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Dimensioning, Design, and Evaluation of Small Scaled Single Unit Recirculating Aquaculture Systems for Educational Purposes

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Master of Science in Aquaculture

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Master Thesis (60 credits)

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ABSTRACT

Recirculating aquaculture system (RAS) is a production method of raising aquatic organisms in an enclosed environment, in which the growth, health and welfare of the aquatic organism are dependent on a series of recycling water treatment technologies. This water treatment technology comprises of several water purification and enrichment units which ensures the water quality required by the enclosed species is supplied and maintained. RAS offers the farmer many advantages when compared to the traditional methods of raising fish – full control of the rearing environment, waste control, and production in an environmentally sustainable way. RAS is currently in use in several countries, and it is applied to different growth phases in the life cycle of the reared organism. Its use in Norway is mostly concentrated in the freshwater stage of Atlantic Salmon (*Salmo salar*). However, the technology is so versatile it can be easily adapted to raise other fish species such as Nile tilapia *(Oreochromis niloticus),* European eel *(Anguilla Anguilla)*, among others. Despite all these benefits associated with RAS, some challenges are still apparent in its implementation. These challenges range from poor system design, high investment, and operating costs, infection methods, and management. The most detrimental of them are due to human errors (poor management, mistakes in design calculations, etc) caused by poor application of knowledge or inadequate understanding of the system in design and use. Hence, the need for more professionals with a full grasp of the system cannot be overemphasized and this calls for more education in RAS. Although several programs in university and online are available where potential practitioners can learn about RAS, these programs are generally theoretical, and several gaps have been noticed in the application of this theoretical knowledge in practical ways. Therefore, to enhance applied education in RAS usage, compact and affordable systems must be made available, where students can be introduced to practical knowledge in dimensioning, design, and understanding of how the system integrates engineering, technology, chemistry, and biology. The objective of this thesis was to dimension and design two independent small-scale RAS units, purposed to educate students and to evaluate the treatment efficiency of the designed degasser.

In this thesis, two independent small-scale RAS units were dimensioned and designed for the practical education of students. The design and dimensioning of each RAS unit were in line with the mass balance principle and the value of water quality parameters (e.g. O_2, CO_2,

TAN) considered were such that can support fish welfare. Nile tilapia was used as a case study due to its broader water quality requirement and resilience. Other factors that contributed to the design were available funds – which impacted the capacity and quantity of materials that could be purchased and the mode of transporting each RAS unit – which was resolved by mounting each unit on an EPAL wooden pallet. Each RAS unit has a 100L cylindrical/conical tank, which serves as the enclosed environment for the Nile tilapia. The tank is connected to a drum filter with a 75-micron sieve which passes the solid waste out as sludge and directly empties its water content into the MBBR (fabricated) placed under the drum filter. The water in the MBBR (69L) undergoes nitrification, as bio-media with SSA 750 m^2/m are subjected to agitation by air from air pumps. The nitrified water flows into the sump (62 L) and the water pump connected to the sump lifts the water to a maximum height of 1800 mm before it empties into the degasser (which is a 4.4L transparent cylinder with openings on both ends). The degasser passes its water to a 3D-printed water retainer which temporarily holds the water before its O_2-rich and CO_2-depleted water is delivered back to the tank by gravity. The complete RAS can support the growth and well-being of fish with a maximum biomass of 1750 g and a maximum feeding rate of 105 g/day. All components that were not fabricated were purchased online.

The degasser used in the system was one of the units fabricated and in addition to the initial objective to dimension and design the RAS units, the degasser was evaluated to test for the effect of media size (25 and 38mm), flow rate (100 and 300 L/hr) and inlet CO_2 concentration (5, 20 and 40 mg/L) on its treatment efficiency. The test showed that treatment efficiency for the degasser was above 50% and the flow rates had the most contribution to this effective treatment ($p = 0.0010$). However, among the two flow rates (100 and 300 L/hr), the lower rate of 100 L/hr was found to have produced a higher treatment efficiency in the CO_2 stripping process of the designed degasser.

In conclusion, this thesis serves as a foundation for students and future professionals in the aquaculture industry interested in all aspects relating to the dimensioning, design, and evaluation of a RAS unit. During the writing of the thesis, the RAS units already had their first set of students who were able to physically handle and operate several parts of the system. Regarding the degasser, the flow rate in conjunction with the sufficient air volume in the cylinder was observed to be enough to strip CO_2 from the inlet water. The principles used in this study are not limited to Nile tilapia cultivation alone but can be easily adapted and applied to other fish species of choice. It should also be noted that scaling from a small-scale RAS to a commercial facility would require more considerations.

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ABBREVIATIONS

BOD	Biochemical Oxygen Demand
DO	Dissolve Oxygen
GL ratio	Gas to Liquid ratio
MAB	Maximum Allowable Biomass
MBBR	Moving Bed Biofilm Reactor
NMBU	Norwegian University of Life Sciences
RAS	Recirculating Aquaculture Systems
RQ	Research Question
SD	Standard deviation
SSA	Specific Surface Area
SSC	Suspended Solid Concentration
TAN	Total Ammonia Nitrogen
TE	Treatment efficiency
TSS	Total Suspended Solids
UV	Ultraviolet

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1. INTRODUCTION

1.1 Recirculating Aquaculture Systems (RAS)

RAS are intensive, typically indoor tank-based systems that reuse water after a thorough filtration (mechanical, biological, chemical) and other treatment measures (Murray et al., 2014). This system represents a modern and unique way of raising fish; instead of the traditional outdoor methods, usually done in open ponds and raceways, this new system raises fish at high densities in a strictly monitored environment and breeding conditions (Helfrich & Libey, 1991). In summary, the water in RAS is treated and recycled, with less than 10% of the total water volume in the system being exchanged per day (Neethu et al., 2020) and the reduced water usage makes nutrients excreted by the fish and uneaten feed much easier and cheaper to remove, as the volume of sludge removal is much lower than that discharged from the traditional aquaculture practices (Bregnballe, 2022)

In aquaculture, the need for RAS is due to the challenges faced when applying traditional fish farming methods and these challenges include the limitation of space for expansion and very few new suitable farming locations – this is due to competition on the land area for other legitimate purposes (agriculture, infrastructure), also scarce freshwater resources, and concerns about pollution (Badiola et al., 2012). Furthermore, future development in the aquaculture industry is currently confronted by the government's efforts toward a more sustainable and environmentally conscious production. RAS seeks to address these challenges by minimizing waste production and increasing resource (water) recycling (Steicke et al., 2009) while also maximizing production without the acquisition of vast land areas (Helfrich & Libey, 1991) and ensuring efficient use of non-arable lands. Therefore, on a commercially viable level, this system can be considered the most environmentally responsible way of producing fish (Bregnballe, 2022). Also, according to Tidwell (2012), “RASs are the key technology that will allow the world aquaculture community to supply the world per capita needs for aquatic species over the coming decades and will do so in an environmentally friendly manner” (p.259).

Several European countries are moving towards implementing RAS, justifying their change for sustainability and environmental reasons (Badiola et al., 2012). Recirculating technology currently supports a significant increase in extensive commercial RAS facilities, especially for the production of Atlantic Salmon (*Salmo salar*) smolt (Dalsgaard et al., 2017). In addition, RAS has been successfully used in seed production systems for hatcheries, nurseries as well as grow-out production systems in various countries around the world (Neethu et al., 2020). In Norway, for example, between the years 2018 to 2022, there was an 11.2% increase in the number of fish farm sites that are land-based, and most of these new facilities rely on some form of water recirculatory system (Fiskeridirektoratet, 2018, 2023)

However, the successful implementation of this technology is not without its challenges. Therefore, understanding RAS is one of the key considerations in its management because it requires interactions between technology, natural science, and the raising of living organisms (Badiola et al., 2012). RAS has undergone several modifications to achieve better optimization since its introduction in aquaculture. Nevertheless, some challenges persist, and some of these challenges are poor management, lack of knowledge about the technology, energy cost, high initial investment, and occurrence of diseases and pathogens (Aich et al., 2020). These challenges need to be eradicated or mitigated to encourage wider use of the technology and future investments.

Improper management (i.e., lack of adequate training) was the second most common problem faced when operating RAS facilities, after poor system design, due to inaccurate calculations and overly optimistic assumptions (Badiola et al., 2012). The lack of experts with technically sound knowledge about RAS technology, its operation, and management is one of the main concerns for sustainable aquaculture production (Aich et al., 2020), therefore, the development of both theoretical and practical training in RAS operation and management is needed to strengthen the aquaculture sector (Brummett, 1994). Consequently, to develop a sustainable aquaculture industry, we should consider not only advanced breeding techniques, superior feed quality, water quality treatment, and investment but also the quality of the labor force needed to manage these facilities for the continued development of the industry (Engle, 2021). However, having a competent workforce would demand adequate training and preparation to succeed.

Norway has a vast coastline with many fjords and islands of varying sizes, making it an ideal place to raise fish (i.e., salmonids). Many areas along its coastline are protected from the severe effects of wind and waves. The Gulf Stream keeps the coastal region free of ice all year round by approaching the Norwegian shore from the south and moving along the west coast until it reaches the cold Arctic sea (Paisley et al., 2010). Therefore, because of this ocean current, the water in this region is cold, which provides salmonids with the optimal temperature range (8°C – 14°C) for survival. Additionally, the fjords and archipelagos along the coastline offer protection and create the perfect water current conditions (MOWI, 2023) this gives Norway a natural advantage for salmon production in sea cages along its coastline. However, the sea cage method of raising fish in the fjords is not expandable due to several challenges relating to the environment and sustainability. Hence, there is a need to consider alternative methods, such as RAS, to mitigate the issues faced when using the accustomed sea cages.

The two most significant barriers to further expansion in salmon production at sea, according to the Norwegian Scientific Board of Salmon Management, are high infestation of sea lice (*Lepeophtheirus salmonis*) and escapement from fish farms (sea cages) (Olaussen, 2018). These problems are naturally faced at the seawater phase of salmon production. Among other things, technology (i.e., RAS) would be needed to find solutions to these significant obstacles to further growth. Nevertheless, RAS is already being implemented in the land-based phase of salmon production (smolts), and about 70% of the smolts placed in Norway's sea cages come from RAS facilities (Meriac, 2019). Thereby signifying a shift from the traditional flow-through systems to RAS due to its operational and environmental advantages (Ayuso-Virgili et al., 2023). Additionally, it has been observed that the shift to smolt RAS production has resulted in lower mortality rates of transferred smolts to sea cages (Bergheim et al., 2009). The success of RAS with smolt production has made it possible to avoid parasites, reclaim nutrients, and allow for greater control over the rearing environment than cages at sea (Gorle et al., 2018) and as a result of the success of this system in smolt production, it has been suggested that the land-based production phase be further extended – instead of producing the regular smolts sizes (100g – 150g), bigger smolts (up to 1kg) are being recommended to be raised on land, before they are transferred to sea cages, thus reducing the saltwater production phase of salmon (Bjørndal & Tusvik, 2020).

Sea lice infestation, salmon escapement from sea cages, and environmental problems could all be resolved if RASs were to be implemented for the whole stages of salmon production and this is why the technology is of great interest. RAS has the potential to significantly increase salmon production volume without any significant impact on the environment when compared to other production methods. However, salmon aquaculture is not a simple process and needs more understanding and the integration of technology, environmental science, and life science. It should be noted that though RAS is mostly used for salmon farming in Norway, the technology's versatility allows it to raise other aquatic species. RAS has been used to raise Nile tilapia *(Oreochromis niloticus) (Wambua et al., 2021)*, European eel *(Anguilla Anguilla)*, and Artic char *(Salvelinus alpinus)(Summerfelt et al., 2004)*.

Therefore, understanding the system and the potential impact the transfer of this technology would have on global seafood production is of great importance. Hence, requirement for more professionals with practical knowledge and understanding of aquaculture and other disciplines attached to the industry.

The hiring of personnel knowledgeable in the various aspects of aquatic farming is necessary for the advancement of the aquaculture industry (West, 2017). However, there is usually a clear gap between the skill sets that companies require and what employees offer (Pita et al., 2015). Hence, proper education and training are required to bridge this gap in skill development. Workforce development, from a societal perspective, involves programs that teach and prepare people to satisfy the demands of present and future enterprises to preserve a competitive, sustainable economic environment for the sector (Haralson, 2010).

All advanced industrialized countries are experiencing a rise in the need for highly skilled labor (Pita et al., 2015) and the aquaculture industry in Norway is not exempted from this development. The projected growth in aquaculture would be impeded by the lack of a skilled and growing labor force, regardless of the advancement and utilization of technology within the industry. Therefore, practical training and educational solutions are essential to accelerating aquaculture industrial expansion (Webb et al., 2015) and are also fundamental to developing and retaining a skilled workforce (Jensen et al., 2016).

A study by NCE Seafood Innovation (NCE Seafood Innovation, 2021), conducted in Norway, indicated that its members and partners have a pressing demand for RAS professionals and an urgent need to update personnel competency. The institute stated that this need resulted from the numerous RAS facilities being built in Norway and the ongoing investment and development of new technology in RAS. Therefore, many educational initiatives are being created to supply aquaculture with an adequate labor force. These have been at different stages, frequently done in graduate schools and universities (Engle, 2021). Also, the internet has made many online courses about RAS available, where interested students can pay subscription fees to learn about aquaculture. However, these programs do not offer the student an opportunity to operate the RAS physically. Hence, participants in these courses still struggle to put their theoretical knowledge to practical use.

Therefore, this thesis's objectives are to dimension and design two small-scale RAS units for students' practical education and to evaluate the treatment efficiency of the designed degasser.

2. LITERATURE REVIEW

2.1 Aquaculture

Fish, mollusks, crustaceans, and aquatic plants are among the aquatic organisms that are farmed in aquaculture. Also, because of the rising demand for seafood and its current position in the blue economy, aquaculture has emerged as one of the most significant and fastest-growing food-producing sectors in the world (Neethu et al., 2020). According to estimates, 40 million tons of aquatic food will be required by 2030 to sustain the current level of per capita consumption (Aich et al., 2020). Traditional fish farming systems, as illustrated in Fig 2.1 and Fig 2.2, rely on environmental factors such as the water temperature, water quality of the stream, oxygen concentration, and the presence of weeds and leaves drifting downstream (Bregnballe, 2022). Also, almost all of these traditional aquaculture facilities are built as an outdoor system that coexist with other food production systems or some environmental services, and these aquaculture systems often face competition from other users (Neethu et al., 2020). Therefore, more sustainable intensification techniques are needed to produce more food on the same land area while reducing the environmental impact (Aich et al., 2020). Other significant barriers to the continued expansion of the conventional cage-based and flow-through aquaculture systems include limited freshwater resources, concerns about pollution, lack of space for further expansion, and inadequate new farm location (Badiola et al., 2012).

In comparison, traditional aquaculture techniques – like open pond systems and net pen systems – are unlikely to be viable over the long term because of pressing environmental problems and their inability to ensure the safety of their products to the consumer. Conversely, RAS allows for indoor fish production that is environmentally friendly, sustainable, and capable of ensuring the year-round supply, safety, and quality of the fish produced (Tidwell, 2012). Additionally, strict environmental laws with an emphasis on wastewater management have been enacted in northern Europe due to concerns about the potential environmental effects of aquaculture (Dalsgaard, Pedersen, et al., 2013). Given the challenges with the traditional fish production systems, RAS could be highlighted as one of the potential solutions and an opportunity to further advance environmentally friendly and sustainable aquaculture (Neethu et al., 2020). Several nations involved with aquaculture are transitioning to RAS, citing sustainability concerns as justification for the decision (Badiola et al., 2012).

Figure 2. 1: Traditional aquaculture method (sea cages) adopted from (Templeton, 2020)

Figure 2. 2: Traditional aquaculture method (raceway) adopted from (IntraFish, 2018)

2.2 RAS

RAS is fundamentally a system that reuses water in the production process for fish farming or other aquatic species (Bregnballe, 2022), the concept of a recirculating system is illustrated in Fig. 2.3 . RAS is typically used for fish production in indoor tank-based systems, where there is little water exchange, and biofiltration is needed to lower the quantity of ionized and unionized ammonia (Ebeling & Timmons, 2010). RAS can come in varying configurations, with sophisticated and advanced components attached (Fig. 2.4.), but the basic functional units (Fig. 2.5) of the system are always present to ensure optimal and constant water quality conditions are maintained in the system throughout the culture period (Aich et al., 2020) and it is generally applied for a high-density culture of different fish species while requiring a limited amount of water and land (Ebeling & Timmons, 2012; Lekang, 2020; Tidwell, 2012)

RASs ensure minimal water utilization, culture monitoring and allow waste to be fully managed. They also offer some level of biosecurity by separating the tank culture from outside influences (Aich et al., 2020). Compared to the old methods in aquaculture practices, RAS offers substantial benefits in terms of better control over the culture, water quality parameters, and waste management. As a result, it is the most commercially viable means of raising fish that can be regarded as environmentally friendly (Bregnballe, 2022). Also, RAS is likely the only feasible technique that could be applied to guarantee a seafood supply that is safe and void of harmful chemicals or heavy metals (Ebeling & Timmons, 2010). However, switching to RAS from the conventional fish farming practices brings new challenges and also drastically alters the daily schedules on the farm and the skill set required to manage the farm efficiently (Bregnballe, 2022). These newly acquired skills and knowledge are crucial for the successful management of any RAS facility. Every RAS must have a growth unit (tank), solid removal component, a filtration unit (chemical, biological), aeration, pumps, and occasionally, depending on the intensity of production, a system would have a form of water sterilization (i.e., UV, ozone) (Watson & Hill, 2006).

