YAŞAR UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER'S THESIS

THE EFFECT OF MICROALGAE ON INDOOR CO_2 LEVEL

AN EXPERIMENT IN AN OFFICE OF YASAR UNIVERSITY

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MSC IN INTERIOR ARCHITECTURE

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ABSTRACT

THE EFFECT OF MICROALGAE ON INDOOR CO_2 LEVEL

AN EXPERIMENT IN AN OFFICE OF YASAR UNIVERSITY

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Msc, Interior Architecture

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People spent a lot of time indoors and the positive/negative effects of indoor air quality have been the subject of many studies. The positive effects of good indoor air quality on the employees in the offices were also supported and many studies were conducted to improve the indoor air quality. The effects of photosynthesis on the indoor carbon dioxide level is proved by the literature review, and in this context, the effect of microalgae on the indoor CO_2 level was measured in an office in Yaşar University. Studies with microalgae are generally in laboratory environment or concept ideas, and the contribution of algae to indoor air quality has been lacking in terms of measurement by case analysis method. For this reason, this thesis is presented as a step to contribute to closing the gap in this subject and also to make many design alternatives in the future in interior spaces by using microalgae, depending on the results. This thesis was designed to measure the effects of two different microalgae types and quantities (80 L *Spirulina sp.* and 50 L *Chlorella vulgaris* mixtures) on indoor CO_2 levels from the beginning of November 2018 until the end of March 2019 by considering the number of users and occupancy rate. Experiments were performed in two sections, and the results showed that the level of CO_2 in the office was generally acceptable, but due to the lack of natural ventilation, users often complained of tiredness and headache. The effects of different types and amounts of microalgae on the CO_2 level is resulted differently for two altered types. The reduction of the indoor CO_2 levels with 80 L *Spirulina sp.* was measured as 1% on the workdays and 5% on weekends. At the same time, the amount of CO_2 increase was slower than when there was no microalgae in

the office. However, the results of the 50 L *Chlorella vulgaris* mixture is not enough to reduce the indoor CO_2 level on workdays and weekends also.

Key Words: indoor air quality, indoor CO_2 level, microalgae, photosynthesis, bio mitigation

ÖZ

MİKROALGLERİN İÇ MEKAN CO_2 SEVİYESİ ÜZERİNDEKİ ETKİSİ

YAŞAR ÜNİVERSİTESİ OFİSİNDEKİ BİR DENEY

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Ağustos 2019

İnsanların iç mekanlarda çokça zaman geçirdikleri ve iç hava kalitesinin olumlu/olumsuz etkileri pek çok çalışmaya konu olmuştur. Ofislerdeki iyi iç hava kalitesinin çalışanlar üzerindeki pozitif etkileri de çalışmalar yapılarak desteklenmiş, iç hava kalitesini iyileştirmek yönünde pek çok çalışma yapılmıştır. Fotosentezin iç hava kalitesini iyileştirdiği literatür çalışmaları ile kanıtlanmış ve bu bağlamda tez kapsamında fotosentez yaparak karbon tutabilen mikro alglerin iç mekan karbon dioksit seviyesine etkileri Yaşar Üniversitesi'ndeki bir ofis üzerinde ölçülmüştür. Mikro algler ile yapılan çalışmalar ise genellikle laboratuvar ortamında ya da konsept fikirler olup, alglerin iç hava kalitesine katkılarını deney yöntemiyle ölçme bakımından eksik kalmıştır. Bu nedenle, bu tez hem bu konudaki eksikliği kapatmaya katkıda bulunmak, hem de çıkacak sonuçlara bağlı olarak gelecekte iç mekanlarda mikro algleri kullanarak pek çok tasarım alternatifi yapılabilmesi adına bir adım olarak sunulmuştur. Bu tez, Kasım 2018 başından Mart 2019 sonuna kadar iç mekanda iki farklı mikro alg türü ve miktarının (80 L *Spirulina sp.* ve 50 L *Chlorella vulgaris* karışımları) iç mekan CO_2 seviyesine etkilerinin, kullanıcı sayısı ve doluluk oranı gözetilerek, ölçülmesi üzerine yapılandırılmıştır. Deneyler birer aylık döngüler içinde yapılmış olup, çıkan sonuçlara göre ofisteki CO_2 seviyesinin genellikle kabul edilebilir seviyede olduğu, fakat doğal havalandırma bulunmaması nedeniyle kullanıcılarda sıklıkla yorgunluk ve baş ağrısı gibi şikâyetlerin de olduğu gözlemlenmiştir. Farklı türler ve miktarlardaki mikro alglerin CO_2 seviyesine etkileri ise, 80 L *Spirulina sp.* karışımının iç mekandaki CO_2 seviyesini iş günlerinde %1 oranında ve hafta sonlarında ise %5'e kadar düşürdüğü ayrıca CO_2 artış miktarının hiç alg olmayan

zamanlara göre daha yavaş olduğu yönünde olurken, 50 L *Chlorella vulgaris* karışımının iş günlerinde ve hafta sonlarında CO_2 seviyesini düşürmeye yeterli olmadığı yönündedir.

Anahtar Kelimeler: iç mekan hava kalitesi, iç mekan CO_2 seviyesi, mikroalg, fotosentez, biyolojik azaltım

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Fulya Özbey

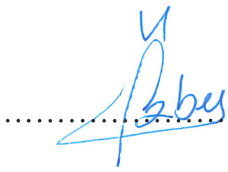
İzmir, 2019

TEXT OF OATH

I declare and honestly confirm that my study, titled "THE EFFECT OF MICROALGAE ON INDOOR CO_2 LEVEL: AN EXPERIMENT IN AN OFFICE OF YASAR UNIVERSITY" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Fulya Özbey

Signature



August 21, 2019

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
BIQ	Bio-Intelligent Quotient
C1	*Chlorella vulgaris*1
C2	Chloerlla2
CW1	ChloeallaWeekend1
CW2	ChloeallaWeekend2
ETFE	Ethylene Tetrafluoroethylene
EPA	Environmental Protection Agency
FPs	Fluorescent proteins
IAQ	Indoor air quality
PBR	Photobioreactor
Ppm	Parts per million
S1	*Spirulina sp.*1
S2	*Spirulina sp.*2
SW1	*Spirulina sp.*Weekend1
SW2	*Spirulina sp.*Weekend2
TSE	Turkish Standard Institution

SYMBOLS:

CO_2	Carbon dioxide
dp	Desipol
O_2	Oxygen
Na2CO3	Sodium Carbonate

CHAPTER 1
INTRODUCTION

Based on the website of United States Environmental Protection Agency "people spend 90 percent of their lives in indoor spaces" (United States Environmental Protection Agency, n.d.-b). Therefore providing suitable interior spaces for the users should be one of the main goals of the interior architects. Creating an appropriate interior space involves not only aesthetical solutions but also technical requirements, such as optimized indoor temperature, humidity, noise control, air quality etc. Even though each of those factors has crucial effects on the interior spaces in this thesis, only indoor air quality (IAQ) will be investigated in depth. To be more specifi,c this thesis investigates for a future-oriented alternative design solution to decrease Carbon dioxide (CO_2) level, in an interior space, which does not have an opportunity for either adequate or any natural ventilation by utlizing photosynthesis of microalgae.

The literature review of the thesis describes the importance on the IAQ primarily focusing on the concentration level of indoor CO_2 by explaining the sources and effects of this gas as well as evaluates the standards and regulations while discussing studies oriented to improve the IAQ in terms of indoor CO_2 levels. Furthermore, description, benefits, cultivation methods and use of microalgae in the urban, architectural and interior architectural design as an alternative and sustainable design solution are analyzed with the examples from around the world.

The experimental part discusses the results of the experiment that was conducted to measure the effects of two different microalgae species, *Spirulina sp.* and *Chlorella vulgaris* on IAQ regarding to mitigate indoor CO_2 concentration.

In the chapter one, the problem statement, aim, scope and limitations of the thesis will be described. In chapters two and three, the background information and literature reviews about IAQ and algae will be analyzed in the following order. The chapter four explains the methodology and experimental case study as well as its results. Finally, in the chapter five conclusion, recommendations, and future studies will be discussed.

1.1. The Problem Statement

With the increasing awareness of human health and employee performance, the importance of creating a more efficient work environment became an important issue. In this context, it was argued with some studies, that the productivity of the employees improved in the environment where the indoor conditions were good. In the cases where the indoor conditions were not sufficient, complaints such as headaches and fatigue were observed. (P. Wargocki, Wyon, & Fanger, 2000; Pawel Wargocki, 2008; Wyon, 2005). Those complaints are mainly caused by the sick building syndrome which is defined in Cambridge dictionary as "An illness that people who work in certain buildings can get, caused by poor air quality inside the building" ("sick building syndrome," n.d.) The ventilation and air contaminants are the factors of the sick building syndrome.

The development in the construction sector and the importance of energy efficiency, enhanced the use of central ventilation, heating, cooling, and caused people to benefit less from natural ventilation and maybe even lighting (Mysen, Rydock, & Tjelflaat, 2003). It is evident that this situation is a problem because of the high amount of CO_2 in the interior, which causes health problems related to sick building syndrome. Therefore, the task of engineers and designers is to search for different design alternatives and solutions in office areas where central ventilation conditions and natural ventilation are not sufficient. Improvements in the air ventilation and reduction in the contaminants such as CO_2 levels may prevent the side effects of the sick building syndrome (Redlich, Sparer, & Cullen, 1997). In this thesis, high CO_2 concentration level was noticed as a problem by causing the side effects of the sick building syndrome as the health issues on the employees in the offices. Then, it is aimed to measure the effect of the microalgal photosynthesis on to the decrease on the CO_2 level in an office area where the general symptoms of the sick building syndrome is perceivable, without changing the central ventilation flow.

1.2. The Aim and Method of the Thesis

The literature reviews show that, the use of microalgae in the architecture and urban design mainly focuses on biofuel production and energy generation by using biomass, but using CO_2 mitigating features of microalgae in the interior is missing. On the other hand, some studies focus on the CO_2 fixation of different species of microalgae in a

controlled laboratory environment. (De Morais & Costa, 2007; Wang, Li, Wu, & Lan, 2008). Therefore, as it is briefly explained in the introduction, **the aim of the thesis is to measure the effect of *Spirulina sp.* and *Chlorella vulgaris* species of microalgae on the indoor CO_2 concentration by using photosynthesis in the selected office space** where the amount of either natural or mechanical ventilation is not enough. During the thesis an experimental method was used. The data collection was made in the Yaşar University Y Block, office 627. The results were obtained by real life case study within the office area. During the experiment time, the indoor CO_2 level and occupancy pattern (after 17.11.2019) were recorded and assessed for the results. Figure 1.1 indicates the overall methodology flow.

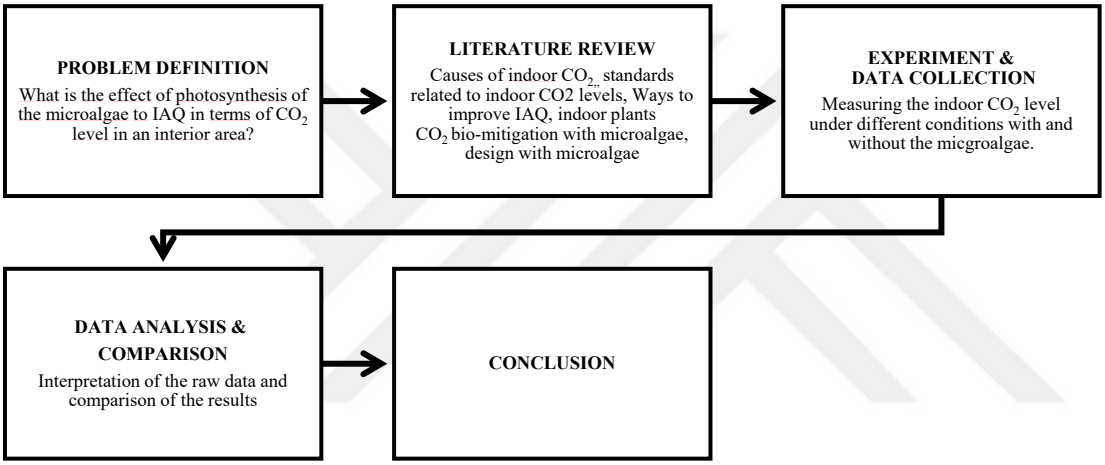

Figure 1.1 Illustration of the Research Process.

IAQ measuring device (testo 160 IAQ) has been used for both experiments and data for every 30 minutes was used. At the first experiment 20 Liters of *Spirulina sp.* has been used. *Spirulina sp.* was mixed with 60 liters of clean water (pH 6.8). PBR was filled with total of 80 liters of microalgae-water mixture. Aquarium air pump (Angora XL-1000F) was placed in the PBR to provide air for an even growing rate.

