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ORIGINAL ARTICLE

Water Quality Improvement Features of Aquaponic Systems and Their Economic Feasibility

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ABSTRACT – Aquaponics is an evolving sector with significant presence in arid regions or areas that have scarce arable land. Since they are a combination of aquaculture and hydroponics, naturally the focus of such systems will be the amount and quality of the food produced. Nevertheless, aquaponic systems also contain large quantites of various microorganisms that helps with fish growth and the assimilation of nutrients by plants. In a way, they are cleaning up the water as well but this aspect of aquaponic systems is largely ignored. In this study, effluent from a sewage treatment plant was fully applied in a media bed unit aquaponic system in place of natural freshwater to investigate the capability of the system in improving the quality of the water. On top of that, economic feasibility of such a system using the benefit-cost ratio method was also studied. It was found through this study that the first 12 hours upon application of the contaminated water is when the rate of change in the parameters were greatest. The water quality parameters tested (biochemical oxygen demand, chemical oxygen demand, total suspended solids, ammonia-nitrogen, nitrate-nitrogen, phosphorous, oil & grease) showed good improvement by the end of each trial. Economic feasibility of the treated sewage effluent aquaponic system was also studied using the benefit-cost ratio and it was found that the system is able to deliver a positive net present value. In short, aquaponic systems is a feasible alternative to traditional farming and agriculture.

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INTRODUCTION

An aquaponic system is a combination of both aquaculture and hydroponics in a single system with water travelling in a loop within the system. Various types of plants can be cultivated and various types of fishes can be reared in such systems, making them a suitable source of food production. In a world where food crisis is looming everywhere, aquaponic systems can contribute a lot to food security. It is also a type of sustainable agriculture where waste produced by the aquatic creatures in the system becomes nutrients instead for the plants, albeit with the assistance of attached or suspended microbial growth [1]. The plants act as a sort of biofilters that improves the quality of the water before it is pumped back to where the aquatic creatures are and the cycle repeats itself. The recirculating water in the system means that the water being used in aquaponic systems will remain in the system until it either evaporates into the atmosphere or is uptaken by the plants. This differs from normal soil where irrigation water will seep away so irrigation has to be done frequently. Therefore, water usage efficiency is very high in recirculating aquaponic systems. Another advantage of aquaponic systems is that they are a type of soilless systems, hence they can be applied even in places where no land is available for farming or agriculture, such as in towns or cities. The modular nature of an aquaponic system add to its suitability to be used in urban areas where they can be constructed on flat rooftops or customized and fitted into vacant buildings. Doing this will help to reduce over-supply of shop lots and industrial lots if properly planned and executed. Having food being produced so close to markets in urban areas or even within a city itself will enable the consumers to receive much fresher products at lower prices [2] due to removal of the need for food preservation as well as the much reduced logistic activities. Furthermore, lessening the import of food items from other places will reduce the carbon emission from transportation of goods [3]. Therefore, it is obvious that there are numerous advantages of adopting aquaponic systems to supplement and even replace part of the food supply chain [4, 5].

Besides all the benefits mentioned previously, the ability of aquaponic systems to treat water in and of itself is a feature that has not been widely studied. It is known that the plants help to clean up the water [6] but the aquatic animals on the other hand will continue to contaminate it with the waste they produced. Therefore, it is even more pertinent to look at water from a contaminanted source compared to clean water. It is still unknown whether water the system will improve the quality of the recirculating water or the performance of the system will decline in general. The study presented in this paper attempts to look into this matter.

The source of contaminated water applied in this research was the treated effluent from a sewage treatment plant. Huge volumes of treated sewage effluent are generated from all corners of the earth. Normally the effluent will be channelled directly to surface water bodies like rivers. If the sewage treatment plant is too far away from suitable surface water bodies, the effluent will be channelled to drains which will eventually convey it to existing surface water bodies.

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Although the effluent is deemed to have been treated, more often than not the content of contaminants in the effluent such as nitrogen and phosphorous compounds still exceeds the natural concentration of those elements found in rivers or lakes. Therefore, even though treated sewage effluent is allowed to be disposed of in surface water bodies provided it adheres to the environmental regulations in force [7] such as Standard A and Standard B of the Environmental Quality (Sewage) Regulations 2009 in Malaysia, they may still become a source of pollution to those water bodies. This will happen when the self-cleansing capacity of the water bodies is exceeded. Such a scenario may happen when there are multiple sources of treated sewage effluent located along the same water body such as a big river, discharging effluent continuously into it. However, the same nitrogen and phosphorous compounds that are categorized as pollutants are in fact nutrients needed for plant growth [8]. This was one of the main reason treated sewage effluent was chosen as the contaminated water in this study. Another reason is that treated sewage effluent is easily available and therefore will be a good alternative to clean water. Using treated sewage effluent to replace clean water in aquaponic systems not only provide a source of nutrients for the plants, they also free up clean water for other usages that cannot do without clean water. The use of treated sewage effluent will also reduce or completely eliminate the need for plant fertilizers.