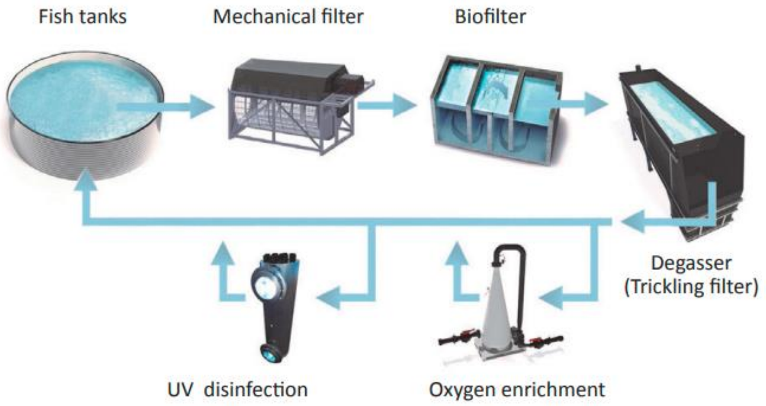

Figure 2. 3: The concept of a RAS, showing the tank, purification, and enrichment components in the system, adopted from (Bregnballe, 2022)

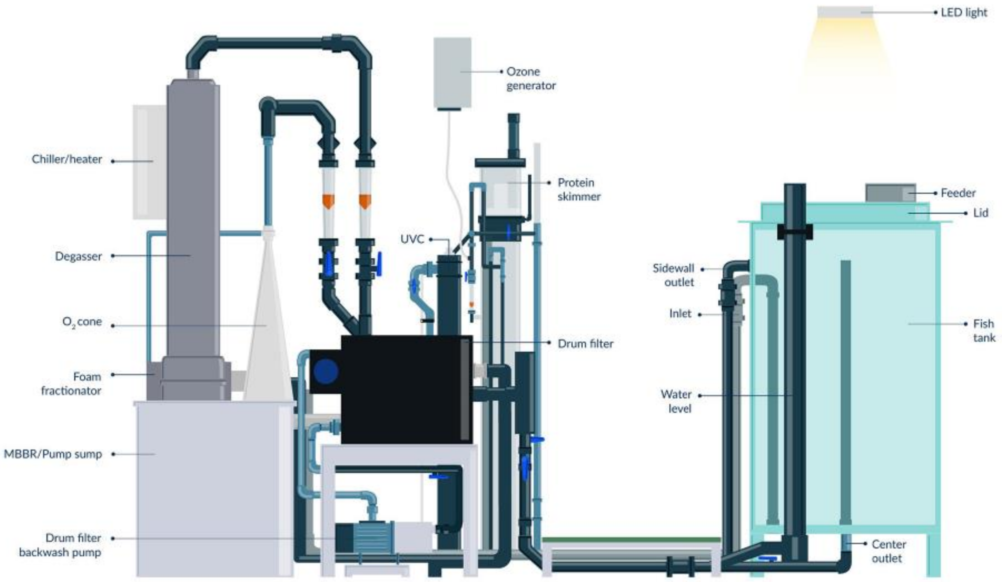

Figure 2. 4: A detailed RAS unit with several essential and advanced components, adopted from (Mota, Striberny, et al., 2022)

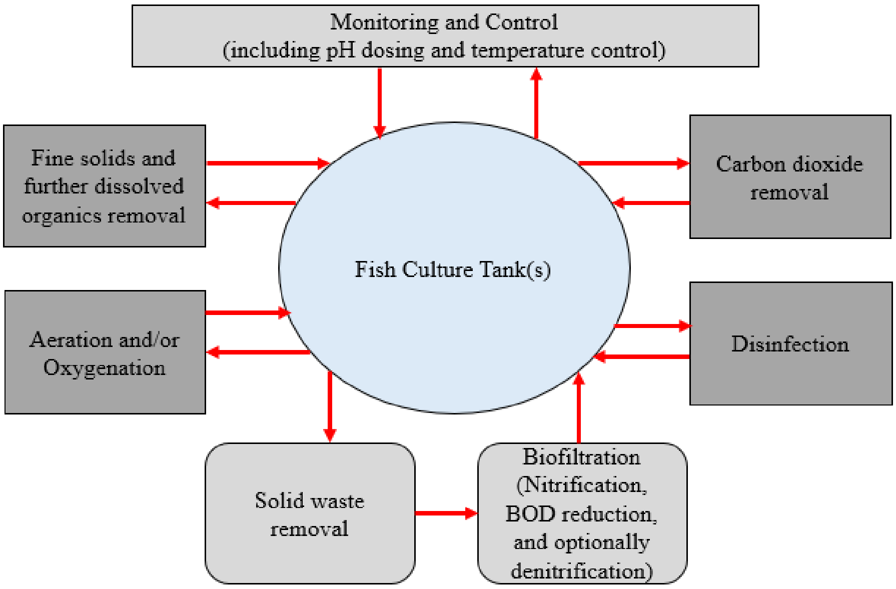

Figure 2. 5: The common unit process used in RAS, adapted from (Murray et al., 2014)

2.3 Water Treatment

Solid removal (mechanical filtration, decantation), biological processes (ammonia nitrification by biofilter, disinfection by UV), and gas control (oxygen supply, CO_2 degassing) are the fundamental RAS water treatment sequence (Roque d'orbcastel et al., 2009) and throughout the culture unit, more than 90% of the water is recycled (Sugita et al., 2005). All the parts of RASs are primarily used to ensure that water quality in the system is continually maintained at the optimal level to support the survival of any specific aquatic species kept in the culture tank. Therefore, the availability of sufficient water in terms of both quantity and quality is the most critical aspect of the system (Wheaton, 2008). Temperature, dissolved O_2, pH, and total ammonia nitrogen (TAN) are the main water quality parameters for aquaculture systems (Mota, Striberny, et al., 2022), and managing these parameters means monitoring and adjusting continuously to create an ideal environment for the fish being culture to thrive, with consideration for the biologically accepted ranges for each of these water quality parameters (Bregnballe, 2022). Therefore, RAS water treatment systems are designed to regulate vital water quality criteria and temperature at the accepted range, which prevents inferior water quality conditions and the corresponding decrease in feed utilization efficiency (Van Rijn, 2013). Moreover, maintaining and controlling the quality of water in the system has become an equally, if not more, crucial task than looking after the fish (Bregnballe, 2022). Most systems use mechanical filters to remove solid waste products from the recycling water. After which, with the usage of nitrifying bacteria, nitrogenous waste like ammonia is detoxified, first into nitrite and finally into the less harmful nitrate (Tidwell, 2012). Aeration or oxygenation is then used to remove unwanted gases from the water, like carbon dioxide CO_2, nitrogen N_2, and hydrogen sulfide H_2S, or in the case of oxygen O_2, to increase its concentration in the water (Lekang, 2020). Disinfection through ozonation and UV irradiation of the recycled water are further forms of water treatment (Van Rijn, 2013) and this is a common practice in commercialized facilities which raises fish at high densities. Good feed utilization and overall fish welfare are generally positively correlated with high water quality.

2.3.1 Culture Tanks

Tanks are generally used in RAS, similarly to how cages are used in seawater or freshwater fish farming (Plew et al., 2015). They come in different shapes and sizes depending on the specific need of the farmer and are typically made of polyethylene, fiberglass (for big commercial use), or other rubber liners that prevent water leakage (Ebeling & Timmons, 2012).

The primary purpose of the culture tank in RAS is to hold the water body and the cultured fish species securely while conditions in a tank must be kept at optimal levels to ensure the growth and welfare of the fish (Plew et al., 2015). The foremost criteria in selecting a culture tank is to ensure self-cleaning, which is dependent on the shape of the tank, among other things (Ebeling & Timmons, 2012). Also, the attribute of the tank's inlet (placed tangentially) and outlet (placed at the center base), coupled with its shape significantly influences the water flow pattern, and rotational flow pattern has been observed to be beneficial to fish health and welfare (Duarte et al., 2011). Ultimately, the tank design must have the proper hydrodynamics, as the success of the RAS operation, in addition to production profitability, relies on it. Tanks used for commercial aquaculture are usually fitted with sensors during operation; these sensor helps to measure water quality parameters, which aid water treatment decisions (Ebeling & Timmons, 2012)

2.3.2 Solid Removal

The most crucial treatment unit process in a RAS is the quick removal of solid wastes (i.e., uneaten feed, feces) (Summerfelt & Penne, 2005); this is because further retention of solid waste in the system makes water treatment and water quality maintenance more challenging, and this could eventually raise the cost of water treatment, and negatively impact the health of the cultured fish due to low water quality (Piedrahita et al., 1996). Formulated pellet feed, which is the primary food source for fish in RAS, and uneaten feed/residues are the primary sources of solid waste (Mo et al., 2018). Therefore, a buildup of this solid waste in RAS can cause water quality to drop significantly, which will ultimately put more stress on the culture (Cripps & Bergheim, 2000). Furthermore, high suspended solids concentration can harm fish gill function, support facultative fish pathogens, raise biochemical oxygen demand (BOD) levels, and provide a growing medium for heterotrophic microorganisms in the biofilter that could replace nitrifying bacteria (Nitrosomonas and Nitrobacter), which are necessary for the conversion of ammonia to nitrate (Summerfelt & Penne, 2005). Also, turbidity associated with suspended fine solid loads can enhance absorption and scattering of light to varying degrees, depending on its concentration, particle size distribution, and shape; turbid water has been observed to cause aquatic organisms that are visually oriented to consume less feed (Schumann & Brinker, 2020).

In most cases, Turbidity is typically used in program monitoring as a substitute and quantitative measure of water clarity or as a replacement for suspended solid concentration

(SSC) (Rymszewicz et al., 2017). The reason for this is that the method of measuring SSC can be costly and laborious, especially if a large number of samples need to be collected and examined (Bilotta & Brazier, 2008). In this thesis, a drum filter will be used for mechanical filtration in the designed RAS units. However, It has been observed that organic matter still passes through the mechanical filter as a dissolved substance (i.e., Phosphate, Nitrogen), which means organic substances in their particulate form are not entirely removed through mechanical filtration; also, nitrogen in the form of free ammonia (NH_3) is toxic to the fish and must be converted to nitrate in the biofilter, but phosphate is an inert material with no harmful effects (Bregnballe, 2022). After solid removal, the next phase of water treatment is known as biofiltration.

2.3.3 Biofiltration

Biofilm reactors, which include trickling filters, rotating biological contactors, and moving bed biofilm reactors (MBBR), are frequently used in RAS for biological water treatment (Wik et al., 2009). Nitrification, the process of converting extremely toxic ammonium nitrogen NH_4^+ into nitrite nitrogen NO_2^- and later to nitrate nitrogen NO_3^-, are the resulting steps in a biofiltration process (Takeuchi, 2017). The primary sources of nitrogenous waste are ammonia excretions, amino acids, uric acid, and urea from the fish; organic materials from dead and dying organisms; uneaten feed and feces; and nitrogen from the atmosphere (Ebeling & Timmons, 2010). Biological filters are used in the nitrification process to eliminate total ammonia nitrogen (TAN). These compounds are of great importance in RAS water treatment and must be either eliminated or transformed into non-toxic compounds (Ebeling & Timmons, 2010). The biofiltration process utilizes microorganisms known as biofilms, which colonize the biofilters' medium and eventually form a complex microbial community made up of various bacteria. These biofilms transform toxic ammonia excreted by the fish into non-toxic nitrates (Roalkvam et al., 2021). For the biofiltration process, two MBBR would be designed and attached to the developed RAS units. In contrast to other biofiltration methods, the MBBR has been selected, due to its small footprint, low maintenance, and operational issues when compared to alternative techniques (Ebeling & Timmons, 2010). The MBBR would be aerated, therefore, there will be sufficient O_2 present for the nitrification process and the turbulence produced in the process will allow the biofilm carriers and water in the reactor to mix properly (Drennan II et al., 2006).

2.3.4 Carbon dioxide

After biofiltration, aeration is the next phase in the essential water treatment procedure in RAS. The primary function of the aerator is to remove unwanted gases, mainly CO_2 (Ebeling & Timmons, 2010). This is because fish welfare and growth are negatively impacted by CO_2 accumulation, which is brought into the water by the fish and bacteria respiration (Bregnballe, 2022). CO_2 is generally toxic to a fish because it decreases the blood's ability to carry O_2 (Ebeling & Timmons, 2010), and levels above 10 – 15 mg/L have been reported to be detrimental to salmonid growth and welfare; however, the exact toxic levels are always a function of the size and species of the fish (Lekang, 2020). Air and water come into contact during aeration, either by driving tiny water droplets through the air or by bubbling air through the water (Tidwell, 2012). Depending on the saturation level of the O_2 in the water, the aeration process will provide some oxygen to the water by a simple exchange between the gases in the water and the gases in the air (Bregnballe, 2022). The RAS units in this thesis are small-scale, and they are expected to be stocked at low density; therefore, they can rely on aeration to meet the oxygen needs in the system. However, for cultures that are kept at fish density ≥ 100 kg/m^3, aeration alone is insufficient to meet the O_2 need in the system and hence the need for O_2 supply equipment that delivers liquid O_2, which effectively dissolves in water (Takeuchi, 2017).

2.3.5 Sludge removal

Though water purification is possible with RAS, the fish waste and other solid dirt produced during the water treatment operations do not automatically disappear; they are usually gathered and removed through the mechanical filter as sludge (Ebeling & Timmons, 2012). The collection of sludge demonstrates one of the environmental advantages of RAS over other traditional aquaculture practices, and in large commercial facilities, the sludge is treated before they are carefully disposed of (Mirzoyan et al., 2010). Overtime, the water component leaving the system through sludge must be replenished by supplying new water to the system (Ebeling & Timmons, 2012)

2.3.6 Disinfection

To avoid the transfer of disease into a facility, it is mandatory to ensure personnel, smolts, and inlet water entering the RAS enclosure pass through some form of screening or disinfection (Ebeling & Timmons, 2012; Lekang, 2020). Disinfection is, therefore, part of the process of guaranteeing good fish welfare through the control of the rearing and immediate environment (Lazado & Good, 2021). Although the design of the RAS facility is expected to provide maximum biosecurity to the entire system compared to other traditional aquaculture practices, cases of pathogen invading facilities still occur, resulting in substantial economic losses (Mota, Striberny, et al., 2022). Therefore, keeping the system clean of pathogens needs to be taken seriously, especially in large commercial farms. In RAS, disinfection of the rearing environment can either be recurring - with the use of chemicals or continuous; an example of a continuous disinfection system is the use of ozone O_3 and UV irradiation, which are usually common with intensive farms; however, proper care needs to be applied in their usage to avoid a negative impact of the disinfection method on the efficiency of the beneficial bacteria which aid nitrification process (Mota, Eggen, et al., 2022). Ultimately, Prevention is always the best practice, as disease outbreak in one tank can be assumed to have spread across other tanks because of the integrated nature of the RAS (Bregnballe, 2022).

2.3.7 System Monitoring and Control

RAS is essentially designed to mimic the environmental conditions and needs of the fish being raised; the controlled nature of the system ensures that these environmental conditions are always met. All the water quality parameters (O_2 level, Temperature, pH, CO_2, Alkalinity, etc.) need to be maintained at optimal levels for the growth and well-being of the fish, especially in intensive RAS facilities with high stocking density. Measuring equipment, which could be manual (in small farms) or automated (commercial use, gives real-time data), is placed at a strategic spot to measure the intended parameter, and the data collected are interpreted by the personnel in charge. Also, the need for a backup solution is essential in case when there is a significant deviation in reading from the optimal condition required for the health of the fish. Such backup solutions can temporarily be used before conditions are restored to the optimal level. Lastly, equipment must be appropriately calibrated during installation and the monitoring system is as reliable as the personnel in charge of it. (Bregnballe, 2022; Ebeling & Timmons, 2012; Lekang, 2020)

2.4 Water Quality

Water quality in RAS is essential for the effective growth and survival of the cultured species, which is why water treatment is essential to maintain good water quality in RAS

(Lindholm-Lehto, 2023). Temperature, dissolved O_2, pH, and TAN are typical water quality measures (Mota, Striberny, et al., 2022) and because these water parameters affect the physical characteristics and chemical composition of the water, they must be measured every day (all day in an intensive system); however, if these parameters are not monitored and managed correctly, the results can be severe and can induce stress, lead to poor growth and even death (Alatorre-Jácome et al., 2011). The requirement for water quality varies depending on the species and the phase of life of the fish (Lekang, 2020), Table 2.1 further shows the varied conditions and requirements needed for raising different aquatic species. Therefore, water treatment plans and RAS designs must be based on the species being raised.

The relationship between water quality parameters, maintaining these parameters at required levels, and their effect on fish welfare and growth are of much interest in RAS. This simply confirms that RASs are not simple systems; instead, they show interaction between technology and biological systems, which constantly need performance supervision (Lekang, 2020) Henceforth, much examination and consideration need to be given to the design, installation, operation, and management of a RAS facility.

Table 2. 1. Water quality parameters observed under general conditions in operating commercial scale RAS adapted from (Dalsgaard, Lund, et al., 2013).

	Temp (ºC)	**O_2 (mg/L)**	**CO_2 (mg/L)**	**pH**	**Salinity (ppt)**	**TAN (mg/L)**	**NO_2-N (mg/L)**	**NO_3-N (mg/L)**	**Density (Kg/m^3)**
Aquatic specie									
Arctic char	5-12	9-11	≤22	6.5-8.5	<24-26	≤10	<0.5	<10	85-130
Salmon smolt	12-14	10	≤12	6.8-7.3	0	<0.2	<0.2	≤90	45-50
European eel	23-28	6-8	10-20	5.0-7.5	0-5	0-5.0	0-1.5	50-100	50-120
European lobster	18-20	>6	n.a.	7.8-8.2	28-35	<0.3	n.a.	n.a.	n.a.
Pike perch	22-25	6-8	10-20	6.5-7.5	0	0-10	0-1.5	<56	15-60
Rainbow trout	2-21	6-8	≤15	6.5-8.0	0-30	<7.5	<1.0	<200	50-80
Sturgeon	18-25	8	n.a.	7.0-8.0	0	<3	<0.5	<25	80-100
Nile tilapia	20-30	4-6	≤30-50	6.5-8.5	≤10-15	<3	0.05-1.0	100-200	85-120

2.5 RAS Challenges

The majority of people still consider RAS a risky venture (Wheaton, 2008), because the use of RAS suddenly requires fish farmers to manage both fish and water quality (Bregnballe, 2022). One of the most important keys to managing the system is having a thorough understanding of it, which calls for interaction between engineers and scientists (Badiola et al., 2012). Therefore, inadequate management, poor knowledge about the technology, high investment, and energy costs are some of the major challenges facing the industry (Aich et al., 2020). Also, welfare issues have been noted as a result of high stocking densities during production in order to cover the high investment expenses (Martins et al., 2010). Other challenges observed are bad system design, which led to the redesign and reconstruction of facilities when an initial design proved ineffective, and finally, a lack of qualified staff (Badiola et al., 2012). All these challenges need to be examined to find appropriate solutions, which in turn would support the wider application of the recirculating system technology.