In the second experiment, the number of the users inside was recorded for each half hour period. 4 Liters of *Chlorella vulgaris* was used and mixed with 46 liters of clean water (pH 6.8). PBR was filled with total of 50 liters of microalgae-water mixture. Two aquarium air stones (35 cm each) were placed in the PBR to ensure even growing rate (the stones have less sound than the previous air pump)

1.3. Limitatons of the Thesis

Since the experiment area was an office that has a central air conditioning system and has no direct opening to the ambient air, the experiment was limited by the factors indicated in below:

- Light intensity,(Weekdays 243 lux, weekends 8 lux, average, lighting (daylight and hourly usage of artificial light have been ignored)
- Temperature (Between 20-25 ^{0}C, shown in Figure 1.2)
- Humidity level (97g/m^3 average)
- Central ventilation rate in the office area (340 m^3/h)

cannot be changed, accepted as the university' limits and not evaluated for the thesis.

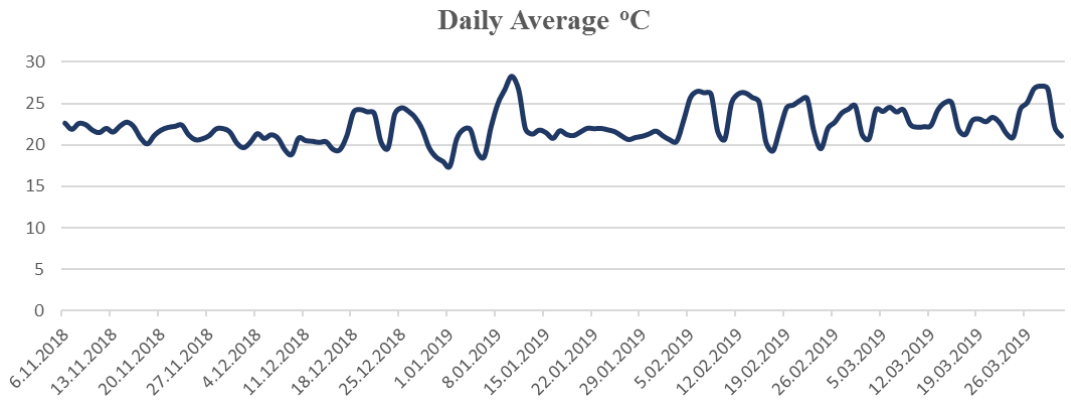

Figure 1.2 Daily Average ^{0}C of the Office Area During the Experiment

In addition, the study was bounded by two different types of microalgae, *Spirulina sp.* and *Chlorella vulgaris* as most common used types and due to the difficulties in finding different types of microalgae. During the experiments, density of the microalgae did not measured. The genders of the users, door openings and staying in the office area less than 15 minutes by one person (in the first experiment number of the users inside did not recorded) and design of the experimental PBR were ignored during the experiment.

CHAPTER 2
INDOOR AIR QUALITY (IAQ)

As it is mentioned in the previous chapter people spend most of their times in indoor spaces. Thus, it is necessary to provide clean air for people in the indoor areas as the necessity of life. In this regard, what is indoor air quality (IAQ) , what are the factors and standards that qualify the indoor air either as clean or polluted and what are the methods to calculate and improve the IAQ will be discussed in this chapter. IAQ is a criterion that indicates how “clean” or “poor” the air which users inhale in an interior space. The acceptable IAQ is described as the indoor air that does not include dangerous contaminants, which are accepted by conscious specialists, when the occupants inhale and majority of the users (80% or more) do not articulate and frustration (ASHRAE, 2016). Also, according to Environmental Protection Agency (EPA), the term IAQ not only includes the quality of air within the building or structure but also the air quality around those, since the quality of ambient air also affects the health and comfort of the occupants (United States Environmental Protection Agency, n.d.-a). The quality of the ambient air changed during the years due to the reasons like, use of fossil fuels which emit CO_2 to the atmosphere when they burn. CO_2 is a greenhouse gas that absorbs the heat and cause global warming. The Figure 2.1 shows the changes in the average global CO_2 concentration level in the atmosphere during the years (Abernethy et al., 2018). This information is worth to mention because the IAQ is mostly depends on the quality of the outdoor air. For example; According European Standard EN 13779, one method to categorize the IAQ is using the CO_2 level of the outdoor air (Comite’Europe’en de Normalisation C. E. N, 2007). The insufficient ventilation, uncomfortable levels of temperature and humidity as well as the indoor air pollutants are some of the factors that cause the poor IAQ. Allergens, Asbestos, Carbon dioxide, Carbon monoxide, organic substances, Ozone, pollens and etc. are some of the major sources of the indoor pollutants (Jones, 1999). However, within the scope of this thesis, the sources and effects of the CO_2 concentration in the indoor spaces, standardizations that includes the indoor CO_2 concentration level as an indicator of the IAQ, some measurement methods and ways to improve IAQ related to this gas will be discussed further.

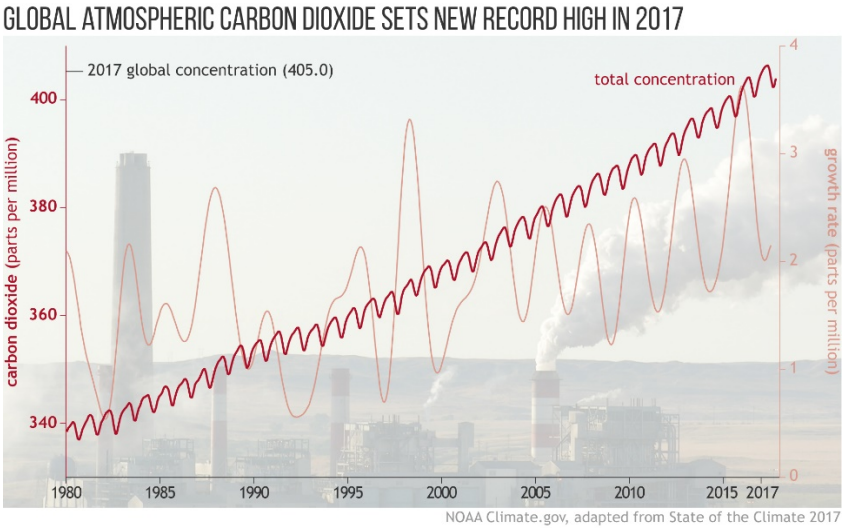

Figure 2.1 The annual growth rate, or the amount by which CO_2 increased each year. ("Estado do Clima 2017 | Laboratório de Climatologia," n.d.)

2.1. The Sources of CO_2 and Effects of CO_2 Concentration in the Indoor Spaces

The sources of CO_2 can be metabolic activities, burning, cigarettes or wood stoves, and exhaust gases from the motor vehicles, which pollute the ambient air around the building and can be carried inside together with the fresh air. The good IAQ provides people healthy living and working environment. According to literature review by Başak et al., the improvements in the IAQ increased the production in Lockheed by 15% while reducing the absenteeism 15%, insurance transactions increased 15% in West Bend Mutual Insurance, absenteeism at ING Bank 15% decreased and production in Verifone increased 15% at the same time absenteeism reduced 40% (Demiraslan & Başak, 2018). On the other hand, studies show the clinical results of the high concentration of the CO_2 are a headache, bounding pulse, fatigue etc. If the CO_2 is very high, it might cause loss of consciousness, sight impairment and even death (Alberts, 1994). Figure 2.2 shows the general outline of the indoor CO_2 levels and its effects on people.

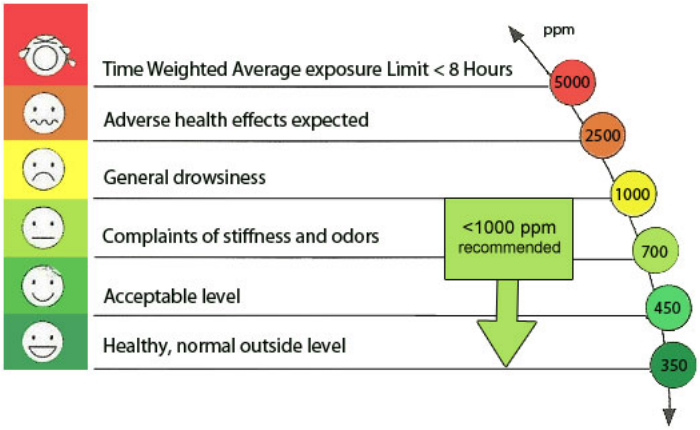

Figure 2.2 General CO_2 Indoor Levels ("CO2 Monitor - Levels and Monitoring Explained," n.d.)

2.2. Standards and Regulations of Indoor Air Quality around the World

Nowadays, there are various global and regional standards related to the IAQ. Some of them are specifically focus on the CO_2 concentration in the indoor areas. Some approaches the air as a mixture of different gases. As the best's knowns AHRAE, ASTM and EN standards, in addition the TSE standard relevant to the IAQ will be discussed further.

2.2.1. ANSI/ASHRAE Standard 62.1 - Ventilation for Acceptable Air Quality

In 1973, the first standard for ventilation and indoor air quality was published by American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) under the ANSI/ASHRAE Standard 62 Ventilation for Acceptable Air Quality. In 1989, ASHRAE standard 62.1 Ventilation for Acceptable Air Quality is mainly includes buildings that are not residential and requests for sustaining the indoor CO_2 concentration under the 1000 ppm. However, that limit value is eliminated from the standard, which was published in 1999 (Persily, 2015). In 2003, ASHRAE standard 62.1 expanded on another version which is called 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings then evolved into "62.2 Ventilation and Acceptable Indoor Air Quality in Residential Buildings" through the revisions in years. Within the limits of this thesis study standard 62.1 is going to be evaluated more.

The standard 62.1 aims to determine minimum ventilation rates and requirements for ventilation system (design, installation, operation etc.) to enable adequate indoor air

quality for building occupants in order to minimize the health hazards based on the chemical, physical and biological contaminants. The 62.1 standard considers the indoor air as a mixture rather than to analyze each contaminant individually therefore, in the latest version of ASHRAE, there is no specific information about the limits of the CO_2 concentration in indoor areas (ASHRAE, 2016). Nevertheless, the value of 1000 ppm from the older version of the standard is mostly referred as guideline value for CO_2 concentration in the indoor spaces and supported with some researches (Berg-Munch, Clausen, & Fanger, 1986; Rasmussen, C., Clausen, G. H., Berg-Munch, B., & Fanger, 1985).

2.2.2. ASTM D6245 - Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation

The second American standard to evaluate IAQ is the American Society for Testing and Materials (ASTM) D6245 – 18, Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation. The ASTM standard explains how the calculated CO_2 level in the interior space might be employed and the use of continuous monitoring method on the ambient and indoor CO_2 concentration in estimations of IAQ. In addition, ASTM standard explains, how the CO_2 generation rate in an interior space changes depending on the user's gender, age, metabolism rate, and physical activity by using the equation below:

$$V_{CO2} = RQ.BMR.M.(T/P).0{,}00021 \quad (1)$$

Where: V_{CO2} is rate of CO_2 generation rate of an individual (L/s per person), RQ is respiratory quotient, BMR is basal metabolic rate, M is metabolic rate per unit of surface area, T is air temperature and P is air pressure. Details about the equation can be find in ASTM D6245 standards. Therefore, considering the equation above, CO_2 concentration in an indoor place depends on the number of the individuals and the other variables in the equation. However, this standard does not suggest any method to calculate indoor CO_2 concentration. The appropriate way to use this guide should be to estimate the anticipated level of user comfort concerning human body odor, occupancy patterns as an interpretation of the indoor CO_2 concentrations (ASTM, 2018).

2.2.3. EN 13779 - Ventilation for Non-Residential Buildings-Performance Requirements for Ventilation and Room-Conditioning Systems

One of the European Standards relevant to IAQ is EN 13779 Ventilation for Non-Residential Buildings-Performance Requirements for Ventilation and Room-Conditioning Systems. As one of the performance requirements of this standard, the required air quality level and the classification method applied will be stated. Unlike ASHARE and ASTM standards, indoor smoking allowed spaces are included in EN standard.

According to EN 13779 standard IAQ is classified into four categories (IDA). The standard offers three different methods in order to evaluate IAQ categories. One of them is classification by CO_2 level. This method is practical if the occupancy pattern is well known and smoking is not allowed while the main source of the indoor pollution is human metabolism. In this method category of the IDA will we decided according to the CO_2 concentration in the ambient environment. Table 2.1 shows the four categories of indoor air depending on the outdoor air. Also, according to this standard total need for fresh air of an interior area is calculated as the total of the requirement per person and requirements for each m^2 (Comite'Europe'en de Normalisation C. E. N, 2007).

Table 2.1 CO_2 Level in Indoor Areas [1]

Category	Description	CO_2 level above level of ambient air in ppm.	
		Typical Range	Default value
IDA 1	High IAQ	<400	350
IDA 2	Medium IAQ	400-600	500
IDA 3	Moderate IAQ	600-1000	800
IDA 4	Low IAQ	>1000	1200

2.2.4. TSE TS CR 1752 Ventilation for Buildings - Design Criteria for the Indoor Environment

TSE TS CR 1752 standard includes the rules and methods, which clarifies the quality of the indoor environments for the design, operation and control of the HVAC systems.

[1] Adapted from (Comite'Europe'en de Normalisation C. E. N, 2007)

TSE standard deals with the indoor spaces that are in use by people and includes design principals relevant to thermal environment, acoustics and IAQ. According to this standard, some design assumptions needed to be made such as, occupancy pattern and their activity, smoking allowance, pollution load caused by the furniture and materials, and quality of ambient air.