Cost is always a factor in any product development or any sort of endeavour. Having such a good system like the aquaponic system but prohibitive cost will also deter people from taking up this type of farming. Thus, the economic feasibility of adopting a treated sewage effluent aquaponic system, specifically the media bed unit type, was studied and the findings presented in this paper.

METHODOLOGY

Aquaponic System

For this study, the media bed unit system was chosen as it is the most suitable for those without much aquaponics background. It is inexpensive, easy to construct and productive but at a small scale. Figure 1 shows the media bed unit aquaponic system used in this study. The main components of this system are a fish tank, three media beds and a sump tank. The water in this system is recirculating in a loop, meaning that from the fish tank, the water will flow to the three media beds via gravity. There is a bell syphon located in the middle of each of the media beds and it will activate once the water reaches a certain level in the media beds, draining all the water from the media bed to the sump tank underneath. A water pump will then pump the water in the sump tank back to the fish tank, completing the recirculation cycle.

Figure 1. Media Bed Unit Aquaponic System at UMP Gambang.

The media in the media beds are in the form of lightweight expanded clay aggregates, which act as a soil substitute for the growth of the plants. The type of aquatic species in this study was selected as catfish (*Siluriformes*). Meanwhile, each of the three media beds was planted with one type of plants, namely red chillies (*Capsicum annuum*), eggplants (*Solanum melongena*) and bird's eye chillies (*Capsicum frutescens*), respectively. The *Siluriformes* is a scaleless, edible catfish species with a flat head and long tactile barbels around its mouth that are usually found in rivers and lakes. It was chosen for this study due to its ability to cope with temperature fluctuations and also the fact that it is not territorial.

Territorial species will initiate fighting that leads to unwanted death in the fish tank. The chillies were chosen as they are better suited to the media bed unit system compared to other types of aquaponic systems. Eggplants on the other hand were chosen as they have high nitrogen and potassium requirements, making them suitable for treated sewage effluent aquaponic systems. Besides that, the large and deep root systems of the eggplant trees work well in media beds. Frequent care need to be ministered to the plants and catfishes such as pinching off fresh blooms towards the end of the cycle to encourage ripening of existing fruits [9] and frequent harvesting throughout the project period to stimulate flowering, fruiting and growth [10]. Pests also need to be kept at bay and this was done via a mixture of manual removal and spraying of organic, plant-based pest repellant.

The treated sewage effluent was taken from the effluent pipe of a sewage treatment plant around 100 metres away from the aquaponic system. Once the system was set up and ready for operation, it was first filled up with fresh effluent mixed with water from previous or existing aquaponic setups and the mixture recirculated in the system for about a week. This step is known as system cycling and is normally done to build up the colonies of beneficial microorganisms especially in the media beds. After completion of the system cycling, the existing water inside the system was drained until around a third left in the fish tank, after which fresh effluent was added to fill up the whole system again. The refilling with fresh effluent was done in conjunction with the introduction of the catfish fries into the fish tank as well as the transplant of the plant seedlings to their respective media beds. This signifies the start of the growing and harvesting cycle where the duration from planting and rearing to harvesting takes around three to four months [11].

Experimental Methods

Investigation on the effect of the aquaponic system on the treated sewage effluent centred around the the effect of hydraulic retention time on the water quality. Due to the aquaponic system being located in an open area, evaporation of the water in the system cannot be avoided. Therefore whenever there is a significant drop in the level of the water as measured in the sump tank, effluent will need to be added and this was done at the sump tank as well. When a large amount of fresh effluent was added to the system, that was when the investigation on the effect of hydraulic retention time was carried out. For each trial, a sample of the water from the sump tank was taken right after effluent addition (0 hour), then 12 hours, 24 hours and 36 hours after effluent addition. It should be noted that within this 36 hours window when samples were taken, no effluent was added. This was done to ensure that any effect to the water will be due to the system itelf, not due to any extraneous factors.

