		x														x															
Frier, From, Larsen, & Rasmussen, 1995								x	x	x	x							x	x												
Funge-Smith & Briggs, 1998	x		x	x		x	x	x	x	x	x					x		x		x											x
Glouannec & Noel, 1999					x							x								x											x
Gomiero, Giampietro, Bukkens, & Paoletti, 1997			x	x														x	x	x	x							x		x	x
Gross, Boyd, & Wood, 2000			x						x	x								x		x											
Gutierrez-Wing & Malone, 2006	x								x	x								x					x								x
Gutiérrez-Estrada, de Pedro-Sanz, Lopez-Luque, & Pulido-Calvo, 2004									x																						x
Gutiérrez-Estrada, Pulido-Calvo, de la Rosa, & Marchini, 2012	x					x		x	x											x										x	
Halachmi, 2013		x														x										x					
Hargreaves, Sheely, & To, 2000							x													x											
Hari, Madhusoodana Kurup, Varghese, Schrama, & Verdegem, 2006			x	x					x	x								x		x								x			
Hu et al., 2013			x						x	x						x	x	x													x
Hu et al., 2014			x						x	x							x														x
Huysveld et al., 2013	x		x		x															x											
Islam, 2005			x						x	x	x							x	x							x				x	x
Islam, Sarker, Yamamoto, Wahab, & Tanaka, 2004			x	x	x				x	x	x			x				x		x										x	
Iwama, 1991			x						x	x	x							x	x									x		x	x
Jamu & Piedrahita, 2001			x	x		x			x	x	x									x											
Jamu & Piedrahita, 2002		x	x	x	x	x		x	x	x						x		x		x					x						
Keppler & Martin, 2008	x							x	x		x							x			x										
Kristensen, Åtland, Rosten, Urke, & Rosseland, 2009	x						x		x	x		x	x										x								x
Lamoureux, Tiersch, & Hall, 2006					x							x								x											
Langford, Øxnevad, Schøyen, & Thomas, 2014														x				x								x					
Lekang, Bergheim, & Dalen, 2000					x			x													x										

	Inputs					Treatments										Outputs				Types of systems								Intensity			
Authors	Supplying water	Stocking	Feeding	Fertilizing	Providing light	Controlling dissolved gas	Controlling the pH, hardness and alkalinity	Removing or controlling solids accumulation	Removing, transforming or controlling N compounds	Removing or controlling organic matter accumulation	Removing or controlling P compounds	Controlling temperature	Controlling metal concentrations	Preventing diseases	Controlling disease outbreaks	Harvesting	Controlling GHG	Processing effluent water	Processing solid waste	Pond	Closed production units	Flow-through system	Recirculating aquaculture system (RAS)	Raceway system	Mixed/Integrated system	Marine/Cages or net pen	Partitioned aquaculture system (PAS)	Extensive	Semi-extensive	Semi-intensive	Intensive
Li, S., Willits, Browdy, Timmons, & Losordo, 2009					x							x												x	x						
Li, W., & Li, Z., 2009						x			x	x	x							x		x					x						
Liao, 1995												x								x											
Liao, B.C. Chen, Lin, & J.W. Chen, 2000													x																		
Lima, Rivera, & Focken, 2012			x	x		x								x				x								x				x	
Lin & Wu, 1996							x		x																						x
Liu, Xu, Wang, Wu, & Bao, 2014									x	x	x							x		x			x								x
Losordo & Hobbs, 2000	x		x			x		x	x									x					x								x
Malone & Pfeiffer, 2006			x						x	x								x					x								
Mariscal-Lagarda & Páez-Osuna, 2014	x	x	x	x					x	x	x					x									x						x
Martins et al., 2010			x						x	x	x			x			x	x	x				x								x
Mook et al., 2012								x	x	x	x							x					x								x
Moore, 1986			x	x																								x	x	x	x
Partridge, Sarre, Ginbey, Kay, & Jenkins, 2006			x			x		x	x		x				x	x				x										x	
Read & Fernandes, 2003			x						x	x	x			x	x			x	x							x					
Reid & Moccia, 2007											x															x					
Sanni & Forsberg, 1996						x	x											x				x									x
Seawright, Stickney, & Walker, 1998			x						x		x												x		x						
Seginer & Halachmi, 2008		x																					x								x
Seginer, Mozes, & Lahav, 2008	x						x					x											x								x
Siikavuopio, Sæther, Skybakmoen, Uhlig, & Haugland, 2009					x																										
Singer, Parnes, Gross, Sagi, & Brenner, 2008									x	x								x					x								x
Steeby, Hargreaves, Tucker, & Kingsbury, 2004								x		x										x											
Summerfelt, 2003														x				x					x								x
Summerfelt, Davidson, Wilson, & Waldrop, 2009																x					x										x
Summerfelt, Sharrer, Tsukuda, & Gearheart, 2009	x								x					x				x					x								x
Summerfelt, Vinci, & Piedrahita, 2000						x	x																x								x
Tacon, Phillips, & Barg, 1995			x	x																										x	x
Thakur & Lin, 2003		x	x	x				x	x	x								x			x										x
Todd & Josephson, 1996					x				x		x		x					x	x						x						x
Tollner et al., 2004	x																			x											
Tovar, Moreno, Manuel-Vez, & Garcia-Vargas, 2000a			x			x	x	x	x	x								x	x												x
Tovar, Moreno, Manuel-Vez, & Garcia-Vargas, 2000b			x			x		x	x	x								x	x	x											x
Trepanier, Parent, Comeau, & Bouvrette, 2002			x					x	x	x	x							x	x												
True, Johnson, & Chen, 2004a			x					x		x	x							x	x			x		x							
True, Johnson, & Chen, 2004b								x			x							x	x			x		x							
True, Johnson, & Chen, 2004c								x			x							x	x			x		x							
Twarowska, Westerman, & Losordo, 1997			x					x	x									x	x				x								x
Unger & Brinker, 2013			x					x										x	x				x								x
van Rijn, 1996			x					x	x	x								x	x					x							x
Wahab, Bergheim, & Braaten, 2003	x	x		x			x		x		x							x		x								x			
Wang, Turton, Semmens, & Borisova, 2008	x	x	x			x			x							x								x	x						x
Webb et al., 2012			x	x	x				x	x								x													x
Widmer, Carveth, Keffler, & Bonar, 2006	x											x	x										x								x
Wilfart, Prudhomme, Blancheton, & Aubin, 2013			x		x		x							x						x			x					x	x		x
Yang, 1998			x	x	x	x			x			x								x										x	
Yi, 1999		x	x		x	x			x		x	x													x						
Yu & Leung, 2009																x															
Zhang & Fang, 2006			x					x			x							x		x											
Ziegler et al., 2012																	x														

3.1 Input functions

The group of input functions includes supplying water, stocking, feeding, fertilizing and providing light. These functions are grouped together because they serve the most basic needs of aquaculture production systems. Making sure that the production system is supplied with water and stocked with fish is the basis of all aquaculture systems. Without an enclosed or fenced waterbody with aquatic species to culture inside it, there is no aquaculture production. Feeding and fertilizing serve the basic need of providing the cultured animals with nutrition. The function of providing light is also considered in this group because of its importance in terms of the ecosystem of the water and some species' survival.

Having said that the input functions serve the most basic needs of aquaculture systems, it is important to clarify that not all the functions are always applied. Some production units are open and located within larger waterbodies, such as tidal based or sea based cages or net pens. For such systems the water is already there and does not need to be allocated to the production area. Further on, additional feed or fertilizers do not always need to be applied in those types of systems if the structure of the unit allows natural feed sources to enter the rearing area. Production units that are not overbuilt or located inside a building receive natural light from the environment. Such types of aquaculture systems do not necessarily require any additional artificial lighting. The only function that seems to be always applied is stocking even though a truly sustainable aquaculture system, where the cultured animals would maintain the population with reproduction, could in theory function without frequent stocking activities.

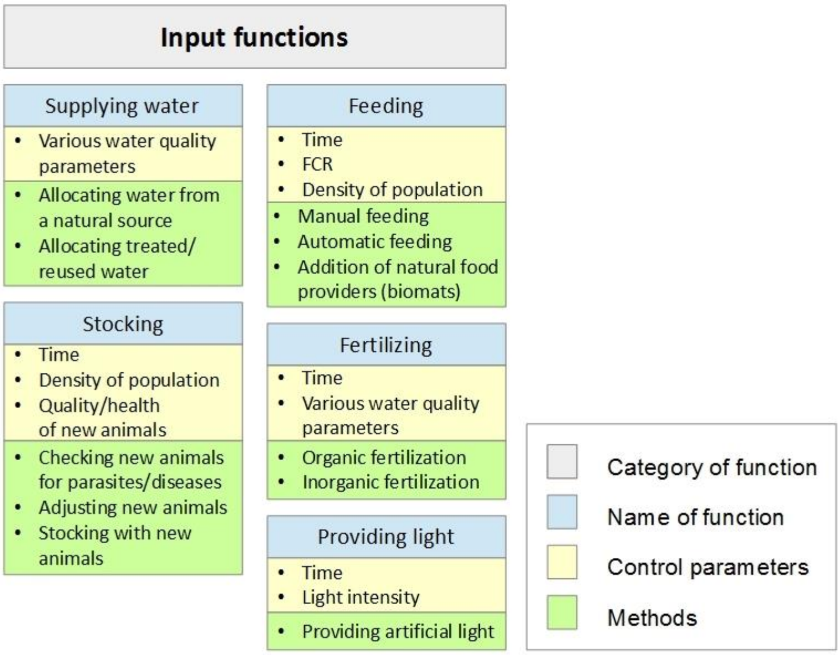
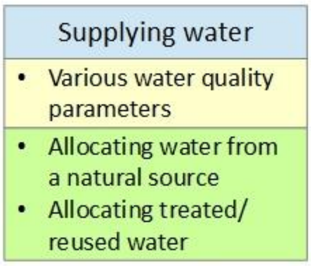


Figure 2: The group of input functions.

Figure 2 displays the group of input function. Each box representing an input function has three layers. The top blue layer includes the name of the function, the yellow middle layer shows the control parameters that affect the application of the function and the bottom green layer includes the methods used to carry out the functions.

3.1.1 Supplying water



We define supplying water to be the function of providing water for the rearing area. The water can be supplied to the system from a natural source or it can be wastewater that has been treated before being allocated to the system.

Water is essential for all aquaculture systems. When focusing on the water as an input to the system there are some factors that need to be considered. One factor is the quality of the water source. In this context, the term water quality refers to physical, chemical, biological, and aesthetic properties of the water (Boyd & Tucker, 1998). Quality requirements are specie specific so not all systems have the same quality standards. If the source does not fulfill the quality standards of the system of concern, the operator needs to consider whether the water source is usable at all or if it is, the necessary treatments to reach the desired quality level (Boyd & Tucker, 1998, pp. 3-4; Kristensen, Åtland, Rosten, Urke, & Rosseland, 2009). In some areas, water availability is scarce and for that sake, wastewater reuse and treatments for wastewater have been studied (Bunting, 2007).

Another important factor is the reliability of the water source. The availability of water differs between sites and sometimes it is necessary to take some percussions to ensure enough availability for a production system (Tollner et al., 2004). Where there is limited water supply or where rainfall is highly seasonal, supplying water for aquaculture farms can be a challenge. At such places it can be necessary to use some water harvest techniques to ensure that water supplies are abundant. Some studies have been conducted to find solutions to those problems. Farnworth and Petrell (2005) created a model to predict the behavior of seepage from ponds in order to collect water to increase streamflow during temporary low precipitation periods. Tollner et al. (2004) developed a model to determine supplemental water requirements for ponds under given environmental circumstances.

