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Article

Taxonomy of Means and Ends in Aquaculture Production—Part 2: The Technical Solutions of Controlling Solids, Dissolved Gasses and pH

Bjorgvin Vilbergsson, Gudmundur V. Oddsson * and Runar Unnthorsson

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, Centre for Productivity, Performance and Processes, University of Iceland, Hjardarhagi 6,107, Reykjavik IS-107, Iceland; bjoggivil@gmail.com (B.V.); runson@hi.is (R.U.)

* Correspondence: gvo@hi.is; Tel.: +354-525-4635

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Abstract: In engineering design, knowing the relationship between the means (technique) and the end (desired function or outcome) is essential. The means in Aquaculture are technical solutions like airlifts that are used to achive desired functionality (an end) like controlling dissolved gasses. In previous work, the authors identified possible functions by viewing aquaculture production systems as transformation processes in which inputs are transformed by treatment techniques (means) and produce outputs (ends). The current work creates an overview of technical solutions of treatment functions for both design and research purposes. A comprehensive literature review of all areas of technical solutions is identified and categorized into a visual taxonomy of the treatment functions for controlling solids, controlling dissolved gasses and controlling pH alkalinity and hardness. This article is the second in a sequence of four and partly presents the treatments functions in the taxonomy. The other articles in this series present complementary aspects of this research: Part 1, A transformational view on aquaculture and functions divided into input, treatment and output functions; Part 2, The current taxonomy paper; Part 3, The second part of the taxonomy; and Part 4, Mapping of the means (techniques) for multiple treatment functions.

Keywords: aquaculture production; transformation view; treatment function; taxonomy; technical solution

1. Introduction

The role of aquaculture is becoming more important as a solution to feeding an increasing planet population. At the same time, aquaculture practitioners are feeling the pressure to make the production more environmentally friendly and sustainable [1]. With limited freshwater supply and increased emphasis on the conservation of marine waters, utilizing the water resources in the best way possible is key. Recirculating aquaculture systems are designed to treat and recirculate the process water, therefore minimizing the amount of water intake and maximizing waste management and nutrient recycling [1]. Recirculating systems are closed systems that offer a high level of security and control over the environment the fish grow in, maximizing their potential to achieve the highest growth and survival rates. They are constructed out of multiple modules (subsystems), each designed to control specific water quality parameters.

Recent developments in recirculating aquaculture systems are focused on technical improvements of individual components and re-utilization of nutrients through integration of fish and plants/algae [1]. Recirculating systems, however, are not perfect and have various problems. Many different solutions for recirculating systems exist and many have failed or are having difficulties that often can be traced back to the system design [2]. A general overview of available technical solutions and "how to integrate it all together" is missing [2].

Answering the call for more production in an environmentally friendly way will require an excellent understanding of how the aquaculture system works and how each function is performed. The purpose of this paper is to create the next step in such an overview by finding all the technical solutions and aligning them in a taxonomy. This is done to facilitate design information sharing, formalize design approach with the aim to someday be able to create a successful aquaculture engineering design methodology.

This research builds on a study by Bjornsdottir et al. [3] and uses the transformation view on aquaculture production [3], i.e., input, treatment and output functions. The input functions are identified as: supplying water, stocking, feeding, fertilizing and providing light, while the output functions are harvesting, processing effluents, processing solid waste and controlling greenhouse gas (GHG) emission. However, the input and the output of the transformation process is not within the scope of this work. The treatment functions are shown in Figure 1.

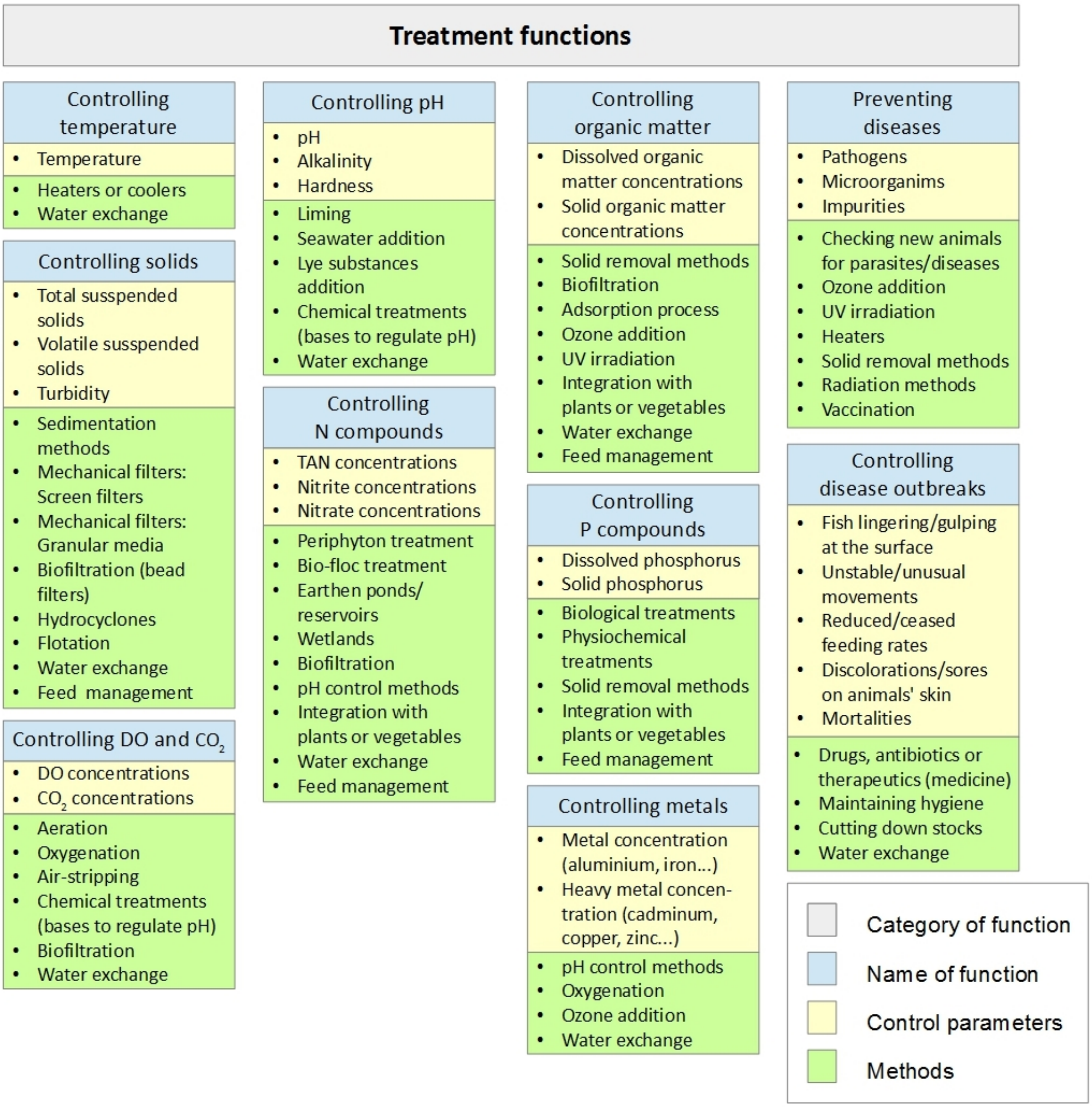

Figure 1. Treatment functions in aquaculture production [3].

The main aim of this work is to map out all the known technical solutions to each treatment function, describe them briefly and lay out a taxonomy of technical solutions. The purpose for doing this is to facilitate the creation of aquaculture engineering design methodology and highlight possible gaps for further research in this field.

2. Materials and Methods

The method used in this research is an extended synthesis of previous work on a taxonomy. This is done with a comprehensive literature review on the basis of keywords generated by Bjornsdottir et al. [3] previous work (in Part 1). The scope, execution and synthesis of the literature review are described in the next few sections.

2.1. Scope

This article is limited to the functions identified by Bjornsdottir et al. [3]. Only a general description of technical solutions is given here. Certain design attributes, often specific to each producer, are not covered; this paper only intends to create an overview of available solutions. Later, further research is planned for discovering how they can affect the treatment functions. Designing a system or giving any indications on how a system should be designed, is out of scope of this paper. The taxonomy of technical solutions is presented in two articles (Parts 2 and 3); part of the technical solutions are described in this article and the other is described in Part 3 [4]. A holistic view of this series of research is in Table 1.

Table 1. Overview on how the research is divided into articles.

