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Development of an Arduino-based photobioreactor to investigate algae growth rate and CO_2 removal efficiency

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ABSTRACT

Global carbon dioxide (CO_2) emissions are rising, and microalgae have been a primary focus for alleviating the negative impacts of increasing CO_2 levels. CO_2 sequestration is influenced by pH level, temperature, light, nutrient levels, and aeration. This study adapted a 2-chamber system with a 6-Liter vertical-column photobioreactor. It was constructed to remove CO_2 from the air using microalgae. Arduino sensors, namely temperature, pH, and CO_2 gas, were incorporated to monitor microalgal growth. Two 7-day trials, with an initial algae mass of 15 g, were implemented to investigate the growth and CO_2 removal rates. The results showed that trial 1 yielded 21.5 g with a growth rate of 0.56 gxin-2 x day-1, and trial 2, a final sample of 19.7 g with a growth rate of 0.51 gxin-2 x day-1. The CO_2 removal rate for trial 1 increased from 10.17% to 22.04%. However, the CO_2 removal rate for trial 2 decreased from 15.66% to 3.55%. In terms of relative percent error, the Arduino sensors' accuracy was also determined to be low, ranging from 0.85 to 1.94. With accurate readings, the findings show that the CO_2 removal efficiency rate and algae growth rate are directly proportional to each other.

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1. INTRODUCTION

Carbon dioxide (CO_2) levels in the atmosphere have risen by a significantly large amount. An estimated data of 407.4 parts per million of CO_2 was gathered in the year 2018, and this is higher than the levels 800,000 years ago [1]. Boden *et al.* [2] stated that these concentrations are in constant relationship with fossil fuels, contributing 78% of the total greenhouse emissions. The United States Environmental Protection Agency [3] reported that CO_2 is the primary greenhouse gas secreted in the atmosphere due to human activity. Trees and terrestrial plants combat greenhouse emissions since CO_2 and other nutrients like phosphorus and nitrogen serve their food [4]. Although trees play a fundamental role in carbon absorption, Lamm [5] stated that between 1994 and 2007, 34 gigatons of CO_2 were absorbed primarily by our oceans through algae, corals, and vegetation.

Researchers seeking carbon reduction approaches are especially interested in microalgae because of the known fact that microalgae are among the most active biological systems for biomass production and carbon fixation [6]. Besides this, microalgae have provided numerous potential uses for the benefit of society,

namely extensive application potential in the renewable energy, biopharmaceutical, and nutraceutical industries [7]. Microalgae is a rich source of carbon compounds that can be explicitly specialized for atmospheric CO_2 mitigation [8]. These are organisms that reproduce fast with growth rates of five to ten times quicker than ordinary food crops [9] and rapid growth is a feature that can be used on a broad scale to absorb CO_2 [10]. Microalgae has a simple cell structure but is adaptable to grow in extreme environments with a photosynthetic mechanism comparable to land plants [11]. Hence, microalgae systems provide the best technological alternative across all biological methods in sequestering CO_2 [12].

As innovation and robotics developed furthermore, organizations built several projects to find alternatives that can work with trees and terrestrial plants through a device that captures CO_2 directly from the atmosphere and the utilization of the growth of microalgae in bioreactors. An example of such an organization is EcoLogicStudio's Photo.Synth.Etica, Space 10's Algae Dome, and Bio Intelligent Quotient (BIQ). These are international companies with promising outputs that are equipped to assist in removing CO_2 extensively. EcoLogicStudio, a private architectural and urban design studio specializing in environmental design used microalgae with their eco-friendly project, the Photo.Synth.Etica or in simpler terms, algae curtain. The studio mentioned above established a plant-filled plastic curtain, a photobioreactor, draped on building facades [13] seeking to clean the air of polluted urban cities. This photobioreactor sequesters CO_2 by supplying unfiltered urban air at the bottom of the bioplastic photobioreactors. The algae inside absorb CO_2 molecules, and air contaminants released at the top within each module are clean oxygen [14].

Differently, Space 10 is a private autonomous research and design laboratory situated in Denmark supported and committed to IKEA, enabling the aforementioned supported furniture retail company to provide new perceptions and designs that make our everyday life better [15]. Space 10 developed a closed-loop photobioreactor mimicking a dome-like shape hence the project name, Algae Dome. The official website of Space 10 states that Algae Dome is a 4-meter-high plywood-based photobioreactor designed to use the microalgae cultivated as a system mainly to produce supplement-filled food and can also be utilized in developing biofuels and animal feed.

Furthermore, in Hamburg, Germany, the first algae powered five-story residential building in the world with 15 apartments is developed by Splitterwerk Architects and Arup, an active workshop for fine arts and contemporary architecture, and a private engineering company consecutively is monitored by the Colt Group hoping to market the system [16]. The building, called the BIQ, has been in operation since 2013 and utilizes algae in a flat-panel photobioreactor which acts as the buildings' façade enabling algae and solar thermal heat to be harvested in the system powering the heating of water and air in the building. To boost the growth rate, the algae in the controlled environment are fed with liquid nutrients and CO_2 [17]. Although the people who reside in the 15 apartments in the BIQ have no heating bills, the limitation of commercializing this is its initial upfront cost to construct the building for more extended benefits.

Several companies and organizations have created their own devices and innovations to combat climate change, which means photobioreactors by cultivating algae. The researchers came up with a project called Project Ginhawa: an Arduino-based photobioreactor for a more personalized device with cost-efficient materials aiming to lower CO_2 levels in the atmosphere. This photobioreactor uses green algae to absorb CO_2 in the air to achieve designated results using Arduino as its motherboard. Through the development of this project and as the study continues, the purpose remains to be the same, it is to determine the effectiveness of the device in absorbing CO_2 in the atmosphere to serve as a counterintuitive approach to tackling climate change, hoping to help in reducing CO_2 from the air by cultivating algae alongside trees and plants for a better Ginhawa (Filipino term which means breath).

This study is based on three fundamentals, algae growth mechanics, dynamics of photosynthesis, and aeration principles. The first fundamental, algae growth mechanics, determines what limits and maximizes algal production in a photobioreactor. It focuses on utilizing the factors affecting the growth of algae, including algae cultivation systems and the existing environmental impacts and constraints.

Another fundamental basis for this research is the dynamics of photosynthesis. Rochaix [18] stated that plants and algae adapt to environmental conditions by adjusting their photosynthetic apparatus to maintain efficiency during photosynthesis. The principal energy needed is light. Light quality is crucial in this study as its utilization is one of the most important factors to consider. If the light is regulated, there are high chances of photosynthetic efficiency and increased absorption of CO_2.

The last fundamental basis for this study is aeration principles. These principles consist of the specific optimum aeration conditions to ensure the adequate flow of algae within the photobioreactor. With efficient culture mixing, aeration principles also prioritize the collision of algal cells to CO_2 and light to coincide with algae growth mechanics and optimize algal growth. Schematic diagram of the fundamental principles adapted in the photobioreactor project is shown in Figure 1.

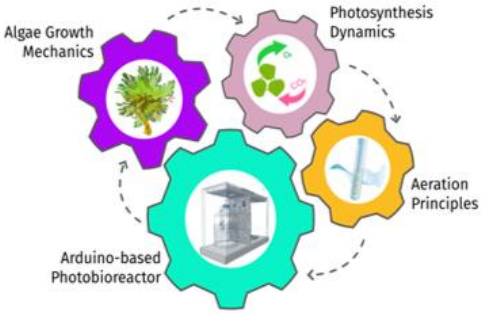

Figure 1. Schematic diagram of the fundamental principles adapted in the photobioreactor project

The success of this research project was determined by the balanced application of the three fundamentals, namely algae growth mechanics, dynamics of photosynthesis, and aeration principles as green algae (Chlorophyta) is the main component of this project. Through this, the researchers are responsible for regulating and gathering data to gauge designated results fully. The photobioreactor is aimed at lowering CO_2 levels in the atmosphere and simultaneously progressing, leading to a counterintuitive approach to tackling climate change and global warming.

