Phytoremediation and UV sterilization In the treatment of wastewater; A design of a prototype

Progress Report

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Summary

The current wastewater management sector in Lebanon, particularly in the Bekaa region, is facing significant challenges. These challenges have had a detrimental effect on the health and livelihoods of local Lebanese communities and Syrian refugees, particularly during the ongoing economic crisis in the country. This project proposes a system that utilizes three main components to enhance wastewater quality and make it suitable for irrigation. The components include sedimentation tanks for solids decantation, a phytoremediation-constructed wetland that utilizes macrophytes to eliminate organic and inorganic contaminants, and a final stage where biological disinfectants are removed through UV sterilization. The duckweed Lemna gibba, which is widely available, was used for its remediation properties, and the removal of 82.77% of BOD and 79.6% of COD was proven by multiple researchers.

Background

Today, the wastewater management sector in Lebanon is heavily burdened due to economic constraints, political instability, regional conflicts coupled with climate change, and the extra pressure of the high number of Syrian refugees. Inadequate working sewage and sanitation systems pose a serious threat to human health and the environment (UNDP, 2018). This situation is highly prevalent in critical regions such as Bekaa hosting a high concentration of refugees particularly living in Informal Tented Settlements (ITS) (UNHCR, 2018). Such ITS have largely expanded and become more polluted due to large increases in their populations. The capacity of the current wastewater network in Bekaa is not adequate to meet the growing demands and is currently exposed to overloads leading to a direct impact on the livelihoods and health of refugees and local Lebanese communities. Currently, wastewater management in ITSs is based on desludging or even almost absent. Much of the generated wastewater is dumped in an already aged and outdated infrastructure, and in most cases, it is released into a nearby river of natural land contaminating the natural underground water reservoirs and rendering them useless and harmful for the people and environment (FAO, 2016). In addition, limited water availability and lack of proper sanitation and hygiene have resulted in sharp increases in the prevalence of communicable diseases and the emergence of previously eradicated diseases in the region (UNICEF, 2016). For example, diarrhea has been reported to affect 35% out of 1529 Syrian refugees and 21% out of 758 Lebanese citizens taking into consideration that the study included only females specifically mothers (UNICEF, 2016). Lebanon has recently experienced an outbreak of cholera, which has been linked to the discharge of untreated wastewater into water bodies. The inadequate treatment of wastewater in Lebanon and the lack of proper sanitation infrastructure have led to the contamination of surface water, which in turn has led to the spread of cholera and other waterborne diseases (WHO, 2022). Considering these challenges, there is an imperative need to adapt nature-based solutions that act as alternative and decentralized systems that can work complementary to conventional infrastructure. These solutions are viewed as cost-effective and sustainable due to the low costs of their establishment, operation, and maintenance along with the straightforwardness in operation. Among such technologies, phytoremediation in constructed wetlands (CWs) represents one of the most effective for alleviating a wide range of pollutants from aquatic ecosystems and wastewater (Herath and Vithanage, 2015; Naghipour et al., 2018). This technology is based on the use of macrophytes (freshwater plant species) that have a high capacity to uptake and bioaccumulate different pollutants while enhancing the protection and restoration of the environment and natural resources (Alsghayer et al., 2020). In addition to direct uptake, macrophytes employ explanta mechanisms through which pollutants are transformed/mobilized by phytochemicals or enhancing microbial activities (Farraji, 2014). Some macrophytes may also release oxygen by roots enhancing the level of dissolved oxygen (DO) in water and decreasing the level of biological oxygen demand (BOD) which are key factors in the determination of pollutants dynamics, oxidation processes, and enhancement of microbial activity. Therefore, a decentralized phytoremediation system established in ITSs of Syrian refugees in Bekaa may potentially be a sustainable alternative for wastewater management solutions leading to safe and clean treated wastewater suitable for irrigation. To date, there have not been any phytoremediation initiatives in ITSs in Bekaa. This may be due to the lack of scientific information on the performance efficiency of such alternative systems.

This project will contribute to enhancing the sustainable management of wastewater in the Bekaa region and increasing the availability of clean safe water through a nature-based technology. It will contribute to increased availability of water for irrigation purposes, food security, and the protection of health and the environment in the region. The project also exhibits good alignment with the goals of the Wastewater Strategy of Lebanon (2012), and Lebanon Crisis Response Plan and is expected to contribute to Sustainable Development Goal (SDG) 6 (clean water and sanitation) along with other SDGs such as SD 9 (innovation and infrastructure).

Objectives

- To design a phytoremediation mini prototype using the indigenous duckweed (*Lemna gibba* L.) and UV disinfection for wastewater treatment.

- To assess the potential efficiency of the designed system in decentralized wastewater treatment in one of the Informal Tented Settlements of Syrian refugees (ITS) in Bekaa.

Methodology

I. Design of Constructed Wetland Prototype

The wastewater porotype is in principle a plant-based mini-constructed wetland (CW) designed based on three main compartments that work together (Figure 1). The proposed system does not contain many mechanical or electrical components. This will decrease the maintenance cost and the power demand of the system, so an off-the-shelf low-cost solar system can be implemented as an energy source to power the designed system.