Article	Description
Part 1—The Functions [3]	The transformational view on aquaculture is introduced and functions are divided into input, treatment and output functions. There are 5 input functions, 10 treatment functions and 4 output functions. Key parameters used to control are identified and a nearly exhaustive list of possible methods of technical solutions is provided. The results are presented as a map.
Part 2—Technical solutions for controlling solids, dissolved gasses and pH functions (the current article)	The map of aquaculture production is used to find all possible technical solutions for all the methods in 3 treatment functions: the controlling solids, dissolved gasses and pH functions. The result is a partial taxonomy of treatment functions through methods to technical solutions.
Part 3—Technical solutions for controlling N compounds, organic matter, P compounds, metals, temperature and disease prevention functions [4]	The map of aquaculture production is used to find all possible technical solutions for all the methods in the 6 treatment functions, the controlling N compounds, organic matter, P compounds, metals, temperature and disease prevention functions. A complete taxonomy of technical solutions is presented.
Part 4—The mapping of technical solutions onto multiple treatment functions [5]	The one-on-one relationship between a technical solution and a treatment function relaxed. The technical solutions from Parts 2 and 3 are analysed and all their effects on treatment functions are mapped out. Each relationship is put into one of three categories: intended, positive effect and negative effect. The result is a quality-function-deployment presentation of the interaction between solutions and functions.

2.2. Literature Review

This work is based on a literature review. Literature searches were carried out using The Web of Science^{TM} online service. Two search sets were selected to be further analysed for this study, with the keywords "aquacultur*" and "RAS" vs. "aquacultur*" and "reus*". Search 1 delivered 126 results and search 2 delivered 96 results. After the results were combined and the duplicates were deleted, the total count of 210 results, the articles were then analysed in order to filter out those that did not discuss specific technical solutions to the relevant treatment function. The first filtering stage resulted in 116 articles. In the end, only 48 articles from the original search were used, backward search resulted in 43 articles and books and specific searches resulted in 37 articles. Occasionally companies' websites were searched for more detailed descriptions of certain technical solutions. Searching The Web of Science^{TM} using relevant search terms produced very few publications that provided a general overview of available technical solutions [6]. Most were specific to certain types of components [7–9]. No taxonomy of technical solutions used in aquaculture was discovered. Furthermore, no publication could be found providing an overview of how these technical solutions influence other treatment functions. This paper is a beginning to bridging this obvious gap in literature.

2.3. Synthesis

After the literature review, the material on technical solutions was grouped by the treatment functions and methods identified by Bjornsdottir et al. [3]. The methods were classified wherever they were relevant. The authors strove to use existing classification whenever it was available; however, this was not always possible, so some classifications where suggested by the authors. Figure 2 explains the taxonomy setup and shows as well as how this paper adds to previous work.

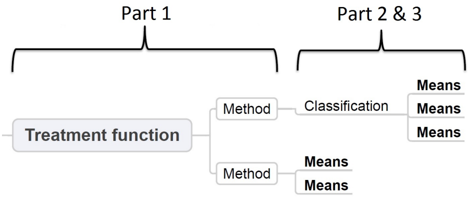

Figure 2. Scope of this paper.

The following section is the first part of the taxonomy of technical solutions.

3. Resolving Treatment Functions for Controlling Solids, Controlling Dissolved Gasses and Controlling pH, Alkanity and Hardness

In aquaculture, it is important to maintain optimum water quality, a healthy culture and high growth rates to achieve a satisfactory harvest. For this reason, certain treatment functions need to be applied. Treatment functions can be solved in various ways through different methods. In this section, the technical solutions to these methods, referred to as "means", will be identified and explained. Figure 3 displays the taxonomy of means discussed here (shown in boldface) and linked to the main treatment function they solve. In some cases, the methods themselves are boldfaced, either because they are discussed within another treatment function or because further classification has not yet been done. This section begins by examining the general solutions that apply to many treatment functions—i.e., feed management and water exchange—before explaining each treatment function more thoroughly: controlling solids, controlling dissolved gasses (or DO and CO_2) and controlling pH, alkalinity and hardness, respectively. Partial taxonomies of means are shown in Figures 4–14, which are presented in the remainder of this section.

3.1. General Solutions: Feed Management and Water Exchange

The feed is the source of most of the nutrients in intensive aquaculture systems, and its management can have a major impact on the water quality within the system. Consequently, water exchange is used to maintain the water quality in all the aquaculture systems. Flow-through systems rely mainly on water exchange while recirculating aquaculture systems aim to minimize their water usage, therefore applying other treatment functions as well. Feed management and water exchange are used in the control of multiple treatment functions [3]. To avoid redundancy, these topics will be discussed separately from other methods.

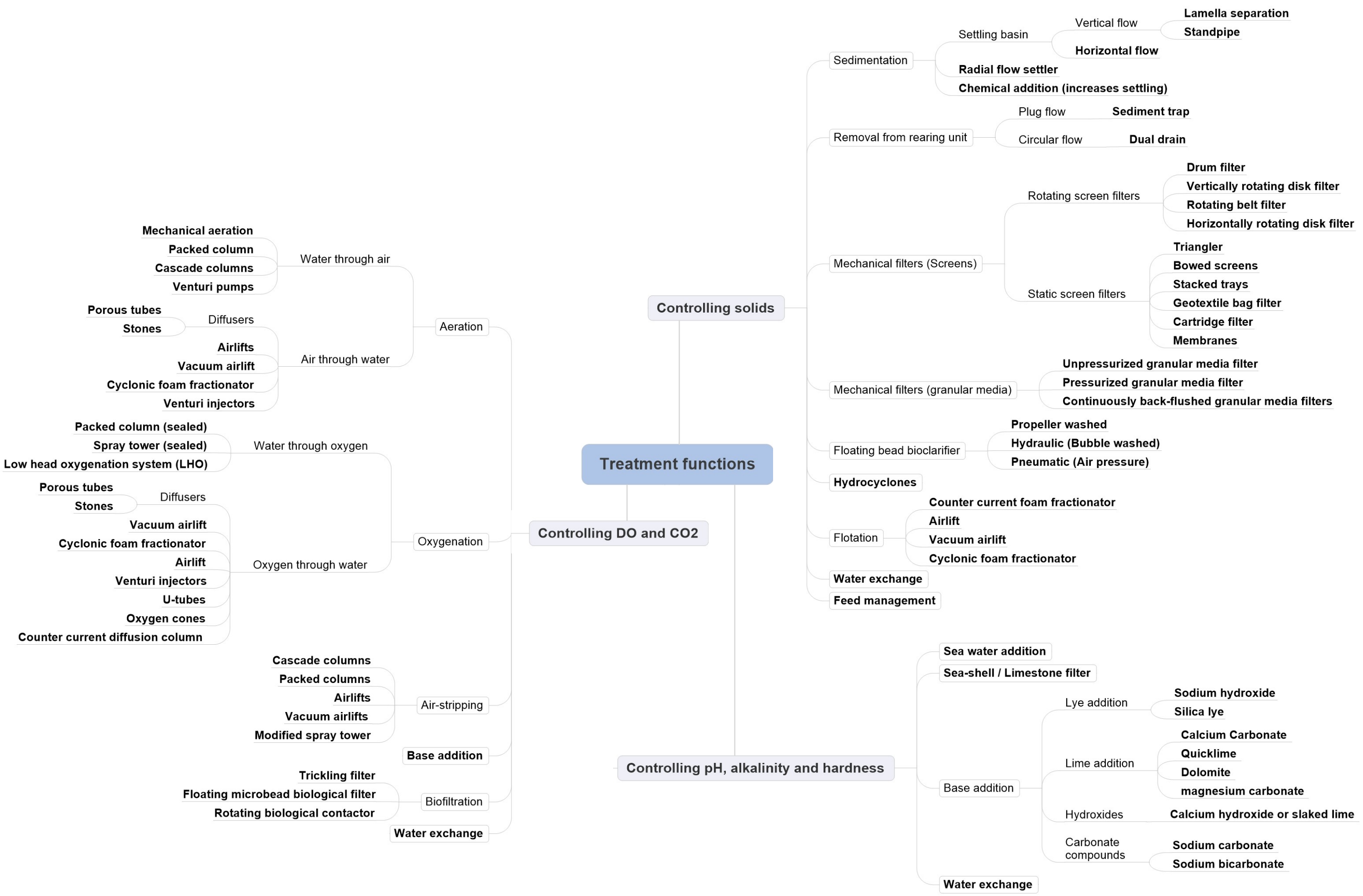

Figure 3. Taxonomy part 1.