TSE standard divides the air quality into three categories A, B, and C. A indicates the best air quality where the C is the worst but still acceptable. TSE standard suggest an equation below to calculate the sensed indoor air:

$$1\ dp = 0{,}1\ (\frac{olf}{l/s}) \tag{2}$$

Where, the sensed indoor air is expressed as desipol (dp) and "olf" stands for the air pollution that is caused by one person. Therefore, 1 dp is equal to the quality of the air which has 1 olf pollution source and a fresh air source that blows fresh air 10 l/s. Also, as reported by the standard, power of many of the pollution source inside the building can be expressed as "olf". However, according to the standard CO_2 is a source of air pollution in general but only accepted as a disturbing pollution source for IAQ if the users are sitting inside. Therefore, in order to calculate CO_2 concentration in an indoor area; the physical activity of the user, smoking permissibility, type of the building, outdoor air quality and size of the interior area should be determined. To make the precise dp calculations, detailed charts and tables can be find in the standard. In the standard, the relationship between the indoor CO_2 level and category of the IAQ is explained by how high the CO_2 level in the interior is relative to the ambient CO_2 level. Ambient air CO_2 level is generally 350 ppm. Therefore, if the interior CO_2 concentration is 460 ppm higher than the exterior level, this categorized as A, if it is 660 ppm higher, this categorized as B, and if it is 1190 ppm higher, the IAQ categorized as C. Table 2.2 shows the connection between the categories of IAQ and percentage of unsatisfied populace in relation to the dp and indoor CO_2 level. Unsatisfied population states for the first impression of the visitor. (Türk Standartları Enstitüsü (TSE), 2002).

Table 2.2 The relationship between IAQ categories, unsatisfied populace, dp and indoor CO_2 level. [2]

Category	Unsatisfied populace %	dp	The difference between indoor and outdoor CO_2 level
A	15	1,0	460 ppm
B	20	1,4	660 ppm
C	30	2,5	1190 ppm

2.3. Measurement Methods of CO_2

CO_2 is an odorless and colorless gas. Therefore, it cannot detected by naked eye or by smelling, can only be measured by measurement instruments. Even tough CO_2 is not a toxic gas itself, it is safely critical when it reaches very high concentrations. In addition, it might cause other problems like fatigue, sickness within the certain indoor concentrations. Hence, the importance of the IAQ increases as the use of central ventilation systems increases (Daisey, Angell, & Apte, 2003; Ferng & Lee, 2002). Analysis of CO_2 dates back approximately 200 years ago and depends on the developments is the various physical and chemical methods (Pandey & Kim, 2007). CO_2 concertation can be measured by use of calorimetric gas detections tubes and calculated by color changes in the acid (U.S. Patent No. 2,487,077, 1949). Nowadays, use of sensor measuring devices is the most common method to measure the real time CO_2 level. Those devices can be both continuous or instant monitoring. Some of the devices can simultaneously measure CO_2, humidity, temperature and different types of gases in the air while allowing the data logging nearly every five minutes. Figure 2.3 shows two types of CO_2 measuring devices.

Figure 2.3 Instant and Continious IAQ Measurement Devices. ("Pentaotomasyon.com.tr," n.d.; "WiFi data logger testo 160 IAQ | Air temperature measurement | Temperature | Parameters | Testo Indonesia," n.d.)

The IAQ can be improved by using some methods. The first one is source control because the easiest way to keep the indoor air clean is not letting the pollutants to get

[2] Adapted From (Türk Standartları Enstitüsü (TSE), 2002)

inside of the building. Also, this method is more economical than the increasing the ventilation rate. However, if the location of the indoor air pollutant is already known and relatively stable using the local aspirator can be another solution such as in the kitchens and medical laboratories. The second method to improve the IAQ is designing, operating and maintaining the appropriate ventilation system according to the usage area. Ventilation systems that has a demand control system keeps the interior area within the acceptable limits while providing energy save and makes the IAQ better. The third method is using the air cleaning devices and plants. Air cleaning devices has various types from price to size. They capture the pollutants within their filters to keep the air clean, and require systematic maintenance to work accurately (Köksal, 2001). In addition, indoor plants have an effect on the indoor CO_2 concentration. The initial studies by National Aeronautics Space Administration (NASA), seeks for ways to find ways to reduce pollutants inside habitats and some research conducted on issue (Wolverton, Johnson, & Bounds, 1989; Wolverton, McDonald, & Mesick, 1985; Wolverton, Mcdonald, & Watkins, 1984). Based on those previous studies more current studies, from 2000 to 2019, about measuring the effect of the indoor plants on the indoor CO_2 levels are searched on the Yaşar University's library's databases and the results that have the similar aim with this thesis are presented below.

2.4. Ways to Improve IAQ in terms of CO_2 Concentration Level

The study by Çetin and Sevik aims to measure the effects of five different indoor plants to the indoor CO_2 level. The method which is used in the study, is putting the indoor plants into the air tight containers and placing that container to a place where the plants can have day light. Each plant kept in the container at least five days and the CO_2 level inside the container is measured every five minutes with an IAQ data logger device. The studies are conducted from June to July when the daytimes are longer. The results show that, all of the indoor plants ameliorated the indoor CO_2 level up to some point during the daytime and the reduction in the CO_2 level during the day is higher than the increase during the night (Cetin & Sevik, 2016). On the other hand, in this study there is no outer source of CO_2 such as occupancy, to change the indoor CO_2 level. Therefore, the results may be different in terms of CO_2 reduction if the plants were not kept in an airtight glass walls and the measurements were taken in a real life indoor environment.

The second study is conducted by Oh et. al. in Korea from December 2009 to April 2010. The study aims the offer a new method in order to understand the CO_2 reduction capacity of the indoor plants not only focusing on the pre-arranged laboratory area but also trying to create a realistic working environment. To understand the effect of the indoor plants two different case studies are done and compared with each other. In the first case study, three different types of indoor plants are placed into a 0.5 m^3 glass container where the CO_2 level is already higher than 1000 ppm. The temperature, humidity and illumination levels are set for the values that the typical office environment can be created. Two silicon hoses are installed around the glass container, one for to the CO_2 inlet and one for the outlet. The IAQ device is placed on the outlet to understand the reduction difference. In the second case study, instead of pre-raising the CO_2 level within the container, the starting value is set as neatly 350-400 ppm. In addition, three individual hamsters are located in another container, as their occupancy is simulated as an office environment, and two containers are connected with each other. Thus, the CO_2 level in the container where the plants are kept, raise by the respiration of the hamsters. The results indicated that, all of plants are more successful to reduce the CO_2 concentration in the second case study when the CO_2 level gradually increase by the respiration (Oh, Jung, Seo, & Im, 2011).

The third study is engaged by Tarran et. al. Their study focuses mainly on the VOC reduction by using indoor plants both as the real-life case study in an office area and in the laboratory. Also, as a novel approach they tested the impact of the plants on the indoor CO_2 and CO levels in offices. In order to carry out this research two different buildings one with air conditioning and the other with natural ventilation are chosen in Sydney. Three indoor plants are placed in six 10-12 m^2 offices with single user, and six offices in remained unplanted in both of the buildings. The study in done from May to October and weekly air samplings are taken from different parts of the offices by using portable IAQ measuring device. According to the results, the indoor plants reduced the CO_2 level in the air-conditioned offices nearly 10% and 25% in the naturally ventilated ones compared to unplanted offices (Tarran, Torpy, & Burchett, 2007).

Finally yet importantly, the study to measure the effect of the photosynthesis to in indoor CO_2 level is done by Brennan. The study targets to understand the effect of the potted plants so as to enhance the IAQ. The study composed of two parts, the real life

case study and the laboratory experiment. The case study was carried out to understand how many indoor plants should be used to reduce the level of indoor carbon dioxide in an office environment without changing the ventilation rate. For this purpose, different numbers and species of indoor plants are placed in eleven similar offices in Sydney, where the volume, ventilation rate, window locations, number of the users, and the occupancy pattern is known. Also, a control group with no indoor plants is established. The measurements are taken for six weeks and two different periods. The air sample is taken once a week from the offices and results are calculated in the laboratory. The results show that minimum three indoor plants have a respectable effect to reduce the indoor CO_2 level and the second period is more effective than the first six weeks. The laboratory experiments are conducted to understand the effect of the lighting in order to increase the photosynthesis, since the indoor lighting in the office, areas are not sufficient for the optimized photosynthesis environment. The laboratory results indicated that, the more intense the light, the better the photosynthesis is and the plants are more successful to ameliorate the indoor CO_2 level (Brennan, 2011). However, as a critic to both of the studies above, although the air sampling is done only once a week, since it is not continuous data logging, the sample air is limited only for the measurement time, day and may not be include all the changes in the CO_2 level. Table 2.3 shows the comparison of the studies mentioned above. As the studies show that photosynthesis has positive effects on reducing the amount of carbon dioxide in the interior spaces, therefore, not only indoor plants but also other living things which are able to photosynthesize, such as microalgae, which are the main component of this thesis, can also be used to reduce the amount of CO_2 in the indoor areas. The information about CO_2 capturing features of the microalgae will be discussed in the chapter three.

Table 2.3 Comparison of the Studies

Rerefences	Year	Place	Duration	Study Type	Indoor Plants	Measurement Frequency	Measurement Device	Results
(Cetin & Sevik, 2016)	2016	Kastamonu, Tukey	From June to July 2015	Laboratory experiment	• Ficus elastica • Yucca massengena • Ocimum basilicum • Sinningia speciosa • Codiaeum variegatum	Every five minutes with a continuous data logging IAQ measurement device.	Extech Desktop Indoor Air Quality CO2 Datalogger	The study results showed that all the plants diminished the CO_2 level. The most noticeable change was by Ficus elastic and Yucca massengena. Also, the amount of CO_2 which was consumed during the day was higher than the production of CO_2 during the night time.
(Oh et al., 2011)	2011	Busan, Korea	December 2009 to April 2010	Simulation of a real life environment in a smaller scale.	• Peace lily: • Spathiphyllum clevelandii • Weeping fig: Ficus benjamina • Areca palm: Chrysalidocarpus lutescens.	Every 1 minute for 90 minutes. Between 10:00 PM to 16:00 PM	IAQ Analyzer (ISR400)	The results showed that the indoor plants reduced the indoor CO_2 level more when the CO_2 level increases in time due to respiration of the lab animal than the case where the CO2 level was already higher than the acceptable level.
(Tarran et al., 2007)	2007	Sydney, Australia	From May to October	Real life case study (Office)	• Dracaena 'Janet Craig'	Weekly, 5 minutes samplings	Portable IAQ-Calc Indoor Air Quality Meter	The results indicated that indoor plants diminished the CO_2 level in the offices that have air-conditioner 10% percent and 25% in the offices with the natural ventilation compared to the unplanted offices.
(Brennan, 2011)	2011	Sydney, Australia	From March to June (1^{st} round) From August to October (2^{nd} round)	Laboratory experiment (Under Two Different Illumination) Real life case study. (Office)	• Spathiphyllum Petite (Both) • Dracaena Janet Craig (Real life experiment only) • Zamiocu/cas zamiifolia (Laboratory experiment only)	Once a week	Portable IRGA CO_2 monitor	The results showed that minimum three indoor plants were required to observe reduction in the CO_2 levels in the office areas.

CHAPTER 3
THE ALGAE

The term algae can be defined as a photosynthetic, polyphyletic, and unnatural grouping of O_2 evolving organisms. Therefore, plants could be considered in an algal division. Although algae and plants have some similarities such as being able to photosynthesis and using similar protection tactics against parasites and predators, algae do not have any roots, leafy shoots and lack of vascular tissues (Van Den Hoek, Mann, & Jahns, 1995). According to AlgaeBase, there are species of living algae between 30.000 to more than 1.000.000 and 152,278 species and infraspecific names are in the database (Guiry & Guiry, 2018). The term algae refer to both macro algae and microalgae. Macro algae is also known as seaweed is defined as large aquatic photosynthetic plants, which are visible without the help of a microscope. However, the macro algae is not in the scope of this thesis. Microalgae is the single celled organism which has characteristic of both animal and/or plant cell depending on the specie. They cannot be seen directly, but when they form a group, they can change the color of the water that they grow inside (Hemming, Sapounas, & Voogt, 2012). There are many benefits of microalgae and they are already cultured and harvested to use as a livestock and fish food as well as a supplement in human food. Moreover, they are used as an ingredient for cosmetics, fertilizer, and bioplastics due to their high-value oils (Bindu & Levine, 2011). The first benefit and characteristic of the microalgae is, they can grow fast and stores the energy in the form of oil, which makes them a suitable candidate for clean renewable energy generation such as biomass and biofuels. (Hossain, Salleh, Boyce, Chowdhury, & Naqiuddin, 2008). Compared to other biofuel sources such as corn, sugar cane, sunflower etc. microalgae can produce up to 300 times more oil (Shalaby, 2013). Secondly, microalgae can survive in hostile environments and grow in areas that are not suitable for traditional agriculture. They can also grow in the seawater and wastewater at the same time they filter the wastewater. They have an ability to eliminate heavy metals and toxic organic components from the water. Furthermore, they use hazardous materials in the water such as inorganic nitrogen and phosphorus in order to grow by fixing the wastewater in the end (Abdel-Raouf, Al-Homaidan, & Ibraheem, 2012). Finally yet importantly, microalgae has an ability to fix the CO_2 that is considered as one of the main subject of this study. In this chapter cultivation techniques, CO_2 mitigation features, and usage

areas of the microalgae, within the borders of architecture and design, will be examined.