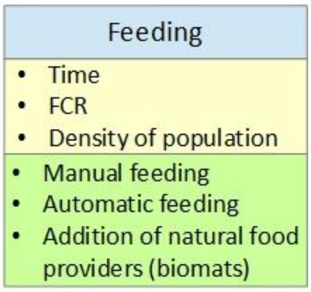
Many intensive systems have high water exchange rates to maintain water quality (Gomiero et al., 1997; Tacon, Phillips, & Barg, 1995) Other types of intensive systems, such as recirculating aquaculture systems, treat the effluent water from the culture unit to be able to reuse it (Seginer, Mozes, & Lahav, 2008). Recirculating system need to use fresh make-up water up to some point to reduce off-flavors, add alkalinity and even to control temperature. But the need for fresh water is much lower for recirculating systems than for systems that use constant in-flowing water to regulate the quality of the water (Seginer et al., 2008). Therefore, recirculating systems have received deserved attention over the last years since they require less water usage than many other systems but still provide the right conditions for intensive fish production (Martins et al., 2010).

3.1.2 Stocking

Stocking is the function of bringing new aquatic animals, fingerlings or seed to the culture unit. Studies have indicated that there is a relationship between stocking density, production, average harvest size and return rate (Tidwell, 2012, p. 166). It is important to ensure that new animals brought to an aquaculture system are of high enough quality. Before new animals are brought in it might be necessary to gradually adjust them to the conditions of their new surroundings, such as the temperature of the system and pH, to prevent them from experiencing a shock. They should also be checked for parasites and diseases to prevent introduction of diseases to the system. It can be hard to control diseases when outbreaks have already occurred in the production system (Masser, Rakocy, & Losordo, 1992).

Some studies have focused on optimizing the production under different conditions in terms of stocking. Efforts have been made to optimize stocking frequency (Halachmi, 2013), stocking size (Forsberg, 1996; Halachmi, 2013) and the time dependency of stocking rates (Seginer & Halachmi, 2008). A study by Yi (1999), where growth of tilapia was modeled, indicated that under some conditions growth can be limited by the size of stock. Other studies have indicated that for some species, such as shrimp, weight gain and production can be increased with higher stocking density (Thakur & Lin, 2003). That suggests that optimal stocking management can differ between species and systems and should therefore be considered carefully in each case.

3.1.3 Feeding



We define the function of feeding as providing the cultured animals with nutrition in the form of feed. This function can take up a lot of time and effort, especially in systems of higher intensities. Feeding can be done manually and automatically (Lekang, 2013, p. 286) and supplementary feeds can be classified as processed or non-processed. Processed feeds consist of animal or plant products that are processed before being used as feed. Non-processed feed items are alive animals (invertebrates or vertebrates) or fresh plants introduced to the system as feed (Tacon et al., 1995). For some facilities, natural sources of feed are set up within the rearing area, such as microbial mats, that produce feed by transforming ammonia and organic matters, originated from waste and excretion from the cultured animals, to food (Bender & Phillips, 2004).

Feeding and feed development is also important from an environmental point of view. A large part of waste from aquaculture is originated from feeding activities (Frier, From, Larsen, & Rasmussen, 1995). Intense systems with high stocking densities generally carry out high feeding rates in order to maximize the growth of the cultured animals (Funge-Smith & Briggs, 1998; Gomiero et al., 1997). For those systems it is important to focus on maximizing the feed efficiency in order to minimize feed waste and water pollution (Tacon et al., 1995). Improving the quality of feed and optimizing feeding systems can result in less waste being produced within the system (Cripps & Bergheim, 2000) and reducing the feed conversion ratio (FCR) can reduce environmental impacts caused by aquaculture (Martins et al., 2010). It has also been suggested that the frequency and timing of feeding contributes to the FCR (Islam, 2005). Furthermore, the effects of different feed compositions and diets have been studied in order to increase feed efficiency, reduce negative environmental influences (Hu et al., 2013) and to be better able to design effective solid waste management depending on fecal waste properties resulting from different diets (Unger & Brinker, 2013).

3.1.4 Fertilizing

Fertilizing
• Time • Various water quality parameters
• Organic fertilization • Inorganic fertilization

We define the function of fertilizing to be the adding of organic or inorganic fertilizing substances in order to stimulate the ecosystem within the culture unit. Fertilization is mainly performed in order to improve the production of natural food for the cultured animals (FAO, 1997). Nitrogen and phosphorus compounds are the major nutrients that are added to aquaculture systems through fertilizing (Tidwell, 2012, p. 216). A commonly used organic fertilizer are animal manures such as cow-dung, and inorganic ones usually contain a combination of urea and triple super phosphate (TSP) (Islam, Sarker, Yamamoto, Wahab, & Tanaka, 2004).

When fertilizers are added to the system it is important to monitor and control the application. Fertilizers can decrease the quality of the water and also affect the receiving waterbodies around the aquaculture system (FAO, 1997).

3.1.5 Providing light

Providing light
• Time • Light intensity
• Providing artificial light

The function of providing light is used when additional lighting is provided for the rearing area. Light is important for aquatic species, aquatic plants and the ecosystem of aquaculture systems. How aquatic species need and receive light varies between species but few species can grow at very low light intensities or completely without light. The intensity of light exposed to the culture area should be considered carefully. Too intense light can cause stress or as well as it can be lethal (Boeuf & Le Bail, 1999).

Some species are adjusted to specific light conditions from their natural environments. The arctic char, northern freshwater fish species, seem to have adapted their life cycle to artic light conditions. Studies have indicated that farmed Arctic char, that are exposed to changes in light conditions similar to those that occur in their natural environment, have higher growth rates than those who are exposed to constant lighting (Siikavuopio, Sæther, Skybakmoen, Uhlig, & Haugland, 2009).

3.2 Treatment functions

Treatment functions are various functions carried out in order to optimize the conditions of the culturing environment. All the functions in this category are applied to maintain and increase the water quality in order to maintain a healthy culture of aquatic animals, maximize their growth rate, and ensure that the harvested animals will be of sufficient quality. This grouping of functions is neither classified as inputs or outputs since some of the functions can take place both inside and outside the culture unit. Some of the functions are applied on early stages (to treat inputs), others on mid stages (to treat the culture unit) and other on later stage (to treat outputs). Some functions are applied at more than one stage of the production. The treatment functions are not ranked by importance since the need for them differs between types systems. Figure 3 displays all the treatment functions. Each function is represented with a box of three color layers like the input functions.

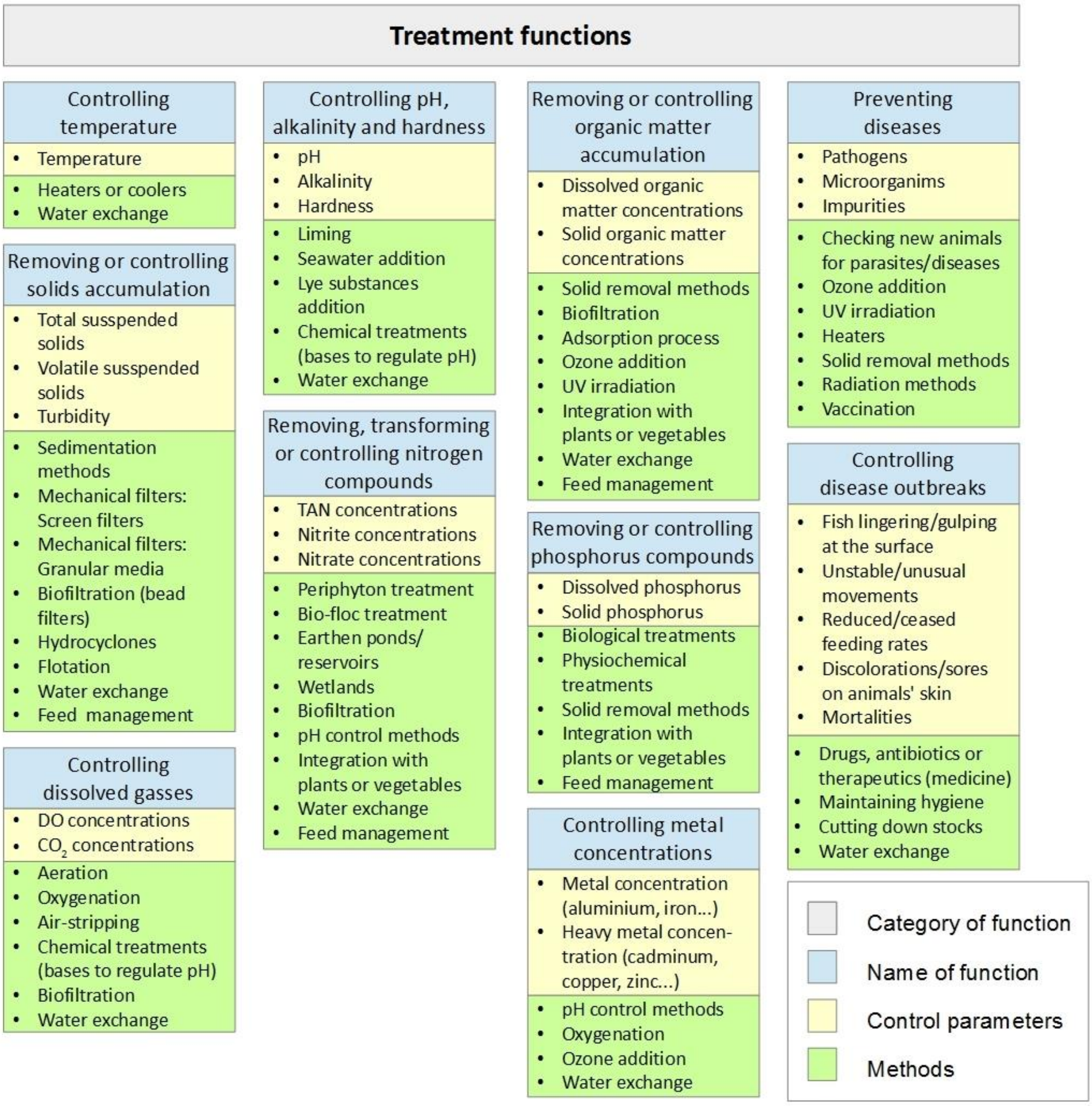


Figure 3: The group of treatment functions.

3.2.1 Controlling temperature

Controlling temperature
• Temperature
• Heaters or coolers • Water exchange

The function of controlling temperature includes all methods and actions taken to change the temperature of the water for the rearing unit or to tune it towards an optimal temperature level.

Temperature control is an important function for many aquaculture systems. Studies about aquatic animals and their temperature tolerances suggest that keeping the temperature within the right toleration range is a critical factor to ensure survival of the cultured (Beitinger, Bennett, & McCauley, 2000; Widmer, Carveth, Keffler, & Bonar, 2006). Rapid changes in temperature can induce stress and even cause mortality (Tidwell, 2012, pp. 56-57) so it needs to be ensured that the water temperature does not change too fast. There can also be temperature variations within the waterbody that should to be considered when the temperature of the water inside the rearing area is measured and controlled (Liao, 1995). For indoor aquaculture systems it is possible to control the temperature using heaters or coolers. But for outdoor systems it is more complex to control the water temperature because of heat losses to the environment (Lamoureux, Tiersch, & Hall, 2006). In order to contradict those difficulties, steps have been taken to simulate and predict temperature changes for different systems exposed to heat losses (Lamoureux et al., 2006; S. Li, Willits, Browdy, Timmons, & Losordo, 2009) and to identify thermal characteristics of systems (Glouannec & Noel, 1999).