3.1.1. Feed Management

Feed management concerns multiple treatment functions in aquaculture systems: controlling solids, organic matter, phosphorus (P) and nitrogen (N) compounds [3]. Oxygen requirements are influenced by feed management [10]. Minimizing solid production by maximizing feed utilization reduces the "required capacity of treatment systems" [8]. Feed can end up as a waste in two ways: either after being consumed and excreted by the fish or not being consumed at all and becoming settleable and suspended waste. As a result, if the fish is fed too much, the non-consumed feed becomes waste in the system, but if it is fed too little, its growth will be limited. To minimize feed waste, first of all, the nutritional composition and formulation of the feed needs to be adequate for maximizing the fish's nutrient uptake and minimizing the P and N compounds in its excretions. Second, the amount of feed required daily needs to be determined by using feed charts, which are often provided by feed manufacturers or in publications, or by using models to predict the growth and energy requirements of the cultured species. Finally, the fish needs to be given adequate time to consume their determined amount of feed [11].

Due to the high water recirculation rate used in recirculating aquaculture system facilities, feeding the fish only once per day is not likely to give it enough time to consume all the feed before it is washed out of the tank. It is important to remember that feeding frequency and regime could greatly influence the production of waste (e.g., solids and P and N compounds), causing peaks in its concentration [12–15] which requires increased capacity in certain treatment functions. Practicing continuous or high feeding rates, however, would result in more stable production of waste, lowering the treatment capacity requirements.

Monitoring the fish's behaviour helps determine when is the best time to feed it. A human observer can evaluate the fish's appetite to determine when and how much to feed it. Computer techniques that have been developed for monitoring fish behaviour [16] and uneaten pellets [8] could save labour cost and increase feeding accuracy.

3.1.2. Water Exchange

Water exchange can be used to manage nearly all the treatment functions. In flow-through systems, water exchange is used to bring the water quality to acceptable levels. The removal rate of waste products by water exchange needs to equal their mass production rate to avoid waste accumulation within the system [17]. In systems where water is recirculated, the water quality is maintained by recirculating the water through the water treatment system, in addition to the water exchange. The water exchange rate then becomes dependent on the recirculation rates and the efficiency of the water treatment [18]. The recirculation rate, the water treatment and the water exchange need to be calibrated together to meet the cultured species requirements for oxygen and concentration of waste products such as CO_2, ammonia [19], nitrate [20], solids [17], etc. Too high levels of water exchange indicate that the water treatment system is not effective enough [21]. Consequently, if the water treatment system cannot restore the water quality to acceptable levels, water exchange needs to take place.

3.2. Controlling Solids

The rapid removal of solids is a critical function in aquaculture systems. Solids mainly originate from feed and fish excretions. Particles can irritate fish gills, nourish fish pathogens [22], consume dissolved oxygen and disrupt the functions of other units in the system. Therefore, solids must be removed as soon as possible from the rearing tank. The function of controlling solids covers all the methods used to remove or control the accumulation of solids in the culture water, whether they are floating or settling. Solids can be either inorganic or organic matter, so the means presented here can be used in the control of organic matter as well. By removing solids, the biochemical oxygen demand (BOD) in the system is reduced along with the N and P compounds [23]. Several methods are used for solid control: sedimentation methods, mechanical filters (screens or granular media), biofiltration (bead filters), hydrocyclones, flotation along with previously mentioned water exchange and feed management. This section deals with the means used to carry out the treatment function of controlling solids.

3.2.1. Removal of Solids from the Rearing Unit

Settleable particles can be separated from the main water flow from the rearing unit by controlling the water flow in and out of the tank and by proper positioning of drains. Figure 4 displays the partial taxonomy categorized as removal of solids from the rearing unit. In raceways with a plug-flow (the flow parallel to the long axis of the raceway), the water flow, near the bottom of the rearing unit, can be increased and a sediment trap can be placed at the end across the entire width of the raceway [6]. Dual-drain systems are a way to extract suspended solids from a circular fish-rearing tank and are often the first step in the solid control. One drain is placed in the bottom centre, and the rotational motion of the water flow is used to attract particles towards the drain. Concentrated sludge can then be removed through this drain while the majority of the water flow is withdrawn through an elevated drain [18,23]. Several designs exist such as the Cornell dual-drain system with a centre and a sidewall drain [24] and the particle trap "ECO-TRAP" with both drains in the centre, one on top of the other [25].

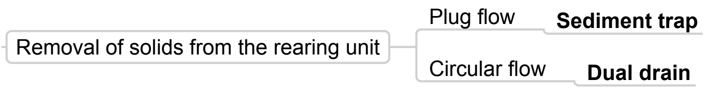

Figure 4. Removal of solids from the rearing unit—from the controlling solids section of the taxonomy.

3.2.2. Sedimentation Methods

In sedimentation methods, the relative higher density of particles is used to separate settleable solids from the main water flow. It is often used as the first stage in solid removal [8]. Figure 5 displays the partial taxonomy categorized as sedimentation.

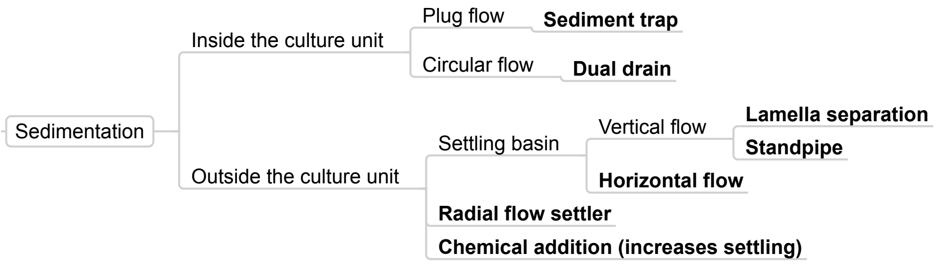

Figure 5. Sedimentation—from the controlling solids section of the taxonomy.

A radial-flow settler (or "gravity thickening settler") is a circular tank with the water inlet at the periphery of the unit. Water flows outwards in a radial direction and is collected at the perimeter of the settler. Settleable particles are gathered at the center of the settler and sink to the bottom, where they are extracted [26]. Chemicals (polymers, alum or a combination of both) can be added to increase the coagulation or flocculation of fine particles, increasing their size and settling speed [27]. This technique makes the removal of small particles easier.

Settling Basin

A settling basin is a tank or unit where the water flow is slowed down in order to let solids settle by gravitational forces [24]. The settled particles collect at the bottom or on constructed surfaces and need to be extracted from the unit later. Clarified water exits the basin from an elevated position. In high intensity recirculating systems, settling basins can be located inline for water reuse [23] or offline, where they are used for further sludge treatment [8,28], and various different designs exist. The settling basin can be designed to have a horizontal or vertical flow, but in either case, the water flow through the unit must not exceed the sinking velocity of the particles. The simplest design is a tank with large surface area and a horizontal flow, and with the inlet and outlet at the opposite end. The outlet is positioned so that it collects the top water flow, where the particles have had time to sink below the outlet.

A simple vertical flow design is the standpipe where the water flow moves upwards slower than the settling velocity of the particles [23]. A lamella plate or tube separation filter can also be added to increase the efficiency of the basin [6]. Plates or tubes are angled, arranged only a few centimetres apart. Process water flows upwards while the plates regulate the water flow and allow particles to have a short settling distance. Another method is called "biological lamella sedimentation" in which a biofilm is established on bioblocks that attract small particles and increases the settling basin efficiency [29]. Cleaning of settling basins needs to be done regularly due to potential nutrient leakage and re-suspension of particles [30]. This can be accomplished in various ways, either manually or automatically using scrapers, vacuums, vibration, tank design for sludge collection, flushing or air diffusers.

3.2.3. Mechanical Filters: Screen Filters

Studies show that recirculating aquaculture systems are dominated by fine particles [8,31]. To remove fine and suspended solids, special methods need to be applied. Chemical addition can be used to increase flocculation of small particles, therefore increasing the performance of these methods. When removing suspended and fine solids, which pass through settling methods or swirl separators, screens are often the next step. Screens are made of fine mesh material stretched on a frame. Water is passed through it, leaving small particles on the mesh surface; eventually, these accumulated particles need to be removed—either manually or by backwashing, mechanical vibration or vacuuming [18]. These filters can have different shapes and designs, which can be classified into static and rotating screens, as shown in Figure 6.

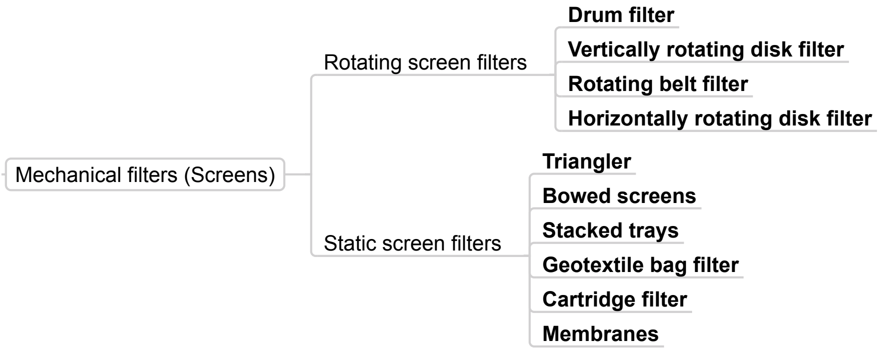

Figure 6. Mechanical filters (screens)—from the controlling solids section of the taxonomy.