It’s been observed that RAS uses the most energy per mass of fish produced when compared to other aquaculture systems (Ayuso-Virgili et al., 2023). Also, the dynamics of infection in RAS differ from those in other production systems because of the potential for increased pathogen proliferation and infections due to higher fish densities and nutrient availability (Mota, Striberny, et al., 2022). Therefore, to mitigate all these challenges around RAS, it can be said that increased communication and interactions between those working with RAS is of utmost importance, as well as the need for more specialized personnel for its operation, which further presents additional challenges (Badiola et al., 2012). Generally, the mode of management has an impact on both the system’s operation and economics (Wheaton, 2008). Nonetheless, many industrialized countries hold RASs in high regard and have demonstrated their support for the system development through policy, law, and investment fund (Sun & Liu, 2016)

2.6 RAS Utilization in Norway

Norway has an extensive coastline (Fig. 2.6) and an abundance of marine life. Norwegians have relied on fishing, whaling, and sealing as means of survival throughout history. Fishing of Atlantic salmon for Norwegians has always been a major social, cultural, and economic activity. Although salmon was historically fished as an essential food source, the advent of salmon farming in the 1970s altered the dynamics of the salmon industry and seafood business as a whole, both in Norway and worldwide (Liu et al., 2011). Today, salmon is one of the leading farmed finfish species globally, with a yearly production of about 2.4 million tons (FAO, 2020). Over the past ten years, salmon production in Norway has been growing rapidly (Ayuso-Virgili et al., 2023), driven by the rising demand for fish products worldwide (Webb et al., 2015). Consequently, Norway is the largest producer of salmon, with over 50% of the global supply (Iversen et al., 2020). About 1.5 million tonnes of total global demand for Atlantic salmon was supplied by Norway in 2022 (FAO, 2023). This development was enhanced by Norway's vast coastline, which offers perfect conditions for aquaculture, particularly salmon farming. The fjords and archipelagos along the coastline offer protection and create the ideal water current conditions. Consequently, the cold water provides the ideal temperature range (8^oC–14^oC) for salmon (MOWI, 2023).

Figure 2. 6: The Norwegian coastline shows salmon aquaculture regions and site distribution in 2020. Orange circles show sites with farm licenses, adopted from (Wang & Olsen, 2023)

There are two distinct production phases in salmon aquaculture: a land-based smolt production in freshwater followed by an on-growing phase in cages, kept at sea till maturity (Bergheim et al., 2009). The usual land-based production phase has been changing from using traditional flow-through systems to RAS, and it is estimated that about 70% of smolts kept in the sea cages in Norway are from RAS (Meriac, 2019). This change in practice is due to the poor performance observed during the seawater on-growing phase in cages from smolts raised with a flow-through system; therefore, around the year 2000, all flow-through farms were converted into RAS facilities, and mortality in sea cages has relatively declined (Bergheim et al., 2009). Also, the expansion of the sea cages is significantly restricted by insufficient and suitable fjord space and its detrimental environmental impact on the welfare of wild salmon (Liu et al., 2011) Therefore, RAS is considered the preferred land-based aquaculture model and has consequently been receiving increased attention (Ayuso-Virgili et al., 2023).

In recent times, the focus has gradually shifted into increasing the inland phase of aquaculture, and this is because of the benefits offered in this phase, such as an end to fish losses through escapes, a decreased risk of infections contracted from contact with external pathogens, and the capacity to offer conditions for vaccination under controlled settings (dos Santos et al., 2023) and limited interaction with the wild salmon population. A further reason for the need for more RAS facilities is due to the rapid rise in sea lice infestations in recent years, which has resulted in high expenses for the salmon industry due to wound treatment and fish delousing (Abolofia et al., 2017). Sea lice infestation at sea cages poses a serious threat to the Norwegian salmon aquaculture industry's ability to grow further (Brakstad et al., 2019) and the industry is currently facing significant challenges related to the high expenditure on lice control (Costello, 2009). However, post-smolt production—which entails growing the salmon larger in a protected environment before transferring it into conventional sea cages—is one of the techniques taken into consideration to resolve this problem (Brakstad et al., 2019). Furthermore, ensuring the saltwater phase in salmon production is shortened.

To encourage innovation in the industry toward mitigating current challenges, the Norwegian government unveiled a new initiative in 2015, known as the Development licenses (Hagspiel et al., 2018). The initiative is to facilitate the development of new technology that might help the industry resolve its water, waste, and environmental concerns (Fiskeridirektoratet, 2020) but generally, in Norway, the production of salmon in sea cages is commonly regulated by granting of farming licenses to corporations, and each license permits the organization to raise a specified amount of salmon biomass at sea per time; this specified biomass is referred to as Maximum Allowable biomass (MAB) (Hagspiel et al., 2018). A single farming license typically has a MAB of 780 tons (945 tonnes in Troms and Finnmark) (MOWI, 2023). Consequently, farming licenses ensure that the regulatory body can control production volume and observe the health and welfare of the fish species being produced.

2.7 Need for practical education in RAS utilization.

Aquaculture development requires knowledge, a good breeding plan, and patience, among other things. Also, moving from traditional fish farming to RAS does not necessarily resolve all the challenges facing aquaculture; however, the change does make many things easier, but it also requires a new and greater skill set. Using RAS technology, the fish farmer has complete control of all the parameters in the production, and the farmer's ability to operate the system itself becomes just as important as his ability to take care of the fish (Bregnballe, 2022). Dissolve O_2, pH, temperature, CO_2, alkalinity, and ammonia are the most important production parameters (Summerfelt, 2000). Most significant to consider is that the values for these various water quality parameters differ depending on the species, i.e., the optimal temperature for Atlantic salmon is (12ºC – 14ºC), and for tilapia is (20ºC – 30ºC) while the O_2 and CO_2 for the two species are 10mg/L and 4 – 6mg/L respectively, and ≤12mg/L and ≤30 – 50mg/L respectively (Dalsgaard, Lund, et al., 2013).

It has been noted that carefully regulated culture conditions when operating RAS greatly aid efficient feed consumption and utilization (Van Rijn, 2013). Therefore, the varying water quality parameters for fish growth and welfare, in addition to other production inputs to consider, show the complexity of operating a RAS and the need for adequate knowledge and understanding of its utilization. Also, salmon aquaculture is a profitable industry that is growing quickly, it is a knowledge-based sector that is leading the way in aquaculture production development, technology, and innovation (Asche & Bjorndal, 2011). An essential component of operating a RAS is understanding how the system responds to changes, particularly in an emergency before an issue arises (Wheaton, 2008), understanding this feedback and the technology as a whole has the potential to completely transform the aquaculture industry, even as more knowledge about the system and its components interactions are fully understood (Aich et al., 2020). Also, the careful design and management of a RAS significantly impacts its waste management strategy and treatment (Van Rijn, 2013). As a result, the aquaculture industry's growth can only be developed at a faster rate through educational solutions (Webb et al., 2015). RAS also presents unique educational opportunities because they require more specialized knowledge, which presents additional challenges and the need for more communication and exchange between people working with RAS (Badiola et al., 2012). It has been observed that transiting from theoretical knowledge to practical applications has been most effective for students who could physically see the recirculating system while receiving lectures on the system (Cline et al., 2005). Therefore, the need for practical classes on its usage can not be overemphasized.

A recent study by NCE Seafood Innovation (NCE Seafood Innovation, 2021), conducted in Norway, indicated that its members and partners have a pressing demand for RAS professionals and an urgent need to update personnel competency. The institute stated that this need resulted from the numerous RAS facilities being built in Norway, as well as ongoing investment and development of new technology in RAS. However, Due to cost-related concerns, the size of the facility, and the welfare of the fish raised, operating RAS to gain proficiency and competency in an already established facility might be challenging. Nonetheless, the technology is unique and can be scaled down to a small space and operated with limited water availability (Webb et al., 2015). This scaled-down model, which is relatively inexpensive, can assist in providing practical experience to anyone interested in RAS education.

The need for adequately skilled personnel to operate RAS facilities cannot be overemphasized as bigger and more advanced commercial facilities are being constructed. The complexity of operating these facilities continues to increase. Also, most RAS research facilities are designed toward understanding fish biology and nutrition, therefore restricting the need for system manipulation to fully understand the engineering dynamics of its operations. Therefore, to improve the knowledge and practical training gap in RAS, this thesis aims to dimension, design, and evaluate small-scale RAS for educational purposes.

3. AIMS AND HYPOTHESIS

This thesis aims to dimension and design two separate small-scale RAS units, purposed to educate students. Furthermore, the treatment efficiency of a water treatment unit, i.e. degasser, will be assessed as a case study.

The decision to evaluate only the degasser was due to the non-availability of measuring instruments (the tool for measuring water velocity in the tank was not sensitive enough for the flow range in this thesis and no alternative was available) and time constraints (the two RAS units were fully setup at the end of March), also the minimum start-up time for MBBR maturation is 4 weeks) (Cardoso et al., 2024)

The specific objectives are further described:

I. to dimension and design two small-scale RAS units for educational purposes
II. to evaluate the treatment efficiency of the designed degasser with different media, water flow rates, and inlet CO_2 concentrations

Research questions (RQ) & hypothesis

No RQ was proposed for the first specific objective, as the main goal was to dimension and design the RAS units, therefore the designed RAS only needed to be usable for educational purposes.

While the second specific objective has three RQs

RQ1. Does the characteristic of the media in the column of the designed degasser affect its treatment efficiency?

H0: the characteristic of the media in the column of the designed degasser does not affect its treatment efficiency.

RQ2. Does the water flow rate into the designed degasser affect its treatment efficiency?

H0: the water flow rate into the designed degasser does not affect its treatment efficiency.

RQ3. Does the CO_2 concentration in the designed degasser affect its treatment efficiency?

H0: the CO_2 concentration in the designed degasser does not affect its treatment efficiency.

4. MATERIAL AND METHODS

4.1 Dimensioning

4.1.1 Water requirement, biomass, and feeding rate.

The decision on the choice of the fish species to dimension the RAS units was between salmon and tilapia. After much consideration, involving water quality needs, economy, and general welfare, the designed RAS units in this thesis are dimensioned to raise a Nile tilapia, and the water quality requirements for a tilapia are factored in for its welfare. The reasons for the selection of the tilapia are further itemized below:

1. Budget – educational budgets are generally limited, therefore financial constraints influence the size, quantity, and capacity of components that can be purchased (Webb et al., 2015)
2. Water quality requirements – O_2 is the major limiting factor in RAS design, the loss of O_2 means the loss of fish (Ebeling & Timmons, 2010). The O_2 requirements for salmon and tilapia are 10 mg/L and 4-6 mg/L respectively (Dalsgaard, Lund, et al., 2013). Therefore, it was considered that the lower limit of O_2 demand by Nile tilapia could be achieved with smaller components, therefore making the RAS design affordable and less sophisticated.
3. Versatility – the choice of tilapia in this design fully expresses the flexibility of the technology and how it can be dimensioned to meet the needs of other aquatic organisms.
4. Resilience - tilapia are generally considered to be hardy (can withstand CO2 concentration as high as 50 mg/L). The nature of the purpose of these RAS units dictates that the system must be handled, and frequent parameter adjustment will be prevalent during usage. Therefore, a fish specie that can survive such fluctuation in water quality best suits this thesis.
5. Potential economic value - the use of tilapia will introduce new opportunities to participants in the practical classes, whereby an economic niche around tilapia can be created. Gårdsfisk, a fish farm in Sweden already produces about 20 tonnes of Nile tilapia a year using RAS (Fletcher, 2023).

In summary, finance, water quality requirements, and potential economic value were the deciding factors. The water quality requirements of choice for the tilapia in the system are in line with those mentioned by (Dalsgaard, Lund, et al., 2013) Also, an essential part of the RAS's dimensioning is fitting all the components perfectly on a wooden pallet. The reason behind this is to allow for a compact design and ease of movement of each RAS unit as a single entity.

The RAS would be designed to accommodate an initial fish size of 5 g, which is the size at which tilapia enters Phase 2, Pre-growth stage (Kubitza, 2019). Also, a maximum size per fish of 175 g has been chosen to ensure good welfare within the system. The average feed intake (% of body weight/day) for the duration of fish growth from 5 g to 175 g has been set at 6% bw/day (Kubitza, 2019). The Fig. 4.1. captures details relating to biomass and feeding schedule for the cultivated fish.

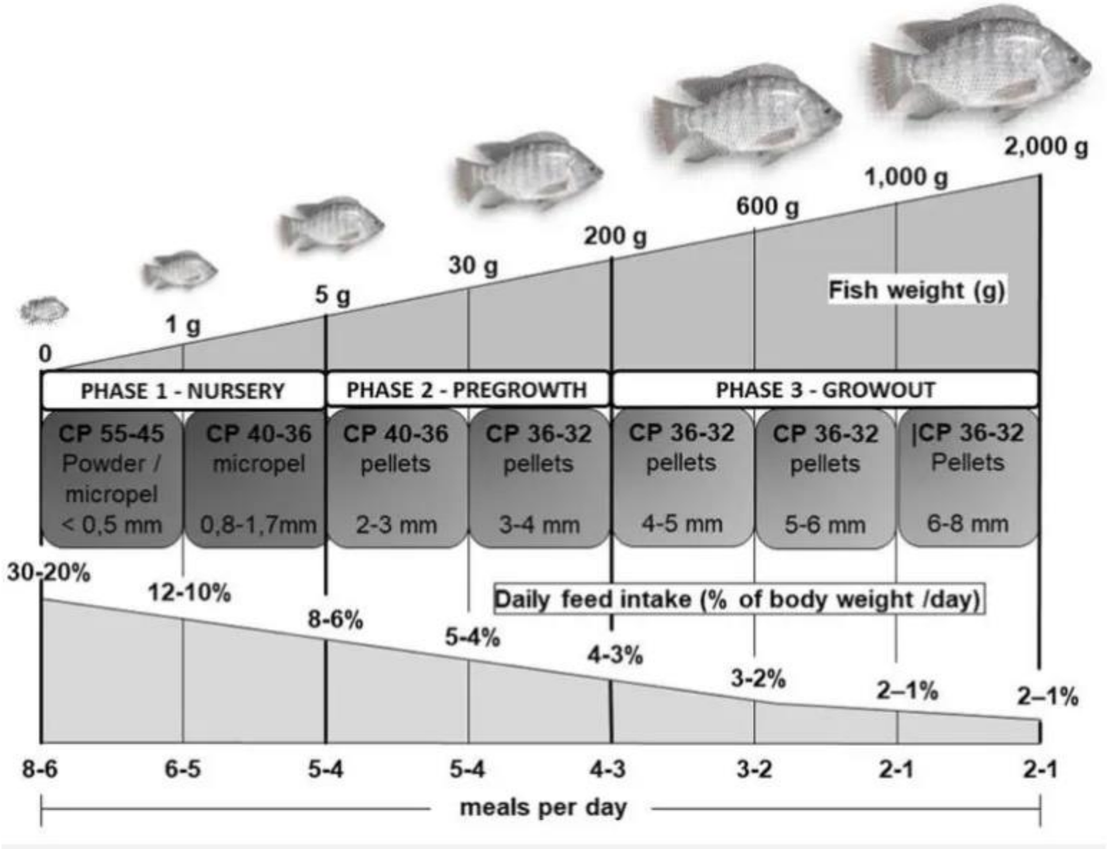

Figure 4. 1: The feeding schedule and growth phases of a tilapia

About 10 individuals (Nile tilapia) would be stocked per time in the fish tank and the dimensioning of the water quality requirement for the fish, the expected maximum biomass in a single unit, and their average feeding rate are shown in Table. 4.1.

Table 4. 1 Summary of the dimensioning for water quality requirement, maximum biomass, and feeding rate for tilapia kept in the designed RAS

	Item	**Formulae**	**Value**
Water Requirement			
	O_2 (mg/L)	Obtained from (Dalsgaard, Lund, et al., 2013)	5
	TAN (mg/L)	Obtained from (Dalsgaard, Lund, et al., 2013)	2
	CO_2 (mg/L)	Obtained from (Dalsgaard, Lund, et al., 2013)	30
Biomass and feeding rate			
	Initial weight (g)	Tilapia pre-growth phase	5
	Final weight allowable (g)	Tilapia pre-growth phase	175
	Number of fish	Assumed	10
	Initial biomass (g)	Initial weight * No of fish	50
	Final biomass (g)	Final weight * No of fish	1750
	Average feed intake (%bw/day)	Obtained from available data	6
	Initial and final feeding rate (g/day)	Final biomass * average feeding rate	3 and 105
	Final Feeding rate (kg/day)	Feeding rate / 1000	0.105

4.1.2 Tank

A cylindrical/conical-shaped tank was selected as the preferred tank shape because of its potential to help with self-cleaning and rotational flow pattern (Ebeling & Timmons, 2012). The volume of the culture tank is set at 100 L, as this volume will set the maximum stocking density at 26 kg/m^3. The Fig. 4.2. illustrates the proposed tank shape.

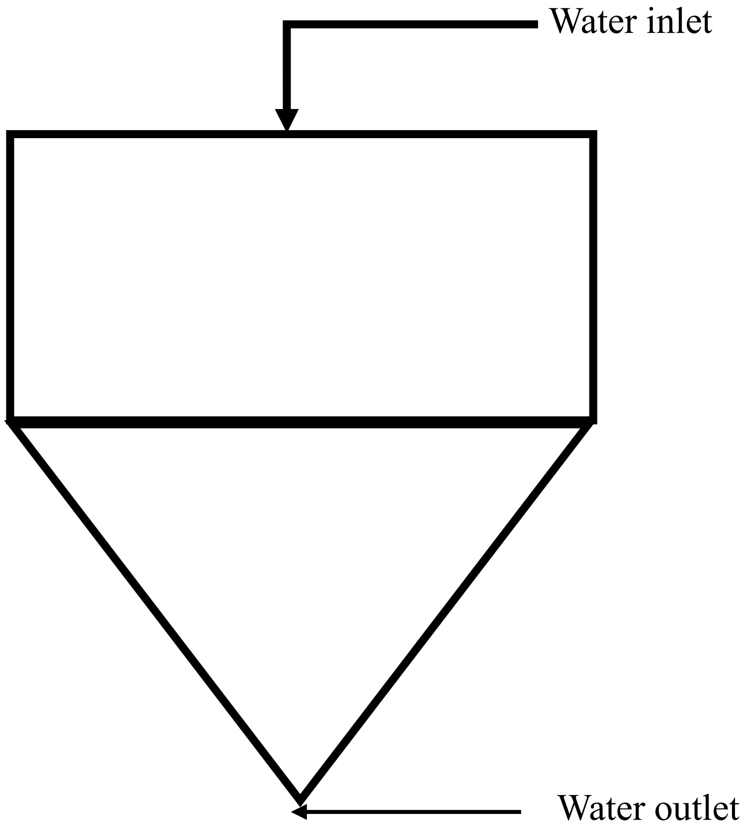

Figure 4. 2: Proposed shape of the 100L culture tank

4.1.3 Water Flow (Q)

To arrive at the desired pump capacity sufficient for the system, the minimum water flow rate Q (L/hr) necessary to operate the RAS and meet all the water quality requirements needs to be determined. The Q is responsible for transferring O_2 into the tank and then diluting or transporting pollutants (TAN or CO_2) out of the culture tank. The mass balance equation would be employed to find Q.