Both direct and indirect methods are used for heating water in aquaculture systems. Direct heat sources can be electricity, gas or oil. Example of heaters used in aquaculture systems are immersion heaters and oil and gas burners. Heat pumps are also used and heat exchangers can be used for both heating and cooling (Lekang, 2013, pp. 135-150). Indirect heating can be accomplished with water exchange. Methods can be used to manipulate the temperature of the water that will enter the system (Seginer et al., 2008).

3.2.2 Removing or controlling solids accumulation

Removing or controlling solids accumulation
• Total susspended solids • Volatile sussepended solids • Turbidity
• Sedimentation methods • Mechanical filters: Screen filters • Mechanical filters: Granular media • Biofiltration (bead filters) • Hydrocyclones • Flotation • Water exchange • Feed management

Solids removal or particles removal is a very important function in aquaculture systems and a crucial function for systems of higher intensities where water exchange is limited. Many authors have addressed the issue of solids buildup in aquaculture systems, substance compositions of suspended solids and sediment or various methods to monitor and control solids accumulation (Islam et al., 2004; Steeby, Hargreaves, Tucker, & Kingsbury, 2004; True, Johnson, & Chen, 2004b; Twarowska, Westerman, & Losordo, 1997). Here we identify the function of removing and controlling solids accumulation to be the grouping of methods applied to remove solids, whether they are floating, settling or mixed with water in the form of sludge, or to control their accumulation rate.

Generally, solids are classified into three groups: Settleable, suspended, and fine or dissolved solids. The first two are the main concern when solid removal techniques are considered but concentrations of fine or dissolved solids often need to be controlled when water exchange rate is low (Tidwell, 2012, p. 250). Total suspended solids (TSS) are the amount of particles that cannot pass through a fiber filter with a mesh size of 0.45 μm. The suspended solids can be both inorganic and organic. The organic ones, or volatile suspended solids (VSS), consist of feces or bio-floc. Such organic substances decay so monitoring and controlling them is of great importance (S. Chen & Malone, 1994).

An important factor of solid management is to try to control and minimize solid accumulation. Using quality feed, maintaining accurate feeding quantities and keeping the feed conversion ratio low are all factors that contribute to minimizing accumulation of solid waste originated from feed within the system (Cripps & Bergheim, 2000). Several methods are used to remove solids and those mentioned here are based on groupings of methods originally identified by S. Chen and Malone (1994) but with some modifications. Sedimentation processes involve techniques that allow solids to settle before being removed. Sedimentation is a rather inexpensive option to remove settleable solids from the main flow and is often used as the first step in particle separation. A large part of the TSS produced in intensive systems can settle which makes sedimentation a feasible option for many systems (S. Chen & Malone, 1994; Cripps & Bergheim, 2000). Settling tanks or basins are used to remove suspended solids from the water, collect and discharge settled sludge and deliver a thickened sludge of minimal volume. They are designed in such a way that turbulence is minimized (Cripps & Bergheim, 2000). In recirculating systems the water within the settling basin can be re-used after being separated from the sludge sediment (Singer, Parnes, Gross, Sagi, & Brenner, 2008). Some systems use flushing to remove settled solids. Then the water inflow is increased and water level lowered so the accumulated solids can be flushed out of the culture unit. Then the solids or the sludge can be stored in a separate holding unit for further treatment. Removing dead cultured animals from the rearing area can also be considered a part of the solid removal functions and some systems have waste collectors not only intended to collect sludge or suspended solids but also to trap and collect dead animals (Twarowska et al., 1997).

Hydrocyclones or swirl separators create a centrifugal force that amplifies density differences between suspended solids and water, pushing the particles against the edges of the unit (S. Chen & Malone, 1994).

Suspended and fine solids can be removed by using mechanical filters (van Rijn, 1996). A popular type of mechanical filters is a screen filter (Cripps & Bergheim, 2000). The size of the solids removed depends on the mesh size of the screen filter media. Another type of mechanical filters use granular media filters to remove solids. Water is passed through a bed of granular material that separates suspended solids from the water (S. Chen & Malone, 1994). A bead filter, or an expandable granular biofilter, is a type of biofilter that combines sludge removal and nitrification (Cripps & Bergheim, 2000; van Rijn, 1996). There are also methods intended to remove fine solids that do not settle easily such as foam fractionation or flotation (Cripps & Bergheim, 2000).

There are systems, such as aquaponics, where solid accumulation can be beneficial up to some levels. An aquaponic system is a type of recirculating system where plants without soil are cultured together with aquatic species. In those systems the plants can recover nutrients from the solids. However, solid removal devices are often applied as well to maintain the water quality (Tidwell, 2012, pp. 343-353).

When solid particles have been removed from the rearing unit they might need to be processed further before being discharged or used for other purposes. The function of treating solids will be explained in chapter 3.3.3.

3.2.3 Controlling dissolved gasses

Controlling dissolved gasses
• DO concentrations • CO_2 concentrations
• Aeration • Oxygenation • Air-stripping • Chemical treatments (bases to regulate pH) • Biofiltration • Water exchange

Maintaining the right level of various dissolved gasses concentrations is one of the most important water quality functions in aquaculture systems (Colt, 2006; Jamu & Piedrahita, 2002). The function of controlling dissolved gasses includes all methods used to ensure that dissolved oxygen levels are kept close to an optimal value while carbon dioxide levels are limited.

Dissolved oxygen needs to be kept over a certain value in the water of the rearing system to ensure viable conditions, especially in systems where water exchange is limited. The optimal concentrations value of oxygen varies between species and too high concentrations are not recommended (Colt, 2006). But as the intensity and stocking density of the system increases the demand for oxygen also increases. Two common methods to increase dissolved oxygen concentrations in the water are aeration and oxygenation. Aeration is a method where bubbling air is pumped into the water or when water droplets are forced in contact with air. Oxygenation is where pure oxygen gas is injected into the water (Summerfelt, Vinci, & Piedrahita, 2000).

When oxygen is consumed by the cultured species or other organisms, it will increase carbon dioxide concentration in the rearing area resulting from fish metabolism (Tidwell, 2012). Carbon dioxide in too high levels can be toxic for the cultured animals. In intensive systems, where pure oxygen is injected to the system, there is a risk of excess carbon dioxide concentrations buildup within the rearing area resulting from low water exchange and because pure oxygen system do not facilitate sufficient carbon dioxide removal (Summerfelt et al., 2000). Carbon dioxide accumulation can also affect other characteristics of the water. For some alkalinity values respiratory carbon dioxide can lower the pH and create a suboptimal life condition for the cultured animals (Colt, 2006; Colt, Watten, & Rust, 2009). Aeration limits the accumulation of carbon dioxide as carbon dioxide is stripped out during the process up to some extent. (Colt et al., 2009). There are also other methods that can be used to remove excess carbon dioxide from the water. Air-stripping columns can be used to remove dissolved carbon dioxide from the water. In some recirculating systems chemicals are used to remove carbon dioxide. Two types of chemicals can be used to control carbon dioxide but also regulate pH; strong bases that do not contain carbon, such as sodium hydroxide, and bases without carbon, such as sodium bicarbonate (Summerfelt et al., 2000). Biofilters such as trickling filters, that are mainly used in recirculating systems to remove ammonia from the water, also serve the purpose of removing carbon dioxide from the water (Eding, Kamstra, Verreth, Huisman, & Klapwijk, 2006).

3.2.4 Controlling the pH, hardness and alkalinity

Controlling pH, alkalinity and hardness
• pH • Alkalinity • Hardness
• Liming • Seawater addition • Lye substances addition • Chemical treatments (bases to regulate pH) • Water exchange

The pH scale measures the acidity and alkalinity in water or other aqueous solutions. The alkalinity is a measure of the water's capacity to keep the pH constant by neutralizing acids. For low alkalinity values the pH of the water is more likely to fluctuate. Hardness measures the sum of all metal ions in the water (Lekang, 2013, pp. 43-44). This function includes all methods used to adjust the levels of the above mentioned parameters.

Generally, aquatic animals can tolerate a pH range from 6–9.5 (Masser et al., 1992). Extreme pH values or rapid change in pH can induce stress or even cause mortality (Tucker & D'Abramo, 2008). Dangerous pH conditions are not likely to occur since a suitable water source should be chosen for each system (Masser et al., 1992). Therefore the pH value might not need to be managed so much in systems with high water exchange rates. However, other substances in water, such as carbon dioxide and ammonia, that need to be kept under acceptable limits, are dependent on the pH and their concentrations and transformations can be affected by the pH (Sanni & Forsberg, 1996).

As was mentioned earlier, there are chemical treatments such as addition of sodium bicarbonate or sodium hydroxide, that serve the double purpose of regulating the pH as well as removing carbon dioxide from the water (Summerfelt et al., 2000). Liming is another common method applied that involves adding liming substances to the water to increase the pH. Among other methods used to increase the pH of water is addition of sea water to increase the pH or lye substances for pH regulation (Lekang, 2013, pp. 43-47). If alkalinity is too low, dolomite can be applied to raise the alkalinity level. If the alkalinity level is too high, organic acids can be added to reduce the level (Funge-Smith & Briggs, 1998).

3.2.5 Removing, transforming or controlling nitrogen compounds

Removing, transforming or controlling nitrogen compounds
• TAN concentrations • Nitrite concentrations • Nitrate concentrations
• Periphyton treatment • Bio-floc treatment • Earthen ponds/ reservoirs • Wetlands • Biofiltration • pH control methods • Integration with plants or vegetables • Water exchange • Feed management

Impurities in water can be classified as nutrients and organic matter. High level of nutrients in aquaculture effluents can pollute receiving waters and cause problems within the rearing unit (Crab, Avnimelech, Defoirdt, Bossier, & Verstraete, 2007). This function includes methods used to transform or remove organic or inorganic nitrogen compounds from the water or controlling accumulation of those substances.

Nitrogen is a nutrient that mainly enters aquaculture systems in the form of feed or fertilizers. It is one of the key nutrients needed for plants in fertilized ponds to grow but it can also transform to ammonia and nitrite that can be toxic for the animals cultured within an aquaculture system (Tidwell, 2012, p. 218). Total ammonia nitrogen (TAN) concentrations are frequently measured in aquaculture systems in order to monitor water quality. Total ammonia nitrogen is the sum of un-ionized ammonia (NH_3) and ionized ammonia (NH_4^+). As explained earlier, there is balance between the concentrations of those two forms of ammonia in water that depends on the pH of the water (Crab et al., 2007). In wastewater these substances are considered to be one of the major contributors to environmental pollution (Ali et al., 2005; Bergero et al., 2001).

Accumulation of nitrogen can be minimized through feed management but for systems of higher intensity it might be necessary to apply some methods to remove or transform nitrogen compounds from the water. Crab et al. (2007) grouped nitrogen removal method in two categories; removal methods inside the culture unit and removal methods outside the culture unit. They mentioned two methods within the rearing area, pheriphyton treatment and bio-flocs technology. Both methods remove nitrogen compounds or convert them to less toxic forms. A positive side effect of applying these treatments is that the they can also be an additional food source for the cultured animals and so decrease the need for direct feeding (Hari, Madhusoodana Kurup, Varghese, Schrama, & Verdegem, 2006). Biomats that were discussed in the chapter about feeding functions can also be grouped with other biological methods to transform ammonia and organic matter to food (Bender & Phillips, 2004). And for integrated systems such as aquaponics, the plants growing in the system can recover a part of nitrogen supplied to the system (W. Li & Li, 2009; Mariscal-Lagarda & Páez-Osuna, 2014).