2. LITERATURE REVIEW

As observed in Mauna Loa Observatory in Hawaii, atmospheric CO_2 levels have been increasing every year since 1950. This gradual escalation is due to the excessive use and dependency on fossil fuels and human activities such as deforestation [19]. Photoautotrophs, for instance, algae, are species that can produce their energy through photosynthesis using light and CO_2. The usage of these organisms in green technology for capturing CO_2 through photosynthesis has attracted the attention of environmental specialists to fix carbon directly into microalgae [20]. Microalgae can generally be produced in open ponds or closed systems (e.g. photobioreactors) regarding algal cultivation considerations and environmental impacts. Within cultivation practices, several factors can limit microalgal growth [12]. As stated, sunlight (or an artificial light source) and CO_2 are direct photosynthesis contributors and thus fundamentally affect microalgae cell growth and biomass production [21].

2.1. Algae

Algae come in different colors and forms and are typically found in aquatic environments. Raven and Giordano [22] stated that algae are not readily defined; they can be characterized as an organism that can emit oxygen through photosynthesis and is not vascular plant. Khan *et al.* [8] proclaimed that there are several types of algae, namely Rhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green algae), and are classified by size as macroscopic or microscopic. Macroalgae, often called seaweeds, are visible algae and are found in large ponds and oceans. They are the source of food for many herbivores as they are attached to surfaces such as dead coral or rock, contrary to seagrasses or vascular plants that can grow in mud and sand due to the presence of their roots [23].

On the other hand, microalgae are microscopic algae commonly found in water, marshes, and swamps. Microalgae presumably possess the ability to convert atmospheric CO_2 into organic compounds such as lipids and carbohydrates [8]. The utilization of these organisms is depicted for a broad scope of biotechnological applications such as biodiesel production, wastewater bioremediation, and dietary supplements for animal and human nutrition [24]. Algae are organisms composed of 50% CO_2 enabling the photosynthetic process to be 86% faster than a terrestrial plant. They become a vital source of atmospheric oxygen and can sequester CO_2.

2.2. Microalgae cultivation systems

2.2.1. Open pond systems

Open pond systems are used for extensive scope microalgae development. Open ponds come in different forms and can frequently be categorized as biological systems or artificial ponds and containers. These ponds are usually referred to as raceway ponds because of their shape. Other leading types of open pond cultivation systems that have been studied and utilized are i) thin-layer inclined ponds, ii) circular ponds, iii) raceway ponds, and iv) unmixed open ponds [25]. These open pond cultivation systems remain the most commonly used methods because of the undemanding, low-cost requirement during operations and

maintenance [12]. However, in open-type pond systems, the cultivation process is exposed to the environment [22] making microalgae vulnerable to the poor utilization of light from the sun and contamination (biological and chemical). This type of algae cultivation system is popular in the commercial market because it can boost economic concerns. Furthermore, the growth of microalgae is dependent on the structure of the pond because of the organism's specific needs.

2.2.2. Closed systems

Microalgae may be cultivated in closed systems or so-called photobioreactor systems under controlled conditions such as light consumption, required area, and CO_2 percentage [20]. The culture is not exposed directly to the environment, but rather it is enclosed within the photobioreactor system. The closed pond system is supposed to outdo the limitations of the open pond system [22]. Relatively, the closed pond systems are what environmental researchers have focused mainly on and this is because it is controlled and beneficial. Closed-type systems are ideal for an efficient carbon fixation which commentates on allowing better control of contaminants [26] versatility in managing and sustaining optimal reproducible cultivation conditions such as temperature and light [27]. Temperature and the proper utilization of light are critical parameters throughout algae cultivation to absorb CO_2. Although photobioreactors significantly diminish the growth of competitive algal weeds, they cannot eradicate contaminants growth. Two drawbacks of this method are that it is challenging to build, run, and costly [20].

2.3. Types of photobioreactors

2.3.1. Tubular photobioreactors

Their cylindrical geometries characterize these photobioreactors by utilizing tubes covering a large surface area [28]. The tubes are usually made of transparent material permeable to light for the photosynthetic processes of the microorganisms being cultured. Common types of materials used are glass and plastic. According to Posten [29], the diameter of tubular photobioreactors should generally range between 10 mm to a maximum of 60 mm for the homogenous distribution of light. Suppose tubular photobioreactor designs adapt to a bigger tube diameter. In that case, microalgae cultivated within the middle region of the tube may not have direct access to sunlight, which negatively affects the efficiency of the photobioreactor in cultivating microalgae. The main advantage of using tubular photobioreactors is that they cover a large surface area which accounts for a better rate of microalgae production. To go along with these advantages, there are significant drawbacks to the design of a tubular photobioreactor, one of them being its poor mass transfer [7] which may result in inconsistencies in the medium along the tubes. This happens because this design incorporates long tubes that can run for meters on end. For that very same reason, this design requires a massive land space, which is another major drawback. However, because it is a closed cultivation system, land use requirements are not too demanding. Depending on the system's orientation, tubular photobioreactors can be further classified into horizontal tubular photobioreactors or vertical tubular photobioreactors [30].

2.3.2. Vertical-column photobioreactors

This type of photobioreactor is similar to a vertical tubular photobioreactor. The vertical-column photobioreactor uses transparent cylindrical vessels that are positioned vertically. Each cylindrical vessel should be taller than twice the diameter to achieve efficient cultivation processes such as heat and mass transfer, high surface to area volume ratio, and good mixing via aeration techniques [31]. Unlike the vertical-tubular photobioreactor, the vessels/tubes are not interconnected, which means that the medium is separated and contained to each cylindrical vessel, as opposed to passing through each tube as the mixing process takes place [28].

Vertical-column photobioreactors can adapt to multiple aeration techniques depending on the scale of cultivation. One of the most common aeration techniques used in vertical-column photobioreactors is sparged systems. A sparger is used at the bottom of the photobioreactor to convert the air containing CO_2 into bubbles, allowing the medium to mix. A more simple photobioreactor design by Orlando *et al.* [14] study incorporated an aeration technique that directed the supply of air from the top of the cylindrical chamber to the bottom (submerged in the medium). Both studies resulted in reasonable microalgae production rates under recommended cultivation techniques.

2.3.3. Flat plate photobioreactors

Flat plate photobioreactors are characterized by their cuboidal shape and minimal light path design [31]. This design can achieve one of the highest photosynthetic efficiencies out of all the other photobioreactor designs. It supports the most significant proportion of total surface area for light exposure

with low oxygen build-up. But just like any other photobioreactor, the flat plate photobioreactor design uses transparent materials [30]. It can be set up in a horizontal or vertical position [32].

Aeration and agitation of the medium in flat panel photobioreactors can be a challenge. One major disadvantage of flat panel photobioreactors is that they tend to have issues with the channels due to the reduced turbulence flow caused by their narrow rectangular shape [32]. In a 2008 study by Sierra *et al.* [33] a flat-panel photobioreactor with dimensions of 0.07 m in width, 1.5 m in height, and 2.5 m in length showed the great potential of shear stress on the microalgae cultured due to the aeration in a flat-panel photobioreactor. However, multiple designs have been implemented and tested to resolve and improve the basic structure. The study modified the basic design into a twin-layer flat plate design to enhance the system's overall efficiency in producing microalgae and incorporated baffles into the vessel/container to improve agitation. Lastly, they used an inclined V-shape design to maximize the system's mixing rate and simultaneously reduce the stress on the microalgal cells due to adhesion on the walls of the photobioreactor.

2.3.4. Tank photobioreactors

This photobioreactor can be of various shapes and is characterized by its extensive volume to surface area ratio [30] resulting in a decreased light-harvesting efficiency [31] when the light source is daylight or artificial external light. Tank photobioreactors are mainly used to manufacture first-class chemicals and pharmaceuticals [22]. Egbo *et al.* [30] in the year 2018 also stated that only a few of these photobioreactors is developed over the years because of their limitations that regard illumination provided externally but have the most advantage in producing higher biomass when illuminated internally. In the 2016 study of Bělohlav [34], the internally irradiated photobioreactors are developed to keep the light supply coefficient constant and deliver excellent mixing properties, making it possible to use solar and artificial light as a light source simultaneously. In internally irradiated photobioreactors, the fluorescent lamps are situated inside the photobioreactor in glass tubes considering the impeller's characteristics.

Tank photobioreactors are usually most used with the application of light-emitting diodes as a light source [35] with a scale of roughly less than about 50 L since it cannot be upscaled in an account of illumination driven photosynthetic culture, except maybe if individual units are doubled [36]. Mechanical agitation is achieved with the help of an impeller carefully designed to be kept away from the glass tubes, which also perform as baffle plates [37] resulting in better mixing, and CO_2 is provided at the bottom for the cultivation of algae [31].