Various parameters influence the performance of screen filters; their pore or mesh size, the size of the submerged area and the backwashing frequency all have major influences on a filter's flow capacity and particle capture ability [32]. With time, the layer of solids on a filter gets thicker, stopping smaller and smaller particles. Eventually, the cloth gets blocked, and water can no longer pass through the filter; this layer is called "filter cake". The thickness of the filter cake can be controlled with the frequency of backwashing and used as a method to filter out particles smaller then the filter's pore size [32]. High-pressure water or air is used to wash the particles of the filter in a direction opposite from the one which they landed on the filter surface. Backwashing is either continuous or is intermittent; its frequency is automatically controlled using sensors [8,18,27].

Rotating Microscreen Filters

Microscreen drum filters are most widely used in recirculating aquaculture systems [2]. In a drum filter, a straining cloth is fixed to a drum frame rotating on a horizontal axis. Partially submerged, water flows into the drum and passes radially through the straining cloth, which captures fine particles if it has an appropriate mesh size. A vertically rotating disk filter is a set of vertical disks that the water needs to pass through perpendicularly. The disks are arranged having decreasing mesh size gradually capturing smaller particles and rotating them out of the water [6]. A rotating belt filter is a belt cloth set at an incline. The process water passes through the submerged part of the belt, and particles collect on the belt. The belt rotates, lifting the particles out of the water [27]. A horizontally rotating disk filter is placed above the water surface. The processing water comes in from above and filters through the circular cloth, which then rotates for easy removal of trapped particles [18].

Static Screen Flters

Static screens are a fixed obstruction in the process water path. It can be from either fine mesh material, a grading (perforated) plate or a bar rack. The Triangle$^{\mathrm{TM}}$ filter is a static screen set at an angle. The main water flows down onto and through the screen while it simultaneously carries particles down the filter's sloped surface to the sludge collector [33]. Bowed screens are similar in design to triangle filters. The mesh surface is bowed; water enters from the top and passes through the filter. Part of the water travels with the filter's surface and carries the filtered particles to the sludge collector. Stacked perforated trays allow water to trickle down through the stack. Each tray can be set at an incline, leading overflow water to the next tray below and leaving particles on the tray's surface [34].

Geotextile bag filters are mostly used in sludge dewatering. Process water is pumped into the bag, which retains particles inside while water leave through the bag walls [35]. The bag is placed in a containment basin for water collection [36]; when the bag starts to become clogged, it is either replaced or washed.

A cartridge filter is an easily replaceable filter unit that is replaces when it becomes clogged. Depending on the supplier, it can be made of different materials and collect particles below 1 µm [18] (p. 51).

Membranes have been tested for controlling colloidal particles (30 nm–1 µm) in reuse systems [37]; they can reduce turbidity and potentially be used for advanced water treatment in recirculating aquaculture systems where extra high water quality is needed [38]. A challenge with membranes is that particles form a cake layer and the pores are clogged by colloidal particles. Biofouling, caused by dissolved and submicron colloidal particles in the system, can also become a problem in membranes. To control this issue, air-scouring and periodic backwashing and relaxation techniques are used [37]; chemical cleaning needs to be used occasionally as well [38].

3.2.4. Mechanical Filters: Granular Media

In granular media filters, the process water is forced through a layer of granular material such as sand, gravel or plastic. Based on their hydraulic capacity, granular media filters can be classified, as unpressurized, pressurized or continuously back-flushed [18]. Partial taxonomy is presented in Figure 7.

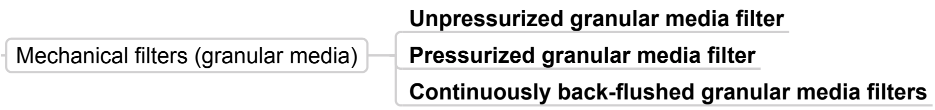

Figure 7. Mechanical filters (granular media)—from the controlling solids section of the taxonomy.

The process water is filtered through a medium, trapping suspended solids. The filter medium can be of various shapes, sizes and densities, all depending on the filter's application. The filter can be packed with media ranging in size and density, creating layers that capture different particle sizes [18]. The process water travels with either an upward flow through the filter's bed or a downward flow. Common types used in aquaculture are the down-flow pressurized sand filter and the up-flow sand filter [39]. If not continuously back-flushed, solids accumulate in the media bed and within the unit. When backwashing, water is flushed in the opposite flow direction, the fixed bed is expanded and solids trapped within the medium are released [40].

3.2.5. Floating Bead Bioclarifier

Bead filters offer both biofiltration (covered in part 3 [4]) and solid capture, although optimizing it for both functions might be difficult [8]. Bead filters (Figure 8) have a fixed bed of low-density plastic beads that are kept afloat by upward water flow. The beads come in various shapes, sizes and densities. Solids are trapped in the beads as the process water passes up through the bed. In a bead filter, solids are caught by four mechanisms: sedimentation, straining, interception and adsorption [41]. Solids accumulate in the bed and within the unit and need to be backwashed on a regular basis. Backwashing can be done by mechanical (propeller), hydraulic (hour glass) or pneumatic means [41].

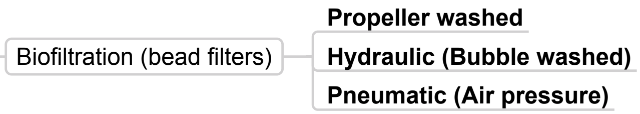

Figure 8. Biofiltration (bead filters)—from the controlling solids section of the taxonomy.

A propeller-washed bead filter uses a propeller located within the bed of beads to expand the bed, releasing solids that were trapped within [42]. After the expansion, the beads are allowed to re-float and form the filter bed while the solids settle and concentrate at the bottom of the chamber [6]. The sludge is then removed through a bottom valve, which can be either automated [39] or manual [42].

Another bead filter design is the bubble washed bead filter. Shaped like an hourglass, the filter has two chambers connected by a narrow "throat". In the upper chamber the fixed bed filtrates solids out of the up-flowing water. When backwashed all the water is flushed out of the unit and the chamber filled with air. The beads pass through the narrow throat, and air bubbles release trapped solids [42].

The third type of bead filter is a filter that uses charged air for backwashing. Water flows upward through the floating bead bed, and at the same time, air is forced into a separate charge chamber. When a certain amount of air pressure is reached, the air is released below the media bed. The sudden release of air agitates and expands the bead bed, releasing trapped solids, which then collect in the charge chamber and are later removed [43].

3.2.6. Hydrocyclones

In a hydrocyclone or swirl separator, a circular flow is created inside a cylinder by letting the inlet water in tangentially. Centrifugal forces move heavy solids towards the wall and down to the bottom, of a cone shaped bottom where the discharge is continuous [6]. One of the downsides of hydrocyclones, however, is that they need constant water speed and only remove large, heavy particles.

3.2.7. Flotation

Flotation, also known as protein skimming or foam fraction, can be used to concentrate solids. Fine suspended solids and dissolved organic compounds can be removed by using foam fraction [24] (p. 254). Bubbles of air are introduced at the bottom of a closed column of water and particles attach to the surface of the bubbles, which collect at the top and form foam [6]. The partial taxonomy is shown in Figure 9.

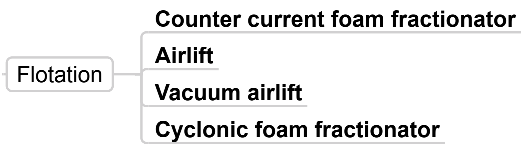

Figure 9. Flotation—from the controlling solids section of the taxonomy.

Counter current flow has been used to increase the contact time between the water and the air, increasing the efficiency of the equipment. Water is introduced at the top of the column and flows down against a stream of rising bubbles [6]. In airlifts [44] and vacuum airlifts [45], the diffused air is used to create an upward flow of water within the pipe, providing water transport in addition to foam fraction [45]. Bubble size and quantity influence the performance of airlifts [45]. Cyclonic foam fractionators use high water flow to create foam in a foam chamber. The foam is collected in a condensation chamber that is equipped with a suction pump for removing the separated foam [46].