Each of these water samples were then tested for the following parameters: pH, temperature, biochemical oxygen demand, chemical oxygen demand, total suspended solids, ammonia-nitrogen, nitrate-nitrogen, phosphorous, and oil & grease. These water quality parameters were selected based on the Second Schedule (Regulation 7) of the Malaysian Environmental Quality (Sewage) Regulations 2009. The trial was repeated three times for a total of four experimental trials. It just happened that the trials were conducted roughly once a week consecutively, so the results are presented in terms of Week 1 to Week 4.

For the economic feasiblity part, a benefit-cost ratio analysis as shown in Equation 1 was performed to know whether the treated sewage aquaponic system is profitable. This type of analysis is usually used to summarize the overall relationship between the relative costs and benefits of a project. Projects with a benefit-cost ratio value of larger than 1.0 is supposed to provide a positive net present value. The total cost for one cycle of the current project included the cost of energy consumed, the cost of fish food, and the cost of the fish fries plus the plant seeds. The treated sewage effluent was obtained at no cost so it was not included. Since the benefit-cost ratio is calculated for just one cycle of the project, the cost of materials and setting up of the system was excluded as doing so would be unjustifiable. As for the total return from the aquaponic system, the calculations are shown in Table 3.

$$BCR = \frac{Total\ Return}{Total\ Cost} \quad (1)$$

RESULTS AND DISCUSSION

The results from the investigation of the effect of hydraulic retention time on the water quality parameters tested are shown in Figure 2 to Figure 10. Figure 2 shows very different patterns of pH over time for all four trials. There doesn't seem to be any discernible trend based on the pH results. There should be a relationship between temperature and pH but this is also not evident when comparing Figure 2 to Figure 3. However, all the pH and temperature values measured within the sampling period were well within the range for optimum growth of the catfishes and plants. Figure 4 shows the biochemical oxygen demand values over time and from the graph, there is a clear reduction in biochemical oxygen demand values when the hydraulic retention time increases. Similarly, the total suspended solids value in each trial dropped to 5 mg/L or below, regardless of the initial amount measured as can be seen from Figure 5. This probably means that any suspended solids still present in the treated sewage effluent is organic in nature and had been rapidly oxidized by the microorganisms in the aquaponic system within the first 12 hours. This led to the steady decrease of biochemical oxygen demand as the microbial reactions slowed down due to lack of organic matter in the system. Figure 6 shows the results for chemical oxygen demand from the four trials and unexpectedly, the values increased with the increase in hydraulic retention time. Since chemical oxygen demand measures all organic compounds that can be chemically oxidized instead of just biodegradable organic compounds, it is suspected that the increase in non-biodegradable organics could have come from the fish feed. This was based on the fact that there were no other external inputs to the system within the sampling period. Except for the anomalous increase towards the 36^{th} hour of retention time in the Week 2 trial, the ammoniacal-nitrogen in the aquaponic system basically showed a general decline in concentration as the hydraulic retention time increases. This can be attributed to the nitrifying bacteria in the system that break down the ammonia into nitrate-nitrogen in a two-step process known as nitrification. Nonetheless, the amount of nitrate-nitrogen in the system did not increase, in fact the concentration of nitrate-nitrogen decreased quite rapidly in the first 12 hours and then stabilized for the subsequent 24 hours as evident from Figure 8. This can be ascribed to much of the nitrate having been uptaken by the plants in the system as part of their nutrient intake. For the parameter phosphorous, Figure 9 shows that aside from Week 2, the phosphorous content in the rest of the trials increased as the hydraulic retention time increased. This could be caused by a lower absorption rate of phosphorous by the plants compared to addition of phosphorous rate via the fish feed. The final parameter tested was oil & grease and only two trials were managed due to limitations of budget. From the test results shown in Figure 10, the concentration of oil & grease in the system declined steadily. This occurrence could have been caused by microorganisms that can break down the oil and grease in the system [12]. An overall view of the removal efficiency for the pertinent parameters is shown in Table 1.