3.1. Microalgae Cultivation Techniques

Researches about the energy production from algae have been conducted for many years. The first efforts have been started during the II World War and in the sixties, biomass production from algae has been started to use on a larger scale in open systems (Burlew, 1976). With the help of developing technology more investigations has been developed to increase the efficiency of production of biodiesel and use of algae in photobioreactors among the countries (Lo, Chen, Lee, & Chang, 2010). The culture of algae and production can be done by using various methods, beginning from fewer foreseeable techniques like open system pounds to more controlled techniques in closed laboratories. The main concern to choose the most suitable method is mostly related to the usage area of algae culture (Acién Fernández, García Camacho, & Chisti, 1999).

3.1.1. Open Systems

Open systems are generally used and preferred due to the economic concern in the industrial scale (Dębowski M, Zieliński M, Krzemieniewski M, Dudek M, 2012) They use open ponds and aquifers under the satisfactory environmental conditions with a very simple design. Open systems are sensitive for contamination and losses by evaporation. The system uses the CO_2 directly from the atmosphere, however does not able to use the offered CO_2 with a full efficiency (Pacheco, Hoeltz, Moraes, & Schneider, 2015). Open systems mainly use *Spirulina sp.* and *Chlorella vulgaris* as algae culture (Demirbas & Demirbas, 2011). Open systems has its own advantages such as having low cost construction, not affecting from overheating and no problems because of oversaturated oxygen. However, they also have some disadvantages like low productivity, east to contaminate, significant decrease of water, and during the night diffusion of the CO_2 to the atmosphere (Lassing, Merit; Mårtensson, Peter; Olsson, Erik; Svensson, 2008). Figure 3.1 shows an example of open system microalgae cultivation pond.

Figure 3.1 Open System Microalgae Cultivation Pond ("Kültür Sistemleri-Algler," n.d.)

3.1.2. Closed Systems (Photobioreactors)

Another technique to cultivate algae is closed systems, also called photobioreactors (PBR). The system has various developed systems depending on their reactor geometry such as, tubular (curved, straight, helical or spiral), flat panel and column, big bag systems and dark systems. The design of them should be chosen according to the algae's growth rate and special characteristic (Sierra et al., 2008). Closed systems are more controlled than the open systems and able to allow monitoring as well as can be used under different climatic conditions and minimize contamination (Pacheco et al., 2015). Unlike, open systems, closed systems allow to use more variable types of algae (Demirbas & Demirbas, 2011). The advantages of the closed systems are; having higher productivity than the open ones, easier to avoid pollution by being close to the environment and smaller loss of water by evaporation compared to the open systems. Nevertheless, they still have disadvantages by being more expensive, having problems with overheating and oversaturation of the oxygen and being difficult to clean inside of the clear surfaces (Lassing, Merit; Mårtensson, Peter; Olsson, Erik; Svensson, 2008).

3.1.2.1. Big Bag System Photobioreactors

Big Bag Systems are the first type of closed PBRs (Watson, 1979).The system composed of big sterilized plastic bags (Figure 3.2) and has a low cost initial. However, they do not have enough research to compare with the other types and use as an alternative (Lassing, Merit; Mårtensson, Peter; Olsson, Erik; Svensson, 2008).

Figure 3.2 Big Bag Systems (Huang, Jiang, Wang, & Yang, 2017)

3.1.2.2. Vertical (Bubble) Column Photobioreactors

Vertical column PBRs (Figure 3.3) are cylindrical containers, which have been researched a lot since their cultivation capacity (Daisey et al., 2003; Kaewpintong, Shotipruk, Powtongsook, & Pavasant, 2007; López et al., 2006; Vega-Estrada, Montes-Horcasitas, Domínguez-Bocanegra, & Cañizares-Villanueva, 2005). The system is low cost, relatively compact also capable of large-scale algae cultivation Moreover, they are easy to clean and due to the homogenous distribution of the algae culture, the heat and mass transfer is pleasing. On the other hand, their construction necessitates the use of complex materials and there is a chance for hydrodynamic pressure (Dębowski M, Zieliński M, Krzemieniewski M, Dudek M, 2012).

Figure 3.3 Vertical (Bubble) Column Photobioreactor ("Kültür Sistemleri-Algler," n.d.)

3.1.2.3. Tubular Photobiorectors

Tubular reactors (Figure 3.4) mostly made of glass and polycarbonate and can be constructed vertical, horizontal, helical, and inclined (Molina, Fernández, Acién, & Chisti, 2001; Ugwu, Ogbonna, & Tanaka, 2002). Pumps or airlift system achieves the medium's flow and supply of CO_2. In addition, a gas exchanger removes the produced O_2 (Molina et al., 2001). In spite of they have a danger of becoming dirty inside the tubes due to the CO_2 and fluctuations in the culture, tubular PBRs are acceptable for outdoor use and because of the large surface area exposure; they provide high productivity and biomass (Dębowski M, Zieliński M, Krzemieniewski M, Dudek M, 2012).

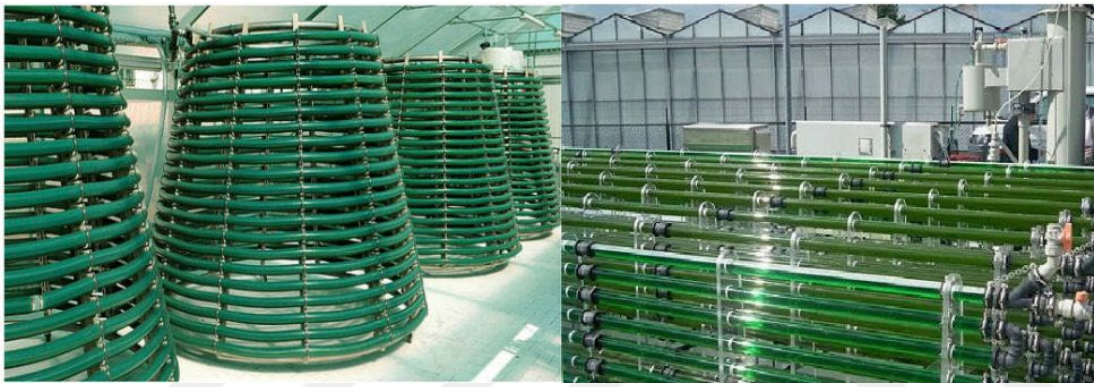

Figure 3.4 Tubular Photobioreactor ("Kültür Sistemleri-Algler," n.d.)

3.1.2.4. Flat Panel Photobiorectors

Flat panel PBRs (Figure 3.5) made of transparent materials like glass plates polyethylene film where the algae culture is filled in the space between those materials (Reyna-Velarde, Cristiani-Urbina, Hernández-Melchor, Thalasso, & Cañizares-Villanueva, 2010). By using pressurized air, the mixing is done in the panels itself (Sierra et al., 2008). Flat panel PBRs have many benefits such as being good for outdoor cultivation, sufficient distribution of light, being easy to clean and control the O_2. In spite of the advantages, they can require many support structures when there is a need to increase the size which may cause to control the temperature and risk of contamination in the clear surfaces (Dębowski M, Zieliński M, Krzemieniewski M, Dudek M, 2012).

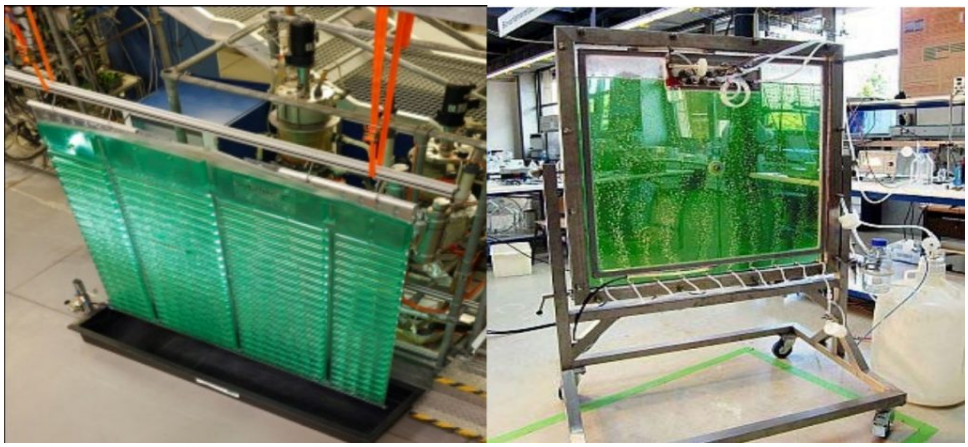

Figure 3.5 Flat Panel Photobioreactor ("Kültür Sistemleri-Algler," n.d.)

3.2. CO_2 Fixation by Microalgae

Microalgae capture and consume CO_2 in order to grow at the end of the photosynthetic reaction. They are responsible for 1/3 of the Earth's carbon fixation while producing atmospheric oxygen's nearly amount of 70% (Chinnasamys, S., Hanumantha, R., Bhaskar, S., Rengasamy, R., Singh, 2012). In addition, in terms of mitigating CO_2, microalgae is 10 to 50 times more effective than the conventional plants (Usui & Ikenouchi, 1997). Therefore, microalgae can be used in order to reduce the CO_2 level, since the microalgae requires more CO_2 so as to grow faster thus, they can clean the air as well. To evaluate the studies on the CO_2 mitigation and enhancements methods of the CO_2 fixation of microalgae, databases in the Yaşar University was scanned, with the keywords, CO_2, mitigation, microalgae and their synonyms, in the journal articles from 2000 to 2019 and 79 studies found it total. Some of the selected studies are evaluated in detail.

A review paper by Zhou et. al. investigates the how different sources of CO_2 effects the bio-mitigation, impact of environmental and nutritional factors, economic viability of currently used systems and challenges in the CO_2 bio-mitigation involved perspectives. The remarks of the study shows that, many of the microalgae harvesting techniques can be used for carbon fixation in the small-scaled areas. Nevertheless, to use microalgal CO_2 fixation in the larger scale or commercial use of microalgae for CO_2 sequestration, subjects such as, the characteristic of the microalgae, cost effectiveness, improvisation of CO_2 transfers should be studied more and requires better understanding (Zhou et al., 2017). Another mini review study by Wang et. al. investigates the developments in the field of CO_2 bio-mitigation by microalgae. According to the review, the studies by microalgal bio mitigation mainly focus on three

different categories. First, using different CO_2 sources to the test CO_2 reduction level by different species. Second, combining bio-mitigation and bio-fuel strategy techniques. Third, combination of wastewater treatment and bio-mitigation techniques (Wang et al., 2008). However, as the review paper indicates that most of the studies are conducted under the laboratory environment and the results may not be as feasible as in the real life. Similarly, the study by Kumar et. al. aims to analyze enhanced bio-mitigation techniques which are mainly combined by the wastewater treatment for production of biomass. According to the authors, the results show that most of the studies are still in under strictly controlled laboratories or small-scaled closed PBRs. Also, the study indicates that there is a need for the studies which uses larger-scales or atmospheric conditions of CO_2 to test the bio-mitigation of microalgae to provide common use of biological CO_2 amelioration. (Kumar et al., 2010). A study by Suryata et al. aims to reduce the CO_2 produced by geothermal power plant in Iceland by using bio-mitigation techniques. The small-scaled PBR, which is 1400 liters in total volume, is set up in Varicon Aqua Solutions Ltd, UK. The pH value, temperature, salinity and the illumination levels are optimized to provide the optimal growing rate for the Blue Lagoon blue-green algae, which is unique type from the Blue Lagoon at the Reykjanes peninsula. The results of the CO_2 reduction rate indicated that the blue-green algae can reduce the CO_2 level of the flue gas up to 18-19% (Suryata, Svavarsson, & Einarsson, 2010). Another similar study by Moheimani targets to observe the influence of flue gas a source of CO2 to the growth of microalgae, Tetraselmis. The study was done in Australia for seven months in 12 hours of day light florescent 12 hours of dark period. 1000 L industrial scale airlift photobioreactor set up was used. During the study the exhaust gas, which contains 11% CO2, pumped from the chimney directly into the photobioreactor and the CO_2 mitigation rate was calculated by looking at the microalgae's growth rate. The outcomes demonstrated that outdoor trial for CO2 reduction is successful for the flue gas (Moheimani, 2016). Moreover, a study on the flue gas mitigation by the microalgae is conducted by Borkenstein et.al. Their study aims to discuss the choices of cultivating the green alga, *Chlorella vulgaris* emersonii, under laboratory conditions with the flue gas comes from a cement factory. The experiment composed four parts and conducted for 30 days in Australia. In each part 2 liters of microalgae culture was separated and dried under the sun and the dry mass weighted to calculate CO_2 mitigation. A pilot scale PBR was used and flue gas to test and pure CO_2 gas to control were used. The results show that there was not a drastic