Crab et al. (2007) identify earthen treatment ponds or reservoirs as nitrogen removal methods applied outside the culture unit but they serve the purpose of removing unwanted concentrations of substance outside the rearing area. Natural or constructed wetlands have also been used for the purpose to remove ammonia and nitrate compounds from the outlet water (Costa-Pierce, 1998). Wetlands also serve other treatment purposes such as to remove solids, phosphorus, trace elements and microorganisms (Mook et al., 2012).

Using biofilters to treat effluents outside the culture unit is another prominent technique to control total ammonia nitrogen concentrations. Many types of biofilters exist but here we mention two categories of biofilter technologies that have been identified in the literature: Fixed film filters and suspended growth filters (Gutierrez-Wing & Malone, 2006; Malone & Pfeiffer, 2006). Fixed film filters have been more favored than suspended growth systems because of more stability in their performance (Malone & Pfeiffer, 2006). The main biological process that biofilters perform is nitrification which is converting ionized ammonia to nitrite and nitrate. (Lekang, 2013, p. 179; van Rijn, 1996). The nitrification process results in increasing concentrations of nitrite and nitrate. Denitrification biofilters seem to have received less attention in the literature but their role is to remove excess nitrate from the system and prevent it to exceed the tolerance limits of the cultured animals (Martins et al., 2010; Singer et al., 2008).

Optimal design and techniques to estimate requirements of biofilters for recirculation systems have been studied in the literature (Losordo & Hobbs, 2000) and models to predict ammonia concentrations have also received substantial attention (Gutiérrez-Estrada, de Pedro-Sanz, Lopez-Luque, & Pulido-Calvo, 2004).

3.2.6 Removing or controlling organic matter accumulation

Removing or controlling organic matter accumulation
• Dissolved organic matter concentrations • Solid organic matter concentrations
• Solid removal methods • Biofiltration • Adsorption process • Ozone addition • UV irradiation • Integration with plants or vegetables • Water exchange • Feed management

As was mentioned in the previous chapter, organic matter compounds can be classified as impurities that exist in the water of aquaculture systems. This function includes all methods used to remove or keep organic matter concentrations under acceptable limits.

Organic matter enters culture systems through feed, fertilizers or through other agents added to the system (Funge-Smith & Briggs, 1998). Feed management is therefore an important factor of minimizing organic matter accumulation. Organic substances are also created within the system in the form of metabolic waste (Steeby et al., 2004). When organic matter accumulates in the system it can decrease DO levels and can over-stimulate phytoplankton growth (Ali et al., 2005) and when organic matter mineralizes it can attribute to the emergence of toxic compounds inside the rearing unit (Hari et al., 2006). Organic matter in solid form can be removed from the system using some of the previous mentioned solid removal methods. Fine particulate organics can be removed using foam fractionation with ozone gas (Cripps & Bergheim, 2000). Ozone treatment, that is commonly used to disinfect the water, has proved to reduce total organic carbon (TOC) up to some point but it needs to be used carefully as its byproducts can be toxic for both fish and human. UV irradiation has been used to counteract potential toxic effects as it destroys ozone residuals in the water (Mook et al., 2012). Biofilters, that are commonly used in recirculating systems mainly to control total ammonia nitrogen concentrations, can also reduce concentrations of dissolved organics (Gutierrez-Wing & Malone, 2006). But particulate organic matter can cause problems in their performance if the organic matter loading rates are too high (Eding et al., 2006).

Sufficient water exchange can counteract the build-up of soluble organic matter and for recirculating systems it has been recommended to perform a complete water exchange after each production cycle (Masser et al., 1992). Organic chemicals and total organic carbon can also be removed through an adsorption process (Mook et al., 2012). Studies about aquaponic systems have indicated that the plants can recover part of the organic matter concentrations in the water (W. Li & Li, 2009).

3.2.7 Removing or controlling phosphorus compounds

Removing or controlling phosphorus compounds
• Dissolved phosphorus • Solid phosphorus
• Biological treatments • Physiochemical treatments • Solid removal methods • Integration with plants or vegetables • Feed management

Phosphorus compounds are nutrients that enter culture units mainly in the form of feed or fertilizers. In natural waters phosphorus concentrations are relatively low but they tend to accumulate in aquaculture systems of higher intensity (Tidwell, 2012, p. 222). As environmental disturbances deriving from aquaculture systems have been a concerning matter in many studies throughout the years (Read & Fernandes, 2003; Tovar, Moreno, Manuel-Vez, & Garcia-Vargas, 2000a, 2000b; True, Johnson, & Chen, 2004a), too high concentrations of phosphorus in effluent water have raised concerns due to its role in the eutrophication process (Zhang & Fang, 2006). This function addresses methods used to remove phosphorus compounds from the water of the rearing area or the effluent water or controlling the accumulation.

Phosphorus compounds exist in both solid phase (SP) and dissolved phase (DP). Solid removal methods should decrease the phosphorus discharged but studies have indicated that a large part of the total phosphorus in the discharged water from flow-through systems is in dissolved form. Technologies to remove phosphorus from effluent and sludge can be grouped in two categories: Biological and physiochemical. Biological methods are performed through sludge treatments where phosphorus is removed. Physiochemical methods are more common. They involve adding chemicals that transform phosphorus to solid form so it will settle (True et al., 2004a) and can then be removed with other settleable solids. As was stated before, integrated systems such as aquaponics seem to be beneficial for the fact that the plants or seem to reduce the phosphorus concentrations of the rearing area water and therefore from the effluent water (W. Li & Li, 2009).

3.2.8 Controlling metal concentrations

Controlling metal concentrations
• Metal concentrations (aluminium, iron...) • Heavy metal concen-trations (cadminum, copper, zinc...)
• pH control methods • Oxygenation • Ozone addition • Water exchange

Under this function we group all actions performed to reduce the possibility of metal compounds in the water becoming toxic to the cultured animals, the environment or the consumer. Too high metal concentrations in the water inside the rearing area can be a serious problem as it can result in heavy metal intoxication to consumers (Liao, Chen, Lin, & Chen, 2000) so it is essential to ensure that the level of metals in the water stays within an acceptable level. Heavy metals such as cadmium, copper and zinc have been identified as heavy metals that should be observed closely in recirculation systems. In those systems there is even more risk of heavy metal concentrations building up because of limited make-up water usage. The toxicity of heavy metals is however dependent on other factors such as alkalinity and hardness and it can be reduced when those levels are high (Colt, 2006). Other metals of concern are aluminum and iron compounds.

Metals can enter the water in different ways. At some sites there are metals in the inlet water that need to be monitored and controlled if the levels are too high. Problems with aluminum concentrations have been related to low pH levels. Techniques to treat water with too high aluminum level are the same as for controlling (increasing) pH levels, treatments such as liming, adding sea water or lye addition. Adding oxygen or ozone has been applied to treat water with too high level of iron compounds (Kristensen et al., 2009). Bioculture within the rearing can also help reducing metal levels. The previously mentioned microbial mats sequester can also be used in waters containing high levels of heavy metals as the mats isolate them from the water (Bender & Phillips, 2004). If metal equipment is used or if the tank/rearing unit is made of metallic material it needs to be observed if corrosion occurs to prevent the metal concentrations from reaching toxic levels (Widmer et al., 2006).

3.2.9 Preventing diseases

Preventing diseases

- Pathogens
- Microorganims
- Impurities

- Checking new animals for parasites/diseases
- Ozone addition
- UV irradiation
- Heaters
- Solid removal methods
- Radiation methods
- Vaccination

It has been suggested that outbreaks of infectious fish diseases is an issue that can limit growth of the global aquaculture industry (Bulc, Istenic, & Klemencic, 2011). Therefore the function of preventing diseases is introduced that covers methods that are applied to prevent diseases from manifesting within aquaculture systems.

Some precautions can be made to reduce the probability of diseases, pathogens or any impurities that can cause diseases of entering the culture unit. One of them is checking fish or fingerlings for parasites and diseases before being released into the system. This is important since it can be hard to control a disease outbreak once it has been introduced to the system and contagious diseases can spread fast inside a tightly stocked rearing area. Sterilizing all the equipment used for the system will also reduce the likelihood of disease outbreaks (Masser et al., 1992). There is always the probability of underlying diseases being present within the stock that can submerge if the cultured animals are exposed to some kind of stress releaser, such as suboptimal environmental conditions (Lekang, 2013, p. 32). Thus maintaining optimal water quality reduces the likelihood of disease outbreaks.

As defined by Lekang (2013) disinfection methods are performed to reduce concentrations of microorganisms in the water that can cause outbreaks of infectious diseases for the cultured animals. Disinfection can be carried out during several stages of the production. The inlet water is often disinfected to ensure acceptable concentration of microorganisms. In recirculating systems, disinfecting effluent water before reuse may be necessary for the same reasons. Lekang grouped disinfection methods in four categories. Chemical methods involve using various chemical agents such as ozone for disinfection. Physical methods consist of physical agents such as heating or UV irradiation. In the third group there are mechanical methods that include solid removal techniques that have already been mentioned here. And in the last group are radiation methods such as using electromagnet, acoustic or particle radiation (Lekang, 2013, p. 120).

For some systems and some types of cultured animals, vaccinations are used to prevent diseases. But not all species tolerate vaccination. For example, shellfish in general have primitive immune systems so vaccinations have not proven to be effective and possibly never will (Tidwell, 2012, p. 109).

3.2.10 Controlling disease outbreaks

Once diseases break out inside the culture area some actions need to be taken to prevent further outspread. This functions addresses methods used to address the issue of disease outbreaks within aquaculture systems.

There are numerous fish diseases that are known, infectious and non-infectious. They can enter the system from the incoming water, from new fish entering the culture unit or from equipment used within the area. Infectious diseases spread faster in systems of higher intensity and density of stocks (Tidwell, 2012, p. 128). Sick fish can show symptoms like lingering at the surface, gulping at the surface, unstable or unusual movements or reducing or cutting off feeding rates. Other indicators are discolorations or sores on the skin or mortalities. Drugs, antibiotics or therapeutics are sometimes used to treat diseases but not all species tolerate those treatments. Using chemical treatments can also impact other functions of the culture unit, such as biofilters in recirculating systems (Masser et al., 1992). In shellfish cultures, medicine is generally not used outside of hatcheries. To encourage recovery from disease outbreaks in shellfish cultures it can prove effective to increase the water flow rate, maintain good hygiene or cut down the stock (Tidwell, 2012, p. 109).

Sea lice have caused disease problems in salmon cultures. Sea lice pathogens can be controlled by using medicine but because of the possible harmful effects of chemical treatments on the environment, medicine use must be kept under allowed limits. However, farmed fish are tolerant to sea lice up to some point so their numbers should be monitored (Read & Fernandes, 2003).

3.3 Output functions

The output functions include all functions applied to the outputs of aquaculture systems. In the literature efforts have been made to find acceptable concentrations of contaminants or nutrient budget to encourage sustainability in aquaculture production (Bergero et al., 2001; Thakur & Lin, 2003; Trepanier, Parent, Comeau, & Bouvrette, 2002). Therefore we do not only consider the harvested animals in the category of outputs but also focus on effluent water, solid waste and emission of greenhouse gasses.

Figure 4 displays the group of output functions. Each function is presented by a box of three color layers like the input functions and treatment functions.