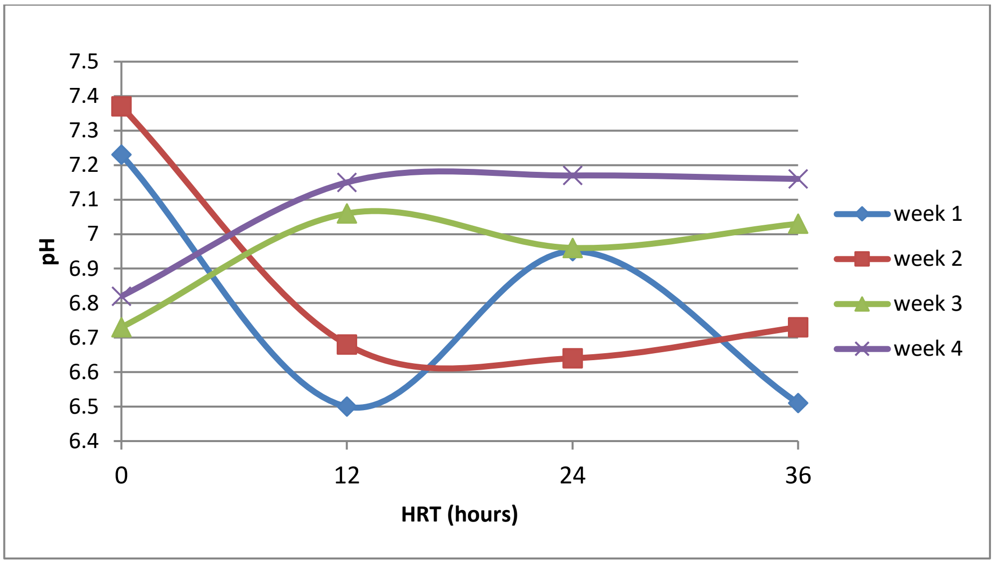

Figure 2. pH versus Hydraulic Retention Time (HRT).

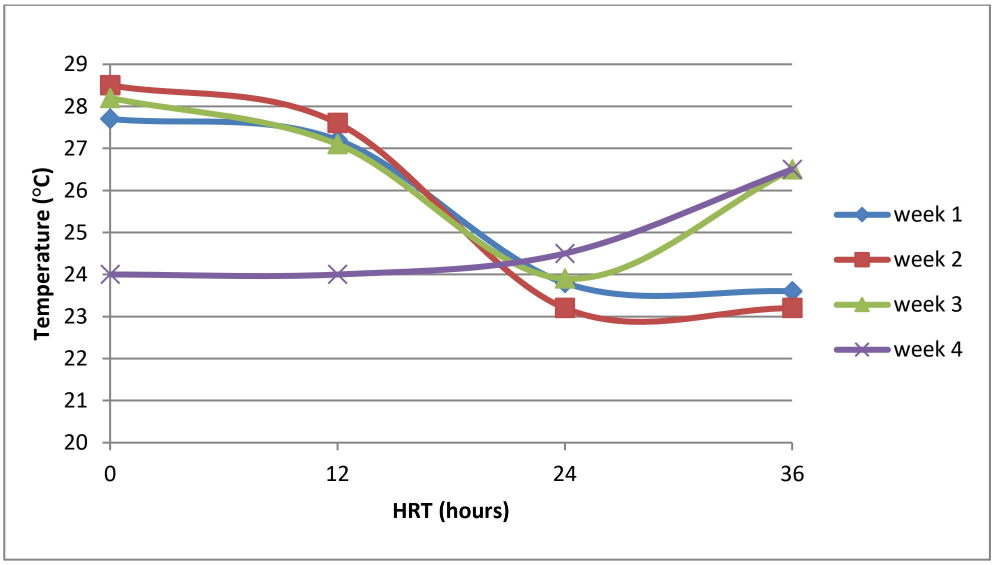

Figure 3. Temperature versus Hydraulic Retention Time (HRT).