change in terms of growth rate and CO_2 mitigation between flue gas and pure CO_2 (Borkenstein, Knoblechner, Frühwirth, & Schagerl, 2011). Although in real life greatly larger scale PBRs are needed to achieve the same percentage of reduction in the CO_2 level of the flue gases, the studies shows that, the microalgae still might be a feasible and sustainable solution in order to reduce the CO_2 level around the power plants. On the other hand there many some studies mainly focuses on to enhance the CO_2 fixation rates of the different species of microalgae by chancing the factors which effects the growth of microalgae such as light intensity, nutrition, pH, ratio of given CO_2, design of the PBS or even genetic engineering. A study by Cheng et al. aims to improve the growth rate of the Nannochloropsis oculata in an open pond to fix the CO_2 from the exhaust gas of the coal-fired power factory. The study was done in China from April 2014 to July 2014. In order to improve the growth rate instead of letting the microalgae to use the ambient CO_2, flue gas which contains around 11%-15% CO_2 used as source. The growth rate was measured and compared to the control mixture by taking 60 ml sample from the raceway pond twice a day. The outcomes indicated that microalgae which uses the flue gas as CO_2 source was more successful to fix CO_2 by having better growth rate (Cheng et al., 2015). Secondly, a study is done by Fu et al in 2019 in Iceland for three days to harvest *Chlorella vulgaris* in different sized (PBRs) and form a strategy using small doses of sugars so as to boost the CO_2 fixation. 500 mL, 1200 mL, 2400 mL and 3600 mL bubble column PBRs under the LED lighting with 2.5% were used in the experiment. 2 ml sample were separated once in a day from all the PBRs and the differences in the dry biomass in were measured. Based on the experiment results sugar stimulated microalgae mixtures performed better in the CO_2 fixation rate than the non-stimulated ones (Fu et al., 2019). Zhao et al. did another research to define the effect of various reactor structures on the photosynthetic effectiveness in the cultivation process of *Chlorella vulgaris* in 2019. In order to try different PBRs a 10L three like, multifubular, tubular 3D PBR is compared with the conventional tubular and multicolumn PBRs. The results showed that CO_2 capture effectiveness of used specie and the growth rate of biomass in the fractal tree PBR have noteworthy benefits (Zhao et al., 2019). Last but not least, the research was done to increase the CO_2 amelioration of the *Chlorella vulgaris* by using static magnetic fields in 2019 by Deamici et al. The aim of this research was to use various magnetic field conditions application during *Chlorella vulgaris* harvest to recess CO_2 reduction. 2 L tubular PBRs in the 12 h light (40 W fluorescent light) /12 h dark period were used

in the study together with the 30 mT or 60 mT magnets applied around the PBRs. Also one PBR without the magnet was used as test subject. According to the results application of magnetic fields increase the CO_2 bio fixation by 49.7% compared to the control PBR which is a non-toxic and inexpensive method (Deamici, Santos, & Costa, 2019). To sum up, as the literature review shows that there are studies to use microalgae to reduce the CO_2 level, combine the technologies to produce biomass and wastewater treatment and enhance the microalgae to capture more CO_2. However, most of the studies are generally in the laboratory environment and lack of using the microalgae in the real-life applications especially to measure the effects on the indoor CO_2. Therefore, this thesis targets to contribute to fulfill the gap between the usages of microalgae to ameliorate indoor CO_2 levels and their use of in the architecture/ interior architecture and design.

Table 3.1 Comparison of the Selected Studies

Reference	Year	Location	Duration	Aim	Type	PBR Type	Illumination	CO2 Source	Microalgae Type	Method	Result
(Suryata et al., 2010).	2010	Iceland	1-3 days for each experiment	To analyze some parameters to optimize the growth of the selected type of microalgae to use as a bio-mitigation of the flue gas.	Pilot scale set-up	Tubular photo bioreactor with total volume of 1,400 liters and lab-scale PBR with 10 liters in total	Artificial	Industrial gas from the geothermal power and pure CO_2	Blue Lagoon blue-green algae	Optimizing the important factors, such as light, pH, temperature for growth of the microalgae in the lab scaled PBR and applying optimized results to the pilot scale PBR and measuring the growth of rate of the microalgae to understand the CO_2 capture rate.	The results show that blue-green algae is successful to mitigate the flue-gas in the pilot PBR while doubling the growth time.
(Moheimani, 2016)	2015	Australia	7 months	To examine the effect of flue gas a source of CO_2 to the growth of microalgae, Tetraselmis.	1000 L Industrial pilot scale set up.	Aairlift photo bioreactor	12h: day light fluorescent lights 12h: dark	Untreated flue gas CO_2:11 %	Tetraselmis suecica	By pumping the exhaust gas from the chimney directly into the photo bioreactor and calculating how much CO_2, the microalgae mitigate looking at their growth rate.	The results show that outdoor trial for CO_2 reduction is successful for the flue gas.
(Borkenstein et al., 2011)	2010	Austria	30 days	To discuss the options of harvesting the green alga, *Chlorella vulgaris* emersonii, under laboratory conditions with flue gas comes from a cement factory	Pilot Scale set up	Tubular		Flue gas and control gas(pure CO_2)	*Chlorella vulgaris*	The experiment composed 4 parts. In each part $_2$ liters of microalgae culture is separated and dried under the sun and the dry mass weighted to calculate CO_2 bio mitigation.	Results indicated that there is not a drastic change in terms of growth rate and CO_2 mitigation between flue gas and pure CO_2.

(Cheng et al., 2015)	2015	China	April 2014 to July 2014	To measure microalgal growth, consumption rates and CO_2 fixation rate from the flue gas under natural conditions	Open raceway	The raceway pond culture system (1191 m2	Day light	Flue gas (CO_2 11%-15%)	Nannochloropsis oculata	Taking 06 ml sample from the raceway pond twice a day and measuring the growth rate.	CO_2 fixation rate in microalgal biomass was approximately 1/3 of CO_2 removal rate from flue gas by the microalgal culture system
(Fu et al., 2019)	2019	Iceland	3 days	To cultivate *Chlorella vulgaris* in various sized (PBRs) and build up a strategy using small doses of sugars for enhancing CO2 sequestration.	500 mL, 1200 mL, 2400 mL and 3600 mL PBRs	bubble column LED-based PBRs	LED light	Flue gas CO_2 2.5%	*Chlorella vulgaris*	2 ml sample are collected once in a day from all the PBRs and the differences in the dry biomass in measured.	Sugar stimulated results performed better in the CO_2 fixation rate than the non stimulated ones.
(Zhao et al., 2019)	2019			To determine the effect of different reactor structures on the photosynthetic efficiency in the cultivation process of *Chlorella vulgaris*.	10 L	Three like, multifubular, tubular	Artificial light		*Chlorella vulgaris*	Fractal tree-like and multitubular PBRs is produced by 3D printer and results compared with the regular column and multicolumn BPR (where the measurement indicators including variation curves of Fv/Fm (Chlorophyll fluorescence parameter-original light energy conversion efficiency of PSII) and dry weight of biomass etc.	As a result, the *Fv*/*Fm*, CO_2 capture efficiency of *Chlorella vulgaris* and the growth rate of biomass in the fractal tree PBR have significant advantages.

(Deamici et al., 2019)	2019		15 days for each	This study targets to use various magnetic field conditions application during *Chlorella vulgaris* fusca cultivation to recess CO_2 bio fixation by the microalgae.	2 L	Tubular PBRs	12 h light/12 h dark and an illumination (40 W fluorescent light)		*Chlorella vulgaris* fusca	30 mT or 60 mT magnets applied around the PBR and one PBR without the magnet is used as test subject.	MF application of 60 mT for 1 h d^{-1}increased CO_2 bio fixation by 49.7%compared to the control assay.

3.3. Microalgae in Technology, Design and Architecture

There are several studies on the use of microalgae in the field of architecture, mainly as integrated PBRs and generally focuses on the energy efficiency, biomass production, wastewater treatment or electricity production. In this section, studies on the use of microalgae in the architecture and design as well as innovations, some competition projects, urban installation and products will be presented.

3.3.1. Literature Review on Use of Microalgae in Architecture

Use of microalgae in the architecture is relatively a new subject. Since this thesis focuses on the effect on the microalgae on the indoor CO_2 levels, literature review about the use of microalgae in architecture is limited by the current studies which are focus on the building integrated PBRs. Depending on the research on the Yaşar University databases, sixty results are found on the building integrated PBRs from 2000 to 2019 which involves keywords; microalgae, PBR, building and combinational variations. According to the relevance to the subject, eight of them explained in below.

The first study by Umdu et al. is done in İzmir in 2018. The aim of this study to find the optimized PBR model to use as a building element by enabling a good thermal condition inside and has an acceptable U value to allow the nannocholorop-sisocculatasp to live in the microalgae mixture. In order to measure the U values of the experimental flat panel PBRs with different thicknesses and layers are measured by using thermocouples and a data logging system. The outcomes indicated that calculated U values were not suitable to use the panel PBR directly as building element on the façade (Umdu, Kahraman, Yildirim, & Bilir, 2018). The second study is a project by Pruvost, Jeremy. The study called Symbio2 is a project to propose an optimized link between façade integration of the flat panel PBRs and *Chlorella vulgaris* harvest. The project designed to be as real life façade installation but started with the theoretical studies. The expected results of the project were the partial flue gas treatment (CO2 bio fixation: 1-1.8t/year) and (0.7-1t/year) microalgae production and reduction in the operational cost as well as thermal and CO_2 treatment (Jérémy Pruvost, 2014). Third and fourth studies are also on the same project by Pruvost et al and Araji and Shahdid. The study by Pruvost et al aims to investigate the case of

integration of airlift PBR to the south-facing facade of a flue gas-emitting plant for simultaneous biomass generation and CO_2 amelioration trough the simulations. The results indicates that the microalgae façades can be optimized to diminish the energy needs of the buildings and operational costs (J. Pruvost, Le Gouic, Lepine, Legrand, & Le Borgne, 2016). Moreover, the study by Araji and Shahdid investigates a theoretical optimization to use of PBRs on the building façades by making simulations to test by using two different species of microalgae's characteristics, *Chlorella vulgaris* and Dunaliella, in terms of energy production, CO_2 bio fixation and land resource preservation. Optimization outcomes indicate that growing microalgae on the vertical higher surface has more effective than open ponds and in some cases, *Chlorella vulgaris* performed better than the Dunaliella and for some cases vice versa (Araji & Shahid, 2018). The fifth study by Kerner et al is search for a development of a control system to maintain optimized heat (20-35°C) both microalgae production and heating on the bio façade as a case study of BIQ building in Germany. The real façade is monitored for one year in order to explain the optimal cultivation conditions and the most heat extraction. The outcomes indicated that algae production and heat supply to a building could be efficiently integrated with a bioreactor façade (Kerner, Gebken, Sundarrao, Hindersin, & Sauss, 2019). Similarly, a study by Chang et al, also investigates the BIQ by aiming to introduce a framework to understand the important factors when applying algae facades in buildings, analyze energy and waste stream encompassing algae facades, and evaluate the performance comparing the different building types. In the BIM simulations, potential needs of the algae façades are defined and applied. Then, potential adaptability of algae façades and its holistic performance are evaluated. The results are helpful to understand initial performance evaluation of algae façades (Chang, Castro-Lacouture, Dutt, & Yang, 2017). A controlled environment test study is done by Elnokaly and Keeling in 2016 for five weeks to recognize the possibility of the use of algal technologies in the building sector as architectural creativity in the design of intelligent buildings and the resulting influence on internal luminance. Two tubular test chambers were constructed and the light transmittance is measured on different algal densities by using Nannochloropsis Oculata. The outcomes demonstrate that as culture density improved, the technological strategies and light transmittance decreased proportionally (Elnokaly & Keeling, 2016). Finally but importantly, the last evaluated study is done by Pagliolico. The study aims to use different disposable plastic bags as PBRs and static screens for windows.

The experiments were done for 21 days and 120 to 250 ml plastic bag PBRs in real life tests and as well as simulation method were used. The results indicate that daylight amount in a room in the presence of the algae-system was higher compared to a glazing with venetian blinds. However; higher daylight amount also results in more frequent visual discomfort for the occupants (Pagliolico, Lo Verso, Bosco, Mollea, & La Forgia, 2017). Table 3.2 demonstrates the selected studies for comparison.

Table 3.2 Comparison of the studies on the use of microalgae in the architecture

Name	Year	Duration	Aim	Type	PBR Type	PBR Application Area	Microalgae Type	Method	Result
(Umdu et al., 2018)	2018		To find and optimal model PBR which has reasonable U values to provide sufficient living condition for nannocholorop-sisocculatasp. while working as a building element and keeps the thermal comfort inside the building in an acceptable level.	Laboratory experiment	Flat panel	Façade	nannocholorop-sisocculatasp	The experimental PBR set up is used to calculate thermal transmission that includes heating and cooling system with electric meters, blower, air control valves and a data logger. Temperature of the test system is monitored.	Result show that calculated U values were not satisfactory to use the panel PBR directly as building element on the façade.
(Jérémy Pruvost, 2014)	2014	One-year theoretical work and after real life construction.	To design an optimized the relationship between façade integration of the flat panel PBRs and microalgae cultivation. (Symbio2)	Real life installation. 300 m2 façade (Currently under theoretical study)	Flat panel	Factory façade	*Chlorella vulgaris* vulgaris		The expected the partial flue gas treatment (CO_2 bio fixation: 1-1.8t/year) and (0.7-1t/year) microalgae production and reduction in the operational cost. Thermal and CO_2 treatment.
(J. Pruvost et al., 2016)	2016		to investigate the case of integrating airlift PBR into the south-facing facade of a flue gas-emitting plant for simultaneous biomass production and CO_2 bio fixation	Simulation	Flat panel	Façade	*Chlorella vulgaris*	Simulations are made to understand the potential CO_2 fixation rate, and energetic analysis	The results shows that the microalgae façades can be optimized to reduce the energy demands of the buildings and operational costs.