2.4. Algae cultivation considerations

2.4.1. Light utilization

An essential aspect of the effectiveness of cultivating algae is a good light source under perfect conditions. Ideally, algae cultivation requires at least ten hours of light with an eighteen-hour exposure limit. Still, there are more factors towards the efficient cultivation of algae. The growth of phototrophic microorganisms, such as algae, is strongly affected by the level of light intensity, which comprises three factors: light limitation, light saturation, or light inhibition [22]. In the process of photo-adaptation or photo-acclimation, algae adapt to variations of light intensity, thus increasing photosynthetic efficiency. However, a further increase in intensity can hinder photosynthetic efficiency and even go as far as damaging the photosynthetic system through oxidative stress [38].

2.4.2. Temperature

Temperature is an essential factor in the cultivation of microorganisms and is associated with growth rate. In algae cultivation systems, an increase in temperature leads to an increase in algae growth rate. However, there is an optimum limit to which an increase in temperature improves the growth rate of algae. Temperatures exceeding the optimum limit have adverse effects on the growth rate of algae, and in most cases, can damage the algae cultivation system due to photo-oxidative damage.

The use of incandescent lights as a light source is often neglected because they generate too much heat. In certain conditions, suboptimal temperatures can also negatively impact the efficiency of algae to carbon and nitrogen use. Lower temperatures can also lead to adverse effects on algae cultivation, such as photo-inhibition. Algae cultivation systems should have an average range of 21 to 26 °C for a steady growth rate and production.

2.4.3. Aeration/mixing

Aeration in a photobioreactor provides multiple benefits in the process of cultivating microalgae. The photosynthetic pathways of microalgae are utilized, primarily when they are being cultivated. In these pathways, CO_2 is used up to produce products like sugars and oils. The supply of CO_2 entering the photobioreactor is supplied through aeration [39], [40]. Moreover, aeration is a form of agitation that circulates the medium, ensuring each microalgae cell gets equal nutrients [14]. In return, it increases

microalgae production rates at the right intensity, but an extremely high aeration rate can induce stress on the microalgae. This shear stress upon the microalgae species can cause cell damage, leading to impaired cell growth and eventually cell death in multiple species of algae [41]. To prevent the inhibition of microalgae production and cultivation, specific aeration intensities are recommended for different strains of algae. For filamentous algae, the results of a study conducted by Orlando *et al.* [14] showed that low intensity showed exponential growth of the filamentous strains of algae for the whole 14-day duration of the study. As opposed to high intensity of aeration, the filamentous strains of algae showed signs of a decrease in algae production in the second week.

Furthermore, the implementation of aeration techniques in photobioreactor systems also yields benefits indirectly. In a study conducted by Fabregas *et al.* [42], results showed that increasing the rates of aeration in microalgae cultivation systems that cultured *Dunaliella tertiolecta*, a type of green algae, causes a decrease in the pH levels of the medium, this occurs due to the increase in CO_2 concentrations transferred from the air to the medium causing a rise of the CO_2 concentration of the medium. Ultimately, it significantly increases the growth rates of the *Dunaliella tertiolecta* cultivated in the system. Similar results can also be observed in a recent study by Magdaong *et al.* [43] which cultivated *Chlorella sorokiniana*, another strain of freshwater green algae, in a simple lab-based photobioreactor. Among the different aeration rates being tested, photobioreactors adapted to a higher aeration rate had a medium with a lower pH level.

2.4.4. pH level

One of the essential conditions of an algae cultivation medium is pH level. According to a study conducted by Lam *et al.* [44], some microalgae species can adapt and cultivate in acidic conditions. However, most of the microalgae species prefer a neutral and alkaline culture medium condition. The pH range for most cultural microalgae species should be between 7 and 9 for favorable results. However, the optimum range is between 8.2 to 8.7.

Naturally, the pH level of the medium in which the microalgae species are cultivated is directly associated with the uptake or concentration of CO_2 in the photobioreactor. During the cultivation process, as CO_2 is consumed, the pH level of the medium increases steadily. In addition, a study by Lutzu [45] resulted in an analysis that a significant increase in CO_2 concentrations within the photobioreactor can lead to a decrease in the pH level of the medium. When the medium is above the recommended pH range for algae cultivation, it will decrease the algae growth rate [46]. This decrease in algae growth was observed when a group of pH-tolerant algae was cultured in a medium that exceeded the pH level of 9.5. Similarly, pH-sensitive strains of algae also experienced a decrease in growth when pH levels were at 8.8 and were entirely hindered when the pH levels exceeded 9.

2.4.5. Nutrient composition

The cultivation of algae requires a constant feed and supply of nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), to ensure good algae growth yields. However, one of the concerns of a large-scale algae cultivation system is the high requirement for nitrogen. This leads to several positive and negative impacts on the nitrogen cycle, as nitrogen can be taken from a waste source.

The choice of growth medium and the type of water used in cultivation depends on the chosen algae species. There is no basis for the nutrient calculation that can be applied, but all species of algae have minimum, optimum, and maximum nutrient requirements. If microalgae are cultivated in a photobioreactor system that utilizes freshwater as a medium, it will require artificial nutrients prepared in the lab. Nutrient preparation done in the lab is costly, and therefore, a method to reduce costs is to look for other free and reliable nutrient sources. The algae could grow in freshwater, brackish water, or seawater. Utilizing wastewater as a medium for cultivating microalgae will benefit both the environment and the cost of microalgae production.

2.5. Environmental impacts and constraints

2.5.1. Water resources

Photobioreactors need a good and reliable source of water to sustain algae cultivation in the long run. In photobioreactor systems, evaporation is a crucial factor in determining the sustainability of the cultivation process. To compensate for the evaporation, freshwater must be added to open pond photobioreactor systems. Previous studies suggest that brackish water and seawater may be used to replenish open pond photobioreactor systems. However, these types of water must undergo treatment to remove growth-inhibiting components found in them. Recirculating and feeding the used water back into the pond is not advisable, for it can potentially lead to infection and inhibition. This will cause bacteria, fungi, and viruses to develop in your system.

2.5.2. Land use and planning

The performance of the photobioreactor design highly depends upon space, location, and orientation. The benefit of the algae cultivation system is that it could utilize marginal land which does not get in the way of food production. Open type photobioreactor systems, specifically raceway ponds, require a flat terrain with perfect soil conditions like porosity when sealing the pond system.

Land planning is also essential when trying to achieve an efficient photobioreactor system. For high levels of algae production, solar radiation is one of the most critical factors. The most suitable locations for algae production are the warm countries that are relatively close to the equator. To this date, most algae production has been done in low-latitude regions such as California, Israel, and Hawaii.

2.6. Addressing the problem ways forward

As mentioned, algae are organisms capable of rapid photosynthetic mechanisms, and if cultivated efficiently, algae can sequester atmospheric CO_2 effectively. There are a lot of aspects to an efficient and sustainable photobioreactor system for the cultivation of algae. Different photobioreactor systems have various factors towards their use and efficiency. An open pond system is more susceptible to evaporation, thus requiring a stable water source to replenish the system and make up for the loss. It is also more complex as it requires deep land planning for the development of the pond itself. A closed system is more versatile and is not at a high risk of evaporation since it is closed, making it less likely to be contaminated by pollutants. Thus, creating a closed system features better control of the cultivation concerning water supply, gas mixing, protection from external contamination, and evaporation loss. Closed systems like photobioreactors have different types, and each kind of photobioreactor yields different algal cultivation results since light exposure and agitation methods may vary.

Regardless of the type of cultivation system, studies have shown that light and temperature are two significant factors when dealing with both sustainable and efficient algae production. The right temperature and a stable light source are needed to facilitate algae production. The lack of light or temperature will cause damage to your system, and it will negatively impact the efficiency of your photobioreactor system. It can even go as far as halting the algae cultivation process. Although light utilization and temperature play a significant role in algae cultivation, the mechanisms of aeration, pH level, and nutrient composition are just as important to be regulated and observed closely during data gathering procedures of the photobioreactor. The lack of supplying sufficient nutrients for algae may inhibit its optimum growth. On the same page, algal cells in the photobioreactor are most likely to be inefficient without aeration or mixing since not all cells are equally exposed to light and the nutrients provided. A noticeable increase and decrease in pH levels are advised to be monitored. There is an optimum range of pH levels that should be held consistent throughout each administered usage of the photobioreactor. Furthermore, water resources and land use must be preconditioned and planned out before running the photobioreactor.