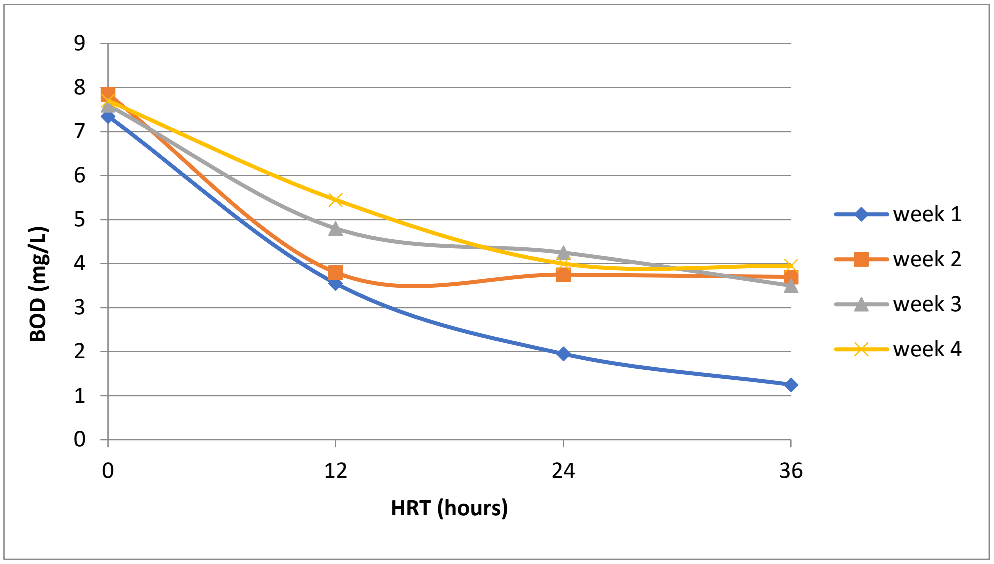

Figure 4. Biochemical Oxygen Demand (BOD) versus Hydraulic Retention Time (HRT).

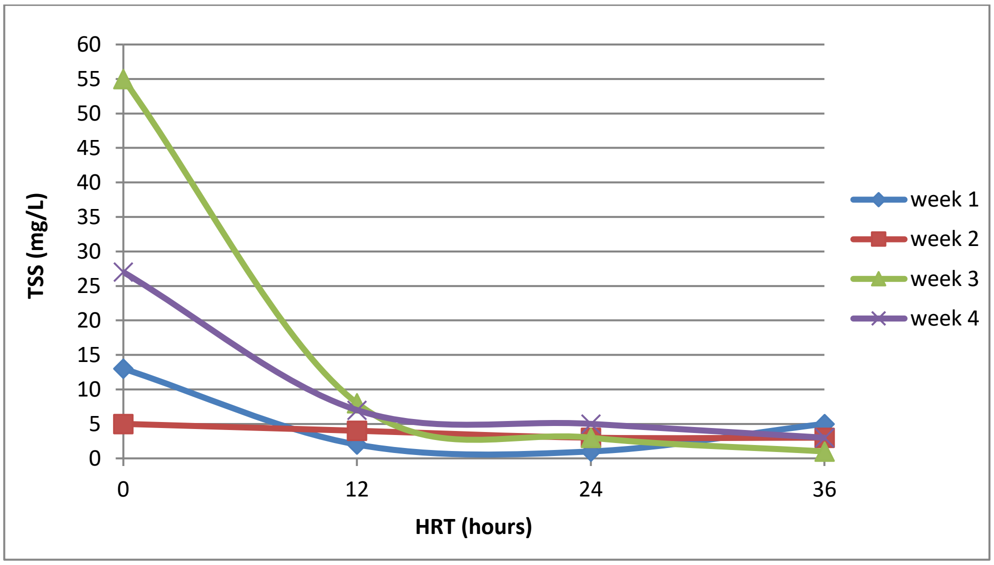

Figure 5. Total Suspended Solids (TSS) versus Hydraulic Retention Time (HRT).

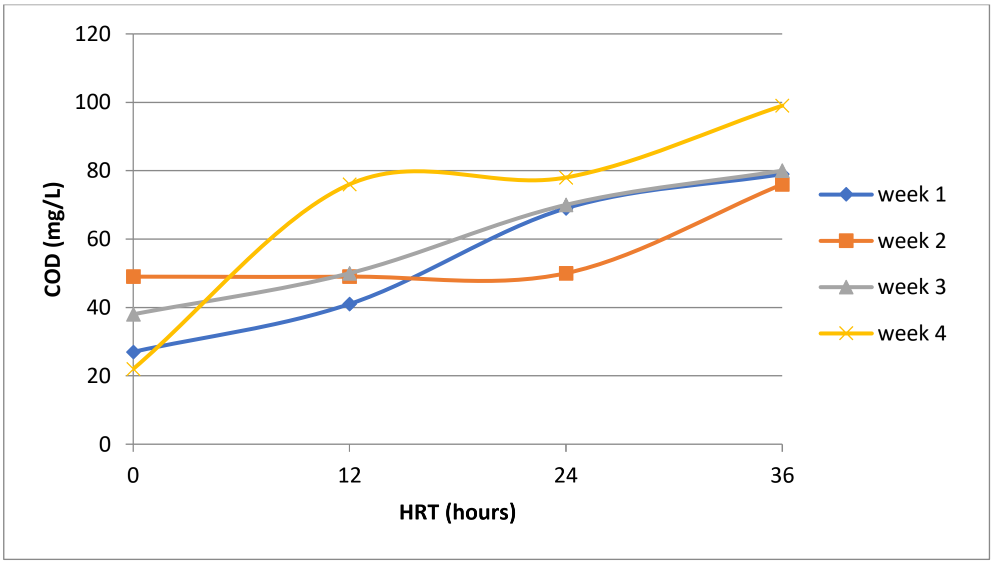

Figure 6. Chemical Oxygen Demand (COD) versus Hydraulic Retention Time (HRT).