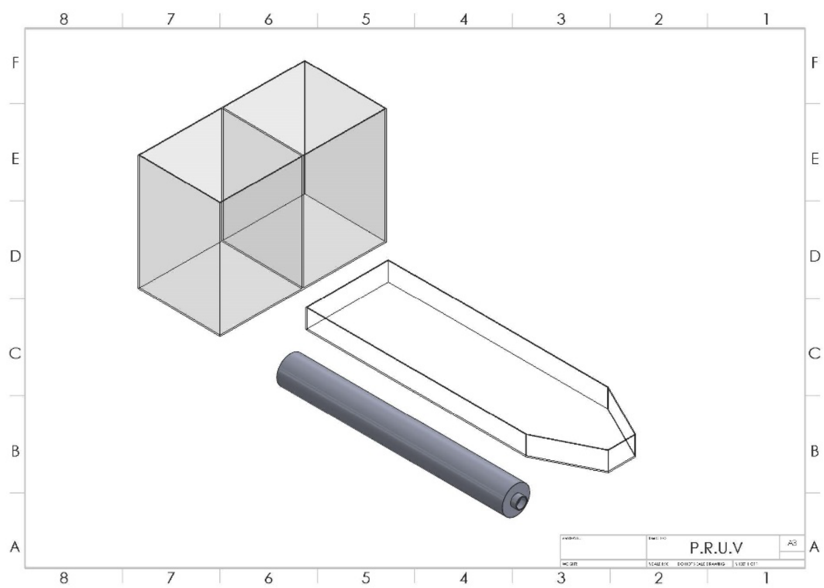

Figure 1: Represent a dimetric schematics view of the phytoremediation and UV sterilization system was based.

1. Sedimentation tanks

The sedimentation tanks of the design receive wastewater from the source and allow the decantation process to take place. The particles found in wastewater require a settling time that ranges between of 3min to 2 hours, with most of the solids settling within the first 10 min at a velocity of 10m/h (Aslam, 2013). The designed system can also be complemented with 2 redundant tanks that can work separately to ensure a continuous supply of water. Both tanks can be linked to a pumping and valving system that connects and regulate the fluid flow (Figure 2).

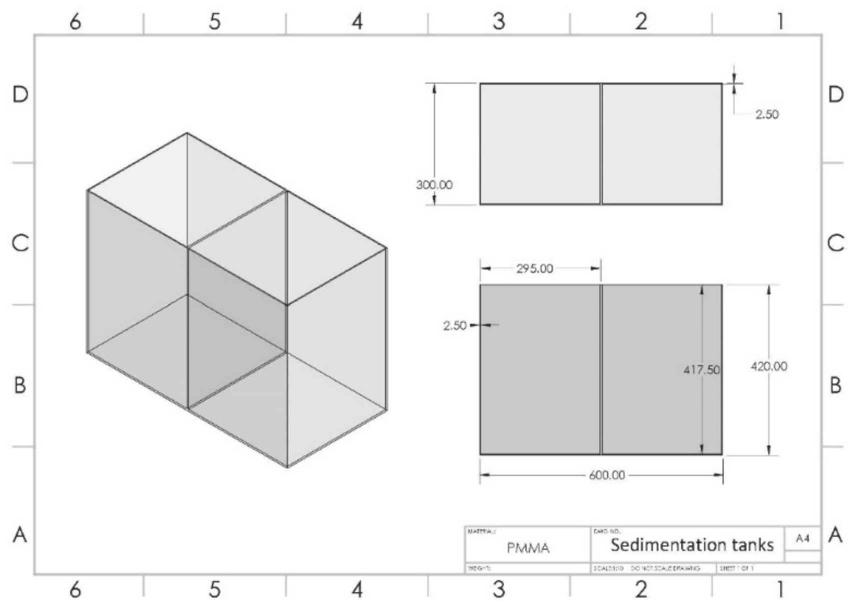

Figure 2: Represents a schematic view of the sedimentation tanks

2. Plant-based Phytoremediation Compartment

Once the decantation process is done, a pump will transfer the liquid from the sedimentation tank to the plant-based phytoremediation unit where organic and inorganic contaminant removal occurs (Figure 3, Figure 4). The liquid portion obtained in the first decantation process will be transferred into this tank where dissolved organic and inorganic contaminants will be treated by phytoremediation using a floating aquatic duckweed *Lemna gibba* (Figure 5). Lemna gibba, also known as Common Duckweed, is a small floating aquatic plant that belongs to the family Lemnaceae. It is a free-floating plant and can be found in freshwater habitats such as ponds, lakes, and rivers. Lemna gibba is a fast-growing plant and can double its biomass in less than 24 hours under favorable conditions (Gao et al., 2018). It is a highly efficient primary producer and can uptake nutrients quickly from the water, making it useful for nutrient removal in constructed wetlands for wastewater treatment. It is also used as a bioindicator for water quality assessment, as it is sensitive to changes in water chemistry (Ghanem et al., 2020). Lemna gibba has been shown to have the potential for the phytoremediation of heavy metal pollutants in water, including lead, cadmium, and zinc. Studies have also found that Lemna gibba can remove high levels of nutrients such as Nitrogen and Phosphorus from wastewater and surface water (Wang et al., 2018). Theoretically, the plant will uptake nutrients and various pollutants of wastewater resulting in improving its quality and making it ready for the final stage, UV sterilization.

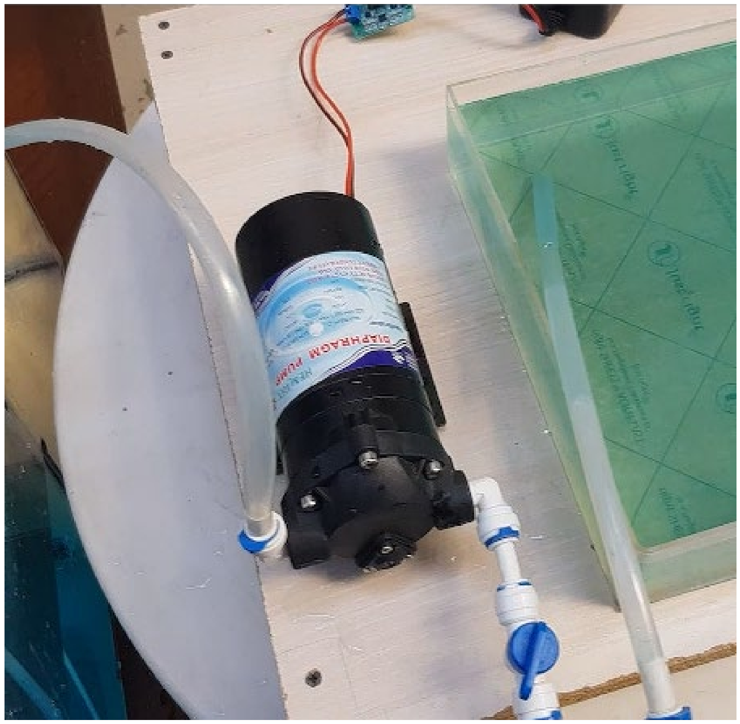

Figure 3: The pump was used alongside a set of valves to maintain and control a constant flow.