Since the fulfillment of the requirements stated above is of great value in operating photobioreactors to cultivate algae because algae can reduce atmospheric CO_2, the failure to maintain any of the factors above may significantly alter desired results. Thus, more initiatives are still required to build and sustain the viability of closed photobioreactors and are anticipated to progress in the coming years with the support of recommended factors and improved photobioreactor technologies.

3. RESEARCH METHOD

This study used an experimental quantitative method to gather the required data to determine the effectiveness of the photobioreactor project in terms of sustainability, performance, and accuracy. With the manipulation of variables, we can determine the overall efficacy of the Arduino-based photobioreactor. This study was conducted and guided by a structured flow, following a set of methods and procedures.

3.1. Research procedures

3.1.1. Choice of microalgae

In this study, the researchers used green algae, Chlorophyta, as the main component to culture in the photobioreactor, specifically extracted from a fish pond to avoid disturbing marine biodiversity from large bodies of water. A fish pond is mainly one of the habitats where green algae thrive, usually in large concentrations, since it is composed of nutrients [47] that aid a fast-growing algal population. Even without commercial processing, green algae is abundant because according to Haoyang [10] algae can grow a centimeter or two each day and sprout rapidly if they absorb extra CO_2.

3.1.2. Construction and design of Arduino-based photobioreactor

After looking into the different types of cultivation systems and photobioreactors, it was determined that a closed cultivation system is the best option given the operating conditions. The photobioreactor itself

was fixed at a particular location that meets all the optimal growing conditions of the microalgae to be cultivated.

The project is composed of a two-chamber, rectangular glass tank to host both the Arduino components and the central cultivation system. Each chamber contains a 12 V computer fan, powered by a 12 V DC power supply and program for both intake and output of air. The first chamber includes the primary aeration system and monitoring components. The monitoring components are composed of the Arduino UNO R3 motherboard and the Arduino compatible sensors such as pH, temperature, and CO_2 gas sensors. The second chamber hosts the primary photobioreactor cultivation system.

A vertical-column photobioreactor is the best design to adapt to due to its simplicity. Its design is not demanding in components, and therefore they are easier to build and modify [28]. The simple vertical-column photobioreactor design by Orlando *et al.* [14] was used and modified to coincide with the small-scale factor that the research implies. The photobioreactor utilized a 6-liter recycled PET container for the main cultivating vessel.

At a small scale and semi-compact design, natural ambient light was used as the main light source for the cultivation process of microalgae. With proper positioning, natural light was sufficient for the growth of the microorganism in the medium.

Aeration and agitation techniques were adapted from the same photobioreactor design by Orlando *et al.* [14] and found in the first chamber of the system. An aquarium aerator was installed in the first chamber to constantly supply raw and unfiltered air through the second chamber and into the photobioreactor as a gas inlet. To deal with gas pressure build-up from within the photobioreactor, a second tube was installed at the mouth of the photobioreactor as a gas outlet to allow gas to escape. The schematic diagram of the research flowchart is shown in Figure 2.

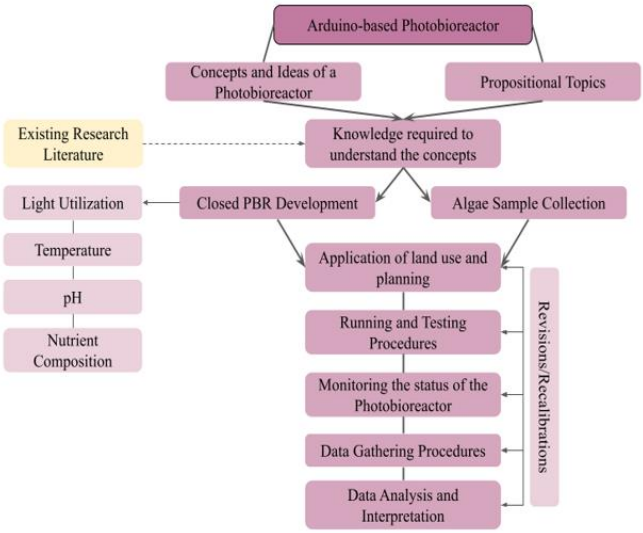

Figure 2. Schematic diagram of the research flowchart

The Arduino components required for the design were installed and fixed in different locations in the system. The first chamber will host water-sensitive components such as the Arduino UNO R3 motherboard. The CO_2 gas sensors were installed on the walls for proper exposure to the air utilized by the system. Arduino-compatible probe sensors were embedded in the photobioreactor vessel itself to operate and come in contact with the medium as required for its function. The monitoring system was mounted at the top of the system design, where the liquid crystal display module (LCD) module was installed. All the Arduino components were powered through the motherboard by a 9-12 V DC power supply.

3.1.3. Media preparation and cultivation process

To start media collection and preparation, it is essential to note that the collection of algae may be conducted by either quantitative or qualitative methods. Quantitative methods are used to determine the ratio between algae to water volume or areas. Conversely, qualitative methods are easier to administer, given that there is no need to determine the surface area or volume ratios. The researchers collected algae qualitatively

since the quantitative approach is commonly used when measuring metabolic activity, and the expression of abundance is required in the study [48]. However, it is worth noting that the researchers added a fixed amount of green algae into the photobioreactor and must be kept constant considering that the addition of different amounts of algae samples may fluctuate the desired results regarding the sustainability of the photobioreactor.

Green pond algae are easily identified as free-floating and are often found in water columns and on the surface of ponds. The researchers collected the green algae by scooping samples into a jar and a fishnet. The amount of algae to be collected depends on how much algae the researchers can retrieve. Due to the presence of algal water upon retrieval, the researchers separated the algae water from the algae by using a filter paper to acquire algae samples. The algae samples were then dried for thirty minutes to one hour before weighing. The researchers decided on the fixed amount of algal samples added to the photobioreactor at the beginning of each operating schedule.

3.1.4. Operating procedures

Before culturing the collected algae samples, the researchers looked for a stable and flat area where the photobioreactor can be situated. The area should receive sufficient natural light to obtain optimum algal growth by meeting the required exposure hours. After the project was developed and programmed, the researchers filled the 6 liter PET container with tap water. In addition, nutrients were added to the medium for algae cultivation. Algae heavily rely mainly on nitrogen or phosphorus nutrients, and these can be quickly supplied through agricultural fertilizers [8] like urea and ammonium sulfate. The researchers then added the algae samples and ran the photobioreactor. Factors considering algae cultivation such as light, temperature, aeration, pH level, and nutrient composition were closely observed.

The project ran in three weeks and divided the allotted time frame into two operating schedules to effectively test the device's sustainability, performance, and accuracy. The Arduino-based photobioreactor continuously ran for seven days for the first operating schedule, with a day allocated for harvesting algal culture from the photobioreactor. Accordingly, twelve days was enough time for the algal culture to reach the peak of its exponential phase of growth wherein the number of algae is usually doubled, and optimum algal cultivation results are obtained; however, due to a tight schedule, the researchers decided to grow the algae in a shorter amount of time yet still ensuring that the microorganism, algae, was cultivated suitably which yields a favorable result. In pursuance of exceptional outcomes, the project should run with minimum light exposure of 16 hours, a pH level between a minimum of 7 and a maximum of 9, an average temperature of 16 to 27 ^{o}C, consistent aeration, and is fed with 30 g of ammonium sulfate and 30 g of urea that consists the nutrient compositions (e.g. nitrogen) at the beginning of each operating schedule.

Thereafter, the researchers gathered the information the external sensors have recorded to assess the accuracy of the project. These data include the amount of CO_2 (ppm) absorbed by the photobioreactor, the time (s), the temperature, and the pH levels. However, the data manipulated will be particularly the series of information regarding the amount of CO_2 (ppm) absorbed by the photobioreactor and the time (s) only to test the project's performance in sequestering CO_2. The second operating schedule followed the processes done in the first run of the project.

Finally, the researchers analyzed the data acquired from both operating schedules and assessed the photobioreactor's accuracy, sustainability, and performance. The researchers then concluded; the conclusions were purely based on the data gathered by the photobioreactor itself with the aid of Arduino.

3.2. Data analysis and statistical treatment

This research utilized sensors to assess the viability of Arduino-based photobioreactors in terms of meeting the optimal requirements to grow microalgae. The accuracy of this project was established by the applied sensors individually based on the accuracy error (+/-) provided by the manufacturers as shown in Table 1.