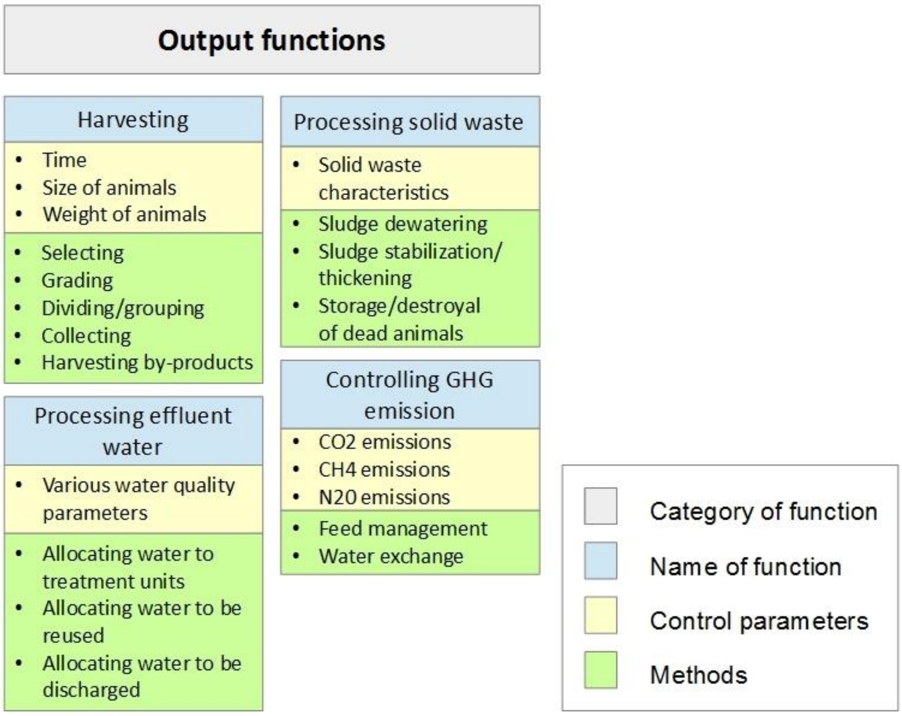


Figure 4: The group of output functions.

3.3.1 Harvesting

The function of harvesting includes selecting, grading, dividing or grouping and finally collecting the cultured animals. It also includes harvesting by-products if they are cultured in the system as well. Harvesting is considered to be the final step of the production in this review.

All functions and methods aim at maximizing the profit from the production by maximizing the output and ensure that it meets set quality standards. Production planning is very important to reach that goal (Forsberg, 1996). As the intensity of the farming increases, the need for interfering with the behavior and location of the cultured species increases. Necessary interfering actions can be dividing, grouping, size grading and weighting the fish. These actions can be considered a step in preparing harvesting. In some cases, size grading takes place during harvesting. If it turns out that the animals are not ready to be harvested they can be redirected to a proper place within the rearing unit (Lekang, 2013, pp. 299,304).

Harvesting methods can induce stress and even increase mortality rate. Studies have indicated that by using harvesting techniques that minimizes handling the animals can reduce stress and mortality (Summerfelt, Davidson, Wilson, & Waldrop, 2009). The timing of harvesting is also critical. In an attempt to maximize the profit of the production, models have been made to optimize harvesting schedules for aquaculture systems (Forsberg, 1996; Yu & Leung, 2009)

Harvesting techniques vary between cultured species but also between systems. In aquaponics the plants or vegetables that are cultured along with the animals need to be harvested as well as the animals (Mariscal-Lagarda & Páez-Osuna, 2014; Seawright, Stickney, & Walker, 1998).

3.3.2 Processing effluent water

Processing effluent water
• Various water quality parameters
• Allocating water to • treatment units • Allocating water to be reused • Allocating water to be discharged

The role of this function is to describe different options to allocate the effluent water depending on its state of quality. Effluent water from aquaculture systems can contain contaminants that negatively affect the environment if it is discharged directly. If an aquaculture facility uses treated wastewater it needs to be verified that the reused water meets quality standards. Aquaculture producers need not only to consider their own quality standards but they also have to consider the laws and regulations of the country they are located in regarding environmental effects and quality of the production (Read & Fernandes, 2003).

Methods used to treat effluent water have already been mentioned in the earlier chapters. Solids concentrations in waste effluents is one of the urgent environmental issues related to aquaculture systems (Tovar et al., 2000a). Solid removal methods are therefore important for systems where solid concentrations are too high. Methods to remove nutrients, such as nitrogen compounds and phosphorus, and organic matter are also important to maintain the water quality of the reused water within recirculating systems (Bergero et al., 2001; Crab et al., 2007; True, Johnson, & Chen, 2004c) as well as to minimize environmental effects on the environment (Ali et al., 2005). Unfortunately, wastewater treatments are often expensive and it has been pointed out that not all systems can afford expensive equipment for treating wastewater and need to employ low cost treatment options (Lekang, Bergheim, & Dalen, 2000).

Some studies have focused on tools to forecast the efficiency of treatment methods applied. An example is a neural network model introduced by J. C. Chen, Chang, and Shieh (2003) to predict reuse potentials of treated wastewater. Bunting (2007) created a bioeconomic model to be able to compare traditional and rational designs for lagoon-based treatments for wastewater to be reused.

3.3.3 Processing solid waste

Processing solid waste
• Solid waste characteristics
• Sludge dewatering • Sludge stabilization/ thickening • Storage/destroyal of dead animals

Various solid removal methods have already been introduced in earlier chapters. Some methods, such as filtration or settling methods, leave the operators with solid waste that needs to be processed before being further used or disposed of. This function addresses methods related to the processing of solid waste after it has been separated from the water.

In some cases, solid waste is collected in containers where it can be treated. As an example, particle concentrators are devices located by the outlet from a rearing area that assist the settling and concentration of solids.

Sludge from aquaculture systems can be disposed of but it might also have beneficial use potentials after being removed from the system (Cripps & Bergheim, 2000). The sludge has proven to be a good fertilizer for agricultural crops. Before being used as such it is commonly thickened or dewatered (van Rijn, 1996). Methods like liming stabilize and thicken the sludge as well as it kills pathogenic diseases and prevents the sludge from decomposing (Cripps & Bergheim, 2000). Biological methods can also be applied to remove phosphorus compounds from the sludge (True et al., 2004a).

3.3.4 Controlling greenhouse gas emissions

Controlling GHG emission
• CO2 emissions • CH4 emissions • N20 emissions
• Feed management • Water exchange

It has been pointed out in the literature that not many studies have focused on the formation and effects of greenhouse gasses (GHG) from aquaculture systems (Hu et al., 2013) but in recent years, more articles have dealt with the issue. The function of controlling greenhouse gas emissions includes efforts made to limit formation of greenhouse gasses from aquaculture systems.

The major types of greenhouse gasses from aquaculture systems are carbon dioxide, methane (CH_4) and nitrous oxide (N_2O) (Hu et al., 2014; Martins et al., 2010). These gasses stem from decomposition of organic materials, from metabolic excretion from the cultured animals or during nitrification or denitrification processes (Hu et al., 2014). Studies have indicated that on average only 25% of the feed nitrogen and feed carbon are transformed into fish biomass and the rest is delivered through the environment in other forms (Hu et al., 2013; Tidwell, 2012, p. 321). New types of systems such as partitioned aquaculture systems (PAS) try to improve feeding efficiency and aim to eliminate feed wastage. Those systems are claimed to be more sustainable and environmental friendly and should discharge less waste in solid or effluent form as well as reduce atmospheric emissions (Tidwell, 2012, p. 321). High greenhouse gasses emissions have been traced to activities of aquaculture systems of higher intensity, such as to high feeding rates and low water turnover rates (Hu et al., 2014).

3.4 The map of the production functions of aquaculture systems

All the functions that have been introduced contribute to the map of the production functions of aquaculture production systems that are presented in figure 5 on next page. The map is a summary of the analysis of the articles selected for this study and therefore it does not represent a particular type of system.

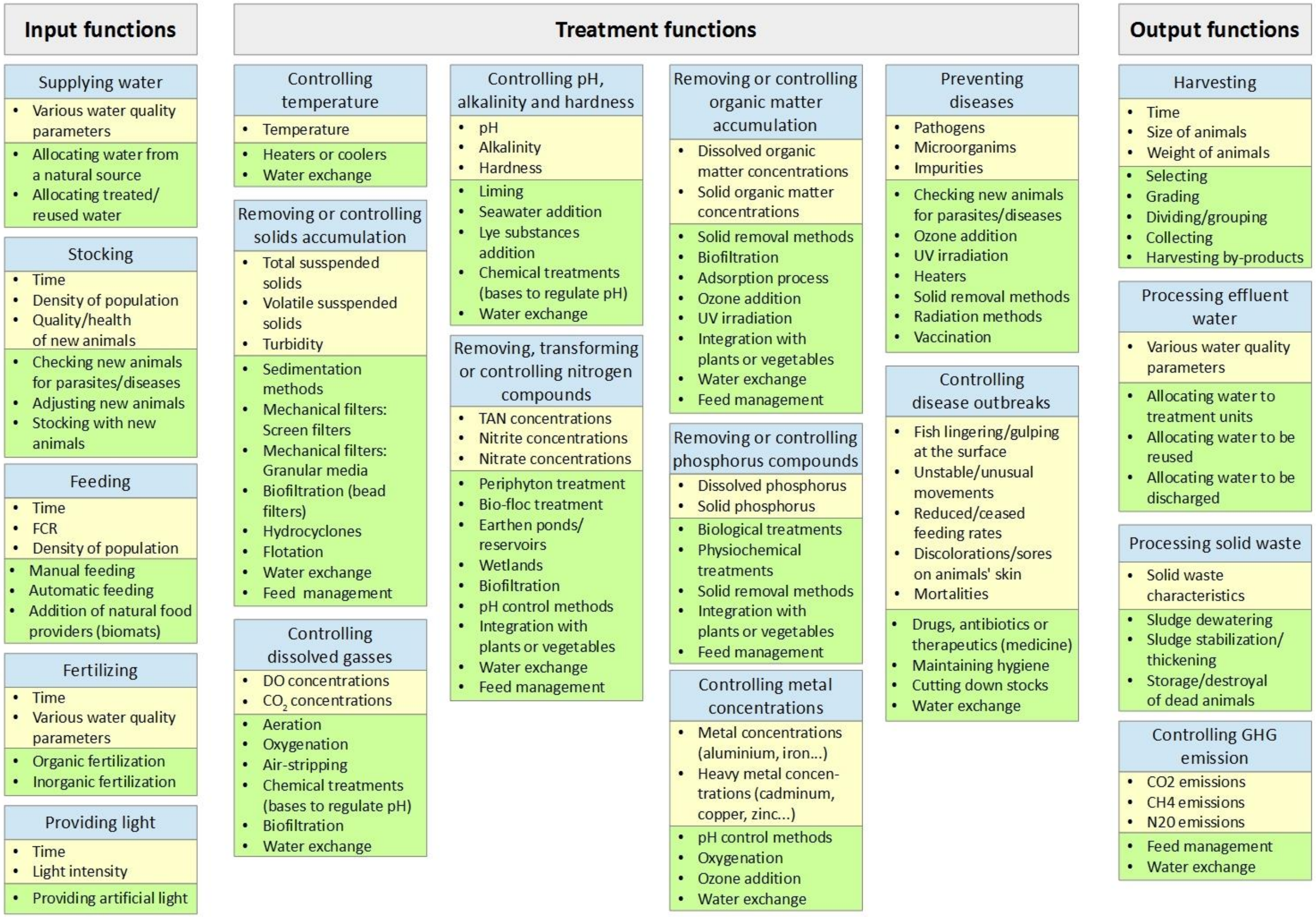


Figure 5: The map of aquaculture systems displaying input functions, treatment functions and output functions.