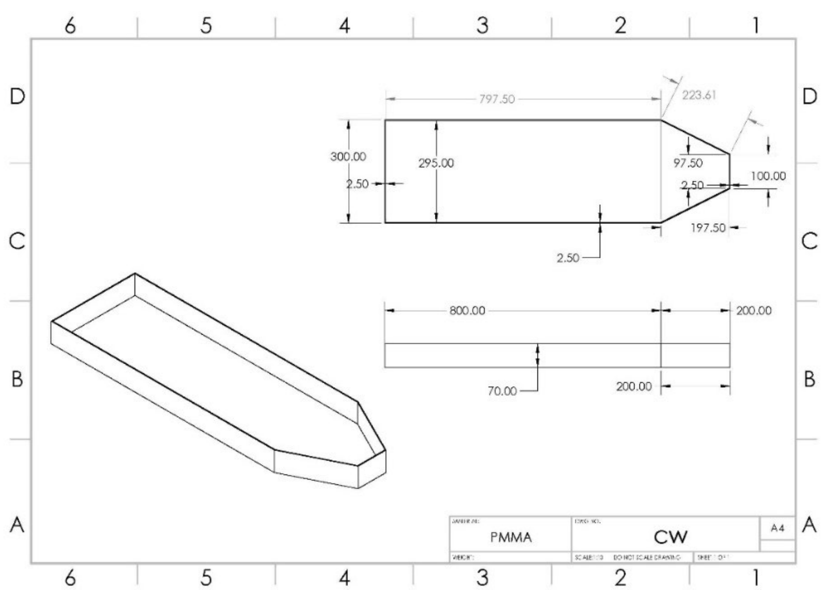

Figure 4: Represents a schematic view of the CW.

Figure 5: Lemna gibba growing naturally in polluted Lebanese waterbodies.

3. UV Sterilization Unit

UV light provides rapid, effective inactivation of microorganisms through a physical process where nucleic acid damage will cause the formation of dimers. To achieve the desired outcome a certain type of UV should be used. The UV sterilizer consists of a high-energy 254 nm Germicidal UVC lamp enclosed in a quartz shielding tube to prevent or reduce the formation of Ozone gas (Figure 6). At this stage, biological agents are rendered incapable of reproducing and infecting by DNA damage (Ashok et al., 2016).

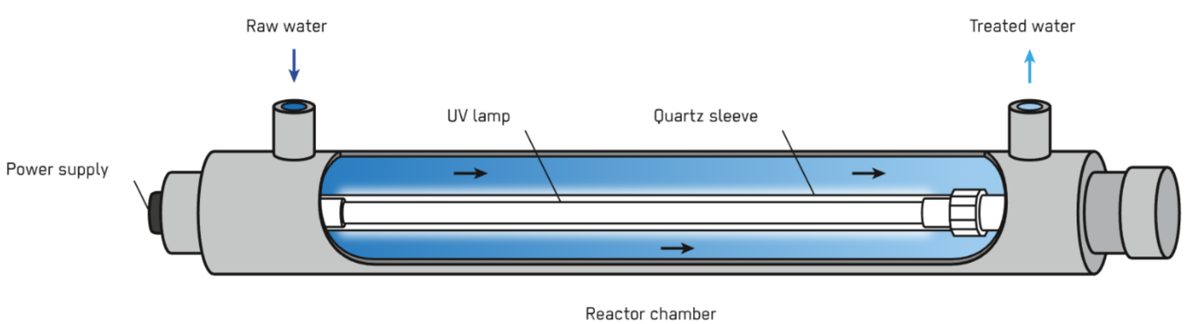

Figure 6: Represent an illustration of the UV sterilization chamber used in this system (Emergency Wash, 2016).

II. Treatment Efficiency Assessment

Assessing the removal efficiency of the proposed system by comparing the level of certain water quality parameters such as total dissolved salts (TDS), dissolved Oxygen (DO), Biological Oxygen demand (BOD), and microbiological quality at the inlet and outlet of the system is still under progress.

For this stage of the study, fresh duckweed stock collected from El Rawda irrigation canal, Bekaa (Figure 7) was cleaned with tap water and then washed with distilled water. Then inoculation of *Lemna* plants was transferred to the phytoremediation tank for wastewater treatment. The experiment is now kept under outdoor local environmental conditions for maximum retention time and optimal growth of the plant to reach suitable conditions for the remediation process. This is especially important as temperature is reported to be one of the crucial design parameters of duckweed ponds. In the present experiment temperature, outdoor temperatures were below 17°C, which is still below the temperature suitable limit for duckweed growth.

Nevertheless, for the sake of this report, secondary data from a previous report on the bioaccumulation potentiality of *Lemna* for heavy metal pollution in Lebanese fresh waters is presented (Ghanem et al., 2020).

Figure 7: Picture sourced from El Rawda social media page showing the irrigation canal where the plants were acquired from.

Key Findings

Plant-based CW systems are not based on new technology. They are widely utilized in Europe, North America, and Australia, but are still in the experimental and piloting stages in the Middle East including Lebanon. However, this green technology has tremendous potential, especially in the climatic and social context of the region. Also, scientists from different regions are still investing much effort and time to test different plants and determine removal efficiencies of pollutants by plants and find better means to provide faster and more sustainable means of remediation.