Table 1. Accuracy errors of sensors

Type of sensor	Accuracy error (+/-)
CO_2 sensor (MQ-135)	20 ppm
Analog pH meter/sensor	0.1 pH (25 °C)
Submersible temperature sensor	0.5 °C (-10-+85 °C)

This research dealt with the intake of gas, primarily CO_2, utilized by microorganisms. When dealing with photoautotrophic organism biomass measurements, growth rate evaluations and efficiency rates are

critical in assessing the potential of the algae photobioreactor in CO_2 removal from the atmosphere. The removal efficiency (%) can be determined the (1), [49].

$$Efficiency\ (\%)\ =\ \frac{Influent\ of\ CO_2 - Effluent\ of\ CO_2}{Influent\ of\ CO_2}\ x\ 100 \quad (1)$$

Furthermore, this research heavily relied on the growth of green algae to mitigate CO_2 in the atmosphere. The sustainability of this project was measured through its algal productivity rate in between two trials with the (2).

$$Growth\ Rate\ =\ \frac{Mass\ of\ Algae}{Surface\ area\ x\ Time} \quad (2)$$

To calculate the algal growth rate, the mass of algae (g) obtained after each trial will be divided by the growth surface area (in^2). The time (days) spent for each trial is assumed that the harvested algae after each trial is equal to the new growth of the microorganism since the last trial [50].

4. RESULTS AND DISCUSSION

This section discusses how the Arduino-based photobioreactor was developed and the presentation, analysis, and interpretation of data to assess the project's overall performance, accuracy, and sustainability throughout the research. The data were obtained through the sensors powered by Arduino and its main microorganism, green algae.

4.1. Design and layout

Project Ginhawa, an Arduino-based photobioreactor, is designed primarily for CO_2 removal from the atmosphere for better air quality. The structure materials used in the following project prototype and design are not demanding and require only common materials such as a glass tank, polystyrene foam panels, and the standard PET water container. This is done to make the project more cost-effective and at the same time easy to construct and develop. The project is 24 inches long, 12 inches wide, and 14 inches tall. It consists of a two-chamber system to host the different parts utilized by the system. The left chamber is where the main aeration system and Arduino components are installed. The right chamber is where the main cultivation vessel is installed. The cultivation vessel is a 6-liter PET container with dimensions 11 3⁄4 inches tall and 8 inches in diameter. These two chambers are separated using polystyrene foam panels to minimize the passage of air between the chambers. The top panel is also made of polystyrene foam material for the minimal escape of air for better and more accurate gas sensor readings.

4.1.1. Aeration

On the top panel of the design, two 40 mm x 40 mm computer fans are installed right above each chamber. The computer fan on the first chamber is positioned as an intake fan that brings air into the first chamber. The computer fan in the second chamber is positioned as an exhaust fan. This allows the air from the second chamber to exit the second chamber. The main aeration system of Project Ginhawa, driven by the aeration pump, is located in the first chamber. A flexible tube, about 28 inches in length and 1⁄2 inch in diameter, is connected to the pump on one end and goes through the divider, and goes to the bottom of the main cultivation vessel on the other end. This ensures that there is proper mixing and agitation of the medium as the photobioreactor functions. Lastly, another flexible tube, 5 inches in length and 3⁄4 inch in diameter is inserted into the cap of the 6 liter PET container as an outlet for air to prevent any pressure and gas buildup inside the main cultivation vessel through constant aeration by the pump.

4.1.2. Light source

A constant source of light plays a vital role in the process of cultivating microalgae in a photobioreactor. At least 10-18 hours of exposure to a stable light source at a certain level of intensity is needed. Project Ginhawa uses natural light, the sun, as its main source and is situated indoors. It is positioned in an open space where it comes into direct contact with sunlight, as it relies on natural ambient light for the cultivation process.

4.1.3. Arduino sensors

All the electrical components are hooked up to the main motherboard, the Arduino UNO R3 board. The Arduino UNO R3 board is installed in the first chamber to prevent any possible contact with water. Project Ginhawa utilizes different gas and probe sensors to monitor the parameters being studied and

observed. Two MQ-135 gas sensors are programmed to measure the CO_2 of the air in parts per million, ppm. The first gas sensor is utilized to measure the concentration within the first chamber, the CO_2 concentration of the air flowing into the photobioreactor. The second sensor is used to measure the concentration within the second chamber, which is the CO_2 concentration of the air flowing out of the photobioreactor. This setup allows the monitoring of the difference in the CO_2 levels to calculate the removal efficiency. The probe sensor setup found in the second chamber of Project Ginhawa comprises the DS18B20 Temperature sensor and the DFROBOT SEN0161 analog pH meter. The electrode tip of the analog pH meter and the metal probe end of the temperature sensor are submerged in the cultivation medium. Components of the developed Arduino-based photobioreactor as shown in Figure 3. Figure 3(a) shows front view showing the chamber system and top panel legend: 1 Polystyrene foam top panel; 2 Chamber 1; 3 PET container; 4 Chamber 2; 5 Polystyrene foam divider; 6 Arduino UNO R3; 7 Aeration pump, Figure 3(b) is showing chambers 1 and 2 aeration system legend: 1 Chamber 1; 2 Chamber 2; 3 P5 ¾" flexible tube; 4 PET container; 5 28 ½" flexible tube; 6 Aeration pump, Figure 3(c) is showing chamber 2 Arduino sensors legend: 1 PET container; 2 Analog pH meter; 3 Temperature sensor; 4 Cultivation medium, Figure 3(d) is showing location and positioning legend: 1 Chamber 1; 2 Pet container; 3 Cultivation medium; 4 Ambient light, Figure 3(e) is showing chamber 1 Arduino sensors legend: 1 CO_2 sensor; 2 Analog pH microcontroller; 3 Breadboard; 4 Arduino holder w/ Arduino UNO R3, Figure 3(f) is showing top panel and monitoring system legend: 1 polystyrene foam top panel; 2 LCD module.