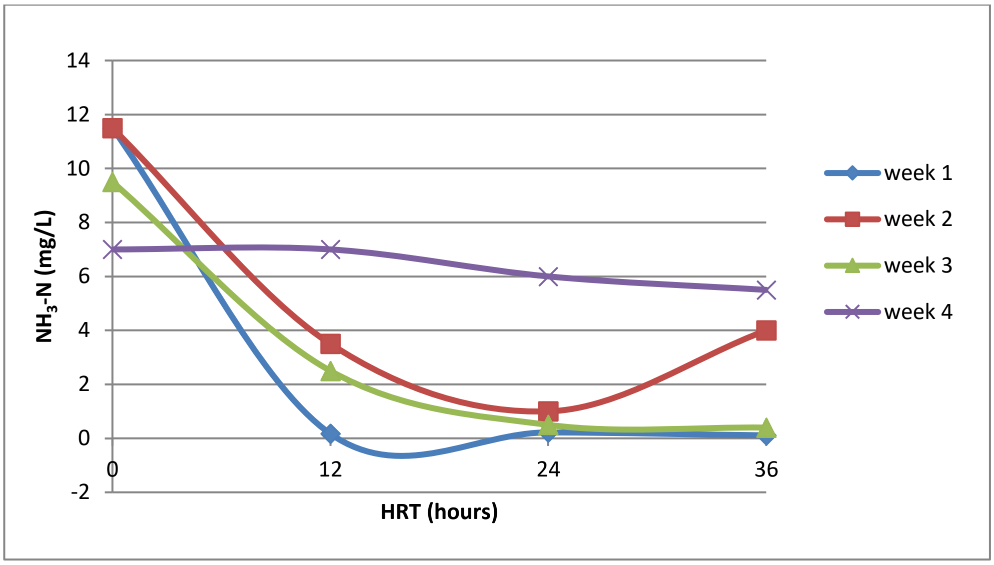

Figure 7. Ammoniacal-Nitrogen (NH_3-N) versus Hydraulic Retention Time (HRT).

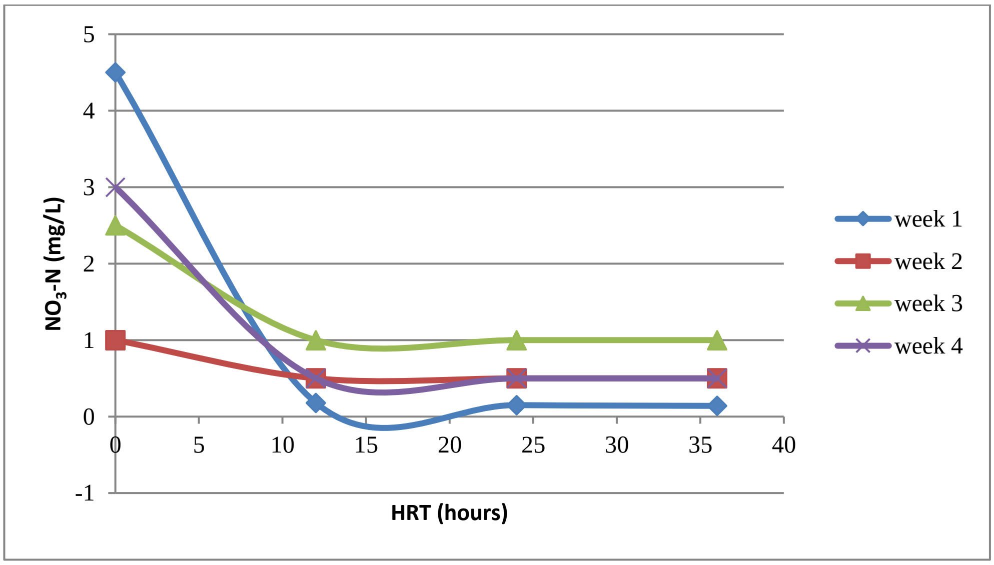

Figure 8. Nitrate-Nitrogen (NO_3-N) versus Hydraulic Retention Time (HRT).