Mass balance equation

$Q_2C_2 + P = Q_1C_1$ Eq.1

Where,

Q_1 = Water flow out (L/hr)

Q_2 = Water flow in (L/hr)

C_2 = Concentration of water quality parameters in (mg/L)

C_1 = Concentration of water quality parameters out (mg/L)

P = Production term (negative if consumed) (kg/day)

However, in a steady state $Q_1 = Q_2$

And Eq.1 can be written as

$Q = -P / (C_2 - C_1)$ Eq2.

Eq2 is illustrated in Fig. 4.3. below

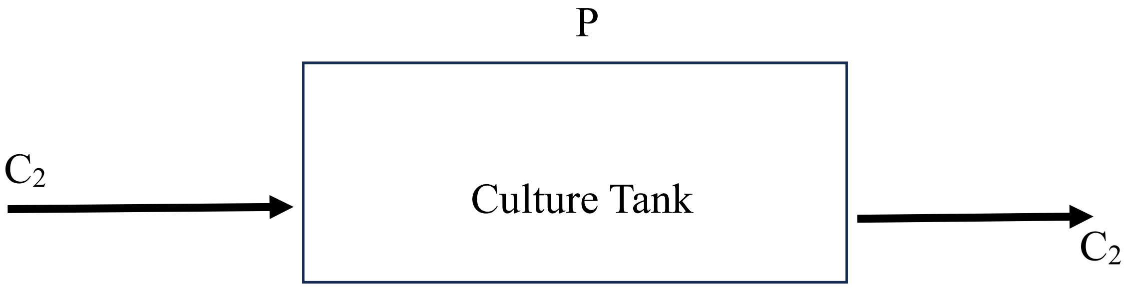

Figure 4. 3: Mass balance illustration at steady state (Q_1=Q_2)

4.1.4 Calculating for the production term (P)

The production term (P**)**, in Eq2. depicts the term for pollutant (TAN, CO_2) or the consumption term (O_2), and in the calculation for (P), all constants used in the formulae were gotten from (Ebeling & Timmons, 2012)

Calculating **P** for the required water quality parameters (O2, TAN, CO_2)

Oxygen (O2

$P_{oxygen} = F * 0.35$ Eq3

Where,

F = Feeding rate (kg/day)

0.35 constant gives an approximate value of O_2 consumed by fish

Total Ammonia Nitrogen (TAN)

$P_{TAN} = F * PC * 0.092$ Eq4

Where,

F = Feeding rate (kg/day)

PC = Protein content of the feed (%) (PC of 25% was adopted)

0.092 constant, which gives an approximate of nitrogen assimilated and excreted.

Carbon dioxide *(CO_2)*

CO_2 production is dependent on O_2 consumed.

$P_{CO2} = F * 0.35 * 1.375$ Eq5

F = Feeding rate (kg/day)

0.35 constant to account for O_2 consumed.

1.375 constant to account for CO_2 produced.

4.1.5 Determining inlet concentration of water quality parameters.

The concentration of the water quality parameter range ideal for raising the Nile tilapia is found in Table. 2.1 above (Dalsgaard, Lund, et al., 2013); therefore, the concentration of these same parameters entering the designed systems needs to be determined,

Determine oxygen concentration.

To find the O_2 concentration in the inlet water, the Table. 4.2. showing O_2 in saturated water under atmospheric pressure is utilized. Tilapia is a freshwater species, and the laboratory water quality used for this thesis is assumed to have zero (0) salinity. Also, the fish thrives in a water temperature range of 20°C to 30°C. Therefore, for this calculation for O_2, a water temperature point of 20°C, at 0 salinity, was used to derive the inlet O_2 concentration. The average water temperature in the laboratory is 14°C consequently, whenever the system is stocked with tilapia, the inlet water temperature will be raised to appropriate levels. The water knob at the laboratory is fitted with a regulator for warm water.

Table 4. 2 Dissolve Oxygen (mg/L) in fully saturated water under atmospheric pressure, adopted from AQP 311, Production technology in Aquaculture, Norwegian University of Life Sciences (NMBU) course.

Dissolved oxygen (mg/l) in fully saturated water under atmospheric pressure.										
		Salinity (ppt)								
		0	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
Temperature (°C)	**0**	14.6	14.1	13.6	13.1	12.7	12.3	11.9	11.5	11.1
	1	14.2	13.7	13.3	12.8	12.4	12	11.6	11.2	10.8
	2	13.8	13.4	12.9	12.5	12.1	11.7	11.3	10.9	10.5
	3	13.4	13	12.6	12.2	11.8	11.4	11	10.6	10.3
	4	13.1	12.7	12.3	11.9	11.5	11.1	10.7	10.4	10
	5	12.8	12.3	11.9	11.9	11.2	10.8	10.5	10.1	9.8
	6	12.4	12	11.6	11.3	10.9	10.6	10.2	9.9	9.6
	7	12.1	11.7	11.4	11	10.7	10.3	10	9.7	9.4
	8	11.8	11.5	11.1	10.7	10.4	10.1	9.8	9.4	9.1
	9	11.5	11.2	10.8	10.5	10.2	9.8	9.5	9.2	8.9
	10	11.3	10.9	10.6	10.3	9.9	9.6	9.3	9	8.7
	11	11	10.7	10.3	10	9.7	9.4	9.1	8.8	8.6
	12	10.8	10.4	10.1	9.6	9.5	9.2	8.9	8.6	8.4
	13	10.5	10.2	9.9	9.6	9.2	9	8.7	8.4	8.2
	14	10.3	10	9.7	9.4	9.1	8.8	8.6	8.3	8
	15	10.1	9.8	9.5	9.1	8.9	8.5	8.4	8.1	7.8
	16	9.9	9.6	9.3	9	8.7	8.5	8.2	8	7.7
	17	9.7	9.4	9.1	8.8	8.6	8.3	8.1	7.8	7.6
	18	9.6	9.2	8.9	8.6	8.4	8.1	7.9	7.7	7.4
	19	9.3	9	8.7	8.5	8.2	8	7.7	7.5	7.3
	20	9.1	8.8	8.6	8.3	8.1	7.8	7.6	7.4	7.2
	21	8.9	8.6	8.4	8.1	7.9	7.7	7.5	7.2	7
	22	8.7	8.5	8.2	8	7.8	7.5	7.3	7.1	6.9
	23	8.6	8.3	8.1	7.8	7.6	7.4	7.2	7	6.8
	24	8.4	8.2	7.9	7.7	7.5	7.3	7.1	6.9	6.7
	25	8.2	8	7.8	7.6	7.4	7.1	7	6.8	6.6

Determining CO_2 concentration

CO_2 is about 0.04% of air, which is about 400 ppm. CO_2 is highly soluble in water unlike other gases (Aitchison et al., 2007). Assuming a constant atmospheric air pressure of 760 mmHg (1 atm) and water temperature of 20°C (inlet water temperature). The concentration of CO_2 in the inlet water can be derived from the Table. 4.3 below.

Table 4. 3 Solubility of water at different temperatures adopted from (Kutty, 1987)

Temperature (°C)	**Solubility (mg/L)**
0	1.10
5	0.91
10	0.76
15	0.65
20	0.56
25	0.48
30	0.42
35	0.36
40	0.31

Determining TAN concentration

For this thesis, a TAN concentration value of zero (0) has been chosen. The laboratory's water is a municipal supply and is assumed to have zero TAN.

Therefore, the Table. 4.4. below summarizes the concentrations (C_2 and C_1) of water quality parameters entering and leaving the culture tank.

Table 4. 4 Summary of concentration of water quality parameters entering and leaving the tank

Water quality parameters	**Entering**	**Leaving**
Temperature (°C)	20	20
Salinity (ppt)	0	0
O_2 (mg/L)	9.1	5
CO_2 (mg/L)	0.56	30
TAN (mg/L)	0	2

4.1.6 Dimensioning for pump capacity

The pump is an essential part of the RAS design because it lifts water into the culture tank, ensuring O_2 is transferred into the tank and pollutants are transported out for treatment. Getting the appropriate pump size will ensure the safety of the fish and can also save costs by avoiding pump overcapacity.

To dimension the pump, the Q (L/hr) from Eq2 for all the water quality parameters needs to be determined. The production term (P) for O_2, TAN, and CO_2 were already derived from Eq 3, 4, and 5, respectively. The concentration (inlet and outlet) of the required water quality parameters have been determined in the Table. 4.4 above; therefore, using the mass balance equation at steady state, Q is calculated. Table. 4.5. shows the water flow required to achieve the preferred water quality parameters.

Table 4. 5 Water flow (Q L/hr) required for the different water quality parameters.

Water quality parameter	**P (kg/day)**	**P (mg/day)**	**C_2 (mg/L)**	**C_1 (mg/L)**	**Q (L/day)**	**Q (L/hr)**
O_2	0.03675	36750.00	9.10	5	7205.88	376.46
CO_2	0.05053	50531.30	0.56	30	1716.41	72.09
TAN	0.00242	26250.00	0.00	2	1207.50	50.71

The water flow needed to supply O_2 adequately is usually the controlling flow rate (Ebeling & Timmons, 2012), therefore a pump with a capacity above 376.46 L/hr would be selected for the RAS. When the assumed fish number (10) and feeding rate (6% bw/day) were calculated on Excel for salmon water quality requirement, the minimum pump capacity needed to meet all water requirements was 1929.38 L/hr, which constitutes more cost and higher capacity beyond what was intended in this thesis.

4.1.7 Dimensioning for MBBR

To dimension the volume of the MBBR, the design considerations are the TAN produced per day, bio-media specific area, and nitrification rate. The TAN produced can be derived from Eq4, and the proposed bio media has a specific surface area (SSA) of 750 m^2/m^3 (RK Bio-Elements, RK Plast A/S, Skive, Denmark) (Mota, Striberny, et al., 2022) and a nitrification rate of 0.2 g TAN/m^2 day was chosen (Ebeling & Timmons, 2012). The Table. 4.6. summarizes the considerations for the MBBR design.

Table 4. 6 Considerations for MBBR design

Parameter	**Formula**	**Value**
TAN Produced (kg TAN/ day)	Eq4	0.0034
Bio-media specific surface area (m^2/m^3)	Obtained from (Mota, Striberny, et al., 2022)	750
Nitrification rate (g TAN/m^2 day)	Obtained from (Ebeling & Timmons, 2010)	0.20
MBBR surface area (m^2)	$A_{media} = P_{TAN}$ / Nitrification rate	16.91
MBBR media volume (m^3) or (L)	$V_{media} = A_{media}$ / SSA	0.02254 or 22.54
MBBR media filling factor (%)	Obtained from (Ebeling & Timmons, 2010) (ranges from 50 – 70)	70
MBBR volume (L)	MBBR media volume * 2	45.08
Aeration requirement (L/hr)	5 * MBBR volume	225.40
Aeration flow (m3/kg TAN)	Aeration requirement * 24 hours/TAN production	1591.10

The required volume of the MBBR has been calculated to be approximately 45 L; however, to fit the MBBR and the sump perfectly into a wooden pallet, an additional 24 L was added to the MBBR. Consequently, the final volume of the MBBR is 69 L, as illustrated in Fig. 4.4. and the sump was dimensioned in relation to the space left on the wooden pallet. Therefore, the total volume of the MBBR and sump is 131 L, as illustrated in Fig. 4.5.

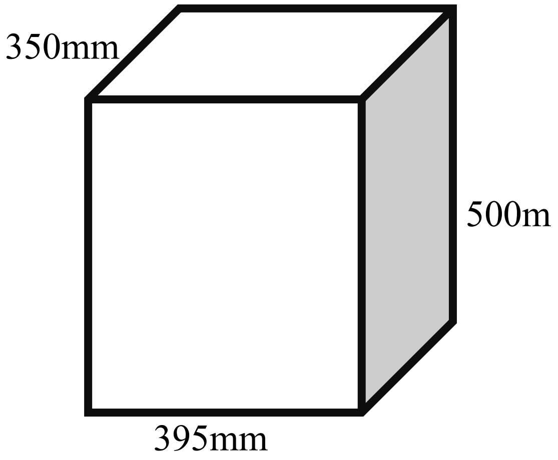

Figure 4. 4: The dimension and volume of the MBBR.

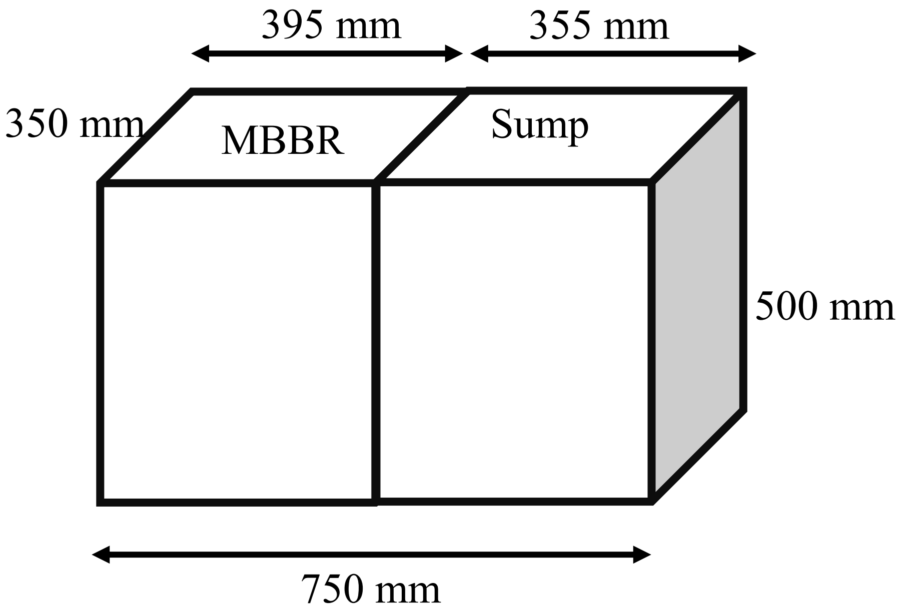

Figure 4. 5: The dimension and volume of the MBBR and sump.

4.1.8 Degasser

The chosen height for the degasser cylinder was based on a sample from AQT 251, a laboratory course in international aquaculture at the Norwegian University of Life Sciences (NMBU). Other design considerations for the degasser are in Table. 4.7. which follows recommendations detailed by (Hargreaves & Tucker, 1999). The degasser cylinder, illustrated in Fig. 4.6. would be filled with media and covered with a perforated distribution plate with holes of diameter 3mm.

Table 4. 7 Degasser design consideration

Consideration	**Value**
Column height	300mm
Column active area /packing height	250mm
Column diameter	150mm

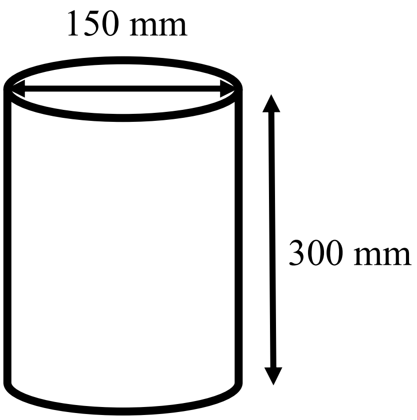

Figure 4. 6: Degasser cylinder

4.2 RAS Design and Layout

The design and layout of the RAS unit (Fig. 4.7, 4.8, 4.9, 4.10) were made using Sketchup (Freeware, proprietary, Google; USA), a 3D modeling program, which provided a proposed physical outlook of the RAS unit in 3D form. The 3D drawings were made with the assistance of Jordan Gould, at NMBU, who is an expert in the use of the program

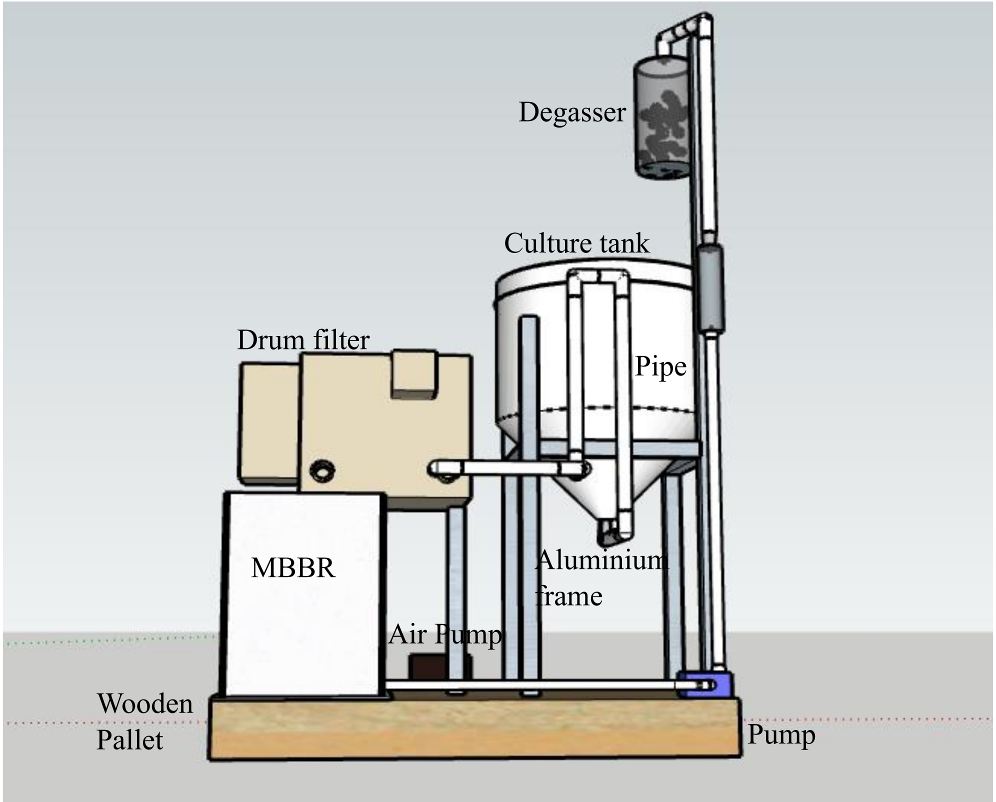

Figure 4. 7: The front view of the 3D prototype, showing all the basic components.