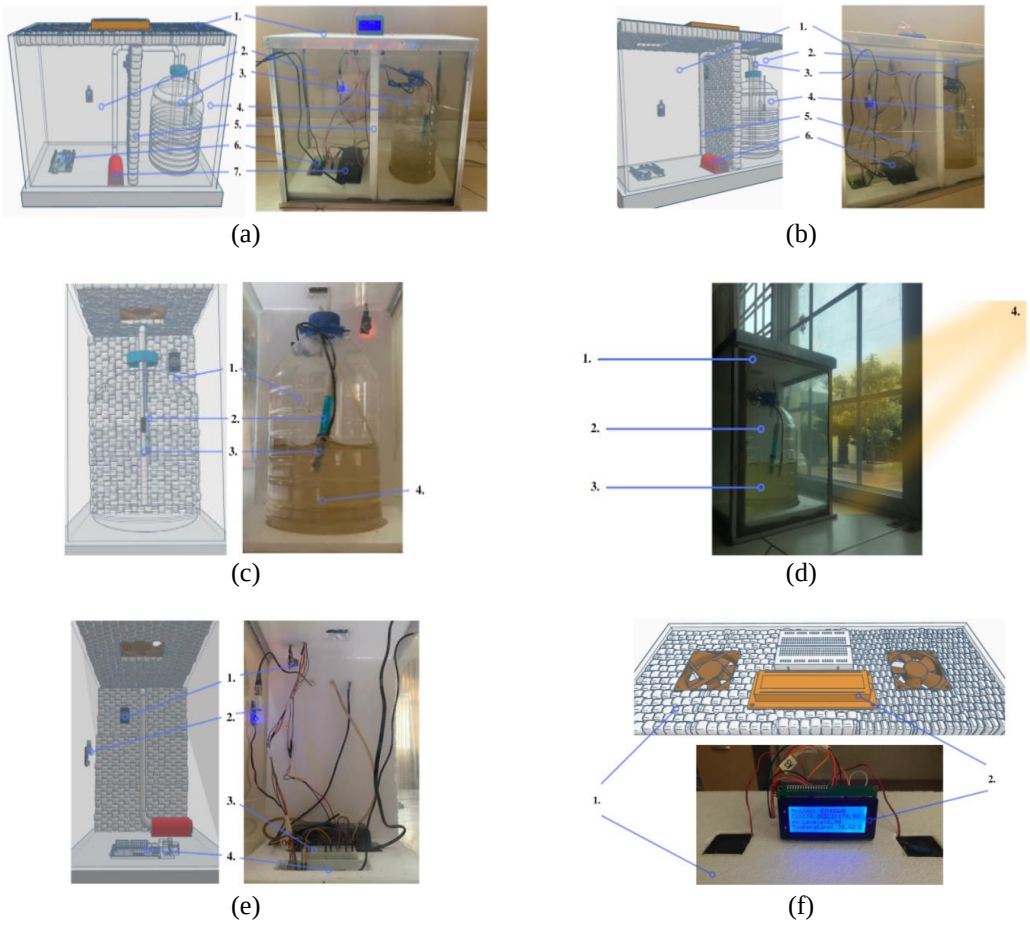

Figure 3. Components of the developed Arduino-based photobioreactor (a) front view showing the chamber system and top panel legend: 1 Polystyrene foam top panel; 2 Chamber 1; 3 PET container; 4 Chamber 2; 5 Polystyrene foam divider; 6 Arduino UNO R3; 7 Aeration pump, (b) chambers 1 and 2 aeration system legend: 1 Chamber 1; 2 Chamber 2; 3 P5 ¾" flexible tube; 4 PET container; 5 28 ½" flexible tube; 6 Aeration pump, (c) chamber 2 Arduino sensors legend: 1 PET container; 2 Analog pH meter; 3 Temperature sensor; 4 Cultivation medium (d) location and positioning legend: 1 Chamber 1; 2 Pet container; 3 Cultivation medium; 4 Ambient light (e) chamber 1 Arduino sensors legend: 1 CO_2 sensor; 2 Analog pH microcontroller; 3 Breadboard; 4 Arduino holder w/ Arduino UNO R3 (f) top panel and monitoring system legend: 1 Polystyrene foam top panel; 2 LCD display module

4.1.4. Monitoring system

The dedicated setup for the monitoring system of the parameters uses a 20x4 character LCD module to project all the readings gathered from all the sensors utilized by Project Ginhawa. The LCD module is installed on the top panel for easy access and viewing.

4.2. Programming

This Arduino-based photobioreactor project contains multiple sensors programmed to function together to monitor the parameters being studied hardware. Figure 4 shows main Arduino components.

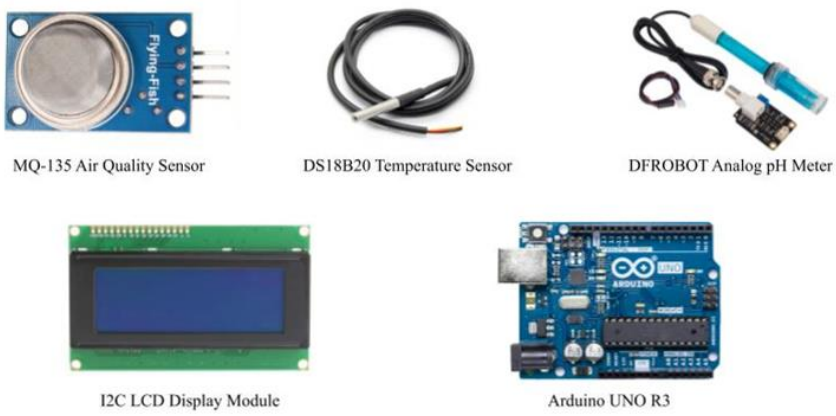

Figure 4. Main Arduino components

The Arduino UNO R3 ATMEGA 328 was used in the project. This is one of the microcontroller boards in the Arduino series. It can be powered through its USB connector and power jack. It has a clock speed of 16 MHz and a simple flash memory storage of 32 KB. The board has 14 digital I/O pins and six analog pins and can supply power of 3.3V or 5V.

The other component is the MQ-135 Air quality sensor. It is a budget sensor used to measure air quality. It is capable of detecting ammonia (NH_3), nitric oxide (NO_X), Alcohol, Benzene, Smoke, and CO_2. The sensor comes with a microcontroller that can program the sensor to detect a particular gas.

The DS18B20 temperature sensor was used to measure the temperature in different areas. It has a 1-wire design with a waterproof metal probe tip that is convenient when measuring the temperature at multiple points like soil, fluid solutions, mines.

The next component is the DFROBOT Analog pH meter, this is a pH meter kit that is specifically designed for Arduino compatibility. It uses an electrode bulb tip to measure the pH levels of fluids, and it also comes with a microcontroller and a simple connector that allows for an easy connection to the mainboard.

Lastly, is the I2 C LCD. A display module for Arduino microcontrollers. It uses the I2 C communication interface to allow easy integration when incorporated into Arduino projects. The I2 C microcontroller has a trim pot for contrast adjustments of the display.

4.2.1. Software and coding

The general circuit diagram of this project used four main sensors, none of which are directly wired to the Arduino UNO R3 board. Instead, they are spread out across two mini breadboards to cater to the design of the project. Arduino circuit diagram (easy EDA software) is shown in Figure 5.

4.2.2. Sketch and codes

The sketch uses the Arduino integrated development environment (IDE) integrated programming language based on C and C++. Arduino IDE is the official software of Arduino for writing codes and uploading them to the board. It is open-source software that is easy to download on the Arduino website.

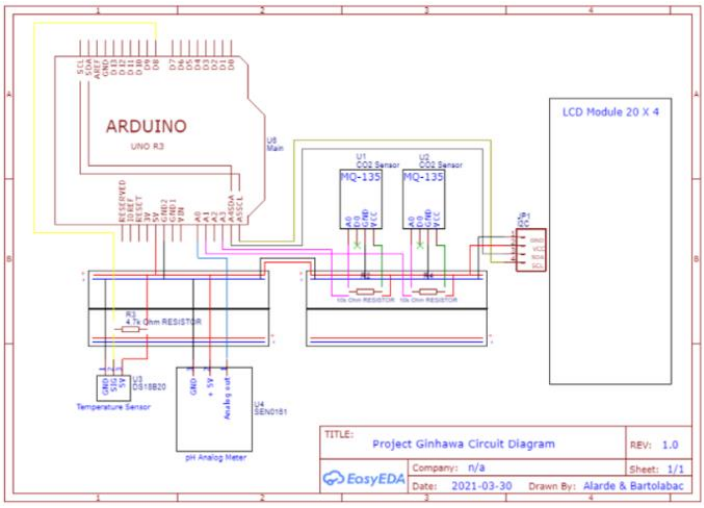

Figure 5. Arduino circuit diagram (easy EDA software)

4.3. Efficacy of the Arduino-based photobioreactor

To determine the overall efficacy of the photobioreactor with the primary purpose of mitigating carbon dioxide in the atmosphere, the accuracy, performance, and sustainability of the device will be assessed. These could be obtained by manipulating data retrieved from monitoring the parameters of each sensor and the growth of algae in a sustainable manner for every trial.

The data gathering procedures of this project lasted for three weeks, divided into two trials, with each trial consisting of a total of seven days. The study does not require achieving a specific number of data throughout the whole operating procedure. However, it is guided by the following ideal parameters for algal cultivation shown in Table 2 to track the device's running functionality and prevent the die-off of algal cells.

The pH level and temperature parameters mentioned in Table 2 are monitored and recorded from the sensors incorporated in the device, namely the pH sensor and the temperature sensor. In the absence of the light intensity sensor, the researchers are required to monitor the exposure hours of the photobioreactor to sunlight since excessive exposure may also be one of the factors that will slow and degrade the cultivation of algae. The ideal range for each parameter suggests that when executed and actual values gathered are within the range, the growth of algae is to be expected and is prevented from diminishing.

Table 2. Ideal parameters for algal cultivation

Parameters	Ideal range
pH level	7-9 (preferably 8.2-8.7)
Temperature	21-26 °C
Light intensity	12-16 hrs/day

The photobioreactor was monitored and was exposed to sunlight for a uniform amount of around 12 hours per day. The presentation of data recorded from the pH, temperature, and CO_2 sensors for each trial is shown in Table 3.