3.3. Controlling pH, Alkalinity and Hardness

Proper pH management is vital for the optimum performance of recirculating aquaculture systems [47]. The treatment function of controlling pH, alkalinity and hardness covers all methods used to control those parameters in the culture water [3]. This section deals with the means used to carry out the treatment function controlling pH, alkalinity and hardness. The pH is an indicator of the hydrogen ion concentration ($[H^+]$) in aqueous solutions. Pure water at 25 degrees Centigrade has a pH value of 7; pH value above 7 are considered basic, and pH value below 7 are considered acidic. Alkalinity is a measure of the buffering capacity of water, i.e., the water's capacity to neutralize strong acids therefore keep the pH constant [48]. Hardness expresses the concentration of metal ions in the water, which are primarily calcium (Ca_2^+), magnesium (Mg_2^+), iron, and manganese [49].

pH and Alkalinity

Most freshwater aquatic species have an optimum pH between 6.5 and 9 [49]. CO_2 production in aquaculture lowers the pH in the system, but with higher alkalinity concentrations, the effect that a CO_2 increase has on the pH is decreased. Furthermore, increasing the pH decreases the CO_2 concentration by shifting the carbonate carbon balance to bicarbonate and carbonate ions [50]. Adding or removing dissolved CO_2 affects the form of alkalinity, but it "does not affect overall alkalinity concentration" [51]. The relationship between pH and alkalinity requires careful monitoring and adjustment of both the alkalinity and CO_2 levels to maintain optimum pH [49]. For better understanding the concepts and the relationship between CO_2, alkalinity and pH, further readings are recommended [48,51].

In addition to being directly crucial to the growth and health of the cultured species, the pH also controls the ratio of un-ionized ammonia (NH_3) and ionized ammonia NH_4^+) that are formed. It also has a major effect on the performance of nitrifying bacteria in biofilters [47] and influences the toxicity of hydrogen sulfide and metals such as copper, cadmium, zinc and aluminium [49].

Hardness

Maintaining appropriate hardness in the culture water is important. Some species thrive better at lower hardness levels (soft water), while others thrive better at higher hardness levels (hard water) [52]. The culture water needs to be relatively hard to support the development of fertilized fish eggs and the calcification of larval skeletal structures. Recommended hardness levels in aquaculture water range from 20 to 300 mg/L $CaCO_3$. By adding calcium and magnesium, the water is hardened, decreasing the toxicity of dissolved metals [49].

Several methods exist for controlling the pH, alkalinity and hardness of the culture water in aquaculture: seawater addition, sea-shell or limestone filter, bases addition (hydroxides or carbonate compounds) and water exchange.

3.3.1. Seawater Addition

Seawater can be added to freshwater aquaculture systems in order to increase the pH of the culture water. Rosseland and Skogheim [53] demonstrated that adding seawater to the culture water (1%–6% seawater) increased the pH and alkalinity of the water and decreased the labile aluminium. Conductivity also increased linearly with an increase in seawater addition [53]. Therefore, measuring the conductivity of the water can be used to control the seawater addition, or the amount of added seawater can be fixed manually, depending on the level of freshwater usage. However, seawater can contain various substances that can be harmful to the fish. Therefore, some preventive measures need to be taken, such as pumping the seawater from greater depths or from boreholes and disinfecting it before use [18].

3.3.2. A Shell-Sand or Limestone Filter

A shell-sand filter is simply a granular filter with marine shells as the medium. Water flows upward through the media bed, the pH increases and labile aluminium decreases [53]. With time, the filter medium needs to be replaced to keep the pH stable. Limestone can also be used as a medium. “Limestone is a major source of alkalinity and hardness”, most often being composed mainly from $CaCO_3$ and $MgCO_3$ [51]. Limestone filters were commonly used in Norwegian hatcheries in the 1930s [53]. The dissolution of limestone is highly dependent on the dissolved CO_2 concentration [51].

3.3.3. Base Addition

Bases are often used to control the pH of culture water in aquaculture. Bases can be split into two main groups: hydroxides and carbonate compounds (see Figure 10). Carbonate compounds increase the alkalinity of the water, i.e., its buffering capacity.

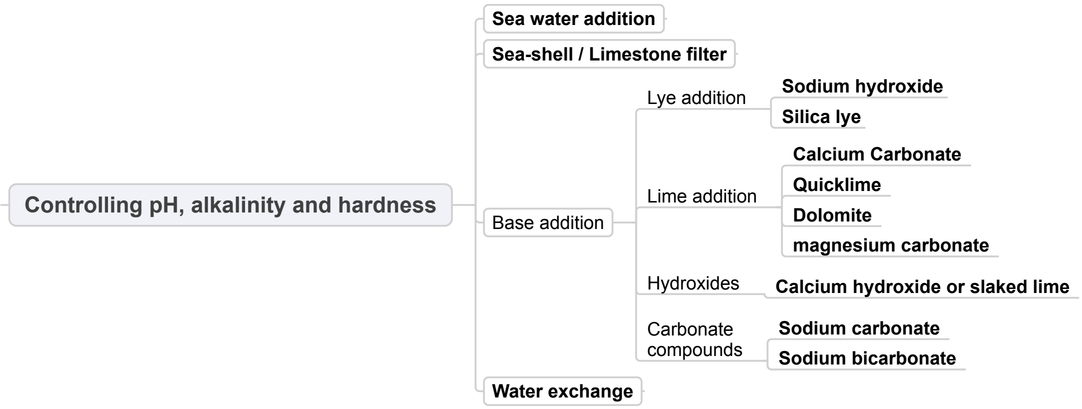

Figure 10. Base addition—from the Controlling pH, Alkalinity and Hardness section of the taxonomy.

Bases in the hydroxides group include the following: lye, i.e., sodium hydroxide (NaOH); silica lye, i.e., sodium silicate ($Na_2(SiO_2)_nO$); calcium hydroxide or slaked lime ($Ca(OH)_2$) and magnesium hydroxide ($Mg(OH)_2$). Bases in the carbonate group include lime, i.e., calcium carbonate ($CaCO_3$) and quick lime (CaO); dolomite ($CaMg(CO_3)_2$); magnesium carbonate ($MgCO_3$); sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$).

Hydroxides

Using lye (sodium hydroxide) is challenging, since it is corrosive to metals and overdosing is a risk. Furthermore, lye does not increase the buffering capacity of the water [18]. However, silica lye is a good alternative for increasing the pH when reducing the toxicity of aluminium is needed [54]. Furtado et al. [55] applied calcium hydroxide to a bio-floc system. Calcium hydroxide of around

10%–20% of the daily feed offered was applied, which increased the pH and alkalinity levels in aquaculture systems without causing negative effects on the bacterial community present in a bio-floc system. Calcium hydroxide can also be used as a flocculent [56].

Carbonate Compounds

Limestone powder can be mixed with water in a separate tank to create lime slurry, which then is then regulated into the system. However, using lime slurry increases the particle content (turbidity) of the water [18]. Limestone, which is most often a mixture of calcium carbonate and magnesium carbonate or dolomite, is a major source of alkalinity and hardness [51]. In an ozonised system, calcium carbonate is not effective in increasing alkalinity [57]. Quicklime can be used to reduce the toxicity of copper [58] and cadmium [59] to fish.

Sodium bicarbonate (baking soda) can be used to adjust the alkalinity of the culture water. With sodium bicarbonate, "a general rule of thumb" is that around 0.25 kg of sodium bicarbonate needs to be added to the water for every kg of feed [49]. Sodium bicarbonate is inexpensive, safe for both humans and fish and dissolves quickly in water [47,49].

An automatic dosing system can be used for adding the base to the water. The base solution is stored in a holding tank and is regulated into the system using a controller and a dosing pump [18,60,61]. Another way is to measure the pH and alkalinity levels and use tables to determine the dose of the base solution that is required to reach the target pH, which can then be added manually [47].

3.4. Controlling DO and CO_2

Maintaining, right levels of dissolved gasses, such as dissolved oxygen and carbon dioxide, is vital to the health of the cultured species and the operation of certain processes [62]. As oxygen is consumed by the cultured species or other organisms in the system, for the metabolic process, the CO_2 concentrations increase. The treatment function controlling DO and CO_2 deals with methods used to maintain DO and CO_2 close to the optimum level; these methods are aeration, oxygenation, air-stripping, base addition (to regulate pH), biofiltration and water exchange—all of which are explained further in the following section.

3.4.1. Aeration

Aeration can be considered as any system where water is brought into contact with air. Either water droplets are moved through air, or air bubbles are moved through water [50]. Figure 11 displays the partial taxonomy of means in the aeration category.