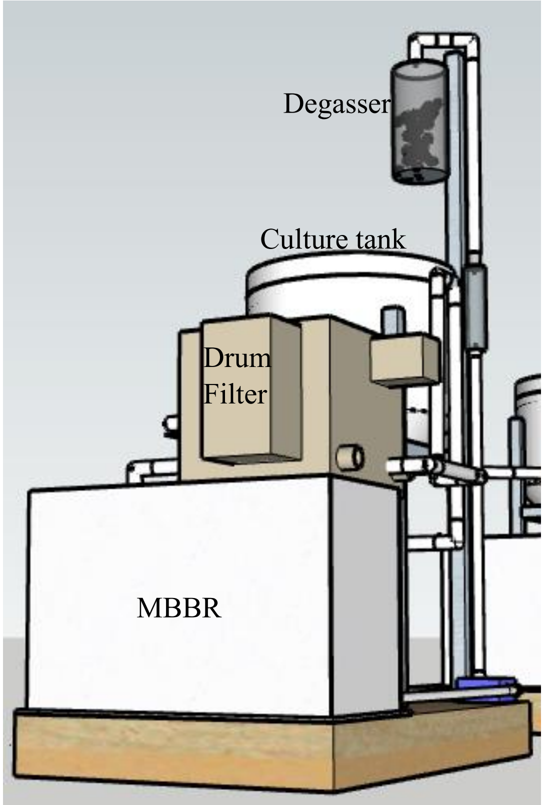

Figure 4. 8: The right-side view of the 3D prototype.

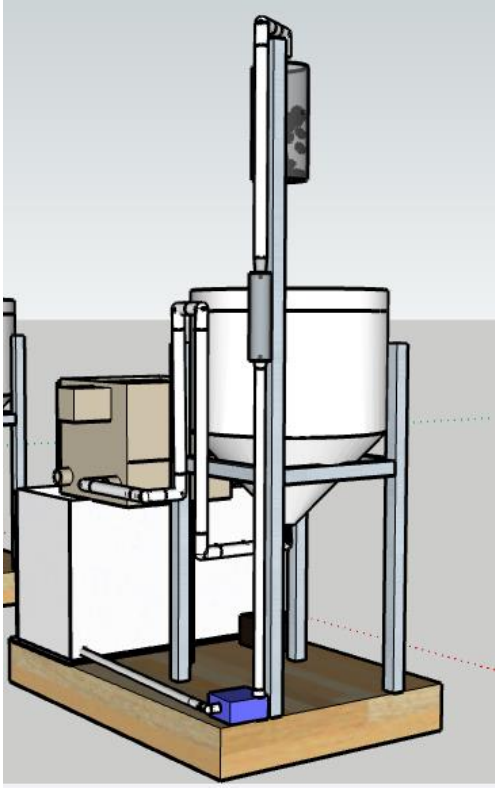

Figure 4. 9: The left-side view of the 3D prototype

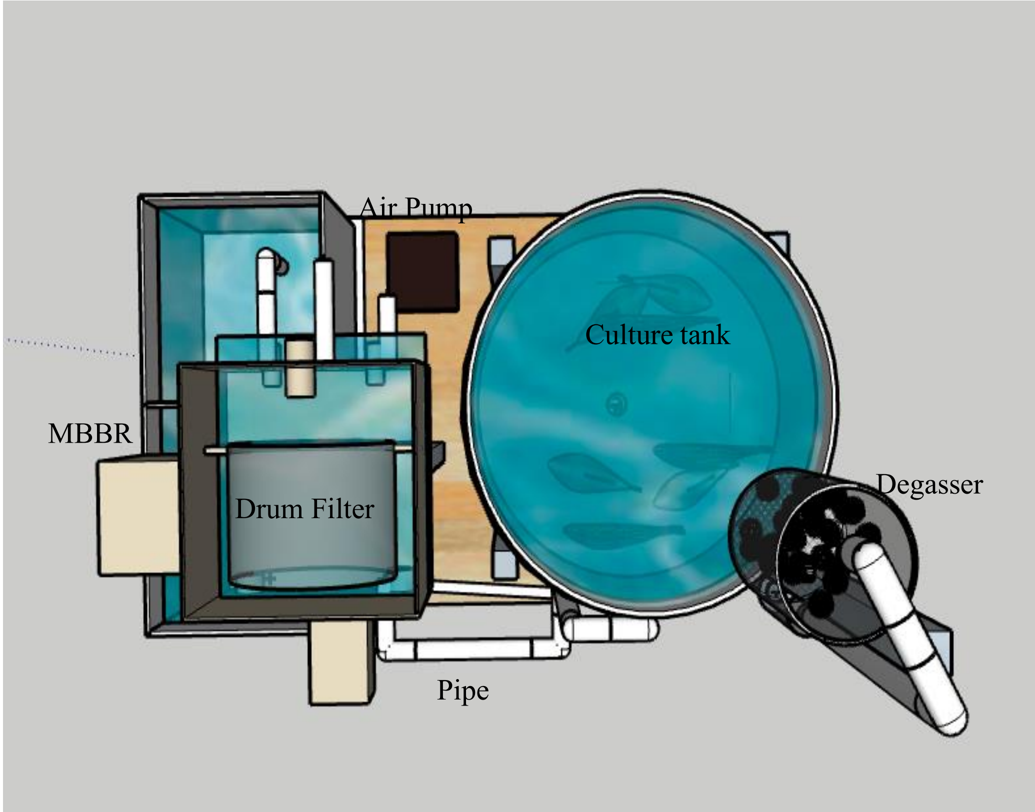

Figure 4. 10: The top view of the 3D prototype

4.3 Materials used.

Table 4. 8 below shows the important details of the materials used in the RAS construction. All materials were purchased online, either via FINN.no, eBay, or Amazon, and were delivered to the Norwegian University of Life Sciences (NMBU), REALTEK, Kajaveien 5, building 51, Ås, Norway.

Table 4.8. Important details of the materials used in the RAS construction

No	**Name**	**Quality**	**Dimension**	**Description**	**Specification**	**Model/Brand, Company, Country**
1	Degasser column	1	Ø 156x150x2000mm	A transparent cylinder		In-house fabrication
2	Degasser distribution plate	6	Ø 144mm	Metal sheet		In-house fabrication
3	Water Pump	7	Pump: 121x62x107mm, Outlet pipe: 16/20mm, Outlet thread: 1", Inlet pipe: 20mm, Inlet thread: 1"	Centrifugal and submersible	Max flow: 1800l/h, Height: 3.5mm (11.5ft), Power: 18W, Power supply: 24V 1A	Reef Motion 1.5KDC, Blue Aquaristic, Spain

4	Rotary Drum Filter	2	430x390x370mm, Mesh size: 75micron	A grey, rigid, square-shaped box	Max flow: 100 L/min, water Inlet: 1", Water Outlet: 2", Sewage Outlet: 1 1/4"	QL - PM - 5, QLOZONE and QihangRAS, China
5	Culture tank	6	Weight: 8kg, Height 675mm, Diameter: 568mm	Cylindrical/Conical water tank	100L Polyethylene White tank	Direct water tanks, UK
6	Air Pump	6	182x95x116mm	A black and grey rectangular box	4 Air Outlet, Power: 32W, Pressure: 0.02MPa	Hailea, ACO-318, Guangdong Hailea Group, China
7	Liquid flow meter	6	230x58x58mm	A transparent cylinder with two openings	Range: 40 - 400 L/H, Pressure: ≤ 0.6MPa	Model: LZS - 20 (D), Tissting, DEWEPRO
8	U-Ball faucet	30	Connecting sleeve: Ø 25mm	Profec PVC faucet with both-sided adhesive nozzles	Type safe 600, 10-16Bar	Tecuro, ew-haustechnik, Germany
9	Pipe Clamp	24	Ø 16mm	A pipe clamp for wall mounting of PVC-U pipes	Max Temp: 75oC, Material: Plastic Polypropylene	Tecuro, ew-haustechnik, Germany

10	Mega Winkel	48	45o, connecting sleeve: Ø 25mm	PVC-U Adhesive sleeve	10-16 bar	Tecuro, ew-haustechnik, Germany
11	Mega Pressure pipe	26	1m long, Ø 25 x 1,5 mm	Smooth PVC-U	10bar	Tecuro, ew-haustechnik, Germany
12	Mega Reducing Sleeve	6	Ø 32/25 mm x 20 mm	PVC-U Adhesive socket	16bar	Tecuro, ew-haustechnik, Germany
13	Mega Winkel	42	90º, Ø 25 mm	PVC-U Adhesive socket	10-16bar	Tecuro, ew-haustechnik, Germany
14	EPAL Pallet	6	1200 x 800mm	Wooden		PallePartner, Finn.no, Norway
16	Hex nipple	10	1", 0.26kg		Male BSP thread to 32 mm, slip socket PVC	Bwintech, BRILLIANT TECH
17	Silicon Adhesive	2	220x63x40mm	An elastic adhesive in tube	290ml, 0.39kg	Aquaforte, Sibo B.V, Netherlands

18	PVC Adhesive	2		PVC Adhesive	250ml, 0.25kg	Griffon
19	Aluminum rod	3	40x40mm, 4m length	Silver, squared shaped rod	SP5050N	Rollco, Norway
20	PE sheet	1	1500x3000mm	White plain PE sheet		Finn løken A/S, Plast halvfabrikata, Norway
21	Degasser media		38mm, 60 kg/m^3,145m^2/m^3, 93%	Cylindrical and hollow-shaped		Pall-Ring, Sterner, Norway
23	Bio-media		750 m^2/m^3	A small, black cylindrical plastic with sharp and flat edges	RK Bio-Elements	RK Plast A/S, Skive, Denmark

4.4 RAS Setup and Assembling

To set up the RAS unit, one of the considerations is to ensure all the components of a single RAS fit perfectly on a wooden pallet, as shown in the 3D prototypes. Once the ordered materials were delivered, they were moved into the engineering workshop to be assembled. The setup steps are briefly described below.

Procedure

Step 1.

The first step for the RAS construction was to paint the EPAL wooden pallet Fig. 4.11. Since the pallet would often have contact with water, an oil-based paint Fig. 4.12. was used to coat the wood as protection against water and moisture. After five days, the paint was fully dried on the wooden pallet, and work could be done on it.

Figure 4. 11: The painted EPAL wooden pallet

Figure 4. 12: An oil-based paint

Step 2.

The aluminum pipes Fig. 4.13 that serve as the RAS framework Fig. 4.14. for the whole system were measured and cut at the engineering workshop into the desired aluminum pipe dimension and connected with bolts and nuts. The dimensions of the pipe are provided in Table 4.9, and their position on the RAS units is illustrated in Fig 4.15 and 4.16

Figure 4. 13: Aluminium pipes used for the RAS support framework.

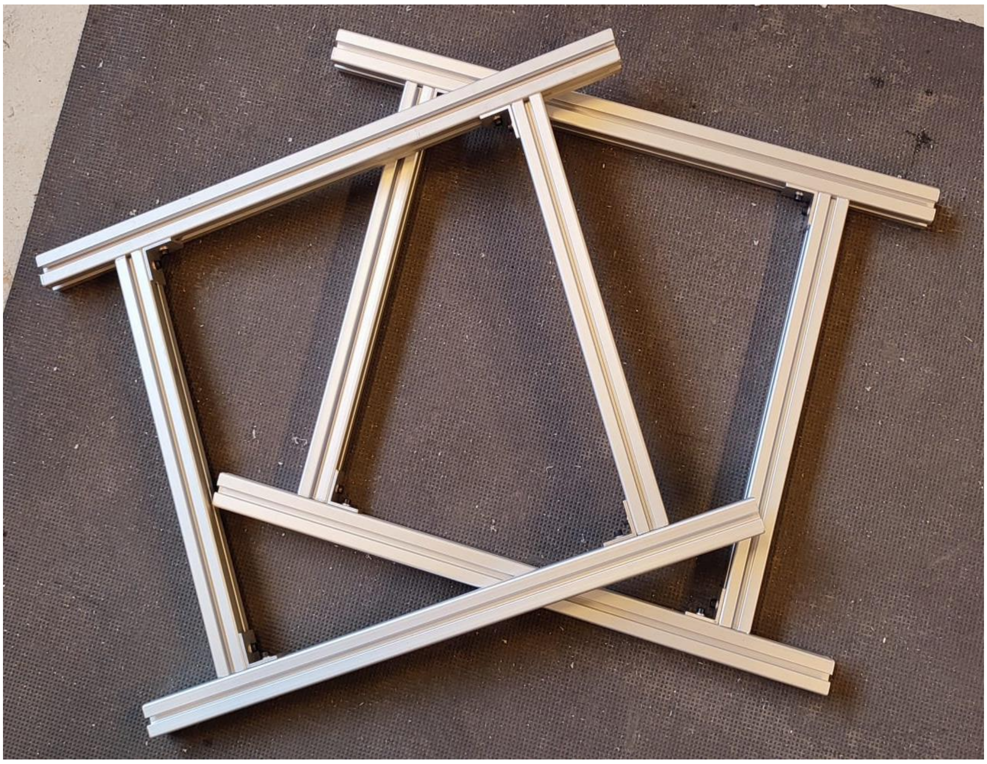

Figure 4. 14 RAS frame under construction, fastened with bolts and nuts.

Table 4. 9 Aluminium pipe dimension per unit

	Number of pieces per system	**Length (mm)**
Point AB	x1	1800
Point CD	x3	800
Point EF	x2	500
Point GH	x2	780

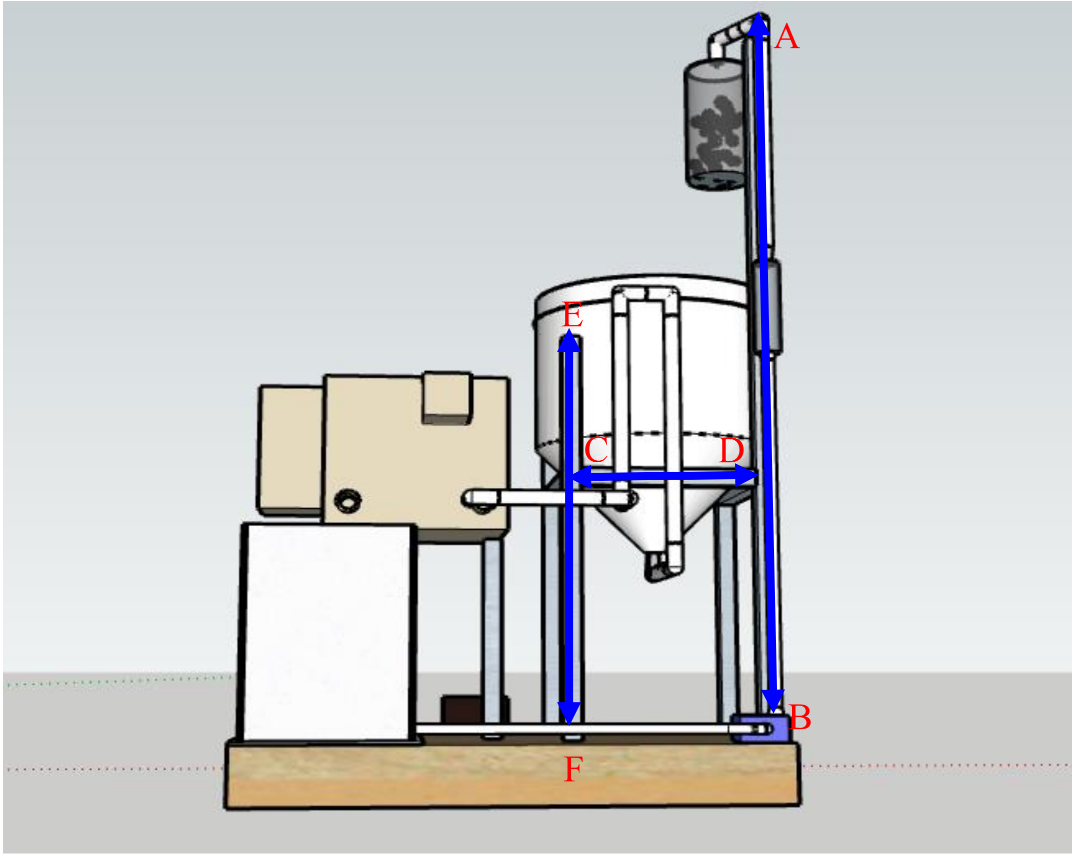

Figure 4. 15: Aluminium pipe framework dimension.

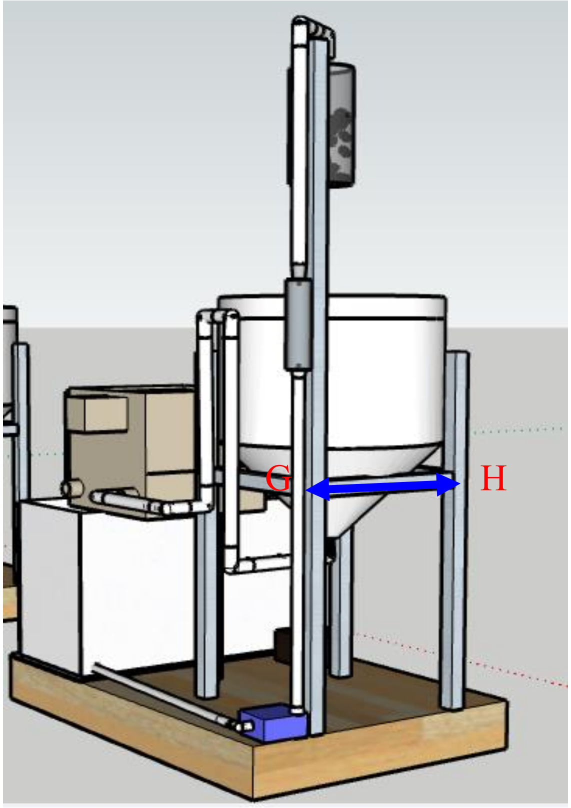

Figure 4. 16: Aluminum pipe framework dimension.

Step 3

The different aluminum pieces were joined with bolts and nuts Fig 4.17 and 4.18. to form a rigid structure strong enough to support the culture tank Fig. 4.19. After which, the aluminum frame was mounted and securely screwed into the wooden pallet. A water retainer (made with a 3D printer), which temporarily holds the water before entering the culture tank, was also fixed to the most extended aluminum pipe in the frame structure. The water retainer would be placed directly under the degasser. Then the culture tank was fitted into the aluminum frame Fig. 4.20.