Some issues related to the production functions were studied and mentioned more frequently than others in the selected literature. The graph in figure 6 shows the distribution of how frequently various issues related to the production functions were studied.

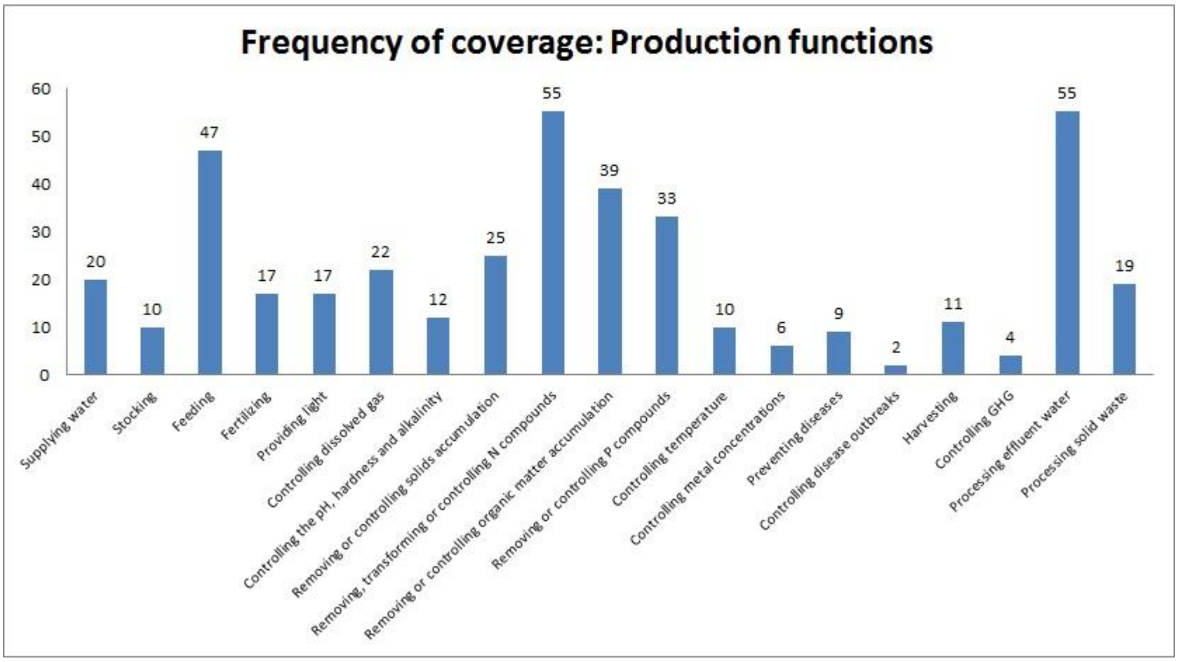


Figure 6: Frequency of coverage of issues related to the production functions.

The graph reveals that some issues have been studied quite thoroughly while other functions have not received as much attention. The functions of removing and transforming nitrogen compounds, processing effluent water, feeding, removing or controlling organic matter and removing or controlling phosphorus have been covered quite thoroughly judging from the set of articles that were analyzed for this study. Functions like controlling disease outbreaks, controlling greenhouse gasses, controlling metal concentrations and preventing diseases were the least covered groups.

4 Mapping systems of different intensity levels

This chapter is dedicated to variations of the system map depending on the intensity of the culturing systems. Not all of the articles that were reviewed were linked to an intensity group. If the intensity of a culture system covered in an article was not mentioned then the article was not linked to an intensity group. Of those articles that used intensity definitions, forty-eight studied issues related to intensive systems, eleven articles studied issues of semi-intensive systems and seven issues of extensive systems. Two articles defined a system to be semi-extensive, but since none of the articles, books or technical reports used for this study included a definition for that type of system intensity, it was decided to exclude semi-extensive systems. Forty-five articles were not linked to any intensity group but seven articles studied or compared two or more types of intensity systems.

4.1 Extensive aquaculture systems

As widely identified in the literature, the most extensive systems are those where there is little or even no human interference. As a consequence, those systems generally produce less than those of more intensity. A common type of an extensive system is where a restricted zone created by a net, cage or some type of a fence is inserted in a larger water body where animals can be cultured inside. Another type can be a pond farm where no additional feeding is used and the ecosystem inside the pond provides feed for the cultured animals (Lekang, 2013, pp. 1,201-213).

Extensive systems do not seem to have gained much attention judging on the material analyzed for this review. That should not come as a surprise when considering the fact that those systems apply a minimum amount of functions. Iwama (1991) stated that extensive aquaculture systems resembled the natural environment of the inhabitants without applying supplemental food. Gomiero et al. (1997) defined extensive aquaculture as lightly stocked systems where water throughput is not boosted and feed or fertilizer inputs not applied. Edwards and Demaine (1998) provided a similar definition and referred to extensive systems as those depending on natural food sources within the culture unit where feed additional feed inputs are not added intentionally. Nevertheless, extensive systems have been connected to functions such as feeding or fertilizing in the literature (Dasgupta, Pandey, Sarangi, & Mukhopadhyay, 2008; Hari et al., 2006; Wahab, Bergheim, & Braaten, 2003). This indicates an inconsistency in the definitions about intensity of aquaculture systems.

In this review we assume extensive aquaculture systems to be the ones that use and require an absolute minimum of functions to operate in accordance with their definitions in the literature. The map in figure 7, that represents extensive systems, therefore excludes all treatment functions. Furthermore, we assume that extensive systems also exclude the function of providing light from the input category since none of the articles reviewed for this study connected the function with extensive systems. We include feeding and fertilizing in the map but to indicate that those functions are not always used the boxes indicating those functions in the map are displayed with a transparent hue. Supplying water is represented in the same way since water does not need to be allocated to extensive systems located inside a larger water body. Finally it only includes the harvesting in the category of output functions since the other functions were not related to extensive systems in this analysis

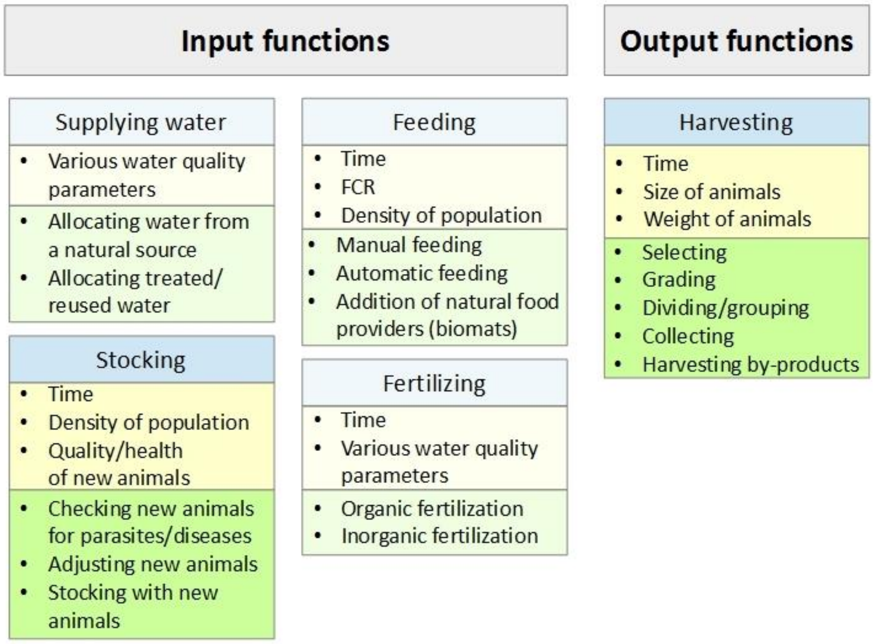


Figure 7: System map describing extensive aquaculture systems.

4.2 Semi-intensive aquaculture systems

Defining what it is exactly that distinguishes semi-intensive systems from extensive or intensive systems is not an easy task. Definitions of semi-intensive systems vary between countries and they do not always consider the same criteria (Islam et al., 2004). Lekang (2013) described semi-intensive system as a combination of an extensive and an intensive production and mentioned as an example an intensive fry production that is combined with an extensive on-growing rearing area. Semi-intensive systems have also been connected to feed and fertilization dependency. Nilson and Wetengere (1994) defined semi-intensive aquaculture systems as a farms where feeding is carried out at least twice per week and fertilizing once per week. Edwards and Demaine (1998) followed a similar line and stated that semi-intensive system mainly rely on natural food within the rearing area but also supported by supplementary feed or fertilization. They also acknowledged that the intensity of the system is not only correlated with the level of feed or fertilizers brought to the system but also with the level of seed, labor, capital and management.

From the articles reviewed here it seems that mechanical treatment methods are generally not applied (Islam et al., 2004) .Water exchange seems to be widely used in semi-intensive systems in order to improve water quality (Gutiérrez-Estrada, Pulido-Calvo, de la Rosa, &

Marchini, 2012) as well as chemicals such as lime can be added to disinfect and dry semi-intensive ponds (Islam et al., 2004; Lima, Rivera, & Focken, 2012).

The map of semi-intensive systems displayed in figure 8 includes the input function of stocking in full color indicating that all systems apply the function. Supplying water has been shaded with a transparent hue to indicate that not all semi-intensive need to allocate water to the system. Feeding and fertilizing have been shaded in a slightly lighter way to indicate that all semi-intensive systems include at least one of those functions. Providing light is presented with a deep transparent hue such as the function of supplying water to indicate that the function is not applied in all semi-intensive systems. In the map we have excluded the treatment functions of controlling pH since it was never linked to semi-intensive systems in the articles reviewed. The remaining treatment functions are shaded with a transparent hue to indicate that those functions can be applied but are not employed in all semi-intensive systems. Harvesting is always included in semi-intensive systems but the functions of processing effluent water, processing solid waste and controlling greenhouse gasses have been shaded since they do not seem to be applied in all semi-intensive systems.