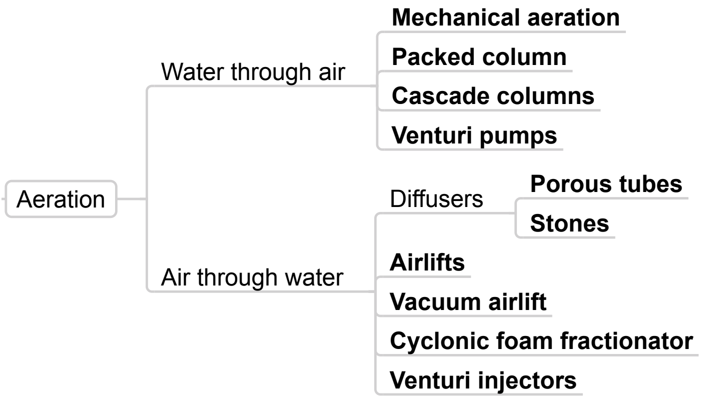

Figure 11. Aeration—from the Controlling DO and CO_2 section of the taxonomy.

Water through Air

Mechanical aeration involves basic aeration techniques. Paddle weels and impeller-type vertical pumps are commonly used in pond systems [24]. Paddle wheels consist of paddles set around the periphery of a wheel and the paddles are partially submerged in the water. When the wheel rotates, water splashes into the air, creating a large surface area and stimulating gas exchange. Impeller-type vertical pumps use submerged pumps to drive an impeller that throws water into the air.

In a packed column aerator (PCA)—sometimes called stripping columns [50]—media with high surface area is packed into a column. Water is distributed from the top (which has a perforated plate or spray nuzzle) and trickles down through the media, exiting at the bottom. PCAs can be used for both oxygen transfer and nitrogen removal [63]. Airflow though the column needs to be sufficient and can be maintained or controlled with fans or blowers; counter current flow is preferred [63]. The column and packing diameter needs to have the appropriate size for preventing poor distribution of the water, which would decrease the performance of the PCA [63].

Media can be randomly packed or structurally packed [50]. Various models have been developed to estimate the CO_2 stripping efficiency [50] and oxygen transfer [63] for packed columns. In cascade aerators, water is distributed at the top and cascades down through obstructions that break up the water flow and create large void spaces; this increases the water-to-air contact surface and time. For instance, these obstructions can be horizontally stacked perforated plates, structured blocks of cross-corrugated sheet media, tall tubular media [64] or randomly packed material [61]. Air is blown through the column, preferably counter-current to the cascading water. Structured packing is not as efficient as random packing, but it is less prone to clogging and fouling [50].

In the literature, packed columns are referred to as columns with randomly packed media with high surface area (>150 m^2/m^3), while cascade columns have structured or random obstruction or media with lower surface area (<110 m^2/m^3) offering a higher air-to-water ratio [61,63–66]. In this paper, all packed columns are considered as cascade aerator, but not all cascade aerator are considered packed columns.

Venturi pumps utilize air as the working fluid. Compressed air is forced through a narrow chamber, which lowers the pressure. Next, water is introduced at this low pressure point and is drawn into the airstream.

Air through Water

A diffuser is simply a construction where small gas bubbles are created below the water surface [18]. The bubbles are allowed to rise in the water column, and gas transfer takes place. A porous tube or ceramic stones can be used to create bubbles. Airlifts, which were briefly mentioned earlier, can be used for aeration and degasification along with their water delivery [44]. Venturi injections utilize the venturi effect to create thousands of fine bubbles in the water stream. When water enters the injector, it is forced through the narrow injector chamber, increasing its velocity. At the same time, the absolute pressure of the water decreases, creating a vacuum and drawing air from the suction port into the water stream. The pipe expands again, increasing the pressure and forming thousands of micro bubbles.

3.4.2. Oxygenation

Injecting pure oxygen into the water to increase its DO levels has been done for many years and can be done in various ways. Providing oxygen for fish cultures has a high operating cost; therefore, it is vital to do it as efficiently as possible [50]. In this study, oxygenation is a method in which water droplets are forced in contact with pure oxygen as well as pure oxygen bubbles are forced in contact with water, as shown in Figure 12.

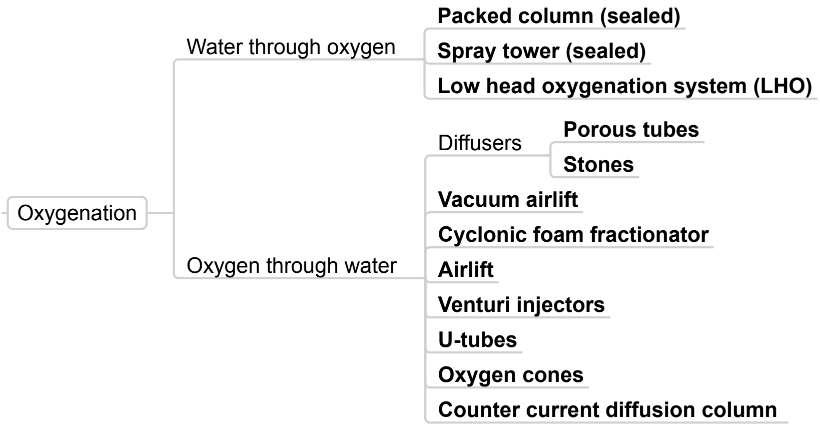

Figure 12. Oxygenation—from the Controlling DO and CO_2 section of the taxonomy.

Water through Oxygen

The pressurized packed columns (i.e., sealed column) mentioned earlier can be used for pure oxygen aeration by substituting the inflow air with pure oxygen [18]. Excess oxygen can be recirculated, resulting in higher efficiency.

In a spray tower, water enters a sealed vertical chamber through a spray nozzle near the top. Pure oxygen is added to the chamber, which can then be recirculated. In aquaculture, spray towers have mainly been used for pure oxygen aeration [67]. Though similar in construction to packed columns, spray towers are less prone to clogging and fouling since they have no packing material [67].

Davenport et al. [68] described a low head oxygenation unit (LHO), which is essentially a box divided into multiple (5–10) vertical chambers. Water is distributed equally at the top via a distribution plate, trickles down the unit and exits below the water level in a receiving pool. Pure oxygen enters from the side and flows from chamber to chamber via holes in the division plates until it is vented out the other side. This provides a simple and efficient way of adding oxygen to water and stripping nitrogen from it [68].

Oxygen through Water

Like in the air, diffusers can be used to dissolve oxygen in water as well. It is important that the bubble size is small enough and the depth is sufficient to allow for sufficient contact time between the water and the bubbles.

U-tubes are two vertical tubes, one inside the other. The outer tube is closed at the bottom, while the inner one is open. Oxygen is added to the water flow as it moves down the inner tube. The depth of the tubes is a minimum of 10 metres (required to add one atmospheric pressure). The U-tube is usually placed below the tank to minimize the pumping requirements [6]; off-gas recycling can increase the efficiency of the U-tubes [69].

In oxygenation cones (down flow bubble contactor, speece cone), water and oxygen enter the cone from the top. The water velocity at the inlet is set higher than the upward velocity of the bubbles, preventing them from escaping through the top. As they travel down the cone, the water velocity decreases until it equals the upward velocity of the oxygen bubbles, creating a long contact time between the water and oxygen. Cones can be used either at low pressure [6] in the main water stream or at high pressure where a part of the main stream is pumped through the cone [18], resulting in higher oxygen saturation, which is then mixed again with the main water flow.

Ebeling [39] described a counter current diffusion column, which is a simplified, less expensive version of the oxygen cone. Water enters a uniform column from the top, while oxygen is introduced from the bottom. The water velocity is set to a certain value that will keep the oxygen bubbles from reaching the top. To manage varying water velocities of the inflow, the column could be constructed from pipe segments with different diameters, approximating the shape of a cone.

3.4.3. Air Stripping

Air stripping is used to strip gasses such as CO_2 and nitrogen gas out of the process water. Several techniques are available, as seen in Figure 13.

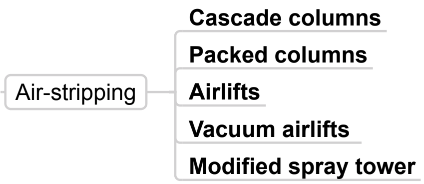

Figure 13. Air stripping—from the Controlling DO and CO_2 section of the taxonomy.

Cascade columns can be used for air stripping. For better CO_2 removal in cascade or packed columns, a high volumetric air:water loading rate (up to 10:1) [64] or higher column [50] is needed. Barrut et al. [70] found that vacuum airlifts could be a promising method for stripping CO_2, although there are other airlifts that could perform this task as well [44,71]. Furthermore, modifications of the spray tower have been tested to provide concurrent CO_2 stripping [66].

3.4.4. Base Addition

Another way of controlling CO_2 is using base addition to regulate pH (covered in Section 3.3.3). Increasing the pH decreases the CO_2. However, this technique requires careful monitoring and needs to be in conjunction with the management of the pH and alkalinity in the system.

3.4.5. Biofiltration (DO and CO_2 Control)

Biofilters have a main purpose of removing ammonia from the process water in recirculating aquaculture systems. Some types of biofilters also provide aeration and some CO_2 stripping. They are listed in Figure 14 and are described in more detail in Vilbergsson et al. [4].