(Araji & Shahid, 2018)	2018		To demonstrate a theoretical optimization approach to use PBR on the building envelope.	Simulations to test energy production, CO_2 bio fixation and land resource preservation.	Flat panel	Façade	*Chlorella vulgaris*, Dunaliella	A mathematical model to calculate the energy generation by considering the micro-algae PBR as a renewable energy source is developed. Then the calculations are followed by optimizing various factors that can impact the overall contribution of the PBR to the building	Optimization results show that growing microalgae on the vertical higher surface has more efficient than raceway ponds and in some cases *Chlorella vulgaris* performed better than the Dunaliella and for some cases vice versa.
(Kerner et al., 2019)	2017-18	one year in Germany	To develop a control system to maintain optimized heat (20-35°C) both microalgae production and heating on the bio façade.	Monitoring on the real façade.	Flat panel	Façade	*Chlorella vulgaris*	To understand the optimal harvest conditions and the most heat extraction, set point parameters and measurement system was developed to balance the ambient air caused heat production and user determined consumption. Impedance sensors measured the outside temperature and the temperature in the culture medium of the bioenergy façade.	This paper has shown that algae production and heat supply to a building can be efficiently integrated with a bioreactor façade.

(Chang et al., 2017)	2017		To present a framework to understand the crucial factors when applying algae facades in buildings, analyze energy and waste stream encompassing algae facades, and evaluate the performance regarding different building contexts.	Simulation on BIM		Façade		Potential requirements of the Algae façades are determined and applied on the simulation program. Then, potential adaptability of algae façades and its holistic performance are evaluated.	This framework paper is helpful to understand the initial performance evaluation of algae façades.
(Elnokaly & Keeling, 2016)	2015	five weeks	To investigate the potential of the use of algal technologies in the building sector as architectural creativity in the design of intelligent building fabrics and the resulting influence on internal luminance	Controlled environment test.	Tubular	Façade	Nannochloropsis Oculata	Two test chambers were constructed and the light transmittance is measured on different algal densities.	The results show that as culture density increased, the technological strategies and light transmittance decreased proportionally
(Pagliolico et al., 2017)	2016	21 days, from July 2 through 22 and 21 days, from October 14 through November 3.	To use different disposable plastic bags as PBRs and static screens for windows.	120 to 250 ml plastic bag PBRS and simulation	Plastic bag PBRs	Façade	Scenedesmus obliquus	Different sized plastic bags are used as PBR in the real room and also the results are simulated in terms of Energy efficiency and light transmittance.	The results show that daylight amount in a room in the presence of the algae-system was higher compared to a glazing with venetian blinds, however higher daylight amount also results in more frequent visual discomfort for the occupants

3.3.2. Microalgal Developments and Innovations

There are some developments in the microalgae world in order to increase the growth rate, productivity, and usage area of the microalgae by changing the genetics of them. For example, researches at UC San Diego successfully created genetically modified algae by using the Fluorescent proteins (FPs) to expand the spectral palette of the green algae. They have created six different rainbow colors, red, orange, yellow, green, cyan and blue, which glow light due to the FPs in their cells (Rasala et al., 2013) (Figure 3.6) and can be used in façade design, interior design, as well as lighting design.

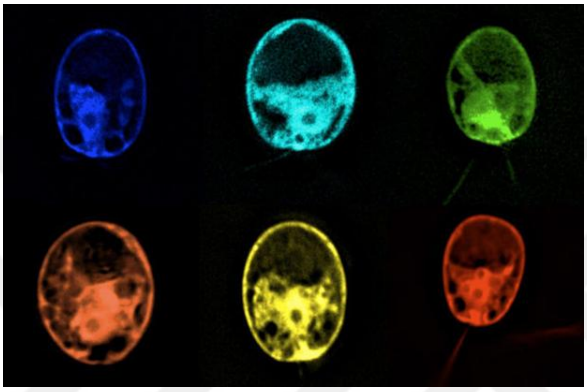

Figure 3.6 Genetically Modified Microalgae (Sandle, n.d.)

Another development on the field of microalgae is the presentation of nanocellulose, which is isolated from red algae. Compared to land plants, isolation of nanocellulose from the microalgae has many benefits by having faster growth rate, requiring no chemical treatments and having a low cost to grow. In addition, thanks to its better thermal stability and significant crystallinity this algae isolated cellulose is a promising source to use as a reinforcement in composite materials and nano-filler for polymer materials which can be applied in the field of architecture as well (Chen, Lee, Juan, & Phang, 2016).

Apart from the scientific researches and developments, there are some innovational designs related to the microalgae, which might be useful in the future as a part of engineering, architectural and interior architectural design. One of them is algae bioreactor design that they call it Verde (Figure 3.7) for residential properties and individual buildings from Grow Energy. Verde is compatible with solar collectors and tubular bioreactors. The company claims that Verde will pay for a return in 5 years and has a capacity to produce up to 12.500kWh/year from 185m^2 of bioreactors. The system works in three stages. Firstly, the light is taken in by solar collectors which are located on the top of the building and transferred to the bioreactor volume via fiber

optic cables. In the second stage, the algae have grown inside the bioreactors where the light is evenly distributed to the algae so as to achieve optimized photosynthetic productivity.

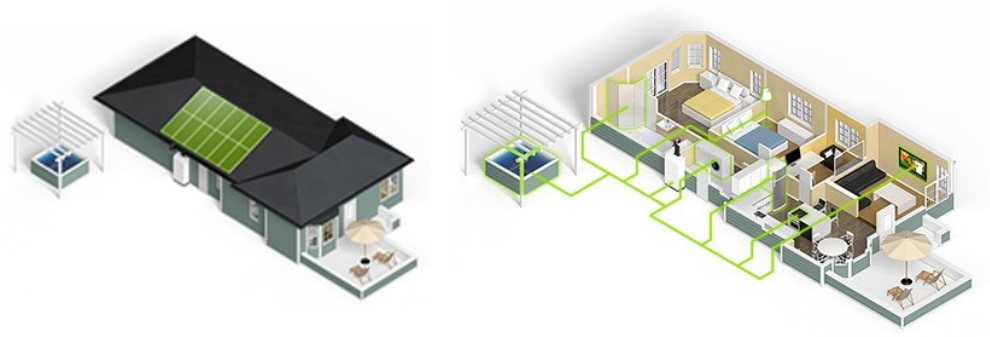

Figure 3.7 Grow energy Verde System ("A Great Solution for Homeowners," 2018)

In the final stage, the grown algae that exit from the bioreactor enter to the combustion chamber, that includes nutrient pump, converter, generator and batteries, where the biomass is converted into the electricity while the released CO_2 is used in the growth process again ("A Great Solution for Homeowners," 2018). Once the Verde is completed to for mass manufacturing and use, the system can provide a unique alternative to generate environmentally friendly electricity and a promising solution for architects in the design process. The second innovative design in the field is an Indoor Farming plant designed by a German company called Mint Engineering (Figure 3.8). The company aims to design a fully automated system which has an aesthetically optimized design, to produce fresh air (O_2) and valuable biomass by using the local CO_2 of the room where the system is located in, whether it is an office or a conference room, etc. with the help photosynthesis of the microalgae ("Indoor Farming," 2018). In the future, although this indoor farming system could be highly efficient design in terms of providing fresh air where it is needed and allows companies or users to decrease their carbon footprint, the system is still lack of technical details and requires some work to function smoothly.

Figure 3.8 Indoor Farming Plant ("Indoor Farming," 2018)

3.3.3. Microalgae in Urban Design

Apart from the developments in the algal technology and innovations microalgae is also used in the urban design elements both as a conceptual and as real-life construction such as pavilions, streetlamps, and urban installations. There some examples are given below in a chronologic order. The first example is Energy Flowers by Emergent Architects (Figure 3.9), which is a functional art installation, built in 2009 and located in a train station in Perth, Australia.

Figure 3.9 Energy Flowers ("Photobioreactor Produces Biofuel as Art," 2011)

The aim of this installation is to generate energy for the train station by using biofuel and produce light during the night. Seven human-sized helix PBRs are installed in the station, which is connected with multicolor twisted biofuel lines from the street nearby to the train station. The outside of the PBRs is made of fiber-composite monocoque structure plated for rigidity. The inside is made of clear acrylic that holds the algae culture, red and green colored algae. The system operates by using the technology, which is developed by OriginOil, Los Angeles based water cleanup technology company. Depending on how the system works, the photosynthetic process uses the local CO_2 from the atmosphere on the front end of the PBR and produces biofuel at the back end. The closed system minimizes contamination and provides the easier controllable environment. The power needed for the system provided by thin-film solar transistors, which charge during the day, embedded in the clear transparent polycarbonate apertures that are backed by the external shell of the PRBs. The system can work during the night as well due to the helix of lights inside of each coil and provides convenient technological ground lighting or the people passing by. This art installation has some advantages to show the public by having a closed system, being able to work during the night and as a source to produce super-localized energy in the

future (“Photobioreactor Produces Biofuel as Art,” 2011). Another example is also from the Emergent Architects, which is a shop window installation called Flower Street Bioreactor in Los Angeles, California, USA (Figure 3.10).

Figure 3.10 Flower Street Bioreactor (“Flower Street Bioreactor,” 2018)

The installation is constructed in 2009 and aims to give light during the night and raise awareness about different fuels and by using new technologies and sense of beauty. An aquarium-like PBR made of clear thick acrylic by 275x580 cm is installed into the façade of the shop window. The PBR uses green algae and has an internal LED lighting armature which has a variation in colors and intensity for optimum output. The system uses ‘Bio-feedback Algae Controller’ by OriginOil (“Bio feedback algae controller,” 2018). The system has an advantage to provide algae growth in a developed way while providing urban jungle effect with the help of LED lights during the night by collecting and storing the solar array in the daytime (“Flower Street Bioreactor,” 2018).

Chlorella vulgaris Oxygen Pavilion (Figure 3.11) is a competition winner as well as a master thesis by Adam Miklosi from the School of Design and Crafts, University of Gothenburg in 2012. The aim of this pavilion is to design a conceptual urban shelter against the air pollution while creating interactive environment with users. The design of the pavilion is inspired from symbiotic relationship between algae and human by offering a solution for users to grow their own fresh air.

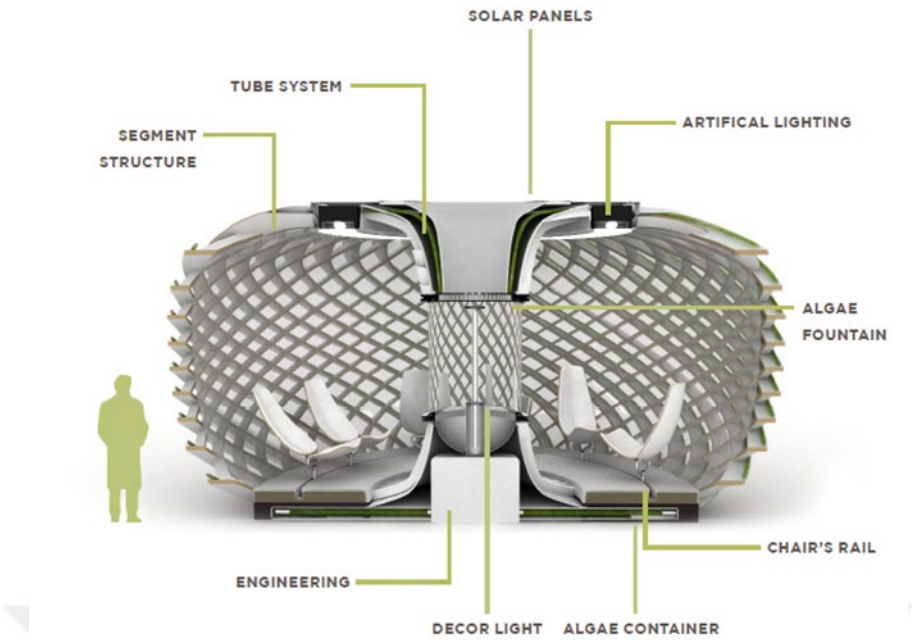

Figure 3.11 *Chlorella vulgaris* Oxygen Pavilion (Miklosi, 2012)

The exterior of the pavilion is constructed as the space frame structure by being lightweight and providing various geometric patterns. The spherical shape is chosen as the best design solution since it provides better indoor air circulation by not having any corners. The interior is designed depending of the function which is relaxation and half-disconnection from the urban environment. The air circulations and calculations are made according to the molar mass of the Oxygen and Carbon dioxide. Since the CO_2 is heavier than the O_2 the design of the pavilion is shaped around it. In the lower part, there is an extraction system for CO_2 and in the upper part; the fresh air is blown to the users. The calculations for air consumption in closed systems is made by using the NASA's research and the results demonstrate that inside the pavilion one person can breathe all the O_2 in two days however, the pavilion is able to generate O_2 to double the period. There are ten chairs around the algae fountain which is a main part of the pavilion and located in the middle. The chairs can be moved easily around the fountain in a variation if there are couple of friends and or individuals. The algae fountain has two critical functions. First one is the absorption of the CO_2 and the second one is decoration. The cleaned air is blown to the users from the above and will slowly go down to the users' level. The smell of the algae in the fresh air is handled by using active carbon filters. Finally, when the pavilion is empty the fresh air will directly flows to outside in order to clean the immediate atmosphere (Miklosi, 2012).