Figure 4. 17: Bolt and nut to join separate aluminum frames I.

Figure 4. 18: Bolt and nut to join separate aluminum frames II:

Figure 4. 19: Culture tank

Figure 4. 20: Culture tank fitted into the aluminium frame.

Step 4

The fabricated MBBR Fig, 4.21 and 4.22. was placed on the wooden pallet, which already had the structural frame and culture tank fastened. Then, a T-support frame Fig. 4.23. with the appropriate dimensions shown in Table. 4.10. was made and placed very close to the MBBR. This T-support frame serves as a support base for the drum filter Fig. 4.24. that would be placed directly on the MBBR. The drum filter sits on a small, flat surface attached to the top of the MBBR.

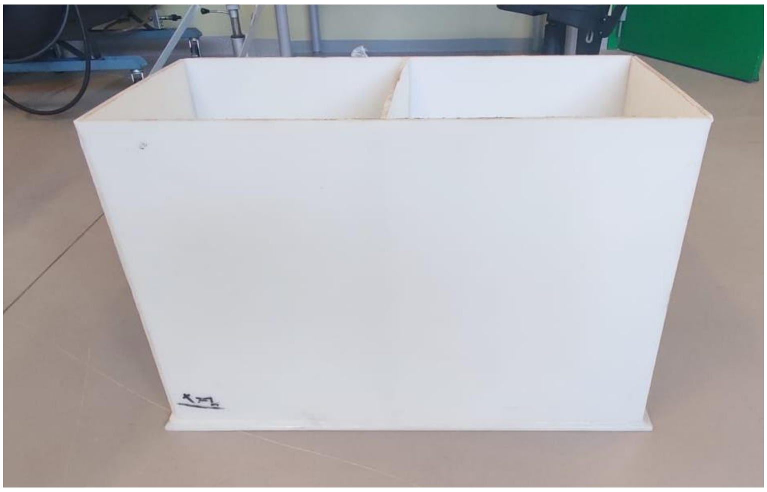

Figure 4. 21: Side view of the fabricated MBBR and sump

Figure 4. 22: Top view of the fabricated MBBR and sump

Table 4. 10 T- support frame dimensions

	Number of pieces per system	**Length (mm)**
Point IJ	X1	390
Point KL	X1	480

Figure 4. 23: T- support frame for mechanical filter

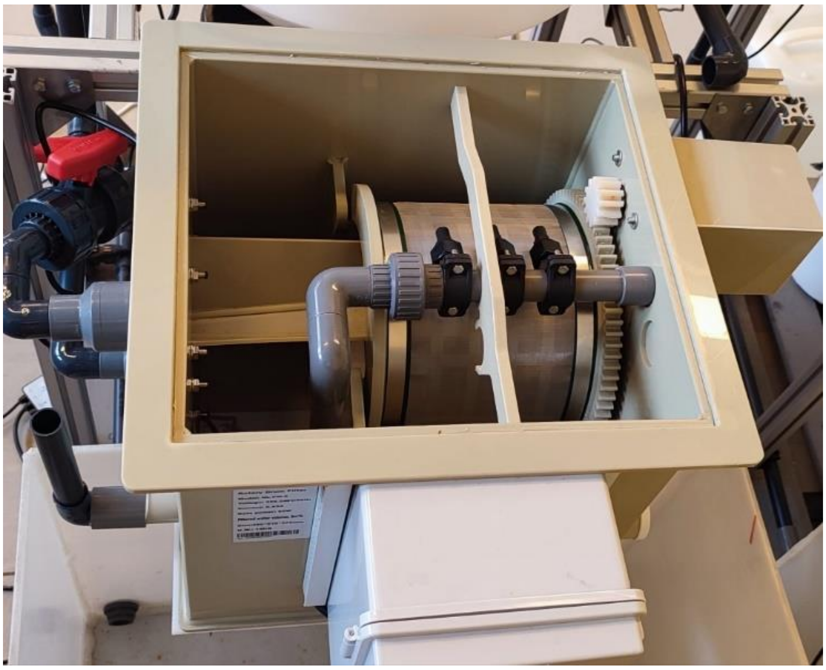

Figure 4. 24: Drum filter.

Step 5.

The water pump Fig. 4.25. and the air pump were Fig. 4.26 fixed on the wooden pallet and situated in the position shown in the 3D prototype.

Figure 4. 25: Water pump

Figure 4. 26: Air pump

Step 6.

The degasser cylinder Fig. 4.27. was filled with media and then attached to the top of the longest aluminum pipe Fig. 4.28. of the framework. As shown in the 3D prototype

Figure 4. 27: Degasser cylinder

Figure 4. 28: The degasser with media and the 3D water retainer attached to the aluminium pipe frame.

Step 7.

After all the RAS components have been installed on the wooden pallet or attached to the aluminum structural frame, Pipes are needed to connect all the RAS components to ensure the transportation of water throughout the system. To ensure smooth pipe installation and operation, all plastic pipes Fig. 4.29. in the system had a uniform diameter of 25mm, and all pipe connectors in Fig. 4.30. were such that was appropriate to this pipe diameter. Itemized below is the pipe system layout and a color code legend Fig. 4.31. to read the pipe layout.

i. Culture tank to drum filter (Fig. 4.32)
ii. Drum filter to sludge outlet (Fig. 4.33)
iii. MBBR to Degasser (Fig. 4.34)
iv. Degasser collector to culture tank (Fig. 4.35)

The pipe leading to the degasser has a flow meter Fig. 4.36, which helps to measure the water flow rate delivered into the degasser. All pipes were attached to the aluminum frames with the aid of pipe clamps Fig. 4.37. to assist in holding the pipes in position.

Figure 4. 29: PVC pipes

Figure 4. 30: Pipe connectors.

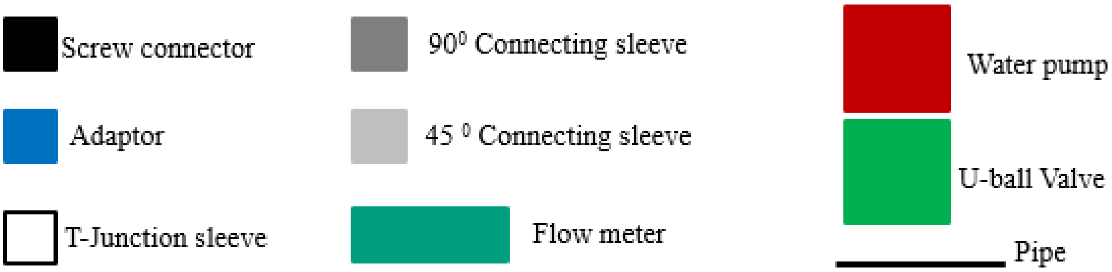

Figure 4. 31: Colour code to read the pipe layout.

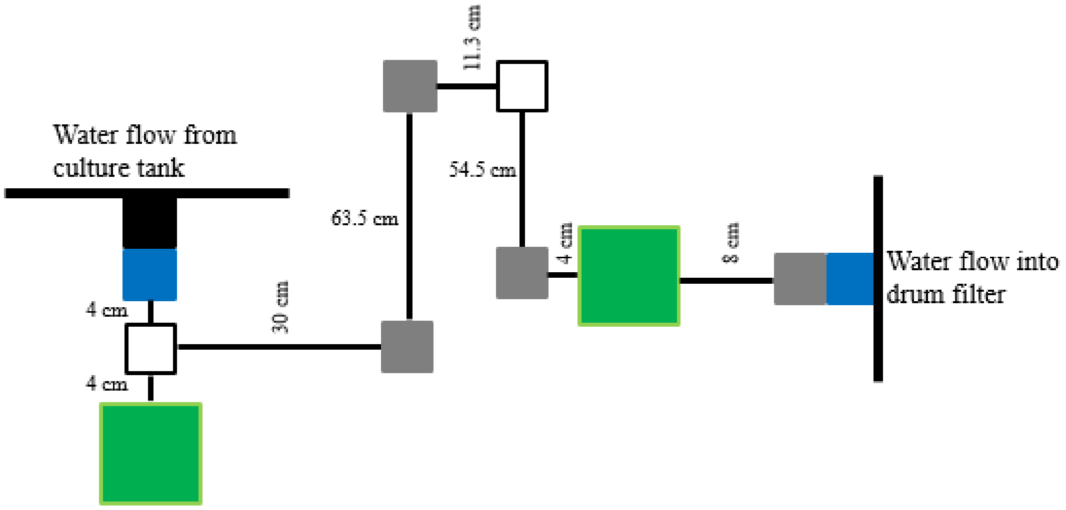

Figure 4. 32: Culture tank to drum filter pipe layout

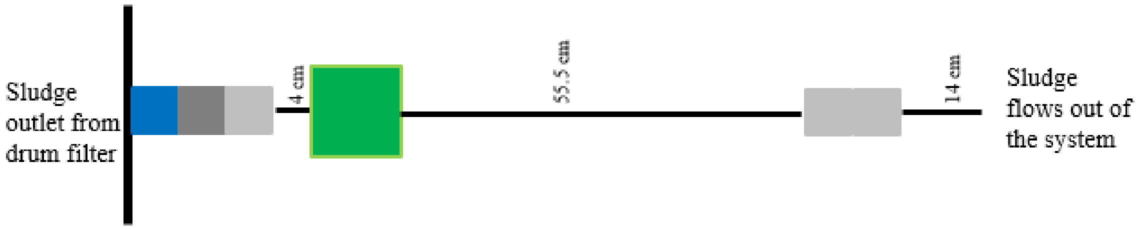

Figure 4. 33: Drum filter to sludge outlet pipe layout.

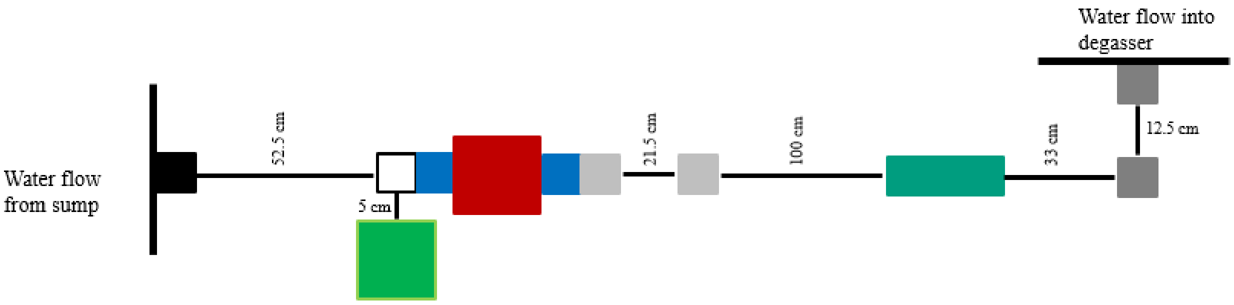

Figure 4. 34: Sump to degasser pipe layout

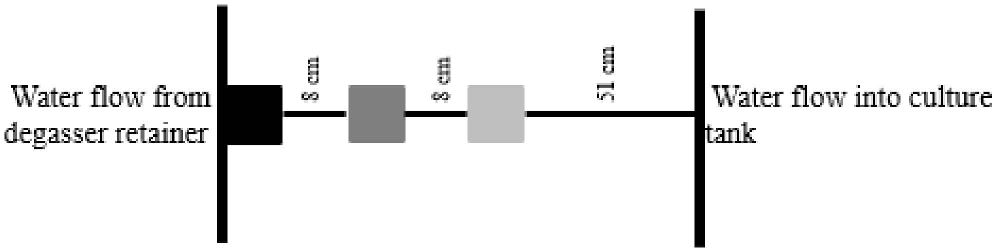

Figure 4. 35: Degasser to culture tank pipe layout

Figure 4. 36: Flow meter.

Figure 4. 37: Pipe clamps.

4.8 Experimental Design

4.8.1 Testing for treatment efficiency of the degasser.

The degasser in this thesis was designed to strip CO_2 from the water flowing from the sump into the culture tank while also enriching the water with O_2 during the process. To test for its treatment efficiency, a degasser with two different types of media (Media 25mm (Fig. 4.38), Media 38mm (Fig. 4.39) (Pall-Ring, Sterner, Norway) was used, and the experiment was carried out in room TF1-115, flerbrukslaboratorie III (maskinelementlab). The characteristics of the two media used for the experiment are in Table. 4.11. Below.

Table 4. 11 Degasser media characteristics (data from Sterner)

Type	**Description**	**Size (mm)**	**Specific weight (Kg/m^3)**	**Specific Surface (m^2/m^3)**	**Free volume (%)**
Media 25mm	Pall Ring	25	80	220	91
Media 38mm	Pall Ring	38	60	145	93

Other parameters that were varied for the evaluation of the treatment efficiency of the degasser were,

i. Q (100L/hr or 300L/hr) into the degasser.
ii. Inlet CO_2 concentration (5mg/L, 20mg/L or 40mg/L) into the degasser.

The pump used during the evaluation had a controller Fig. 4.40 that allowed the pump capacity to either be increased or decreased in percentage and, the pipe leading to the degasser was fitted with a water flow meter (measured range 50L/hr to 400L/hr) to measure Q into the degasser.

Figure 4. 38: Media 25 mm

Figure 4. 39: Media 38 mm

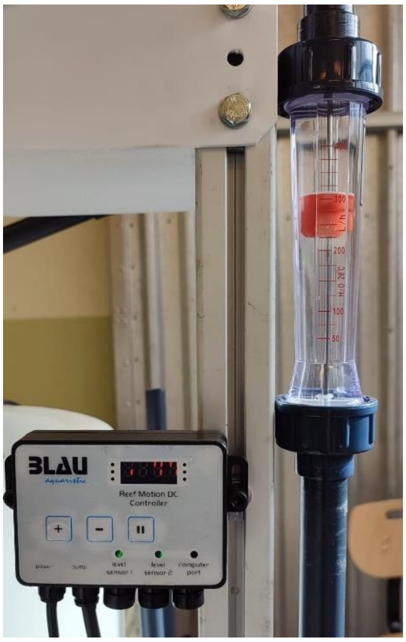

Figure 4. 40: Pump controller and water flow meter.

Experimental design

In this study, the treatment efficiency of the designed degasser will be evaluated. Three variables would be considered to test for treatment efficiency: media type, water flow rate, and inlet CO_2 concentration. In the setup, two separate degassers were filled with media 25mm and media 38mm and then mounted onto the RAS frame. Then, the biofilter's sump was emptied and filled with 20L of water (this volume of water was used as the constant water volume in the sump for the subsequent tests during the entire experiment). An Oxyguard CO_2 analyzer probe (OxyGuard International A/S, Farum, Denmark) (Fig. 4.41) was then placed into the sump to determine the CO_2 concentration in the water (this is usually around 1mg/L) and the water pH in the testing room averages 7.2. Thereafter, the CO_2 concentration in the sump was adjusted to the desired concentration (5mg/l, 20mg/l, or 40mg/l) until a stabilized reading was observed. Sparkling water (REMA Prima Farris, Norway) was added to the water in the sump to increase the CO_2 concentration of the water to the desired level. The Oxyguard CO_2 analyzer probe in the sump was left for 20 minutes to ensure a stabilized reading. This reading on the Oxyguard CO_2 analyzer is recorded as the inlet CO_2 concentration or starting concentration. Then, the water pump controller is adjusted to the percentage of the desired pump capacity, which corresponds to the required Q, and this can be read in the flow meter (i.e., with 20L of water in the sump, the controller was set at 77% to give Q of 300L/hr on the water flow meter). Then, the pump transfers water from the sump into the degasser. The water high in CO_2 concentration enters the degasser column by first spreading over the distribution plate and then cascades down through the media. This process creates water turbulence in the packed column as water flows out at the perforated bottom of the degasser. The degasser outlet is fitted with a water retainer, which temporarily receives the CO_2-stripped water before the water flows into the culture tank. The Oxyguard CO_2 analyzer is then moved into the culture tank Fig. 42. to measure the CO_2 concentration of the outlet water (water in the culture tank). The pump is stopped when there is a drop in the reading on the flow meter, this is due to the drop in water level in the sump. The Oxyguard CO_2 analyzer is allowed to stabilize in the culture tank for 30 minutes, and the data reading is recorded. This data is considered as the final CO_2 concentration and the percentage change between the starting CO_2 concentration and the final concentration gives the treatment efficiency of the designed degasser. Once all the readings are noted, the culture tank is emptied, any water left in the sump is likewise emptied, and new freshwater (20L) is then supplied into the sump for a new experimental test.

The procedure above was carried out for all the varied interactions of the specified parameters (media, flow rate, and CO_2 concentration), and the data generated are shown in the next chapter.

Figure 4. 41: Oxyguard CO2 analyser

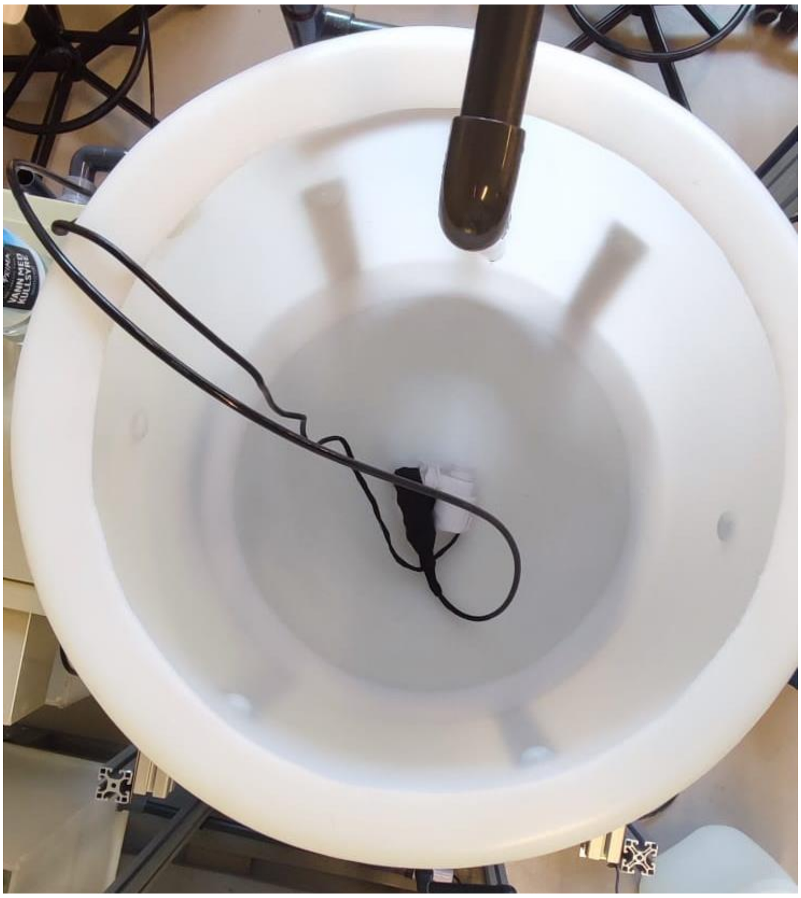

Figure 4. 42: CO_2 concentration measurement in the culture tank

4.9 Statistical analysis

The mean and the standard deviation for the observed data were calculated in Excel. However, for statistical analysis, the program IBM® SPSS® statistics 29.0.x (IBM, Corp, USA) was used. The data collected was checked for homogeneity using Levene’s test. A three-way ANOVA was used to test if there were differences in the effect of media characteristics, flow rate, and inlet CO2 concentration on the treatment efficiency of the designed degasser. Calculations that were in percentage (treatment efficiency of the degasser) were changed to arcsine before using the data in ANOVA. When the p-value < 0.05, the result is considered statistically significant.