Table 3. Data retrieved from each sensor

Day	CO_2 concentration (ppm)				ph Level		Temperature (°C)	
	Influent T1	Effluent T1	Influent T2	Effluent T2	T1	T2	T1	T2
1	443.06	397.98	2799.60	2361.12	7.29	7.03	28.87	30.81
2	606.67	535.59	1947.25	1795.37	8.15	7.07	27.44	30.00
3	657.40	631.70	1727.77	1645.73	7.96	7.16	28.47	30.94
4	954.14	899.47	2146.21	1990.56	8.19	7.12	28.69	30.94
5	1597.80	1358.13	3317.28	2989.67	7.54	7.10	29.19	30.28
6	2046.21	1597.80	2299.69	2199.79	7.56	8.27	29.56	30.94
7	2259.37	1761.35	2160.68	2083.89	7.59	8.02	30.06	30.06
AVE	1223.52	1026.00	2342.64	2146.73	7.75	7.40	28.90	30.57

**T1 Trial 1; T2 Trial 2*

With the data retrieved from the sensors, the researchers further manipulated this information to test the accuracy and performance of the photobioreactor.

4.3.1. Accuracy of sensors

The accuracy of the sensors is established by the accuracy error (+-) provided by the manufacturers. The accuracy error of each sensor was used to determine the percent accuracy error of the average of the values retrieved in each trial. The error was manipulated using the relative error formula using (3) found to determine the percent accuracy error.

$$Relative\ Error\ = \frac{Absolute\ Error}{Measured\ value}\text{x}100 \quad (3)$$

The relative error formula was attained by utilizing the absolute accuracy error provided by the manufacturers of each sensor and dividing it by the average of the actual measured values recorded for each trial. Table 4 exhibits the average of the actual measured values and the percent accuracy error for each of the sensors, specifically pH, temperature, and both CO_2 sensors with their average CO_2 concentrations for influent and effluent sequentially.

Table 4. Average pH, temperature, influent and effluent levels, and percent accuracy error

Parameter	Trial 1		Trial 2	
	Value	Percent Error	Value	Percent Error
pH	7.75	1.29	7.39	1.35
Temperature (°C)	28.29	1.73	30.56	1.63
Influent (ppm)	1223.52	1.63	2342.64	0.85
Effluent (ppm)	1026.00	1.94	2152.3	0.92

For the entire duration of trial 1, the average value of the pH levels was at 7.75 with a percent accuracy error known to be 1.29. Whereas for trial 2, the average pH level was 7.39 with a percent accuracy error of 1.35. The values expressed in the graph suggest that the ideal parameter of pH levels (ranging from 7 to 9) were met, and the condition of the medium was in a neutral state which algae prefer. The relatively low percent accuracy error of the pH levels indicates that the average measured value is close to the actual value.

With an average temperature of 28.89 °C, a percent accuracy error of 1.73 in trial 1, an average temperature of 30.56 °C, and a percent accuracy error of 1.63 for trial 2. It is inferred that although the percent accuracy error implies that the average temperature is nearly close to the real or accepted value, the average temperature in °C did not meet the ideal temperature range where algae can cultivate.

The average inflow of CO_2 concentration for trial 1 was 1223.52 ppm and a percent accuracy error of 1.63. In comparison, the average outflow of CO_2 was 1026.00 ppm with a percent accuracy error of 1.94.

The average inflow of CO_2 for the second trial was 2342.64 ppm, an effluent of 2152.30 ppm, and a percent accuracy error of less than 1, precisely 0.85 accuracy error for the influent a 0.92 accuracy error for the effluent of CO_2.

A comparison of both trials in Table 4 implies that the average inflow and outflow of CO_2 during the second trial was approximately twice as higher than the inflow and outflow from the first trial. The percent accuracy errors of the influent and effluent of both CO_2 sensors were kept at a minimum value. Thus, the values retrieved from each sensor are close to the actual or real value. It is also worth noting that the amount of inflow of CO_2 concentrations was higher than the outflow of CO_2 in both trials. This is to allow the differences between the varying fluctuations of the CO_2 on a day-to-day basis and for the researchers to calculate the efficiency of green pond algae in removing CO_2 through its cultivation by utilizing the removal rate efficiency formula.

4.3.2 Performance of the photobioreactor

The analysis of the performance of the photobioreactor heavily relies solely on CO_2 sensors to determine the influent and effluent of CO_2 concentrations by the use of (1), which calculates the removal rate efficiency of the CO_2 sensors.

As shown in Table 5, the CO_2 concentrations recorded by both CO_2 sensors in ppm and the difference between the influent of CO_2 concentrations and the effluent of carbon dioxide concentrations for both trials. The difference in CO2 concentrations took part in the calculation of the removal rate efficiency.

Table 5. CO_2 concentrations and its difference for both trials

Day	Trial 1				Trial 2			
	CO_2 concentration (ppm) Influent		Difference inCO_2 concentrations (Influent-effluent)	Removal rate	CO_2 Concentration (ppm) Influent		Difference in CO_2 concentrations (Influent-effluent)	Removal rate
1	443.06	397.98	45.08	10.18	2799.6	2361.12	438.48	15.66
2	606.67	535.59	71.08	11.72	1947.25	1795.37	151.88	7.80
3	657.40	631.70	25.70	3.91	1727.77	1645.73	82.04	4.75
4	954.14	899.47	54.67	5.73	2146.21	1990.56	155.65	7.25
5	1597.80	1358.13	239.67	15.00	3317.28	2989.67	327.61	9.88
6	2046.21	1597.80	448.41	21.91	2299.69	2199.79	99.90	6.04
7	2259.37	1761.35	498.08	22.04	2160.68	2083.89	76.79	3.55
AVE	1223.52	1026.00	197.53	12.93	2342.64	2152.30	190.34	7.85

Figure 6 exhibits the differences in the influent and effluent concentrations of CO_2 retrieved from the CO2sensors of the photobioreactor for the entire duration of each trial. The removal rate efficiency values throughout trials 1 and 2 are dependent on the right y-axis.

As expressed in Figure 6(a), the values of the inflow and outflow of the CO_2 concentrations are represented by the blue and red lines, respectively. The removal rate, depicted by the yellow line, represents the data calculated using (1). With a removal rate of 10.17% for day 1 and a 22.04% removal rate for the last day, the efficiency of the removal rate of CO_2 for trial 1 shows that the longer the algae is cultivated, the removal rate of CO_2 increases.

Figure 6(b) shows the influent, effluent, and removal rate of carbon concentrations. The influent and effluent values shown in Figure 6 were higher than in trial 1, but the difference between the inflow and outflow of the CO_2 concentrations was relatively small. The removal rate of CO_2 for trial 2, represented by the yellow line, decreased with a 15.66% removal rate for day 1 and ended with a 3.55% removal rate for day 7.

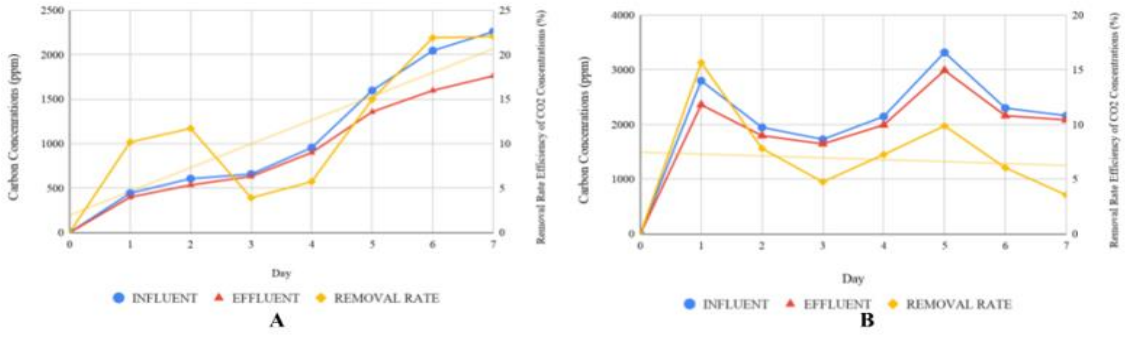

Figure 6. Influent, effluent, and removal rate of carbon concentrations for (a) trial 1 and (b) trial 2

Consequently, as presented in Figures 6(a) and 6(b), the removal rate efficiency of CO_2 from the influent and effluent of the aforementioned gas by the difference of the CO_2 concentrations. It was inferred that if there is only a slight difference between the inflow and outflow of both CO_2 sensors, the removal rate efficiency will result in a smaller percentage of CO_2 removed. In addition, the influent and effluent of the CO_2 concentration were influenced by factors such as the temperature, pH level, and the amount of time the photobioreactor is exposed to sunlight since the inflow and outflow of CO_2 concentrations in the photobioreactor is reliant on how well the algae are cultivated.