I. Design of Constructed Wetland Prototype

The prototype designed in this research works to serve as a decentralized system for treating wastewater generated in small communities and ITS of Syrian refugees in Lebanon (Figure 8). The design consists of three main compartments in which wastewater volume is transported via a pump (Figure 3) from the sedimentation tank into the CW then to the UV sterilization chamber and then offloaded into a discharge pit or irrigation system. This designed prototype can take up to 60L of wastewater that's stored in the sedimentation tanks with a net treatment area of 21000cm^3 and functions based on the use of duckweed *Lemna gibba* for the remediation of wastewater and UV sterilization for biological disinfection. Below is a detailed description of each compartment (Figure 9).

Figure 8: Picture of the ITS found in Lebanon.

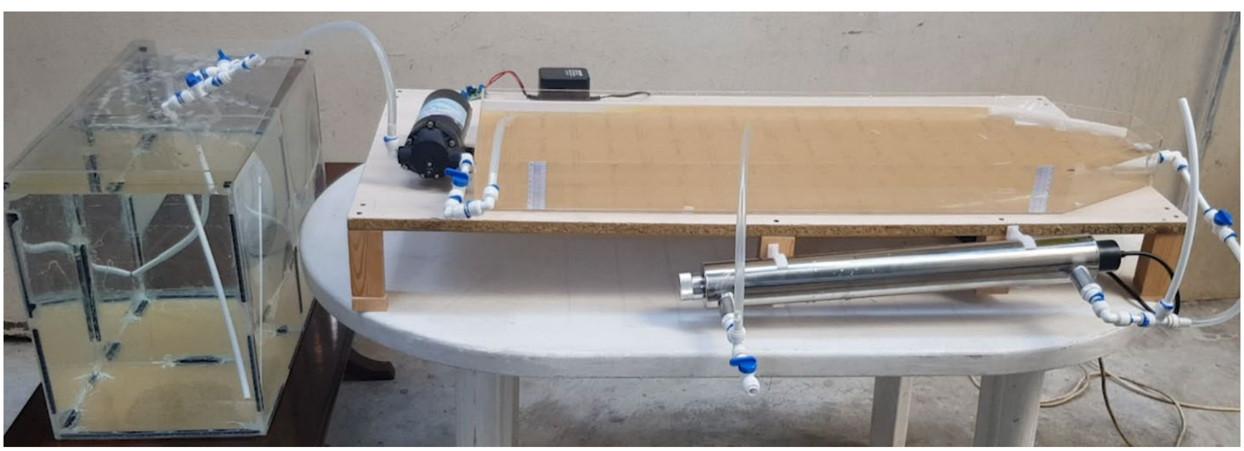

Figure 9: Phytoremediation and UV sterilization system completely assembled and being tested.

1. The Sedimentation Tanks

Dimensions are 30*30*40 cm, having a volume capacity of 36,000 cm^3 (Figure 10, Figure 2) which is a higher capacity than that of the CW to avoid any bottleneck effect. This design contains 2 sedimentation tanks of the same size, ensuring that the system has a continuous supply. Each of the sedimentation tanks can fill the CW one and a half times. They were designed in such a manner to compensate for the settled particles at the bottom and the tank will need less cleaning.

Although the septic tank idea was proposed the original grant proposal was based on the sedimentation tanks in which a lot of time and resources were invested. At such a late stage it was not possible to adopt new ideas since it will add more financial and time constraints to the project. The reason why 2 sedimentation tanks were adopted is to add input redundancy to the system in which the system won't be limited by the water input and risk running the plants dry but instead, it will be limited by the output through the valving system.

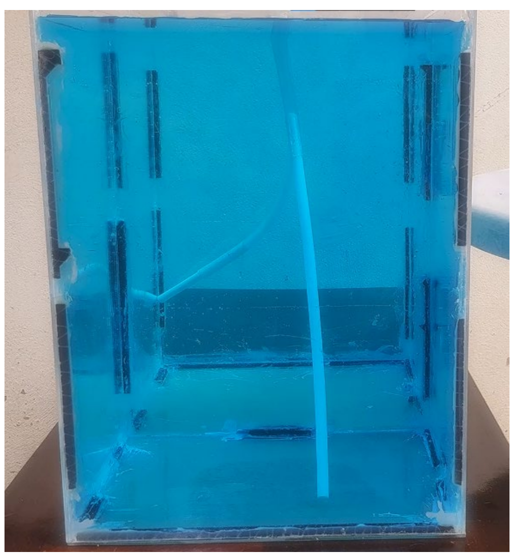

Figure 10: The sedimentation tank containing blue-dyed water. This was a simulation of how will the water behave once the system is operational.

2. Plant-based Phytoremediation Compartment

According to the available research on phytoremediation, the best size for CW is an aspect ratio of 2:1, and the optimal is 3:1 (Jayaratne et al., 2010). Applying these recommendations to the design the dimensions led to the 100*30*7 cm with a total volume of CW is 21,000 cm3 (Figure 11, Figure 4).