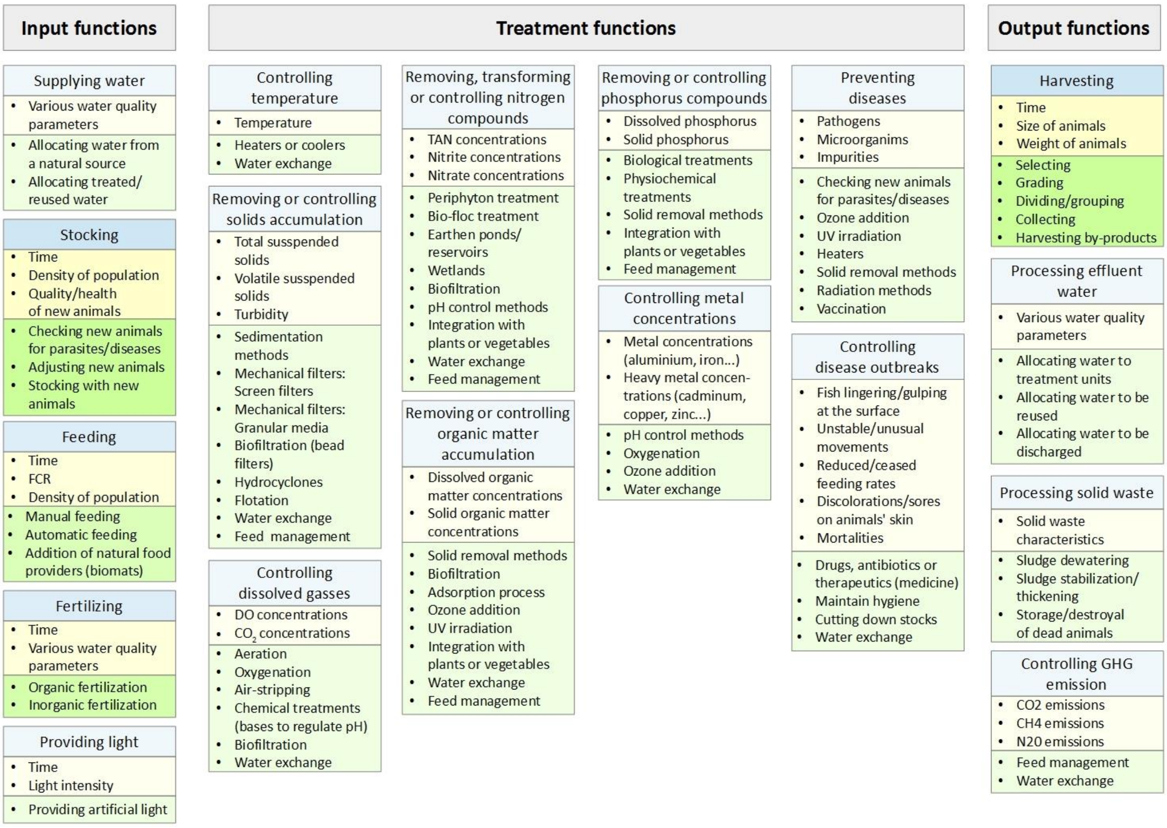


Figure 8: System map describing semi-intensive aquaculture systems.

4.3 Intensive aquaculture systems

Intensive systems have been classified as flow-through systems or recirculating systems (van Rijn, 1996). They were most frequently the issue of the articles analyzed for this study. Forty-eight articles discussed issues related to intensive aquaculture and all together those articles contribute to all the functions mentioned that have been identified in this study. Thus it can be concluded from this analysis that intensive systems can include all functions whether they are basic input function, treatment functions or output functions.

In the map describing intensive aquaculture systems the input functions of supplying water, stocking and feeding are always applied. The fertilizing function and the providing light function have been shaded in the map since not all intensive systems seem to apply those functions. As was stated before, intensive systems maintain high stocking levels and high feeding rates to maximize the production. Therefore we assume that all intensive systems need to apply the treatment functions that focus on maintaining the quality of the water. The functions of preventing diseases and controlling diseases are not applied to maintain water quality. Thus they are represented with a transparent hue in the map. All intensive systems apply the harvesting function as indicated in the map. Some intensive systems, such as flow-through systems, maintain steady water throughput and not all of them seem to apply the functions of processing effluent water or solid waste. Therefore, those functions have been shaded in the map. Controlling greenhouse gasses was not frequently related to systems of high intensities and therefore it is assumed that not all intensive systems apply methods to reduce greenhouse gasses emissions. Figure 9 displays the system map for intensive systems.

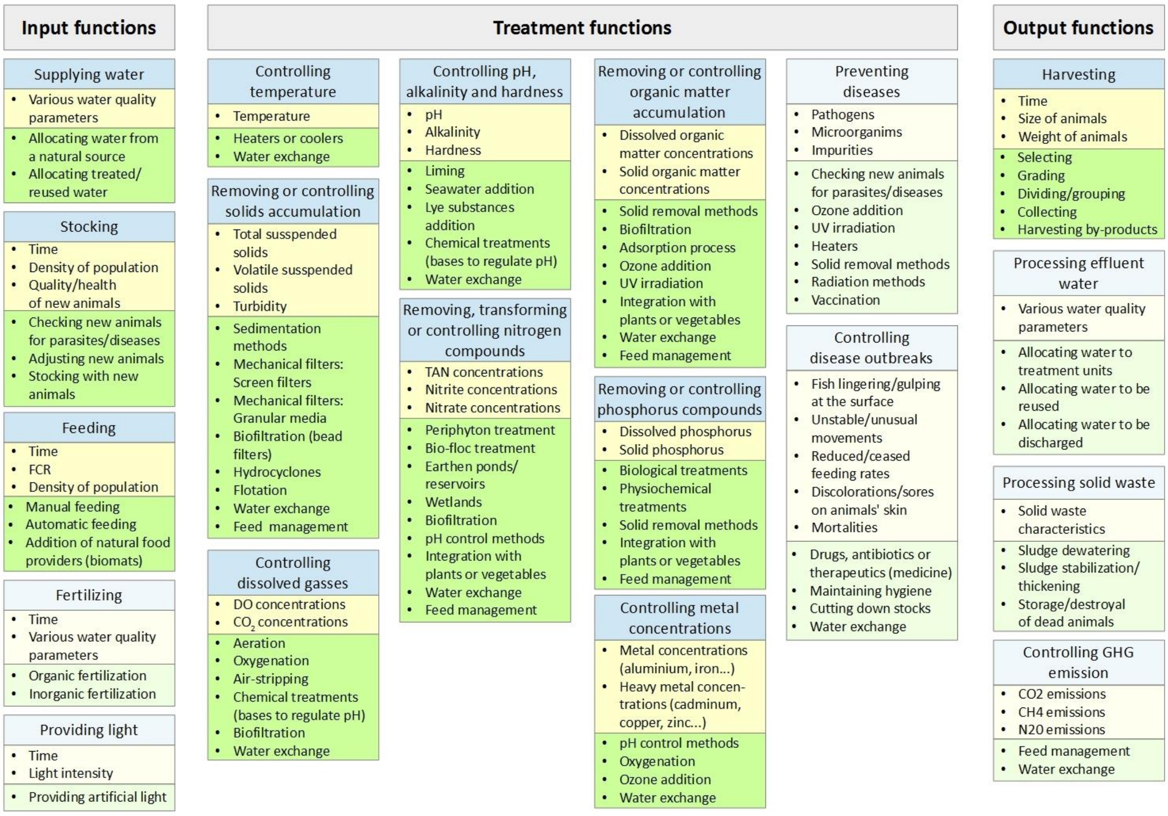


Figure 9: System map describing intensive aquaculture systems.

4.4 New definitions of system intensity levels in terms of the production functions

The analysis of system intensity levels has revealed that systems of different intensity levels differ in terms of their application of the production functions. This has provided a foundation to build new definitions of the intensity levels in terms of the production functions. The new definitions will be presented in the following subchapters.

4.4.1 The definition of extensive aquaculture systems in terms of production functions

All extensive systems rely on the input function of stocking. Extensive systems that are not located in a larger water body also need to apply the function of supplying water. In some cases, the functions of feeding and fertilizing are applied in extensive systems but to a very limited extent. No treatment functions are carried out in extensive systems and the only output function applied is harvesting.

4.4.2 The definition of semi-intensive aquaculture systems in terms of production functions

Semi-intensive systems apply the input functions of supplying water and stocking. Semi-intensive systems generally rely on natural food supplies but feeding and/or fertilizing inputs are added to the system up to some level as well as some systems need to apply the function of providing light. Furthermore, semi-intensive systems can apply the following treatment functions: (1) controlling temperature, (2) removing solids, (3) controlling dissolved gasses, (4) removing, transforming or controlling nitrogen compounds, (5) removing or controlling organic matter accumulation, (6) removing or controlling phosphorus compounds, (7) preventing diseases and (8) controlling disease outbreaks. All semi-intensive systems carry out the harvesting function. Some systems also carry out the functions of processing effluents or solid waste and controlling greenhouse gasses emissions.

In general, semi-intensive systems do not apply mechanical methods to carry out treatment functions. Water exchange and feed management is a common method applied to carry out treatment functions though chemicals or medicine are added in some cases to prevent diseases or to control disease outbreaks.

4.4.3 The definition of intensive aquaculture systems in terms of production functions

All intensive aquaculture systems apply the input functions of supplying water, stocking and feeding. In some cases, fertilizer inputs are added to the systems. Some systems need to apply the function of providing light. All intensive systems apply treatment functions up to some point and these are compulsory to maintain water quality: (1) controlling temperature, (2) removing solids, (3) controlling dissolved gasses, (4) controlling pH, alkalinity, and hardness, (5) removing, transforming or controlling nitrogen compounds, (6) removing or controlling organic matter accumulation, (7) removing or controlling phosphorus compounds and (8) controlling metal concentrations. These functions can be carried out with mechanical methods or non-mechanical methods depending on the type of systems. The treatment functions of preventing diseases and controlling disease outbreaks are applied when needed. All intensive systems include the output function of harvesting. Intensive systems that maintain high water exchange rate do not always apply the functions of processing effluent water and processing solid waste. Systems that do not use frequent water exchange or reuse water generally apply those functions. Some intensive systems apply methods to limiting greenhouse gas emissions.

5 Discussion

The functions introduced in this study have been defined from the results of a literature review of a selected set of articles. The map generated from this literature review may not be entirely complete since the coverage is limited by the articles selected. Numerous types of systems exist and their functions and technologies are constantly evolving in order to improve efficiency and to become more sustainable. Therefore the map needs to be adapted to new technologies and methods when they emerge.

Aquaculture operators strive to reach their production goals and the right application of the production functions helps them to accomplish that. But they also need to make sure that the effluent water or solid waste discharged from their facilities is not heavily loaded with contaminants that can pollute the environment. Each country has laws and regulations that put restrictions on pollutants coming from aquaculture facilities. Therefore it is the task of aquaculture operators to find balance between maximizing the production volume within the capacities of their system while following rules and regulations set by their environment. To reach that goal they need to carefully consider what functions are necessary and what methods are suitable for their type of system. The map that has been introduced in this study could be a good tool for aquaculture operators to analyze their production system and consider possibilities to improve their system.

Aquaculture facilities can take up a lot of land space. Limited availability of land and water for aquaculture systems is an issue constraining further growth of aquaculture production (FAO, 2014). It should therefore not come as a surprise that systems of high intensities have been studied quite thoroughly over the last years since they generally allow higher production rates than systems of lower intensity. The fact that capture fisheries have not increased their outputs for many years while consumption of aquatic animals keeps increasing puts a lot of pressure on improving intensive aquaculture systems. Aquaculture systems need to meet the increasing demand. At the same time, aquaculture operators need to minimize environmental effects from the systems.

As this work progressed it became clear to the author that aquaculture systems can be classified in many ways and therefore it is possible to make variations of the system map depending on the perspective of interest. It was decided to limit this study to intensity variations of the integrated system map but future studies could consider other variations.

A large part of the issues discussed regarding intensive systems are related to water quality. Water quality is of great importance to ensure the health and quality of the animals cultured inside an aquaculture system. Numerous water quality parameters were identified in the literature covered for this study, but not all of them have been mentioned here. Some compounds in the water, such as salinity, calcium, magnesium, chloride and sulfate, seem to be often measured and monitored but no methods intended to address them directly were identified in the set of articles analyzed. Since the purpose of this study was to identify the production functions of aquaculture systems those and other quality parameters that could not be related to a production function were not considered. However, it is likely that some of the methods discussed in this paper affect other parameters or issues than those that have been mentioned before. Some issues were intentionally excluded from the system map if they were considered out of the scope of this study. As an example, problems related to escaping fish were not addressed here since they seem to be closer related to structural issues of aquaculture systems.