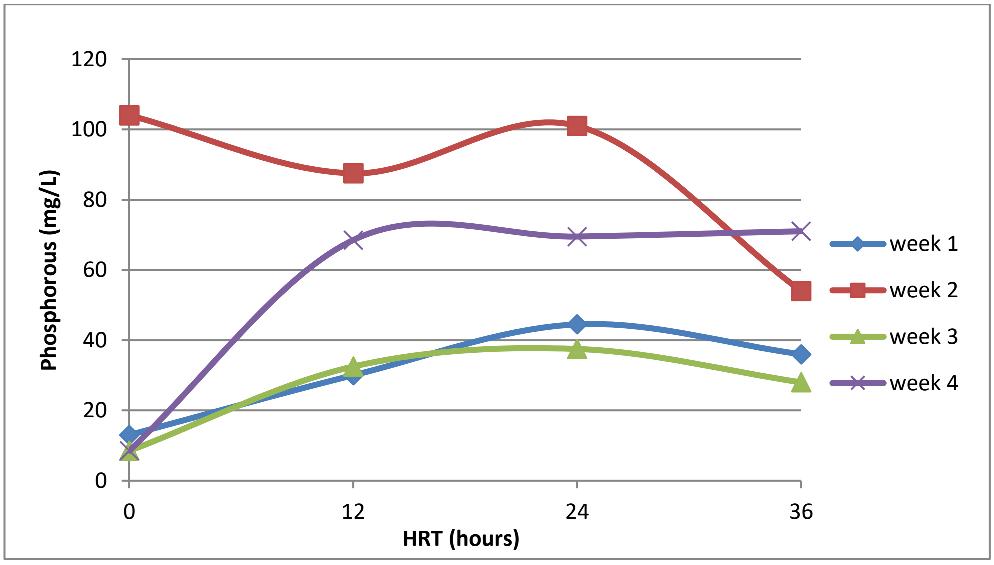

Figure 9. Phosphorous (P) versus Hydraulic Retention Time (HRT).

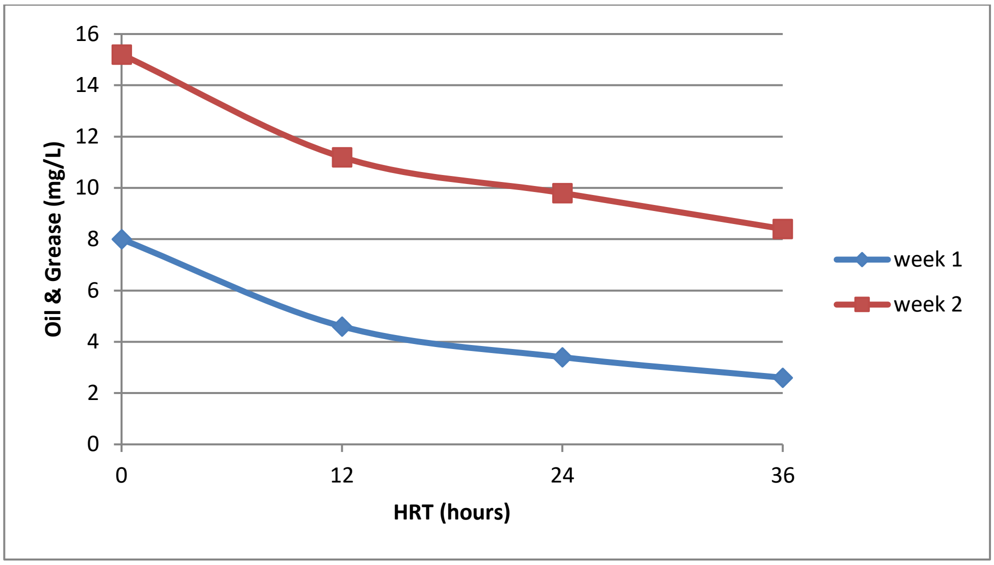

Figure 10. Oil & Grease (O&G) versus Hydraulic Retention Time (HRT).

Table 1. Removal efficiency from 0 to 36 HRT for biochemical oxygen demand, total suspended solids, chemical oxygen demand, ammonia-nitrogen, nitrate-nitrogen, phosphorous and oil & grease.