The fourth urban design example is an ‘Algae Powered Street Lamp’ by biochemist Pierra Calleja (Figure 3.12). The lamp is designed in 2013 in order to generate light during the nighttime by using algal biomass. The lamp consists of a batter system and a tube that is filled with algae culture. Photosynthesis helps the lamp to charge during the day and the battery stores the power to generate light in the night. Moreover, the energy produced by the algae by using CO_2 eliminates the need for sunlight for the operation of the lamp. The CO_2 from the cars in the garages provides the gas needed for the lamp to work. As an advantage, it is claimed that the lamp can absorb to 1 ton CO_2 per year, which means as much CO_2 in one year as a tree does in its whole life. Those lamps can be customized in order to increase the usage of this technology by altering the colors of the algae and the appearance. Last but not the least, the waste algae can act as biofuel when it is separated from the water and the water can be recycled to use to other intentions (Spendlove, 2014).

Figure 3.12 Algae Powered Street Lamp (Michler, 2011)

Another urban design beside the Algae Powered Street Lamp is ‘Algae Garden’ by The Cloud Collective Company in Geneva, Switzerland in 2014 (Figure 3.13). Algae Garden also called as Urban Algae Farm is an installation is designed to demonstrate that algae can grow almost in any environment to produce fuel and food. PBRs are designed as transparent pipes which are filled by green algae and installed to the side of a pedestrian and cycling path footbridge. The support elements like pumps, filters, and solar panels are backed by a steel structure. As a CO_2 source the exhaust gases from the cars that are used. This project is an opportunity for designers and architects to think outside the box in order to use the existing environment for urban algae farming (Mitchell, 2014).

Figure 3.13 Algae Garden (Mitchell, 2014)

Ecologic Studio is London based company that has designs related to microalgae. They have designed two urban gazebos, Urban Algae Canopy and Urban Algae Folly for Expo Milano 2015 (

Figure 3.14). The aim of these gazebos is to produce biomass, food for visitors, and shadow by depending on the algae growth and provide fresh air. With the assistance of German-based company Taiyo Europe a special design ethylene tetrafluoroethylene (ETFE) which is a clear plastic construction material is used to build the gazebos. The interior of the ETFE is filled with water and green algae *Spirulina sp.*. The CO_2 from the atmosphere and the visitors are used as a source for the algae to grow and their growth rate depends on the digital sensors for maximized production. According to the company, the cost of each gazebo is about 1200 € and they are able to create the O_2 almost equal to four hectares of forest and 150 kg of biomass every day (Brooks, 2015) (Laylin, 2015). The last urban installation example is 'Algae Dome' by Danish company Space10 and presented at the Chart Art Fair. The dome is built in 2017 in Copenhagen so as to produce food and increase the local O_2 level. *Spirulina sp.* filled 320 meters of a clear plastic piping system is covered with 4 meters high wooden structure. The dome is a place for visitors to enjoy algae food and "breathe of fresh air" as well as an opportunity to raise awareness about the capability of microalgal designs (Thorns, 2017).

Figure 3.14 Urban Algae Canopy and Urban Algae Folly (Brooks, 2015; Laylin, 2015)

3.3.4. Microalgae in Architecture and Product Design

Although microalgae are used in the urban design more common, they are also used in the architecture. Using microalgae in the architecture field is a relatively new but promising subject. There are some real life and competition winner examples as well as master thesis within the subject and in this subheading; those examples are discussed in a chronological order.

The first instance is an abundance prizewinner of the 2011 International Algae Competition. Influx Studio a French-based company proposed a design called Green Loop Tower as an installation to the existing building of in Chicago, Illinois, USA (Figure 3.15). Depending on the design, the towers aim to produce biofuel, reduce CO_2, produce food and filter the water by using microalgae. The closed PBRs reduce the CO_2 in three different stages; the first one is the CO_2 absorption from the atmosphere as a food for the microalgae in PBRs, the second one is the extraction through plant photosynthesis such as vertical gardening, and the last one is the use of solar and wind harvesting energy as an energy source. The architecture studio developed a PBR design that includes CO_2 scrubbing integrated system also compatible with wind and solar harvesting. The CO_2 scrubbing plants consist of two fundamental parts, PBRs and the CO_2 scrubbing modules where they are positioned on the tops of the two towers.

Figure 3.15 Green Loop Tower (Furuto, 2011)

The design of the CO_2 scrubbing modules is developed by Dr. Klaus Lackner. They have the "humidity swing" which catches the CO_2 from the air and provides needed gas supply for the PBRs. The helix type PBRs are mounted around the carbon scrubbers in both towers as well as in the 18 floors in the east tower that is close to the parking lot. To sum up, although, there no accepted data about the energy efficiency of the project the PRS are designed to cover the energy needs of the towers as a green solution (Elrayies, 2018; Furuto, 2011) . The second example is also a competition winner by HOK, USA based Architecture Company, and Vanderweil, USA based Engineering Company which is called Process Zero (Figure 3.16). The Process Zero is a retrofit solution for the federal office building in the Los Angeles, California, USA as a winner of the both International Algae Competition and the Metropolis Magazine's Next Generation Design Competition in 2011. The aim of the design is to generate biofuel in order to cover 9% of the buildings power requirement from microalgae, provide sun shading to via PBRs and offer fresh O_2 to the interior areas while targeting to reduce the total CO_2 emission of the building by 30% with the help of other integrated renewable energy systems. The tubular panel PBRs cover the 24.000 m2 of the building's envelope. They catch the sunlight, emit CO_2 and generate O_2 while producing lipids for biofuel production on site. The PBRs also work as a sunshade to the interior and give the building a dynamic façade design.

Figure 3.16 Process Zero Building (McManus, 2018)

The tubular PBR system is connected to a central feeding vessel that includes microalgae and other needed ingredients such as CO_2, nutrients, and water to grow the microalgae. The needed CO_2 is collected from a close freeway and the building's grey water is used as a water source while building's black water is processed for the additional nutrition supply. The produced O_2 is released into the building by degassing tank and the lipid-extracted water goes back again to reuse in the feeding vessel when the algal biomass can be burned for heat and electricity or used as algae oil (McManus, 2018).

The third example is Bio-Intelligent Quotient (BIQ) building (Figure 3.17) the only fully operated microalgae powered real-life building that was designed in 2013 by German architecture company Arup. The project of the building is also a prizewinner of the Land of Ideas 2013/14 competition. The aim of the BIQ house is to produce heat and biofuel, shade the interior and diminish the noise that comes from the street by on-site microalgae cultivation. Southeast and southwest façades of the building are covered with 129 flat panel PBRs as a second layer. So as to generate electricity and biofuel the glass panel PBRs are filled with microalgae culture. Each panel has 2.5m x 0.7 m dimensions that are laminated with safety glass and thermal insulation, with the 0.8m thickness which allows 241 liters of microalgae culture inside. The glass PBRs enable sunlight to turn as a heat into the building as well as convert sunlight into the biomass via photosynthesis. There are two separate pipe systems from the bottom as a CO_2 and a wastewater (nutrition) supply source for the PBRs. The compressed CO_2 from the bottom produces air bubbles with the aim of circulation of the algae medium. The circulation changes the position of the microalgae and increases the absorption of the sunlight and carbon. The CO_2 is coming from an external on biogas device which is also used to produce energy and heat through algal biomass. The water system includes nutrients that are needed for microalgae to grow. All the piping system

is hidden under the space of the PBRs. The algae culture is harvested almost once a week. The produced heat is used to warm the building and preheat the warm water while the excess heat is stored under the geothermal wells located under the building. However, the electricity supply of the building from the biogas (methane) is not done on site since the technology is not available to use on the residential buildings. Although, the effectiveness of the BIQ building is still being monitored, the results after one year shows that the building reached 58% energy efficiency (10% for biogas,48% for heat) in total and the electricity generated by algae façade is enough to operate one apartment, while the heat production is even enough for four apartments. Finally, yet importantly, the cost of the multifunctional façade is 6.58 million dollars (Moschopoulou, 2015).

Figure 3.17 BIQ Building and Photobiorector Detail (Moschopoulou, 2015)

Because of being promising and current topic microalgae in architecture is also studied as a master research topic. Fong Qui from Technical University of Delft proposes microalgae integration for Sloterdijk Railway Station in Amsterdam, the Netherlands for his master thesis in 2013. The research aims to use the microalgae as a biomass production source, sunshade for interiors, a street lighting with integrated LED system during the night and a striking installation for the public. Figure 3.18 shows a rendering by Qui as a suggestion of where to use the PBRs. Tubular PBRs are offered to use on the new glass façade and on the supporting construction to use both as a biomass source and as sunshade. The flat panel PBRs are installed to the roof so that they can rotate and follow the sunlight so as so boost the production. Helical PBRs can be used as a street furniture where people can sit and rest and during the night with the help of LED integration, they can light the environment without compromising the microalgae cultivation. Moreover, it is proposed to use the genetically modified glow in the dark microalgae in the banisters as a light source to create special ambiance. According to

the thesis the big elements similar to columns can be placed in the interior in order to show the microalgae production to the people and create a dynamic atmosphere inside (Qui, 2014). To summarize, there is not so many master or PhD thesis about the use of microalgae in the architecture, therefore this study offers different design suggestions to integrate microalgae in the architecture.

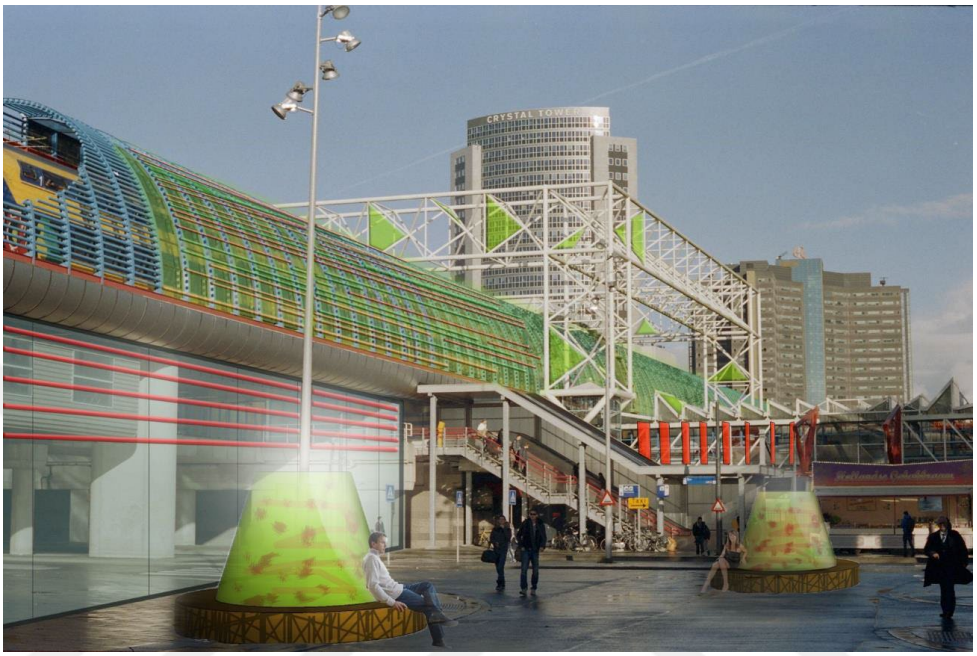

Figure 3.18 Rendering of Suggested Photobiotectos by Qui (Qui, 2014)

Another example about the integration of microalgae in the field of architecture is a PBR installation to the historic gas storage tower which is located in EUREF- Campus, Berlin, Germany in 2015 for the European Algae Biomass Conference. This installation was a demonstration of the MINT's "Urban Farming" PBR system (Figure 3.19). The aim of this installation was to show the cultivation of microalgae as an integrated system to the building itself to offer a different solution to reduce carbon footprint. Fully automated four tubular pipe PBRs are partially installed on the south façade of the building. In order to grow microalgae the system uses the sunlight and exhaust gases from the cement factory which is closer to the location (Albert, 2016). The last example is from is a case study by London based company Aeroplus, that aims to investigate the main question "How can the algae filter be introduced into the market?" by examining their air cleaning features and the economic feasibility of the product. The system that is company works on is photo bioreactor which is going to be located on the top of the building and work with the suck pipe linked directly to the air system in the building. The microalgae is inside the PBR system. The system will work by sucking the CO_2 and cleaning the air (Pierik, 2016) . Figure 3.20 Aeroplus,

air filter system (Pierik, 2016).shows the basic system. This system can be a good candidate to filter and clean the air by considering the whole building. However, the system still requires a lot of effort to work smoothly and be economically feasible.