4.3.3. Sustainability of the project

This Arduino-based photobioreactor was determined by the growth rate of algae-based on the mass of algae after each trial. For a better comparison for each trial to test the sustainability of this project, a uniform weight of 15 g of green pond algae and 30 g for both Urea and Ammonium Sulfate was initially loaded at the start of every trial. However, it should be noted that the algae cultivated for trial 1 is the same

algae cultivated for trial 2; hence the sustainability of algae will be assessed. The same medium was used for both trials, and each trial lasted for a total of seven days.

The mass of algae was determined through the use of a kitchen weighing scale. With careful consideration before measuring the mass of algae, the researchers allowed the algae to dry for a minimum of 30 minutes to a maximum of an hour to get rid of the algal water within the microorganism to prevent weighing the algal water instead of the actual mass of the algae.

Data in Table 6 consists of the mass of algae and its corresponding growth rate for all trials. The growth rate was calculated through (1), and after each trial, it is assumed that the harvested algae after each trial is equal to the new growth of algae [50].

The algae mass was calculated by subtracting the uniform initial amount, 15 g, from the mass of algae after each trial. The difference between the initial mass of algae and the mass of algae after trial 1 is 6.5 g, followed by the second trial, which is 4.7 g. The growth rate was calculated by assuming that the mass of microalgae harvested for each trial was equal to the new growth of the microorganism from the initial mass of algae for each trial which is 15 g. After the first trial, a 0.56 growth rate was reached, followed by a 0.51 growth rate after the second trial. The comparison is shown in Figure 7.

Table 6. Algal mass and productivity rate for both trials

Trials	Mass of algae (g)	Growth rate (g x in^{-2} x day^{-1})
Initial mass for each trial	15.00	-
1	21.50	0.56
2	19.70	0.51

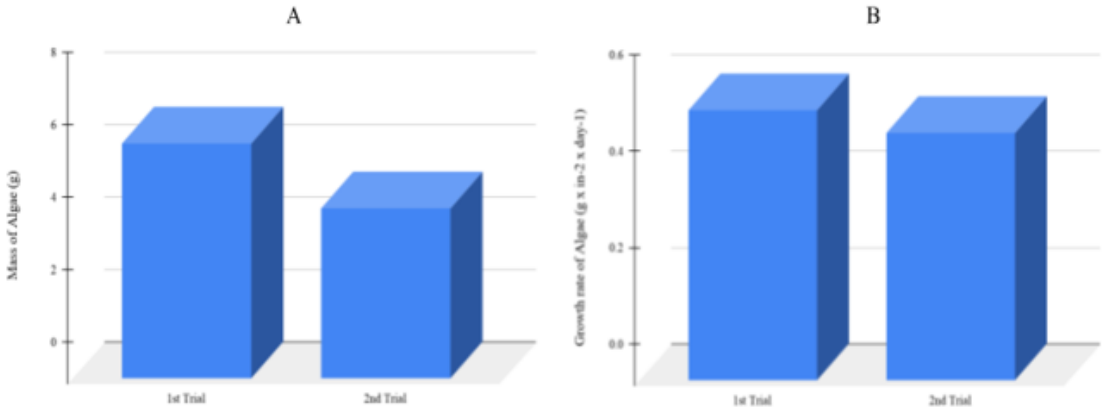

Figure 7. Graph of harvest yield (a) mass of algae (g) and (b) growth rate in g x in^{-2} x day^{-1}

A decreasing trend was observed in the harvest yield and the growth rate of algae. A possible factor that caused the decrease in the growth rate of algae is that the ideal parameters of temperature levels were not met in the duration of trial 2 and hindered the microalgae from reaching their maximum growth rate. Other than this, unforeseen changes in the external environment of the photobioreactor may have been observed and caused the diminution of algal growth.

5. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This section intends to state the improvements that can be made in the Arduino-based photobioreactor concerning its design and layout, programming, and operating procedures to acquire a better yield for the growth of algae which the project depends on for carbon mitigation.

5.1. Design and layout

The chamber system that the photobioreactor features are significant for measuring CO_2 concentration entering and leaving both chambers of the photobioreactor. To ensure that the MQ-135 gas sensors are genuinely reading the corresponding CO_2 concentration within the particular chamber, the

polystyrene foam material can be replaced with air-tight panels or a sealed glass divider to prevent any air from mixing the chambers. Ultimately, this will lead to more accurate readings.

Better algal growth and CO_2 removal efficiency can be obtained by developing a cooling system, especially for high-temperature peaks during summer, to help maintain and keep the cultivation medium at the optimum temperature level for efficient microalgae cultivation. When too high and low-temperature conditions are observed in the cultivation medium, it can cause cell damage and even cell death. This is based on trial 2, showing that the failure to stay within optimum temperature ranges for efficient algal growth showed a decrease in growth rate. It can be inferred that a cooling system must be installed within the photobioreactor to control temperatures within optimum ranges [51].

5.2. Programming

The addition of a light intensity sensor that is capable of measuring the light coming through the photobioreactor. Light utilization is one of the essential factors that affect algal growth. Therefore, it is recommended to monitor it, primarily when the photobioreactor uses natural light from the sun as its main light source. Generally, photobioreactors require a light intensity of 8000 lux for high algal growth rates. A deficient light supply and high light supply can cause damage. They can slow down the algal growth rates making it a must to be monitored throughout the cultivation phase of the photobioreactor [39]. Thus, the addition of a light intensity sensor is necessary and recommended to achieve better algal growth and yield.

To compare the data gathered by the sensors uniformly, a specific time should be observed when gathering the data from the monitoring system of the photobioreactor. In the event of not being able to be on time when taking down the readings from each sensor using the data gathering sheet, programming the Arduino system to record and store the values of each sensor for a specific time would allow for consistent data and better results drawn from the data analysis phase. In addition, this prevents any loss of data and ensures a backup record of the readings.

5.3. Procedures

The data gathered in this study can further be enhanced by increasing the number of days per trial to allow the microorganism to reach its exponential phase wherein algal cells double their growth. The exponential phase is when the growth of algae doubles due to the regular division of cells through binary fission. According to Lavens and Sorgeloos [52], the growth rate of algae comes in five phases: lag or induction phase, exponential phase, phase of declining relative growth, stationary phase, and death phase. The lag or induction phase is the duration of the initial growth of algae, and the division of algal cells is minimal. During the second phase or the exponential phase, algal cell growth doubles for pH, temperature, and light being met. When the factors mentioned above are not met, cell division slows down, and the algal cells are observed to be in the phase of a decline in growth. When algae's limiting factors and growth are balanced [52] an endless number of algal cells will be perceived. Finally, when nutrients and water are depleted, the algal cell will diminish regarding the last stage of algal growth culture, the death phase.

Moreover, the number of trials done during the data gathering procedures of this study depends solely on the researchers. However, for an enhanced perception of varying results about the Photobioreactor's accuracy, performance, and sustainability, it is highly advised to add more trials for the algae to cultivate.

6. CONCLUSION

The photobioreactor is capable of absorbing CO_2 from the atmosphere, thus serving the purpose as a counterintuitive approach to tackling climate change for the fact that the microalgae cultivated releases oxygen in the air through the process of photosynthesis, giving out clean and filtered air in the environment with consideration to the limitation that visible changes in the reduction of CO_2 levels are not noticeable.

The decreasing trend observed in the sustainability and performance of the device indicates that throughout the second trial, the photobioreactor was not able to meet the ideal parameters of the factors necessary for the algae to grow at its optimum level. This implies that algae growth in a closed photobioreactor heavily relies on factors such as the pH level and temperature of its medium, its light intensity, light exposure, and the overall nutrients received by the culture.

Adding a pH analog meter, CO_2 gas sensor, and temperature sensor are crucial to monitor the parameters that directly affect the performance of the photobioreactor and the growth rate and CO_2 removal efficiency rate of the microalgae being cultured studied.

The results of each trial indicate that the measured values recorded from the pH sensor, submersible temperature sensor, and both CO_2 sensors are accurate since each measured value from the corresponding sensors has a relatively small percent accuracy error which means that the measured values recorded from each sensor are close to the actual or real value.

The researchers conclude that the CO_2 removal efficiency rate and the growth of algae are directly proportional to one another. The removal efficiency rate determines how well the microalgae being cultured absorbs CO_2. Accordingly, when there is an increase in the removal efficiency rates, the growth of algae also increases and vice versa.

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