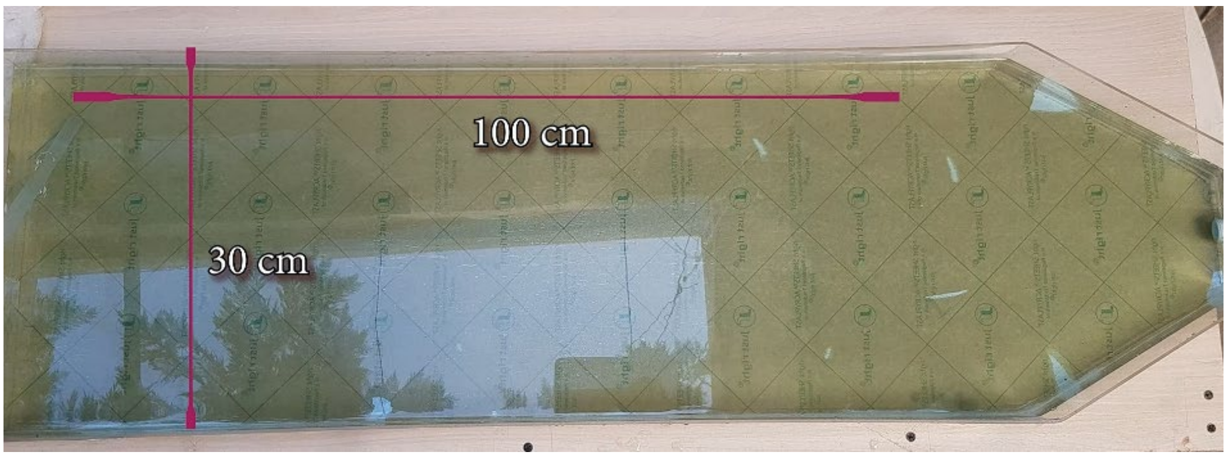

Figure 11: The CW is designed so that the water will travel a longer distance exposing it to more contact with the plants.

The *Lemna gibba* plant needs a certain set of conditions to be moved from one habitat to another. The most optimal time falls between July to mid-September, trying to seed the first set of plants seeded on November 8th, 2022 (Figure 12) didn't prove to be a good idea as the culture only survived for 3 days (Figure.13). An important finding was that the type of water added did not suit them that much. It's suspected that the water contained harmful chemicals so the source was changed.

At this point in the prototype before any testing can be done an optimization period is essential to understand how will this system behave once all the components are combined.

Unfortunately, due to time constraints, this step was rushed. The chemicals that the plant was exposed to was a combination of chloroform, acetoxy silicone, and chlorine. The chloroform and acetoxy silicone was used in the construction of the CW since the CW is made up of Poly(methyl methacrylate) (PMMA) chloroform was used as a binding agent between the different PMMA panels in which the chloroform will interact with the PMMA melting the top layers after which the chloroform will evaporate and the PMMA panels will be fused. This process will result in a bi-product of methacrylate acid, beside the effect of this element on the PH of the water it will cause toxicity to the plants which will inhibit the root and shoot growth (Chen et al., 2016) and effects the cell viability while damaging the plant's cell wall (Chaabane et al., 2014. DCCEEW, 2022). Alongside the chloroform, acetoxy silicone was used to ensure leakage proofing for the CW compartment. Acetoxy silicone is composed of

Methyltriacetoxysilane, Ethyltriacetoxysilane, and Silicondioxide. This material was used in the CW and sedimentation tanks to create a tight seal and prevent leakage from taking place since the chloroform will bind the PMMA panels together but some minor separation will still exist, and such separation will cause fluid leakage. Methyltriacetoxysilane and Ethyltriacetoxysilane under aqueous conditions will result in the formation of acetic acid that has a heavy impact which can destroy cell membranes, which then can result in plant tissue desiccation and plant death (Webber III et al., 2018). Acetic acid functions by inducing desiccation in plants, which leads to dehydration (PP&E, n.d.). This occurs as the acid breaks down the cell walls and fluids of the plant, causing them to leak out. The high concentration levels of chlorine (Cl) were confirmed by the strong smell and formation of bubbles since Cl has a boiling point of -34.6°C the bubbles formed in the water was the Cl evaporating into the atmosphere. According to the available research, *Lemna Gibba* can tolerate and remediate Cl in water (Hareeb, 2015), but since the CL was mixed with multiple different chemicals that the plants were seeded in caused a shock and toxicity that rendered the nonviable.
It's important to note that this was an operator error since plants are a bit sensitive once their habitat is changed. To avoid such incidents the CW and sedimentation tanks were thoroughly washed and prepped for the next seeding round.

Figure 12: First set of plants directly after seeding.

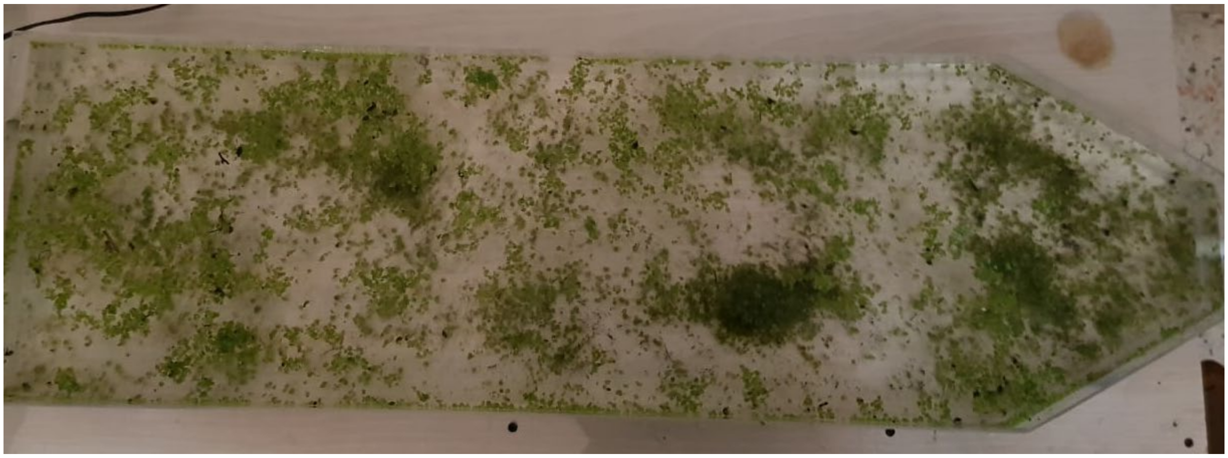

Figure.13: First set of plants 3 days after seeding.