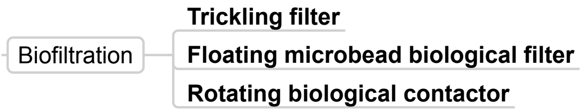

Figure 14. Biofilters for DO and CO_2 control—from the Controlling DO and CO_2 section of the taxonomy.

Trickling filters can aerate the water and provide some CO_2 stripping [6,50]; floating microbead biological filters can also provide CO_2 stripping. If a gas space between the top of the beads and the water spray is created, stripping can be forced [72]. Brazil [19] found that rotating biological contactors removed an average 39% of carbon dioxide from the water.

4. Discussion

The taxonomy of technical solutions that solve the treatment functions—one or many—is now partly presented. The means presented and mapped out in this study are used to solve the treatment functions controlling solids, dissolved gasses and pH. All those functions must remain under the utmost control, for the sake of the health of the cultured species and the effectiveness of the aquaculture system. Rapid removal of solids and stable levels of dissolved gasses and pH is critical for preventing hazardous conditions for the cultured species. We will continue the work in part 3 [4], where the treatment functions, controlling N compounds, organic matter, P compounds, metals, temperature and preventing diseases will be covered.

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References

1. Martins, C.; Eding, E.; Verdegem, M.; Heinsbroek, L.; Schneider, O.; Blancheton, J.; D'Orbcastel, E.R.; Verreth, J. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquac. Eng.* **2010**, *43*, 83–93.
2. Badiola, M.; Mendiola, D.; Bostock, J. Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquac. Eng.* **2012**, *51*, 26–35.
3. Björnsdóttir, R.; Oddsson, G.V.; Thorarinsdottir, R.; Unnthorsson, R. Taxonomy of means and ends in aquaculture production—Part 1: The functions. *Water* **2016**, *8*, 319.
4. Vilbergsson, B.; Oddsson, G.V.; Unnthorsson, R. Taxonomy of means and ends in aquaculture production—Part 3: The technical solutions of controlling N compounds, organic matter, P compounds, metals, temperature and preventing disease. *Water* **2016**, in press.
5. Vilbergsson, B.; Oddsson, G.V.; Unnthorsson, R. Taxonomy of means and ends in aquaculture production—Part 4: The mapping of technical solutions onto multiple treatment function. *Water* **2016**, in press.
6. Losordo, T.M.; Masser, M.P.; Rakocy, J. *Recirculating Aquaculture Tank Production Systems—A Review of Component Options*; Report SRAC Publication No. 453; Southern Regional Aquaculture Center (SRAC): Stoneville, MS, USA, 1999.
7. Crab, R.; Avnimelech, Y.; Defoirdt, T.; Bossier, P.; Verstraete, W. Nitrogen removal techniques in aquaculture for a sustainable production. *Aquaculture* **2007**, *270*, 1–14.
8. Cripps, S.J.; Bergheim, A. Solids management and removal for intensive land-based aquaculture production systems. *Aquac. Eng.* **2000**, *22*, 33–56.
9. Malone, R.F.; Pfeiffer, T.J. Rating fixed film nitrifying biofilters used in recirculating aquaculture systems. *Aquac. Eng.* **2006**, *34*, 389–402.
10. Helfrich, L.; Libey, G. *Fish Farming in Recirculating Aquaculture Systems (RAS)*; Department of Fisheries and Wildlife, Virginia Tech: Blacksburg, VA, USA, 1991.
11. Cho, C.Y.; Bureau, D.P. A review of diet formulation strategies and feeding systems to reduce excretory and feed wastes in aquaculture. *Aquac. Res.* **2001**, *32*, 349–360.
12. Barrut, B.; Blancheton, J.P.; Callier, M.; Champagne, J.Y.; Grasmick, A. Foam fractionation efficiency of a vacuum airlift—Application to particulate matter removal in recirculating systems. *Aquac. Eng.* **2013**, *54*, 16–21.
13. Dalsgaard, J.; Larsen, B.K.; Pedersen, P.B. Nitrogen waste from rainbow trout (*Oncorhynchus mykiss*) with particular focus on urea. *Aquac. Eng.* **2015**, *65*, 2–9.
14. Koko, G.; Sarker, P. Effects of alternating feeding regimes with varying dietary phosphorus levels on growth, mineralization, phosphorus retention and loading of large rainbow trout. *Aquat. Living Resour.* **2010**, *23*, 277–284.
15. Zakęś, Z.; Demska-Zakęś, K. The effect of feeding on oxygen consumption and ammonia excretion of juvenile tench *Tinca tinca* (L.) reared in a water recirculating system. *Aquac. Int.* **2006**, *14*, 127–140.
16. Liu, Z.; Li, X.; Fan, L.; Lu, H.; Liu, L.; Liu, Y. Measuring feeding activity of fish in RAS using computer vision. *Aquac. Eng.* **2014**, *60*, 20–27.
17. Couturier, M.; Trofimencoff, T.; Buil, J.U.; Conroy, J. Solids removal at a recirculating salmon-smolt farm. *Aquac. Eng.* **2009**, *41*, 71–77.
18. Lekang, O. *Aquaculture Engineering*; Blackwell Publishing Ltd.: Oxford, UK, 2007.
19. Brazil, B.L. Performance and operation of a rotating biological contactor in a tilapia recirculating aquaculture system. *Aquac. Eng.* **2006**, *34*, 261–274.

20. Díaz, V.; Ibáñez, R.; Gómez, P.; Urtiaga, A.; Ortiz, I. Kinetics of nitrogen compounds in a commercial marine Recirculating Aquaculture System. *Aquac. Eng.* **2012**, *50*, 20–27.
21. Davidson, J.; Good, C.; Welsh, C.; Brazil, B.; Summerfelt, S. Heavy metal and waste metabolite accumulation and their potential effect on rainbow trout performance in a replicated water reuse system operated at low or high system flushing rates. *Aquac. Eng.* **2009**, *41*, 136–145.
22. Liltved, H.; Cripps, S.J. Removal of particle-associated bacteria by prefiltration and ultraviolet irradiation. *Aquac. Res.* **1999**, 30, 445–450.
23. Summerfelt, R.C.; Penne, C.R. Solids removal in a recirculating aquaculture system where the majority of flow bypasses the microscreen filter. *Aquac. Eng.* **2005**, *33*, 214–224.
24. Tidwell, J. *Aquaculture Production Systems*; Wiley-Blackwell: Oxford, UK, 2012.
25. Losordo, T.M.; Hobbs, A.O.; DeLong, D.P. The design and operational characteristics of the CP&L/EPRI fish barn: A demonstration of recirculating aquaculture technology. *Aquac. Eng.* **2000**, *22*, 3–16.
26. Davidson, J.; Summerfelt, S.T. Solids removal from a coldwater recirculating system—Comparison of a swirl separator and a radial-flow settler. *Aquac. Eng.* **2005**, *33*, 47–61.
27. Ebeling, J.; Welsh, C.; Rishel, K. Performance evaluation of an inclined belt filter using coagulation/flocculation aids for the removal of suspended solids and phosphorus from microscreen backwash effluent. *Aquac. Eng.* **2006**, *35*, 61–77.
28. Fischer, G.J.; Held, J.; Hartleb, C.; Malison, J. Evaluation of brook trout production in a coldwater recycle aquaculture system. *Aquac. Eng.* **2009**, *41*, 109–113.
29. Lekang, O.I.; Bomo, A.M.; Svendsen, I. Biological lamella sedimentation used for wastewater treatment. *Aquac. Eng.* **2001**, *24*, 115–127.
30. Summerfelt, S. An integrated approach to aquaculture waste management in flowing water systems. In Proceedings of the Second International Conference on Recirculating Aquaculture, Roanoke, VA, USA, 16–19 July 1998; pp. 87–97.
31. Fernandes, P.M.; Pedersen, L.F.; Pedersen, P.B. Daily micro particle distribution of an experimental recirculating aquaculture system—A case study. *Aquac. Eng.* **2014**, *60*, 28–34.
32. Dolan, E.; Murphy, N.; O'Hehir, M. Factors influencing optimal micro-screen drum filter selection for recirculating aquaculture systems. *Aquac. Eng.* **2013**, *56*, 42–50.
33. Mäkinen, T.; Lindgren, S.; Eskelinen, P. Sieving as an effluent treatment method for aquaculture. *Aquac. Eng.* **1988**, *7*, 367–377.
34. Fernandes, P.; Pedersen, L.F.; Pedersen, P.B. Microscreen effects on water quality in replicated recirculating aquaculture systems. *Aquac. Eng.* **2015**, *65*, 17–26.
35. Sharrer, M.; Rishel, K.; Taylor, A.; Vinci, B.J.; Summerfelt, S.T. The cost and effectiveness of solids thickening technologies for treating backwash and recovering nutrients from intensive aquaculture systems. *Bioresour. Technol.* **2010**, *101*, 6630–6641.
36. Guerdat, T.C.; Losordo, T.M.; DeLong, D.P.; Jones, R.D. An evaluation of solid waste capture from recirculating aquaculture systems using a geotextile bag system with a flocculant-aid. *Aquac. Eng.* **2013**, *54*, 1–8.
37. Holan, A.; Wold, P.A.; Leiknes, T. Membrane performance and fouling behavior of membrane bioreactors installed in marine recirculating aquaculture systems. *Aquac. Eng.* **2014**, *58*, 45–51.
38. Holan, A.; Wold, P.A.; Leiknes, T. Intensive rearing of cod larvae (*Gadus morhua*) in recirculating aquaculture systems (RAS) implementing a membrane bioreactor (MBR) for enhanced colloidal particle and fine suspended solids removal. *Aquac. Eng.* **2014**, *58*, 52–58.
39. Ebeling, J.J.M. Engineering aspects of recirculating aquaculture systems. *Mar. Technol. Soc. J.* **2000**, *34*, 68–78.
40. Steicke, C.; Jegatheesan, V.; Zeng, C. Mechanical mode floating medium filters for recirculating systems in aquaculture for higher solids retention and lower freshwater usage. *Bioresour. Technol.* **2007**, *98*, 3375–3383.
41. Malone, R.F.; Beecher, L.E. Use of floating bead filters to recondition recirculating waters in warmwater aquaculture production systems. *Aquac. Eng.* **2000**, *22*, 57–73.
42. Malone, R.F.; Beecher, L.E.; DeLosReyes, A.A., Jr. Sizing and management of floating bead bioclarifiers. In Proceedings of the Second International Conference on Recirculating Aquaculture, Roanoke, VA, USA, 16–19 July 1998; pp. 16–19.
43. Malone, R.F. Air Charged Backwashing Bioclarifier. U.S. Patent 5,770,080 A, 23 June 1998.