5. RESULTS

5.1 RAS Dimension and Design

The primary objective of this thesis is to dimension and design two small-scale RAS units, that can be used for practical RAS education. The Table. 5.1. shows the result on all the dimension criteria, capacity, and quantity of materials used per RAS unit to fulfill its purpose while Fig. 5.1 and 5.2, show the right and left side view of the finished RAS design, with all components fully installed.

Table 5. 1 Summary of dimension criteria per RAS unit

Item	**Quantity**	**Capacity**	**Purpose**
Tilapia	10	1750g (maximum biomass)	Aquatic species that would be held in the RAS. The RAS is dimensioned according to its water quality need
Pallet feed	6 (%bw/day)	105g (maximum feeding rate)	Required to supply sufficient nutrients to the fish without overwhelming the water treatment capabilities of the system
O_2	5 mg/L		Maximum O2 required in the system
TAN	2 mg/L		Minimum TAN required in the system
CO_2	30 mg/L		Minimum CO2 required in the system
Tank	1	100 L	It contains the water in which the tilapia will habitat
Pump	1	1800 L/hr	To transport water from the sump to the degasser. Other flows within the system were done through gravity
Flow meter	1	50 L/hr – 400 L/hr	Measures the water flow rate into the degasser

Drum filter	1	100 L/m	Separates undissolved matter from the system and passes it out as sludge
MBBR	1	69 L	The chamber where nitrification takes place
Sump	1	62 L	The chamber where water temporarily waits after nitrification, but before degassing
Degasser column	1	5.3 L	It contains packing media used for degassing
Pipes	5013 mm (Total length)	10 bar	It connects and transfers water across each component
T-bend	3	10 – 16 bar	To direct flow into two separate pipes
Mega Winkel 45°	6	10 – 16 bar	Changes the direction of flow by 45°
Mega Winkel 90°	8	10 – 16 bar	Changes the direction of flow by 90°
U-Ball faucet	4	10 – 16 bar	To control water flow
Adaptors/ reducing sleeves	8		To fit two pipe endings of slightly different diameters
Aluminum rod	7.63 m (Total length)		Provided structural frame and support
Air pump	2	0.02Mpa	Supplies air into the MBBR and helps to agitate the bio-media
Packing media	Pall ring 25mm and 38mm	Surface area 220 $m^2/m^3$and 145 m^2/m^3 respectively	Creates turbulence in water flow within the degasser column
Bio-media	10 L	Surface area 750 m^2/m^3	Hosts and protects the bacteria necessary for nitrification

EPAL pallet	1	800mm x 1200mm	Provides the platform on which the whole RAS is placed. The total floor area occupied by the system

Figure 5. 1: The right-side view of the finished RAS unit

Figure 5. 2: The left-side view of the finished RAS unit.

5.1 Degasser Treatment Efficiency with media 25mm

Tables. 5.2 and 5.3, gives the data collected during the experiment when the degasser was filled with media 25mm, and water with varied CO_2 concentration from the sump was passed through the degasser at a flow rate set at 300L/hr or 100L/hr, respectively.

Table 5. 2 Degasser treatment efficiency results, with media 25, at Q 300L/hr,

Desired CO_2 (mg/L)	5			20			40		
Starting of inlet CO_2 (mg/L)	4	5	5	18	21	21	37	40	39
Final CO_2 (mg/L)	1	2	2	8	9	10	12	7	13
TE (%)	75.0	60.0	60.0	55.6	57.1	52.4	67.6	82.5	66.7
Mean	65.0			55.0			72.2		
Standard deviation	8.7			2.4			8.9		

Table 5. 3 Degasser treatment efficiency results, with media 25, at Q 100L/hr

Desired CO_2 (mg/L)	5			20			40		
Starting of inlet CO_2 (mg/L)	4	4	5	17	18	20	37	41	40
Final CO_2 (mg/L)	1	1	1	4	3	4	8	7	10
TE (%)	75.0	75.0	80.0	76.5	83.3	80.0	78.4	82.9	75.0
Mean	76.7			79.9			78.8		
Standard Deviation	2.9			3.4			4.0		

5.2 Degasser Treatment Efficiency with media 38mm

Table. 5.4 and 5.5, gives the data collected during the experiment when the degasser was filled with media 38, and water with varied CO_2 concentration from the sump was passed through the degasser at a flow rate set at 300L/hr or 100L/hr, respectively.

Table 5. 4 Degasser treatment results, with media 38, at Q 300L/hr

Desired CO_2 (mg/L)	5			20			40		
Starting or inlet CO_2 (mg/L)	5	5	6	19	20	24	40	42	37
Final CO_2 (mg/L)	1	2	1	6	9	7	14	14	11
TE (%)	80.0	60.0	83.3	68.4	55.0	70.8	65.0	66.7	70.3

Mean	74.4	64.8	67.3
Standard Deviation	12.6	8.5	2.7

Table 5. 5 Degasser treatment results, with media 38, Q 100L/hr

Desired CO_2 (mg/L)	5			20			40		
Starting or inlet CO_2 (mg/L)	4	5	4	26	22	25	37	42	36
Final CO_2 (mg/L)	1	1	1	7	3	5	11	10	9
TE (%)	75.0	80.0	75.0	73.1	86.4	80.0	70.33	76.2	75.0
Mean	76.7			79.8			73.8		
Standard Deviation	2.9			6.6			3.1		

Results showed that irrespective of the varied trial conditions, the treatment efficiency of the degasser was over 50%. The minimum and maximum treatment efficiency recorded were 52.4% and 86.4 respectively and this occurred at the CO_2 concentration column of 20 mg/L (range 17 mg/L to 21 mg/L). it was observed that the efficiency recorded 55.6%, 57.1%, and 52.4% in Table. 5.2. marked by (column concentration of 20 mg/L, media 25mm, and flow rate of 300 L/hr) were quite different from those observed in Tables. 5.3, 5.4, and 5.5, this discrepancy is attributed to insufficient water movement in the tank during this test, which probably limited the ability of the Oxyguard CO_2 analyzer to appropriately measure the CO_2 concentration in the tank. Apart from this, other results did not show any significant difference between each other.

Interpreting the result from statistical analysis, showed that, media characteristics and inlet CO_2 concentration did not significantly impact treatment efficiency ($p = 0.5270$) and ($p = 0.4720$) respectively, while water flow rate had a significant impact ($p = 0.0010$) on the degassers treatment efficiency. The full interpretation of the statistical result to the RQs developed in Chapter 3 is further explained in the next chapter.

5.3 Summary of the treatment efficiency result of the degasser.

The Table. 5.6 shows the compilation of all the TE (%) obtained from the results Tables 5.2, 5.3, 5.4, and 5.5 above and the standard deviation calculated for each of the trials, these values were also obtained from Tables 5.2, 5.3, 5.4, and 5.5. Thereafter, the interaction between all the varied experiment parameters - media size, flow rate, and inlet CO_2 concentration – as presented in Table. 5.6. are further analyzed for patterns and trends. The Fig. 5.3. Shows the pattern observed when all the varied experiment parameters were plotted to find their effect on the treatment efficiency of the degasser.

Table 5. 6 Compilation of the TE results and their SD

	Media - Flow characteristics				
		Desired CO_2 (mg/L)	5	20	40
TE (%)	M25 – F100		76.7	79.9	78.8
SD	M25 – F100		2.9	3.4	4.0
TE (%)	M25 – F300		65.0	55.0	72.2
SD	M25 – F300		8.7	2.4	8.9
TE (%)	M38 – F100		76.7	79.8	73.8
SD	M38 – F100		2.9	6.6	3.1
TE (%)	M38 – F300		74.4	64.8	67.3
SD	M38 – F300		12.6	8.5	2.7

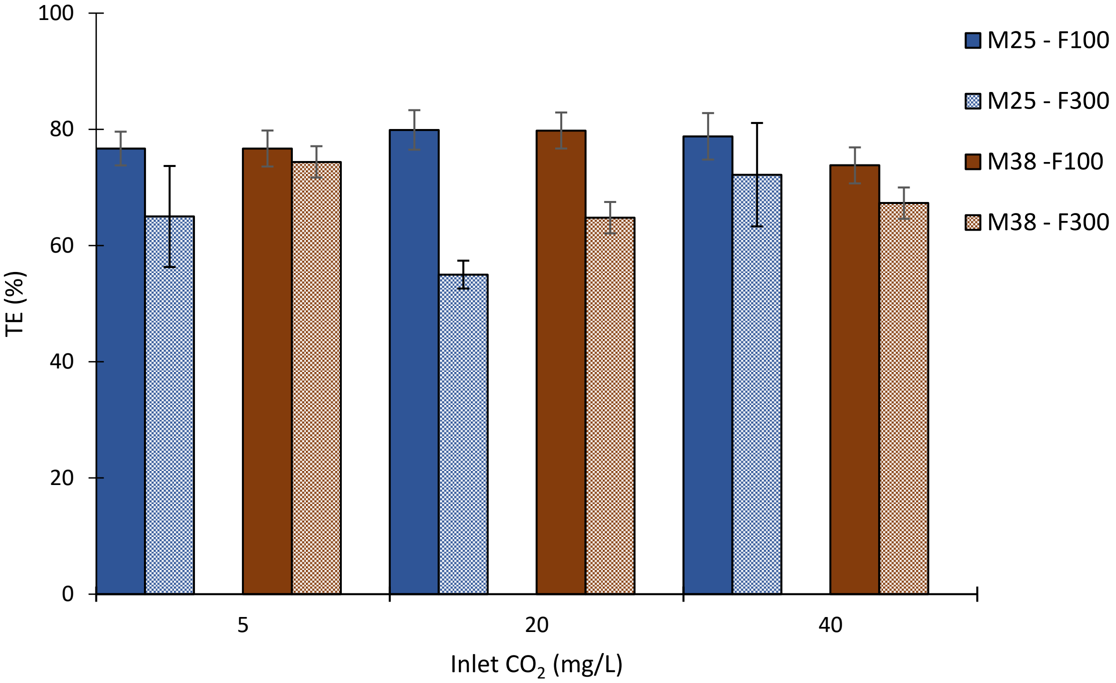

Figure 5. 3: The interaction between the varied experiment parameters on treatment efficiency

Fig. 5.3. Shows the result of the analysis carried out on Excel. It was observed that for each inlet CO_2 concentration of either 5, 20, or 40 mg/L, the flow rate of 100 L/hr had a more significant effect on treatment efficiency when compared to the flow rate of 300 L/hr.

The result from statistical analysis already revealed that the flow rates (100 and 300 L/hr) used during the experiment had a significant effect on the treatment efficiency of the degasser and of the two flow rates, the lower rate of 100 L/hr had a higher effect.

6. DISCUSSION

One of the aims of this study is to dimension and design two RAS units that can be used for practical educational purposes. The RAS dimensioning and design were carried out based on mass balance principles (Ebeling & Timmons, 2010; Terjesen et al., 2013) and other considerations for the RAS units were tailored to support the growth, health, and welfare of a tilapia. Assumptions made during calculation for production term were based on constants from (Ebeling & Timmons, 2010), the water quality requirements employed in this design were those ideal for a Nile tilapia and were adopted from (Dalsgaard, Lund, et al., 2013). These water parameters are those that must always maintained in the system to encourage a good rearing environment and the minimum flow rate (Q) of 376.46 L/hr is necessary to achieve these water conditions. Q was calculated using Eq2 after the production term and inlet/outlet concentration of water requirement had been determined. The feeding requirement for the tilapia was determined from available data by (Kubitza, 2019). The number of fish, maximum biomass, and maximum feed load for each unit were determined to be 10 individuals, 1750 g, and 105 g/day respectively.

Another major consideration during the dimensioning and design of the RAS units was to fit each unit on a single EPAL wooden pallet, therefore, the size and capacity of components purchased, how to move each complete unit, and ease of usage were constant considerations that also influenced decisions made during the project. Funding was a major constraint, and this is supported by the high investment cost associated with RAS facilities (Aich et al., 2020; Martins et al., 2010; Webb et al., 2015). A 3D prototype of the intended units was made using the Sketch-up program.

Two separate RAS units were developed, placed on wooden pallets, and fitted with all the parts needed for water treatment and to keep the fish safe. A cylindrical/conical 100 L tank with a height of 675 mm, serves as the hosting unit for the fish and an opening of 440 mm was made on the top of each tank to create a wider view and ease of access into the tank. The tank was fastened to the pallet with the support of aluminium frames, which were rigid enough to withstand the tank's weight when filled with water. At the base of the tank's conical end, adaptors, pipes, and a valve were connected to easily drain wastewater out of the tank and into the drum filter fitted with a 75-micron sieve to remove particle waste (faces, uneaten feed, etc) coming from the tank. The drum filter has a capacity of 100 L/m and passes the sludge out through the sewage outlet. The drum filter was placed in such a way that it directly empties its content by gravity into the MBBR (69 L) which is placed below it. The MBBR and sump have a total volume of 131 L, its design was made on assumptions and constants from (Ebeling & Timmons, 2010) and it perfectly seats on the pallet. The MBBR was packed with about 10 L of bio-media which has a specific surface media area of 750 m^2/m^3 and between the MBBR and the sump was placed a perforated demarcation, which prevents the bio-media from flowing into the sump but allows the nitrified water to pass through. Tiny holes were drilled into a transparent hose and the two ends of the hose were attached to two separate air pumps. The drilled part of the hose was placed into the MBBR and air pressure coming from these holes creates agitation among the bio-media and supplies O_2 to the nitrifying bacteria. A pipe was placed at the end of the sump to connect it to the water pump. This water pump has a capacity of 1800 L/hr and in this RAS design, it lifts water to a maximum height of 1800 mm, then the pump empties into the degasser. The chosen water pump was able to operate within and above the desired Q for each of the units. However, between the pipe connecting the water pump to the degasser is fitted a flow meter (50 L/hr – 400 L/hr), which measures the water flow rate coming from the pump. This flow rate can be adjusted in percentage with a controller attached to the pump. The degasser used in this thesis was based on an existing model, used for AQT 251, which is a laboratory course in international aquaculture at NMBU. The degasser is a transparent cylinder column of 300 mm in height with openings at both ends. It has a diameter of 150mm and was fitted with distribution plates (diameter 144mm) with holes (3mm). The distribution plates were fitted at both ends and the plate at the top of the degasser allows water to spread across its surface before entering the column while the distribution plate at the base helps to contain the media in the cylindrical column. In this thesis, two separate media were used for the degasser – 2 Pall Ring of diameter 25mm and 38 mm with a specific surface area of 220 m^2/m^3 and 145 m^2/m^3 respectively. At the base of the degasser, a 3D-printed box with an opening was placed to serve as a temporary receiver of water coming from the degasser. The degassed water is transferred into the culture tank through pipes by gravity, and this completes the water treatment cycle within the designed RAS unit. Throughout this thesis, no tilapia was stocked in the RAS units, this means no organic waste was accumulated in the system and the treatment efficiency of all the dimensioned components could not be verified with respect to the desired water quality requirement. However, the treatment efficiency of the degasser was evaluated, and details of the experiment are discussed in the next paragraph.

To test for the treatment efficiency of the degasser, a high CO_2 concentration is needed to be available in the RAS tank, however, since no tilapia was stocked at that period, the desired CO_2 concentration was achieved by mixing sparkling water with 20 L of water in the sump.

During the experiment, achieving the exact inlet CO_2 concentration in the sump (5mg/L, 20mg/L, or 40mg/L) was slightly difficult hence, the use of inlet CO_2 concentration values close to the specified starting point and the Oxyguard CO_2 analyzer readings at this chosen starting point were observed to be stable before proceeding with the experiment. It was also observed that constant water movement is needed (in the sump and tank) for accurate CO_2 measurement; this was resolved by submerging a pump into the sump and culture tank while measuring the CO_2 concentration in these components.

Furthermore, it was observed that at a higher flow rate (300 L/hr), water was distributed over the distribution plate of the degasser when compared to the lower flow rate (100 L/hr) in which the water passes through the distribution plate without spreading across it. It was also observed that at the higher flow rate, some portion of the inlet water flows into the degasser through the tiny opening by the side wall of the column. Nevertheless, the result showed a treatment efficiency of over 50% for all the varied tests. This value is satisfactory, considering the designed RAS was dimensioned for relatively low stocking density. In this study, the degasser minimum and maximum treatment efficiency are 52.4% and 86.4%, respectively. Generally, CO_2 can not be totally (100%) removed through a packed column degasser, however, a degasser is operated at removal efficiency ranging from 40% - 78% (Karimi et al., 2020), with this statement, the higher efficiency of 86.4% in this thesis might seem unlikely, but (Hu et al., 2011) observed treatment efficiency as high as 96%, in his experiment, several GL ratios (1, 5, 8, 10, 15, and 20) were tested to investigate their effect on CO_2 removal, it was observed that the removal rate increased with increasing GL ratio (GL ratio 5 yielded 80% - 88% removal efficiency), (GL ratio 8 yielded 86% - 92% removal efficiency) while the increase in efficiency was minimal at GL ratio > 8, however, it should be noted that a fan was used to supply air through the column of the aerator from its base (counter-current to water flow).