The second set of the *Lemna gibba* was seeded on the 20th of November, 2022 after spending 5 days in their original water from their habitat, then they were moved to the system carefully (Figure 14). The water source used in the second seed was from a natural spring. The culture is sustained up to the point of the report submission (Figure 15) but is not proliferating since the temperature dropped and plants go into some form of hibernation preparing for the winter (Culley et al., 1981, Classen et al., 2000). No actual biological or removal efficiency testing can be performed under the current conditions due to the presence of multiple uncontrolled variables that might interfere with the test, including the possibility of the decreased capacity of the waste uptake since the plants are not in their optimal state.

The water that was used for the plant seeding was not intended to be used as a measurement for the success or failure of the prototype but rather to provide a comfortable environment in which the plants can be situated and avoid inducing any form of habitat shock. As for the Proliferation, it wasn’t the main focus of this experiment as it will require much more time, testing, and resource to understand it better. The main intention of this prototype was to create a suitable habitat for the plants to be sustained in.

Figure 14: The second set of plants 3 days after seeding.

Figure 15: the second set of plants 24 days after seeding. They don't look too healthy judging from the lack of green color

The *Lemna gibba* has the potential to remove pollutants from wastewater which can also be a cost-effective and feasible option, where it was used in other experiments for leachate treatment (Iqbal et al., 2019) and Arsenic uptake (Goswami et al., 2014), but none of the previous researches have tested the *Lemna gibba* in a continues to flow. To accommodate such conditions the system was equipped with a variable flow rate pump and control valves at each stage of the system. The first set of valves controls the sedimentation tanks specifically what tank to be used where an example can be if the valve on tank number 1 is set in its open and the valve on tank two is in its close position the pump will pull water from tank one or vice versa (Figure 16). The same set of valves can be used to limit the amount of water that can be pulled by the pump, for example, the valve can be set in its partially open, halfway open, or fully open position. The second set of valves controls the amount of water being pumped into the CW (Figure 17), most of the time this valve should be in a synchronized position with the third set of valves that control the amount of water leaving the CW to the UV sterilizer (Figure 18), by opening and closing these 2 sets of valves we can control how much time the wastewater is being held inside the CW where the *Lemna gibba* is located ensuring that the plants have sufficient time to perform the remediation process.

The fourth and final set of valves is situated at the end of the UV sterilizer in which the outlet flow can be controlled to discharge the water outside the system through the UV sterilizer (Figure 19).

Figure 16: Top view and close-up view of the valve's situation on the top of the sedimentation tanks.

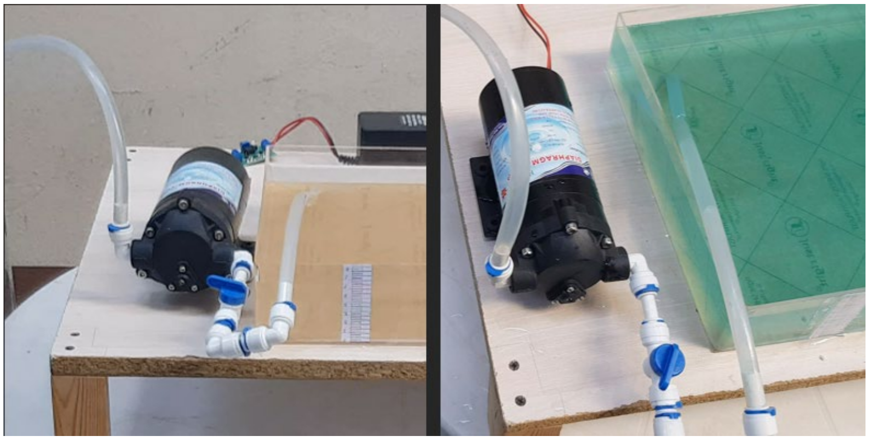

Figure 17: Represents 2 different views of the valve that controls the fluid flow from the pump to the CW.

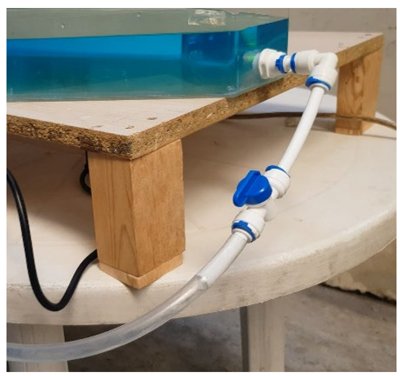

Figure 18: The outlet valve that controls the amount of water that can escape or get trapped in the CW. Usually, this value is set to match the inlet flow to the maintenance continuous flow.