44. Loyless, J.; Malone, R.F. Evaluation of air-lift pump capabilities for water delivery, aeration, and degasification for application to recirculating aquaculture systems. *Aquac. Eng.* **1998**, *18*, 117–133.
45. Barrut, B.; Blancheton, J.P.; Champagne, J.Y.; Grasmick, A. Water delivery capacity of a vacuum airlift—Application to water recycling in aquaculture systems. *Aquac. Eng.* **2012**, *48*, 31–39.
46. Brambilla, F.; Antonini, M.; Ceccuzzi, P.; Terova, G.; Saroglia, M. Foam fractionation efficiency in particulate matter and heterotrophic bacteria removal from a recirculating seabass (*Dicentrarchus labrax*) system. *Aquac. Eng.* **2008**, *39*, 37–42.
47. Loyless, J.; Malone, R. A sodium bicarbonate dosing methodology for pH management in freshwater-recirculating aquaculture systems. *Progress. Fish Cult.* **1997**, *59*, 198–205.
48. Boyd, C.; Tucker, C.; Viriyatum, R. Interpretation of pH, acidity, and alkalinity in aquaculture and fisheries. *N. Am. J. Aquac.* **2011**, *73*, 403–408.
49. Timmons, M.B.; Ebeling, J.M. *Recirculating Aquaculture*, 2nd ed.; Cayuga Aqua Ventures: Ithaca, NY, USA, 2010.
50. Summerfelt, S.; Vinci, B.; Piedrahita, R. Oxygenation and carbon dioxide control in water reuse systems. *Aquac. Eng.* **2000**, *22*, 87–108.
51. Boyd, C.E.; Tucker, C.S.; Somridhivej, B. Alkalinity and hardness: Critical but elusive concepts in aquaculture. *J. World Aquac. Soc.* **2016**, *47*, 6–41.
52. Stickney, R.R. *Aquaculture: An Introductory Text*; CAB International: Cambridge, MA, USA, 2005.
53. Rosseland, B.O.; Skogheim, O.K. Neutralization of acidic brook-water using a shell-sand filter or sea-water: Effects on eggs, alevins and smolts of salmonids. *Aquaculture* **1986**, *58*, 99–110.
54. Teien, H.C.; Kroglund, F.; Atland, A.; Rosseland, B.O.; Salbu, B. Sodium silicate as alternative to liming-reduced aluminium toxicity for Atlantic salmon (*Salmo salar* L.) in unstable mixing zones. *Sci. Total Environ.* **2006**, *358*, 151–163.
55. Furtado, P.S.; Gaona, C.A.P.; Poersch, L.H.; Wasielesky, W. Application of different doses of calcium hydroxide in the farming shrimp *Litopenaeus vannamei* with the biofloc technology (BFT). *Aquac. Int.* **2013**, *22*, 1009–1023.
56. Sharrer, M.J.; Rishel, K.; Summerfelt, S. Evaluation of geotextile filtration applying coagulant and flocculant amendments for aquaculture biosolids dewatering and phosphorus removal. *Aquac. Eng.* **2009**, *40*, 1–10.
57. Whangchai, N.; Migo, V.P.; Alfafara, C.G.; Young, H.K.; Nomura, N.; Matsumura, M. Strategies for alkalinity and pH control for ozonated shrimp pond water. *Aquac. Eng.* **2004**, *30*, 1–13.
58. Das, B.K.; Das, N. Impacts of quicklime (CaO) on the toxicity of copper ($CuSO_4$, $5H_2O$) to fish and fish food organisms. *Chemosphere* **2005**, *61*, 186–191.
59. Kaviraj, A.; Dutta, T.K. Use of quick lime (CaO) as a means to reduce cadmium toxicity in common carp, *Cyprinus carpio*. *J. Appl. Aquac.* **2008**, *10*, 87–95.
60. Hargreaves, J.A.; Sheely, L.D.; To, F.S. A control system to simulate diel pH fluctuation in eutrophic aquaculture ponds. *J. World Aquac. Soc.* **2007**, *31*, 390–402.
61. Summerfelt, S.T.; Zühlke, A.; Kolarevic, J.; Reiten, B.K.M.; Selset, R.; Gutierrez, X.; Terjesen, B.F. Effects of alkalinity on ammonia removal, carbon dioxide stripping, and system pH in semi-commercial scale water recirculating aquaculture systems operated with moving bed bioreactors. *Aquac. Eng.* **2015**, *65*, 46–54.
62. Colt, J. Water quality requirements for reuse systems. *Aquac. Eng.* **2006**, *34*, 143–156.
63. Hackney, G.E.; Colt, J.E. The performance and design of packed column aeration systems for aquaculture. *Aquac. Eng.* **1982**, *1*, 275–295.
64. Summerfelt, S.T.; Davidson, J.; Waldrop, T. Evaluation of full-scale carbon dioxide stripping columns in a coldwater recirculating system. *Aquac. Eng.* **2003**, *28*, 155–169.
65. Summerfelt, S.T.; Davidson, J.W.; Waldrop, T.B.; Tsukuda, S.M.; Bebak-Williams, J. A partial-reuse system for coldwater aquaculture. *Aquac. Eng.* **2004**, *31*, 157–181.
66. Watten, B.J.; Sibrell, P.L.; Montgomery, G.A.; Tsukuda, S.M. Modification of pure oxygen absorption equipment for concurrent stripping of carbon dioxide. *Aquac. Eng.* **2004**, *32*, 183–208.
67. Vinci, B.J.; Watten, B.J.; Timmons, M.B. Gas-phase axial dispersion in a spray tower. *Aquac. Eng.* **1996**, *15*, 1–11.
68. Davenport, M.T.; Timmons, M.B.; Vinci, B.J.; Crum, M.K. Experimental evaluation of low head oxygenators. *Aquac. Eng.* **2001**, *24*, 245–256.

69. Wood, L.G.; Watten, B.J.; Haugh, C.; Libey, G.S.; Dillaha, T.A. Modeling gas transfer and biological respiration in a recirculating aquaculture system. *Aquac. Eng.* **1996**, *15*, 359–379.
70. Barrut, B.; Blancheton, J.P.; Champagne, J.Y.; Grasmick, A. Mass transfer efficiency of a vacuum airlift—Application to water recycling in aquaculture systems. *Aquac. Eng.* **2012**, *46*, 18–26.
71. Seginer, I.; Mozes, N. A note on oxygen supply in RAS: The effect of water temperature. *Aquac. Eng.* **2012**, *50*, 46–54.
72. Timmons, M.B.; Holder, J.L.; Ebeling, J.M. Application of microbead biological filters. *Aquac. Eng.* **2006**, *34*, 332–343.