Treatment functions are a vital part of many aquaculture systems and a large part of the functions within that group address quality issues. This study revealed that there are various methods that can be applied to solve different quality issues. Many of the methods discussed in this study are very technical but for some systems, such as flow through systems, water quality is maintained with frequent or constant water throughput. For other systems such as recirculating systems, which are designed to minimize water renewal, water quality problems are generally not resolved with water exchange. It seems that most recirculating systems need to apply many treatment functions to maintain the quality of the water within the system. Feed management was also a method related to many treatment functions as it seems that feed and feeding regimes are highly connected with many quality issues. When intensity variations of the map were created, the focus was set on analyzing the functions applied in systems of different intensity levels. However, it would have been possible to go deeper into the analysis and find out what methods are applied for each intensity level. Future studies could focus on this issue to get a deeper understanding of the functionalities of aquaculture systems within different categories.

It was noticed that intensity of systems has been vaguely described in the literature and there does not seem to be a concrete definition of what exactly characterizes systems of different intensity levels. As mentioned earlier, extensive systems should according to definition not include the feeding function. In spite of that, some of the articles reviewed classified systems as extensive ones even though they included the function of feeding or fertilizing. Two articles classified their systems as semi-extensive. But since neither the articles or the books and technical reports provided a definition of semi-extensive systems they were not considered in this work. Semi-intensive systems seem to be generally considered to be somehow in between extensive and intensive systems.

New definitions have been provided in terms of production functions from the work of this study but in the future more studies should focus on clarifying this issue. The articles selected for this study were not chosen in terms of intensity so there is no balance between the numbers of articles handling different intensity levels. Most articles discussed issues of intensive systems but a lot fewer focused on extensive or semi-intensive systems. The production functions of extensive and semi-intensive systems should be studied further in the future to verify or refute the results of this study.

It was decided to include all the production functions that were identified without regarding how often they were mentioned in the selected articles. As the graph in figure 6 revealed the frequency of coverage is not evenly distributed between the functions. There could be numerous reasons explaining the uneven distribution. Functions that can be carried out by many different methods might have gained more interest than those that cover only a few methods. As an example, issues related to the function of removing, transforming or controlling nitrogen compounds have been frequently studied in the literature. The function also includes more methods than most of the other functions. Another reason might be that some functions are more complex in application than others. In that case, they might be covered more frequently in order to resolve complexity issues. Another possibility is that there is a gap in the literature when it comes to those functions that have been less considered in the literature.

6 Conclusions

In this study a map of aquaculture production systems was introduced. The map was generated from a systematic literature review of over one hundred articles. It provides an overview of production functions applied in aquaculture systems and various methods used to carry them out. Each function has been defined and the methods belonging to them have been explained. Variations of the map representing systems of different intensities have also been presented to show what functions aquaculture systems of different intensities use. Furthermore, new definitions of the intensity of aquaculture systems in terms of production functions have been introduced. This map can be a good tool for professionals in the aquaculture sector to analyze aquaculture systems in terms of the production functions to look for possible improvements in the production area.

This work has created a foundation that will hopefully be built on. Technologies and methods in aquaculture production will continue to develop and emerge and therefore the map needs to be regularly updated. Extensive and semi-intensive systems should be studied further to verify or refute how they have been defined in this study in terms of production functions. Future studies in this area could also represent the system map from other perspectives depending on factors of interest. As an example, variations of the map could be created depending on the animals cultured and types of systems. Future studies could also focus on creating variations of the map in terms of the methods applied for different types of systems. Important water quality parameters in aquaculture systems could be studied further in order to connect them to production functions and methods used to address them. This study has also revealed that some production functions seem to have been widely covered in the literature while others have received less attention. The reason might be that there is a gap in the literature in terms of the functions that seem to have been studied less.

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Ziegler, F., Winther, U., Hognes, E. S., Emanuelsson, A., Sund, V., & Ellingsen, H. (2013). The Carbon Footprint of Norwegian Seafood Products on the Global Seafood Market. *Journal of Industrial Ecology*, *17*(1), 103-116.

Appendix

Excluded articles and reasons for exclusion

Bibliography	Reason for exclusion
Aitken, D., Bulboa, C., Godoy-Faundez, A., Turrion-Gomez, J. L., & Antizar-Ladislao, B. (in press). Life cycle assessment of macroalgae cultivation and processing for biofuel production. *Journal of Cleaner Production.*	About life cycle assessment of macroalgae (seaweed)
Ayer, N. W., Tyedmers, P. H., Pelletier, N. L., Sonesson, U., & Scholz, A. (2007). Co-product allocation in life cycle assessments of seafood production systems: Review of problems and strategies. *International Journal of Life Cycle Assessment, 12*(7), 480-487.	About LCA categories of fishery and aquaculture
Barbier, E. & Cox, M. (2002). Economic and Demographic Factors Affecting Mangrove Loss in the Coastal Provinces of Thailand, 1976-1996. *A Journal of the Human Environment, 31*(4). 351-357	Not related to aquaculture production functions
Belgis, C., & Guido, P. (2003). Cyst-based toxicity tests. XI. Influence of the type of food on the intrinsic growth rate of the rotifer Brachionus calyciflorus in short-chronic toxicity tests. *Chemosphere, 50*(3), 365-372.	About the ecosystem of aquaculture systems
Bosma, R., Anh, P. T., & Potting, J. (2011). Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. *International Journal of Life Cycle Assessment, 16*(9), 903-915.	About LCA categories of aquaculture
Bougeard, M., Le Saux, J. C., Perenne, N., Baffaut, C., Robin, M., & Pommepuy, M. (2011). Modeling of Escherichia coli Fluxes on a Catchment and the Impact on Coastal Water and Shellfish Quality. *Journal of the American Water Resources Association, 47*(2), 350-366.	About a model to describe ecosystem behaviour
Bourke, G., Stagnitti, F., & Mitchell, B. (1993). A decision support system for aquaculture research and management. *Aquacultural Engineering, 12*(2), 111-123.	About detailed description of a system
Buitrago, J., Rada, M., Hernandez, H., & Buitrago, E. (2005). A single-use site selection technique, using GIS, for aquaculture planning: Choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela. *Environmental Management, 35*(5), 544-556.	About site selection
Cao, L., Diana, J. S., Keoleian, G. A., & Lai, Q. (2011). Life cycle assessment of Chinese shrimp farming systems targeted for export and domestic sales. *Environmental Science & Technology, 45.* 6531–6538.	About LCA categories of aquaculture
Dakui, Z., Martini, L. P., & Brookfield, M. E. (1998). Morphology and land-use of the coastal zone of the North Jiangsu Plain Jiangsu Province, eastern China. *Journal of Coastal Research, 14*(2). 591-599.	About land use, not related to production functions
Dalsgaard, J. P. T., Lightfoot, C., & Christensen, V. (1995). Towards quantification of ecological sustainability in farming systems analysis. *Ecological Engineering, 4*(3), 181-189.	About farming systems in general and sustainability
Davis, J., & Sonesson, U. (2008). Life cycle assessment of integrated food chains-a Swedish case study of two chicken meals. *International Journal of Life Cycle Assessment, 13*(7), 574-584.	About another industry
Fredriksson, D. W., DeCew, J., Swift, M. R., Tsukrov, I., Chambers, M. D., & Celikkol, B. (2004). The design and analysis of a four-cage grid mooring for open ocean aquaculture. *Aquacultural Engineering, 32*(1), 77-94.	About the structure of a system

Fredriksson, D. W., Swift, M. R., Eroshkin, O., Tsukrov, I., Irish, J. D., & Celikkol, B. (2005). Moored Fish Cage Dynamics in Waves and Currents. *Journal of Oceanic Engineering (Vol. 30)*. 28-36.	About the structure of a system
Garcia, F. Kimpara, J. M., Valenti, W. C., & Ambrosio, L. A. (2014). Emergy assessment of tilapia cage farming in a hydroelectric reservoir. *Ecological Engineering, 68,* 72-79.	About emergy evaluation, does not address production functions
Halachmi, I., Simon, Y, Mozes, N. (2012). Simulation of the shift from marine netcages to inland recirculating aquaculture systems. *Annals of Operations Research, 219*(1), 85-99.	About a simulation model
Halachmi, I., Simon, Y., Guetta, R., & Hallerman, E. M. (2005). A novel computer simulation model for design and management of re-circulating aquaculture systems. *Aquacultural Engineering, 32*(3-4), 443-464.	About layout of facilities
Heaven, S., Salter, A. M., Clarke, D., & Pak, L. N. (2012). Algal wastewater treatment systems for seasonal climates: Application of a simple modelling approach to generate local and regional design guidelines. *Water Research, 46*(7), 2307-2323.	About system design and site selection
Holland, D. S., & Lee, S. T. (2002). Impacts of random noise and specification on estimates of capacity derived from data envelopment analysis. *European Journal of Operational Research, 137*(1), 10-21.	About data envelop analysis and fisheries
Hossain, M. Z., Tripathi, N. K., & Gallardo, W. G. (2009). Land Use Dynamics in a Marine Protected Area System in Lower Andaman Coast of Thailand, 1990–2005. *Journal of Coastal Research, 25*(5), 1082-1095.	About land use, not related to production functions
Huan, J., Liu, X., & Chong, Q. (2014). Design of an aquaculture monitoring system based on Android and GPS. *Applied Engineering in Aquaculture, 30*(4), 681-687.	About a monitoring systems, not related to the production
Huysman, S., Schaubroeck, T., & Dewulf. J. (2014). Quantification of Spatially Differentiated Resource Footprints for Products and Services through a Macro-Economic and Thermodynamic Approach. *Environmental Science & Technology, 48,* 9709-9716.	Not related to aquaculture production functions
Jana, B. B., Rana, S., & Bag, S. K. (2012). Use of human urine in phytoplankton production as a tool for ecological sanitation. *Water Science and Technology, 65*(8), 1350-1356.	About the ecosystem of aquaculture systems
Kleisner, K. M., Longo, C., Coll, M., Halpern, B. S., Hardy, D., Katona, S. K., . . . Zeller, D. (2013). Exploring Patterns of Seafood Provision Revealed in the Global Ocean Health Index. *Ambio, 42*(8), 910-922.	About the global health index
Kohler, E. A., Poole, V. L., Reicher, Z. J., & Turco, R. F. (2004). Nutrient, metal, and pesticide removal during storm and nonstorm events by a constructed wetland on an urban golf course. *Ecological Engineering, 23*(4-5), 285-298.	Not related to aquaculture production functions
Kokkinakis, A. K. (2014). Semi-extensive fishery management of environmental sensitive mediterranean coastal wetlands in north-eastern Greece. *Journal of Environmental Protection and Ecology, 15*(2), 630-642.	About fishery management
Lalonde, B. A., & Ernst, W. (2012). Analysis of Benthic Invertebrate Communities as a Function of Distance from Two Fish-Processing Plant Effluent Discharges in New Brunswick, Canada. *Archives of Environmental Contamination and Toxicology*, 63(1), 45-53.	About effluents from fish-processing plants
Lamoureux, J., Tiersch, T. R., & Hall, S. G. (2006). Sensitivity analysis of the pond heating and temperature regulation (PHATR) model. *Aquacultural Engineering, 34*(2), 117-130.	About sensitivity analysis of a temperature model
Lee, P. G. (1995). A review of automated control systems for aquaculture and design criteria for their implementation. *Aquacultural Engineering, 14*(3), 205-227.	A review about aquaculture control systems
Lee, P. G. (2000). Process control and artificial intelligence software for aquaculture. *Aquacultural Engineering, 23*(1-3), 13-36.	About a software for aquaculture

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