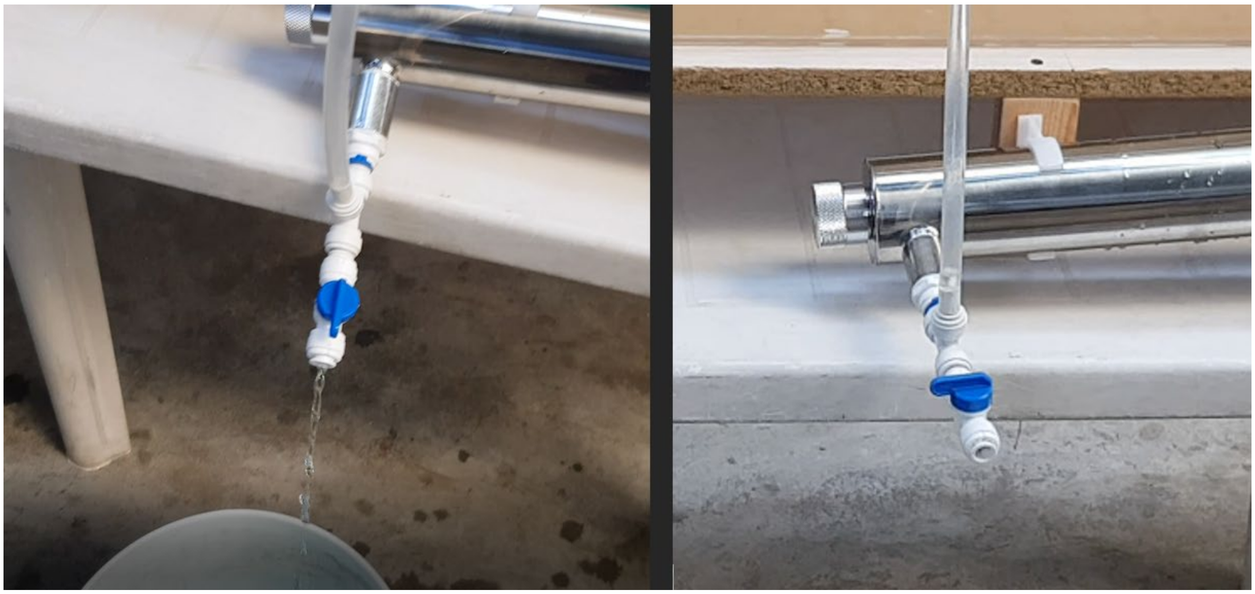

Figure 19: Shows the outlet port responsible for the discharge of the treated water.

3. UV Sterilization Unit

In the first stages the particle removal process took place and what’s left is liquid water containing biological agents like bacteria, viruses, and fungi. The UV sterilizer can handle up to 22.7 l/m (Figure 20) which is much more than what the system can produce, but since this is not a limiting point, the capacity won't affect the processes (Figure 21). In addition, treated water can be stored in the UV sterilizer for more time ensuring better disinfection (Figure 6). UV sterilization is an already well-established technique for biological disinfection. Since no wastewater was treated by the system, running the water that was used to seed the cells will not provide any useful information.

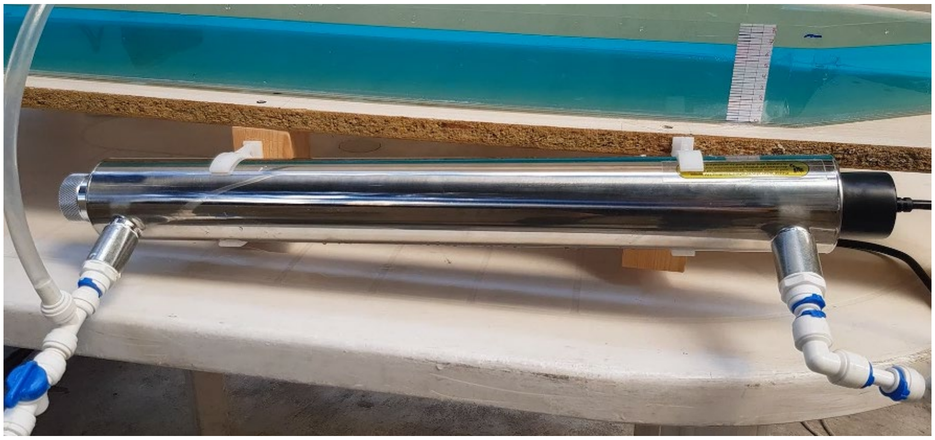

Figure 20: The UV sterilizer is encased in stainless steel to prevent rusting.

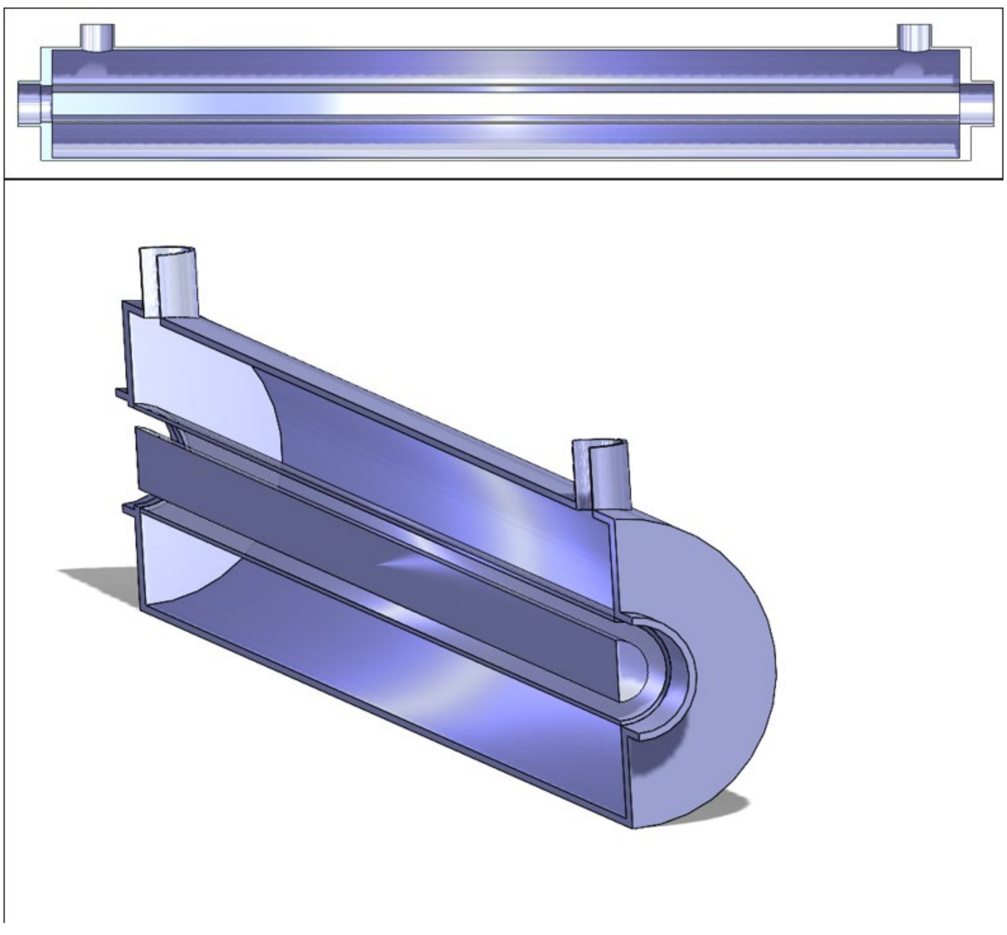

Figure 21: 3D cross-section of the UV sterilization chamber.