	BOD	TSS	COD	NH_3-N	NO_3-N	P	O&G
Week 1	83.0	61.5	-196.3	99.0	96.9	-176.9	44.7
Week 2	52.2	40.0	-55.1	65.2	50.0	48.1	67.5
Week 3	53.9	98.2	-110.5	95.8	60.0	-229.4	-
Week 4	88.9	88.9	-350.0	21.4	83.3	-833.3	-

Regarding the economic feasibility of the treated sewage effluent aquaponic system, the total cost and total benefit, which were obtained in the form of monetary value from sale of the food produced by the system, are presented in Table 2 and Table 3, respectively. The cost of the electricity was based on the rate of electricity used which came up to 3.59 kWh per week as there were only an aquarium-sized water pump and an aerator in constant operation. Since the study took 13 weeks to complete, the total electricity usage at the end of the study was 46.67 kWh. Therefore, at a charge of RM 0.218 per kWh, the total electricity cost calculated was RM 10.17, for one cycle. The amount of fish feed needed weekly on the other hand was not constant as can be seen in Figure 11. The amount of fish feed fed to the catfishes increased in accordance to the increase in catfish sizes as they grew bigger. Based on the cost of RM 5 for each kg of the TP1 fish feed, the total fish feed cost amounted to RM 115.30 over the 13 weeks. As for the sale of the catfishes, chillies and eggplant, they were calculated based on the weight of the products harvested multiplied by the market rate of each food type at the time of harvest. Therefore, the total cost based on Table 2 is RM 151.47 while the total benefit based on Table 3 is RM 231.70. Putting these two values into Equation 1 results in a BCR value of 1.53. This means that this system can be said to be profitable without taking into account the set up cost.

Table 2. Total cost of running aquaponic system for one cycle.

Component	Total (RM)
Electricity	10.17
Fish Feed (TP 1)	115.30
Catfish fries	20.00
Plant seeds	6.00

Table 3. Total benefit/income generated by products from aquaponic system for one cycle.

Food Product	Amount (kg)	Market Rate (RM/kg)	Total (RM)
Catfish	30.42	7.00	213.00
Red Chilli	0.50	20.00	10.00
Eggplant	0.10	12.00	1.20
Bird's Eye Chilli	0.20	37.50	7.50

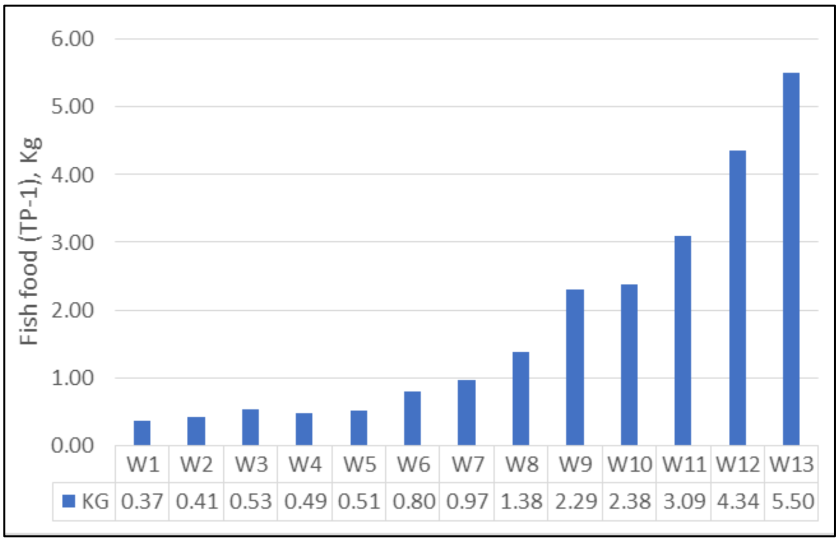

Figure 21. Weekly Amount of Fish Food Consumed by the Catfishes.

CONCLUSION

Overall, the investigation into the effect of hydraulic retention time on the water quality parameters showed that with the exception of chemical oxygen demand and phosphorous, there were improvement to the rest of the parameters studied as the hydraulic retention time wore on. This shows that aquaponic systems are able to increase the quality of the water applied in it. This answers the question of how using treated sewage effluent will affect an aquaponic system by showing that performance of the aquaponic system will not decline when using treated sewage effluent as the recirculating water. In order to overcome the increase in chemical oxygen demand, the type and content of the fish feed used may need some relooking into. On the other hand, the increase in phosphorous can be addressed by including plants in the system that have a high phosphorous requirement. The benefit-cost ratio was calculated to be 1.53. This indicates that in the long run, aquaponic systems can bring in returns to their practitioners and can contribute to sustainability of the environment.

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