Sometimes computer programs are used to estimate the CO_2 stripping efficiency of a packed column before an actual one is designed, an example of such was developed by (Vinci, 1998) which can be used to show the relationship between the packing height of a degasser and GL ratio, however, the precision of the software is dependent on accurate input of certain constants and variables itemized by (Summerfelt et al., 2000). The estimated result from the software program found in (Summerfelt et al., 2000) showed that $\geq$ 50% CO_2 removal efficiency was only achieved at packing height above 500mm (packing height range 0 – 2500mm was tested) for the two inlet CO_2 concentrations (40 mg/L and 20 mg/L) used, irrespective of the GL ratio (1, 5, 10, and 20), these predictions might seem less efficient compared to the designed degasser (packing height 250mm) in this thesis, however, it should be noted that the SSA of the media and alkalinity value computed for the software program were 105 m^2/m^3 and 3.88 mequiv.l^{-1}, respectively which are different when compared to the SSA of the media used (220 m^2/m^3 and 145 m^2/m^3), water alkalinity was not measured in this study. This shows that removal efficiency is not easily predictable due to many factors, however, the interaction between the main variables (i.e., media type, height of packing, GL ratio, water flow, inlet CO_2 concentration, etc.) must always be put in design consideration (Hu et al., 2011)

RQ1: Does the characteristic of the media in the column of the designed degasser affect its treatment efficiency?

Several studies have been carried out on the degassing capability (CO_2 removal) of many water treatment devices and some of the devices tested were airlift pumps, screens, siphons, packed columns, trickling filters, vacuum tubes, and air blowers (Eshchar et al., 2003). However, it has been observed that degassing methods that involve moving water under turbulence through the air (i.e., packed column) are more effective than other techniques of CO_2 striping that pass air bubbles through the water (Summerfelt et al., 2000). In this thesis, the designed packed column was filled with media (Plastic Pall Ring) of high SSA (m^2/m^3) and then used to treat water with low to high inlet CO_2 concentration. The role of the media in the degasser column is to ensure turbulence in water flowing through; this breaking of water droplets and splashing caused by the media allows water to mix with air in the column, thereby stripping the water of CO_2 and adding O_2 (Ebeling & Timmons, 2012). However, the wrong selection of media size could lead to flooding within the column if the hydraulic loading rate into the degasser is such that it causes restriction of airflow, this is usually corrected by either reducing the hydraulic load or by supplying more airflow into the column to create some void as pointed out by (Hackney & Colt, 1982). Nevertheless, the success of a packed column degasser is dependent on gas transfer within its column and this transfer is strongly reliant on the even distribution of inlet water over the media and the height of the column (Colt & Bouck, 1984), hence the use of media with large specific surface area for packed column aerators (Moran, 2010). Generally, the media could be placed in the packed column in a structured way or randomly placed (which was the case in this thesis) (Karimi et al., 2020; Summerfelt et al., 2003). In a study by (Hackney & Colt, 1982), various hydraulic loading rates (0 – 400 m3/m2.hr) were tested on a 1m column aerator packed with 4 different media sizes (Ø 25.4 mm, 38.1 cm, 50.8 mm, 88. 9 mm), it was observed that the intermediate media sizes had the best O_2 transfer under all the varied hydraulic loading rate. In contrast, the smallest media size (25.4 mm) only had the highest O_2 transfer rate at a hydraulic loading rate of ≤ 100 m^3/m^2.hr and loading rate from this point poorly impacted the degasser's performance. The biggest media size in the test had a constant but lower O_2 transfer rate regardless of the hydraulic loading when compared to the other media sizes. This further proves the importance of media size on the treatment efficiency of a degasser However, in this study, the selected media sizes were Ø 25mm and 38mm. The two media were subjected to 300L/hr and 100L/hr flow rates and hydraulic loading rates of 17.0 m^3/m^2.hr and 5.7 m^3/m^2.hr respectively and it was observed that the media did not have any statistically significant effect on the treatment efficiency of the degasser, which is contrary to findings on the performance and design of a degasser by (Hackney & Colt, 1982), this disparity in results can be attributed to the process of selecting the media type and column height of the designed degasser, which was based on empiric knowledge from an existing model already in use for a NMBU course in AQT251. To my knowledge this model did not consider the distribution system or media diameter and was found to be adequate for the course.

However, the relationship between the distribution system and media diameter on column diameter and column height has been suggested by (Colt & Bouck, 1984; Hackney & Colt, 1982), also, (Hargreaves & Tucker, 1999) provided recommendations on selecting column height (i), based on desired outlet water DO and water temperature, and (ii), based on the outlet pressure differential as a function of inlet pressure differential. According to Colt & Bouck (1984), "the design of a packed column for degassing will require measurement of the difference between the pressure of a gas in a liquid and the atmosphere, temperature, barometric pressure, DO, water temperature and salinity (where applicable)" (p.257),

It was also observed during the experiment for the treatment efficiency of the degasser, that tests performed at a flow rate of 100 L/h generally had poor water distribution, as inlet water passed through the distribution plate without spreading across it and tests at the higher flow rate of 300 L/hr had a portion of the inlet water passing down through the side wall of the column. Despite this, results still yielded treatment efficiency above 50% across all tests. This opposes the recommendation by (Colt & Bouck, 1984) on the importance of even distribution of inlet water on the performance of a degasser. Therefore, this high treatment efficiency can be attributed to the over-dimensioning of the degasser's height (active height of 250 mm), which ensured a high gas transfer rate within its column. CO_2 stripping was aided through the passive co-current and counter-current airflow coming from the perforated top and base openings of the degasser (Moran, 2010; Summerfelt et al., 2000), this condition nullified the possible effects of the media size, poor water distribution across the entry plate, and flows down the side walls of the column. This situation is also in line with findings by (Hackney & Colt, 1982) stating that in larger column sizes the effect of poor water distribution and flows down the wall on the performance of a degasser can be reduced. It is, therefore, suggested that the over-dimensioning of the degasser played an essential role in its high treatment efficiency. However, in aquaculture facilities, the height of a degasser is usually limited to 1m – 1.5m because the proportion of performance becomes insignificant with increasing height (law of diminishing return) (Ebeling & Timmons, 2010; Summerfelt et al., 2000). Future research can be tailored to find the ideal column height for the designed RAS to avoid excessive use of material and over-dimensioning. Under-estimation in calculation and over-dimensioning are major issues faced in the design of RAS (Badiola et al., 2012)

RQ2: Does the water flow rate into the designed degasser affect its treatment efficiency?

It has been observed that a packed column aerator's performance is significantly enhanced when a specific volume of gas mixes with a precise volume of water within the aerator's column (Ebeling & Timmons, 2010). A degassers treatment efficiency process corresponds to a portion of its CO_2 that is removed by the gas flowing through the system column (Summerfelt et al., 2000). This gas volume is usually measured using equipment and supplied to the system either co-current or counter-current by a ventilating fan while the water volume into the system is given by calculating the hydraulic loading rate (HLR) from the inlet water flow rate. The relationship between this gas-to-liquid volume ratio is known as the GL ratio.

GL ratio has a significant impact on the stripping of CO_2 in water, leaving a degasser (Hu et al., 2011; Summerfelt et al., 2000) and an effective GL ratio for CO_2 stripping has been found between 5:1 to 20:1 (Ebeling & Timmons, 2010) and 3:1 to 10:1 (Summerfelt et al., 2003) This ratio shows that for efficient CO_2 removal based on mass transfer, large volumes of air are needed for every volume of water passing through the packed column. However, it should be noted that the CO_2 stripping process can cause an increase in the portion of CO_2

concentration in the surrounding air (Summerfelt et al., 2001; Summerfelt et al., 2003), therefore, the degassing unit should be adequately ventilated with good air exchange.

In this study, two different flow rates were used 300 L/hr and 100 L/hr, with a hydraulic loading rate of 17.0 m^3/m^2.hr and 5.7 m^3/m^2.hr respectively. No fan or air blower was applied to the column during the experiment, but the degasser cylinder had a perforated plate at the top and its base for easy airflow, also the volume of air in the column was not measured, however, results suggest that the cylinder column had enough air volume and airflow to support good CO_2 stripping. From the statistical analysis, the water flow rate significantly affected the treatment efficiency of the degasser. This finding is in line with other results that support the significant effect of the GL ratio on the treatment efficiency of a degasser (Ebeling & Timmons, 2010; Hu et al., 2011; Karimi et al., 2020; Mohapatra et al., 1989; Summerfelt et al., 2003; Summerfelt et al., 2000). This concludes that if the GL ratio is satisfied, CO_2 stripping will occur. As the force driving gas transfer is the difference in concentration (pressure) in gas between air and water (Aitchison et al., 2007)

The effect of 8 different GL ratios (range 1.2 – 15.7) was examined in a study on the influence of gas-to-liquid ratio on CO_2 removal in a ventilated trickling filter. It was noted that there was an increase in CO_2 removal with an increase in the GL ratio i.e., at GL 1.2, the concentration of CO_2 removed was 3.1mg/L and it increased to 6.1mg/L at GL 15.7, however, it was also observed that with increasing GL ratio, the concentration of CO_2 removed did not significantly increase, i.e. at GL ratio of 5, the CO_2 removed was 5.9mg/L, while at GL ratio of 7.1, 9.2 and 15.7, the CO_2 removed was 6.5mg/L, 6.1mg/L and 6.1mg/L respectively (Karimi et al., 2020). Therefore, for certain water conditions and treatment requirements, a higher GL ratio may not be necessary to enhance the performance of a degasser (Hu et al., 2011; Karimi et al., 2020), because to achieve this higher GL ratio, an adequate air volume must be supplied with the use of large air blowers, which might not be economically feasible. Future research can be directed towards measuring the air volume needed within the degasser without using an air blower and the appropriate air flow movement (co-current or counter-current) for efficient CO_2 stripping.

RQ3: Does the CO_2 concentration in the designed degasser affect its treatment efficiency?

CO_2 is only affected by aeration as a dissolved gas $CO_{2\,(aq)}$ (Aitchison et al., 2007) and $CO_{2\,(aq)}$ exist in an acid-base equilibrium in water (Summerfelt et al., 2000). Therefore. dissolved CO_2 can be stripped either by aeration due to gas transfer (represented in Eq. 6), pH control, or both (Eshchar et al., 2003).

$dC/dt = K_La\,(C^* - C)$ Eq.6 adopted from (Aitchison et al., 2007; Colt et al., 2012)

where

dC/dt = gas transfer rate (mg/hr)

C^* = saturation concentration of the gas (mg/L)

C = measured gas concentration at time (t) (mg/L)

$(C^* - C)$ = driving force (mg/L)

K_La = volumetric transfer coefficient (1/hr)

It is possible to remove CO_2 in water by pH control because, compared to other soluble gases, CO_2 exists in water as part of a carbonate chemical equilibrium system (Eq. 7, 8, and 9) and high concentrations of CO_2 in water reduce its pH.

$CO_{2\,(aq)} + H_2O \leftrightarrow H_2CO_3$ Eq.7

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ Eq.8

$HCO_3^- \leftrightarrow H^+ + CO_3^{-2}$ Eq. 9

(carbonic acid H_2CO_3, bicarbonate HCO_3^-, carbon dioxide CO_2, and carbonate CO_3^{-2})

Through aeration, the carbonate acid splits into CO_2, and H_2O and this causes a temporal shift in the carbonate content equilibrium, which leads to a larger gas pressure difference within the column, due to CO_2 removal until a new carbonate equilibrium is established. However, the equilibrium is not achieved instantly due to the slow process of the dehydroxylation of bicarbonate to CO_2. Therefore, during the aeration process, the mass gas transfer can be considered independently of the carbonate chemical equilibrium (Aitchison et al., 2007; Hu et al., 2011; Summerfelt et al., 2000)

In this study, the required inlet CO_2 concentration was achieved by adding sparking water into the water sample in the sump and the concentration values used ranged from 4mg/L (minimum) to an inlet CO_2 concentration of 42mg/L (maximum). The result from the analysis showed that the inlet CO_2 concentration did not have a statistically significant effect on the treatment efficiency of the degasser, which is similar to the finding by (Hu et al., 2011) in their experiment on the study of CO_2 removal method in recirculating aquaculture waters. The effect of 3 factors (G/L ratio, flow rate, and inlet CO_2 concentration) on CO_2 stripping was examined and the value for the 3 factors used was G/L ratio (1, 5, 8, 10, 15, and 20), the flow rate was altered at 1000 L/hr interval for a flow measurement ranging from 400 L/hr – 5000 L/hr and inlet CO_2 concentration was (25.07 and 77.20 mg/L). From the results of the test it was observed that the most significant factor for CO_2 removal efficiency is the GL ratio.

Also, (Summerfelt et al., 2003) designed an experiment to evaluate the performance of a full-scale CO_2 stripping column in coldwater RAS. In the test, two separate aerators were filled with two different plastic packing (NORPAC media and CF-3000 Accu-Pac media) of 1m each, a low pressure air blower was attached to each of the aerators for forced ventilated counter-current air flow through their columns, crown nozzles were used to distribute water uniformly over the distribution plate. The inlet CO_2 was kept constant within the range of 33 – 35 mg/L, water flow rate into each cascading column was 97200 L/hr, 152400 l/hr, and 208800 L/hr while airflow supplied was kept to provide a GL ratio of 2.2:1 to 3.4:1 (low), 5.1:1 to 5.6:1 (medium) and 9.5:1 to 9.9:1 (high). During the experiment, both aerators had their air and water flow rates operated independently and the mol fraction of CO_2 in the air entering and leaving the column was measured with a gas-phase monitor. Results showed that CO_2 removal in both systems (structure or random packing) was dependent on the volumetric air: water mixing. The low GL ratio (2.2:1 to 3.4:1) was observed to have resulted in a 21 – 24% CO_2 removal efficiency and this lower efficiency was attributed to the higher concentration of CO_2 in the packed column which was measured to be 2 – 3 times the air concentration entering the column. However, when entering air concentration was increased to achieve the medium and higher GL ratio removal efficiency also improved to 32.4 – 33.6% and 35.8 – 37.2% respectively. From these studies, it can be deduced that the inlet CO_2 concentration on CO_2 removal is not consequential while treatment efficiency in aerators mostly depends on the balance in the GL ratio within the stripping column. In conclusion, in this study, the inlet CO_2 concentration as a single variable does not affect treatment efficiency.

7. CONCLUSIONS

The aim of this thesis was to dimension, design, and evaluate a RAS unit that would be used for educational purposes, thus granting students opportunities for practical knowledge and the ability to utilize theoretical principles in an applicable way. It should be noted that the design considerations and equipment used in this study were few and limited in scope. Therefore, when expanding a small-scale RAS unit into a large-size system more requirements must be brought into consideration, and the results observed in an experimental test in a laboratory may not give the actual data needed for a full-scale system (Dalsgaard et al., 2017).

This RAS affords students first-hand knowledge about the future of aquaculture and the application of theoretical knowledge. RAS design, dimensioning, and operation are important to developing the technology and the application of RAS could be a key to further unlocking of the aquaculture industry. The interrelation between technology and animal science for the future of aquaculture cannot be overemphasized, engineers and technicians must consider the welfare of the animal being raised before designing a system or implementing new technological solutions. Also, the design and dimensions of RAS should not be based on assumptions or experience but on empirical data and calculations to avoid high cost and material wastage.

Finally, in the evaluation of the degasser in this study, it was observed that the volumetric air: water mixing played the most essential factor in its treatment efficiency. However, the actual value of this ratio was not found as the airflow in the cylinder column was not measured during the experiment. Nevertheless, it was deduced that the airflow within the system was sufficient to strip CO_2 from the incoming water with a hydraulic loading rate of 17.0 m^3/m^2.hr and 5.7 m^3/m^2.hr which corresponds to a water flow rate of 300 L/hr and 100 L/hr respectively. From further analysis, it was observed that the lower flow rate of 100 L/hr, had the most impact among the two water flow rates. The relationship between lower flow rates or hydraulic rates to void space in the aerator column was also observed by (Hackney & Colt, 1982), they noted that when a degasser has little void space (due to the size, shape, and arrangement of the packing media) and is operated at higher hydraulic loading rates, the spaces within the column get filled up quickly, causing flooding in the system and consequently impacting on CO_2 removal. This problem is usually resolved by either reducing the hydraulic loading rate or increasing the airflow within the system

7.1 Limitations

The limitations of this thesis are listed below

¶ Budget – impact on the capacity and quantity of items that could be purchased
¶ No Nile tilapia was kept in the system after the RAS was fully assembled, therefore, the capacity of the whole system to fully support the survival and welfare of the fish was not tested
¶ Most of the materials used during the construction of the RAS were purchased outside of Norway, though Norway is one of the leading nations in the practice and implementation of RAS in aquaculture
¶ The cost of assembling the small-scale RAS units confirms that the technology is expensive (see approximated cost in appendix)
¶ The lack of airflow measurement to determine the volume of air flowing through the degasser
¶ The inability to determine the GL ratio during the evaluation of the degasser

7.2 Implications

A small-scale RAS can easily be developed in any aquaculture-focused institution or organization. This allows students and employees alike to have a practical understanding of how the system works. In the case of this thesis, Aquaculture students interested in RAS can now have access to a small-scale design, which can be operated and experimented with. Also, a future master's thesis can be carried out, using this system. Overall, the RAS design is such that each part can be evaluated independently, and modifications can easily be done without significantly altering the structural frame of the system.

The result from the evaluation of the degasser in this thesis showed that the flow rate in conjunction with airflow in the column cylinder was the most crucial factor in the treatment efficiency of the degasser. This implies that flow rate (water) is an important consideration in RAS design, as water flow rate is also responsible for the transportation of O_2 into the tank and the removal or dilution of pollutants. Therefore, arriving at the actual flow rate needed for each RAS would not only affect the function of the RAS but also the total cost

7.3 Future research

In this thesis, apart from dimensioning and designing the RAS units, only the degasser was evaluated for treatment efficiency; therefore, future research is proposed to evaluate the efficiency of the MBBR in TAN removal and the self-cleaning ability of the culture tank. Also, regarding particle waster removal, other methods (mesh filter, radial flow settler, etc.) can be adapted into the system to compare the efficiencies of each component.

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9. APPENDICES

Appendix 1. Approximate cost of a single RAS unit dimensioned and designed in this thesis

Table. 17.

Item	**Unit**	**Cost (NOK)**
Water pump	2	1,170
Tank	2	3,425
Drum filter	2	13,250
Degasser cylinder	1	198
Pipes, adaptors, valves, and connectors (90°, 45°, T- fitting)	Applied for both systems	2,755
EPAL wooden pallet	2	220
Air pump	2	1,375
Air pipe	2	158
Assistance for welding of the MBBR and materials supplied from the workshop (aluminum frame)		12,573
Total		35,124

Please note that this is the approximated cost, as this value does not take into account other miscellaneous.

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