Once the wastewater has passed through all three compartments an improvement in its quality should be obtained where the organic, inorganic, and biological infections where removed the water then can be stored outside the system in storage tanks that can either be linked to an irrigation system or transported to be used in crops irrigation.

II. Treatment Efficiency Assessment

Daily observation of plant growth of *L. gibba* inoculated in the phytoremediation tank indicated some form of dormancy and a high rate of death in individuals. This is mostly due to low temperatures at this time of the year affecting the metabolic processes and contamination uptake by the plant. Previous reports show that the temperature tolerance limit for duckweed growth is around 34^{o} C and a slight decrease in growth occurs with temperatures below 10^{o} C (Culley et al., 1981). Literature also shows that duckweed can survive in outdoor wastewater treatment tanks at below-freezing temperatures to resume growth when the temperature rises above freezing (Classen et al., 2000). This allows duckweed to be used for a year–round wastewater treatment. This finding was confirmed in this prototype where the plant was surviving but not proliferating for this reason the experiment was halted since the acquired data might lose its integrity due to the interference of an unknown variable of the metabolic processes and contamination uptake of the plant. For these reasons, the experiment should run once the temperature increase to the suitable range of *L. gibba.*

The percentage removal of 82.77% of BOD and 79.6% of COD were reported (Arias et al., 2016). Long side the removal of BOD and COD, the *Lemna* was tested for its remediation properties with heavy metals where the accumulation values varied between 4138.13 and 82.28 µg/kg and followed the descending order of Zn>Cu>Mn>Ni>Pb>As>Cr>Cd." (Ghanem et al., 2020).

It is recommended that the current experiment is completed as temperatures are more suitable for *Lemna* growth. It is important to note that a hydraulic retention time of 8 days is suitable according to the literature beyond which duckweed does not show any substantial increase in efficiency (Arias et al., 2016) (Ghanem et al., 2020).

Limitations and Recommendations

Despite the various advantages of the designed prototype for decentralized use of wastewater treatment in the Bekaa region being semiarid and hot in the summer season particularly, there are some limitations. A much larger prototype where much bigger instrumentation can be used will provide better representative results especially the size of the *Lemna gibba* might cause some clogging issues, in this mini prototype since it contains small valves and tubs.

The system may be exposed to high water losses via evapotranspiration (i.e., evaporation and plant transpiration (ET)) that may reach 60% in Bekaa (Karam et, al.). This can alter the water and may lead to increased salinity values. This means that, if treated effluent is considered for reuse in irrigation which is highly likely, there would be a need to reduce ET to control salinity.

The operation capacity of the designed system requires further examination to maintain its long-term operability. One of the most prominent recommendations is to establish a local wastewater network and adopt septic tanks to reduce the remediation load of the plant and increase the overall speed and efficiency.

In addition, sludge generated in the design requires good management and a sludge treatment plant to avoid any desludging process with tanker trucks to centralized wastewater treatment plants or even discharging in freshwater bodies or natural land. Considering the favorable climatic conditions (dry and hot) that enhance the related biological and dewatering processes, CWs can be an ideal alternative to this issue. The *Lemna gibba* plant turns out to be sensitive to habitat change, especially outside the optimal growth period.

The plant that we were planning to use for our experiment is not in its optimal developmental stage due to the recent temperature drop. As a result, it's recommended to delay the testing until a later time when the conditions are more favorable for the plant to grow and develop. This will ensure that the results of the experiment are accurate and meaningful. By re-running the experiment at a later time in one of the ITS, we will be able to obtain more reliable data and ensure that any conclusions we draw are valid. This will also allow us to gain a better understanding of the plant's growth and development patterns in relation to temperature. We will monitor the temperature and will rerun the experiment as soon as it's back to the optimal range for the plant.

Despite the limitation presented the system is still a potential option for wastewater treatment applications as it demonstrates not only potential technical efficiency but also sustainability features. The system can be easily upscaled to represent a feasible solution for wastewater treatment in ITS of Syrian refugees in Bekaa. It can also offer a beneficial reuse potential of the treated effluents in agriculture and water conservation and climate change mitigation in water-stressed regions in Lebanon.

Advocacy Plan

The wastewater management sector in Lebanon got heavily burdened due to economic constraints, political instability, regional conflicts coupled with climate change, and extra pressure caused by the high number of Syrian refugees. The increase in the informal tented settlements exposed the aging system to an overload which led to the dumping of wastewater in a harmful way that impacted the environment and the surrounding residents. Considering these challenges, adapting a nature-based decentralized system or wastewater treatment that can work complementary to conventional infrastructure is viewed as a solution for the issues faced in the wastewater sector.

Phytoremediation in plant-based CWs represents one of the most effective solutions for this issue.

With such ideas opinions will be divided between supporters and opposers. Some of the supporters might be:

- Governments (high): due to the low establishment cost.
- Municipalities (high): these provide a viable water source for irrigation.
- Farmers: the better-quality water will result in better crops hence an increase in value.
- NGOs (high): due to the low establishment cost and high implication versatility.

On the other hand, opposers to this idea include:

- Private water suppliers (medium): its effect on their financial income.
- Farmers (low): prefer the use of wastewater due to the effect it has in increasing crop size and weight which will lead to more profit margins.

Through a pilot scale system to support this project, credibility should be achieved, allowing for data collection, analysis, and future results projection. Once a database setup gets finalized, advocates will have access to reliable data to support the importance of investing more resources in alternative methods for wastewater treatment.

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