Figure 3.19 Demonstration of the MINT's "Urban Farming" PBR System. (Albert, 2016)

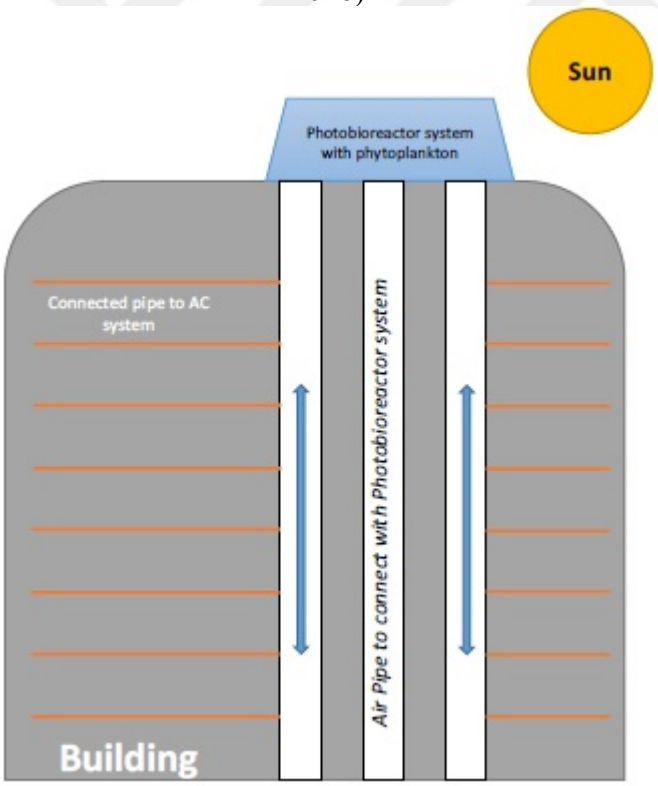

Figure 3.20 Aeroplus, air filter system (Pierik, 2016).

Moreover, there are some product designs that includes microalgae as a main element. One of them is living chandelier by UK based design engineer and biotechnologist Julian Melchiorri. A modular chandelier composed of 70 glass petals filled with microalgae aims to purify the air with photosynthesis while lighting the environment.

The chandelier designed as to use both for indoor and outdoor with a sophisticated look which is inspired from nature, Art-Nouveau and İslamic art collections. Bionic Chandelier is only produced as a prototype and now became an art piece in the permanent part of the V&A Museum (Melchiorri, 2017). Figure 3.21 shows the photo of the design.

Figure 3.21 Bionic Chandelier (Melchiorri, 2017)

CHAPTER 4
THE EXPERIMENT

This study started by the fact that people spend most of their times in indoor spaces and the necessity of the providing of high-quality indoor air. Therefore, intended for the aim of this thesis, a literature review was carried out with the importance of indoor air quality, related standards and improvement methods. As far as the studies are analyzed, it has been understood that there are many studies that benefit from indoor plants to improve indoor air quality. Similarly, as an interior architect, rather than by changing ventilation flow rates, it was aimed to measure the effect of microalgae on indoor air quality, which was claimed to be more successful than indoor plants by photosynthesis (U. B. Singh & Ahluwalia, 2013). However, when the studies on microalgae were examined, it is determined that there are studies conducted in the laboratory environment and the lack of studies in the literature where these studies were tried in a real interior environment. For this reason, an experimental setup was established at Yaşar University in order to contribute to cover the gap that was found in the literature as well as perceiving usage of microalgae in the design as a promising aesthetic and efficient candidate for the future by based on the design proposals in the chapter three.

4.1. The Set-up Area

The office where the experimental PBR was set up is located at Yaşar University Y Block 6th floor in İzmir, Turkey. The size of the office is 6x5 m and the total volume is 75 m^3. There are two doors, two fresh air suppliers and two air outlets in the office. The ventilation options for fresh air are mechanical central ventilation and keeping the doors open, since there is no window for natural ventilation. The mean temperature during the experiments was between 20-25 ^oC. Figure 4.1 and Figure 4.2 show the plan and interior elevation of the experiment area, location of the data logger device and PBR. Moreover, the only solution for lighting is artificial lighting and there is no daylight coming in. Therefore, the photosynthesis rate of the microalgae is limited by

the illumination level of the office. Figure 4.3 and Figure 4.4 show the indoor photos of the office.

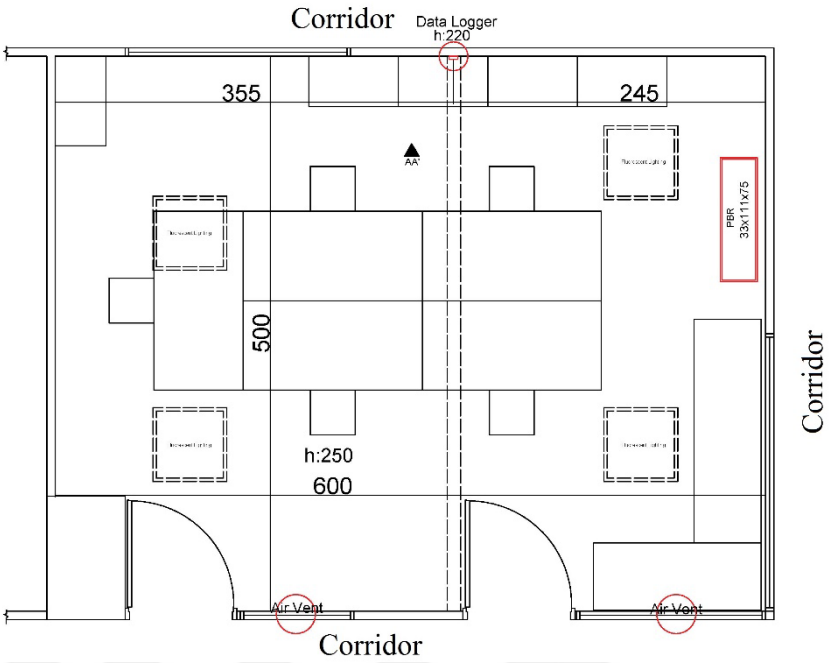

Figure 4.1 Plan of the experiment area. (Not in scale. Dimensions are in cm)

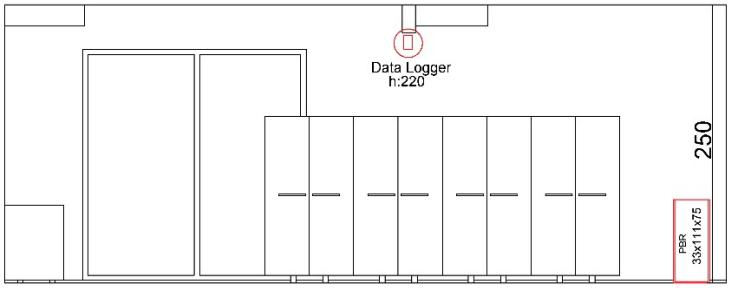

Figure 4.2 AA' Interior Elevation (Not in scale. Dimensions are in cm)

4.2. The Experiment and Data Collection

The PBR that was used during the experiment and observations is made of clear acrylic with 1.5 cm thickness. The size of the PBR is 33x111x75 cm and the total interior volume is nearly 275.000 cm^3 that is equal to 275 liters. Figure 4.5 demonstrates the experimental PBR. The PBR is indented use for domestic areas or small office areas; therefore, the size is determined accordingly. The tare weight of the PBR is nearly 45 kg which is an acceptable weight to carry by two people, one woman and one man (Matheson, Verna, Dreisinger, Leggett, & Mayer, 2014). The height of the PBR was decided as 75 cm to make the operational processes such as cleaning the PBR and harvesting the microalgae achievable by one adult. However, the quantity of the PBRs and amount of the microalgae can be increased accordingly. The PBR was placed on

the North side of the office in such a way that the occupancy comfort was minimally affected. The experiment was done from beginning of November 2018 to end of March 2019. From 6th of November to 11th of December 2018, the PBR was filled with 20 liters of *Spirulina sp.* and 60 liters of clean water. 16 grams of Sodium Carbonate (Na2CO3) for each liter was added to the PBR as nutrition (16x80=1280 grams). Feeding process was done once in 10 days. To provide equal growing and photosynthesis rate an aquarium air pump was located in the PBR. Figure 4.6 shows the PBR filled with 80 liters of *Spirulina sp.* From 12th of December to 31st of January, the CO_2 concentration in the office was measured without any microalgae while the official number of the users was five. Then, from 1st to 21st of February, CO_2 level in the office area without any microalgae and official number of users as one measured. Finally, from 22nd of February to 31st of March, the PBR was filled with 4 liters of *Chlorella vulgaris* and 46 liters of clean water. One milliliters of nutrition mixture were added for each liters of the microalgae mixture (total of 50 milliliters). The feeding process was done for every 10 days. However, due to being quieter and providing better mixture from the bottom, instead of aquarium pump, two air stones, 35 cm each, were put in the PBR. Figure 4.7 shows the *Chlorella vulgaris* filled PBR.

As given at the literature review most common types of algae are *Chlorella vulgaris* and *Spirulina sp.* For that reason Ege University, Faculty of Fisheries provided all these two types of microalgae and the nutrition. During the experiments, there was no external source of CO_2 rather than the respiration of the users to boost the photosynthesis of microalgae.

Figure 4.3 Office from the South West Corner.

Figure 4.4 Office from the South East Corner.

Figure 4.5 Experimental PBR in the Office Area.

Figure 4.6 *Spirulina sp.* Filled PBR.

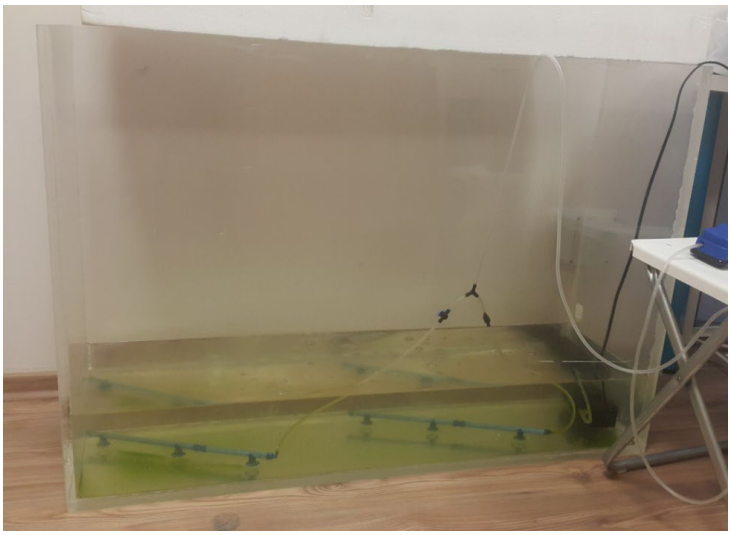

Figure 4.7 *Chlorella vulgaris* Filled PBR

In order to start to measurements of the CO_2 level in the office area, a data logging **IAQ measurement device, testo 160 IAQ**, had installed on the back wall of the office area, where is not easily affected by outer factors such as, direct respiration of the occupants, door opening and air ventilation channels. Figure 4.4 also shows the location of the measurement device. The device was data logging in every 5 minutes, however, during the experiment, in order to calculate the mean CO_2 ppm and to create the occupancy pattern every half hour data was used. The office is located between two corridors. In order to keep the silence in the office the door was always closed if anyone was at the office. For that reason period of open door position has been ignored. The occupants were four women and one man with the average age of 28 during the first experiment. In the experiment II, four of the users moved from the office. The occupancy pattern started recorded on 17.12.2018. The occupancy pattern was created as if one person stays in the office area for half an hour it calculated as 1/2 (person/ hour), if a person stays for 15 minutes it calculated as 1/4 (person/ hour). Similarly, if two people stay in the office for 15 minutes it calculated as 1/2. In addition, going out from the office for 10 minutes or being in the office less than 15 minutes up to three people was ignored. Also, initial hour ppm and the end hour ppm levels were recorded for each half-hour period for everyday from November to April. For each day, forty-eight rows of data were collected and a data collection table similar to Table 4.1 was created.

Table 4.1 Data Collection Table Example

Data Date	Time From-To	Initial Hour CO_2 (ppm)	End Hour CO_2 (ppm)	Number of Users (person/half-hour)	Microalgae Amount (L)
1.11.2018	00:00-00:30	576	566	0	0
1.11.2018	00:31-01:00	566	553	0	0
⋮	⋮	⋮	⋮	⋮	⋮
31.03.2019	23:30-00:00	377	379	0	50

The lowest value was measured as 370 ppm on 31.3.2019 (Sunday) at 19:30 PM and highest one was 1763 ppm on 30.01.2019 (Wednesday) at 15:00 PM. The reason of the highest value was the unexpected occupancy in the office because of the moving out from the office. While calculating the mean values 1763 ppm which was the highest value ignored because of being an extraordinary situation.

In Figure 4.8 overall hourly distribute on of the average CO_2 level, with and without the microalgae is demonstrated including all the days of the experiment. **The lowest values measured as 435 ppm at 07:30 AM and the highest value was 776 ppm at 15:30 PM, mean value is 584.** In addition, in Figure 4.9 general distribution of ppm levels during the experiment is indicated, which shows that the ppm level is mostly in the acceptable range as the total experiment time expressed at 100%. Figure 4.9 is created by including all the dates from beginning of the experiment to the end, all the occupancy and days both with PBR in actively in use and PBR is inactive is added.

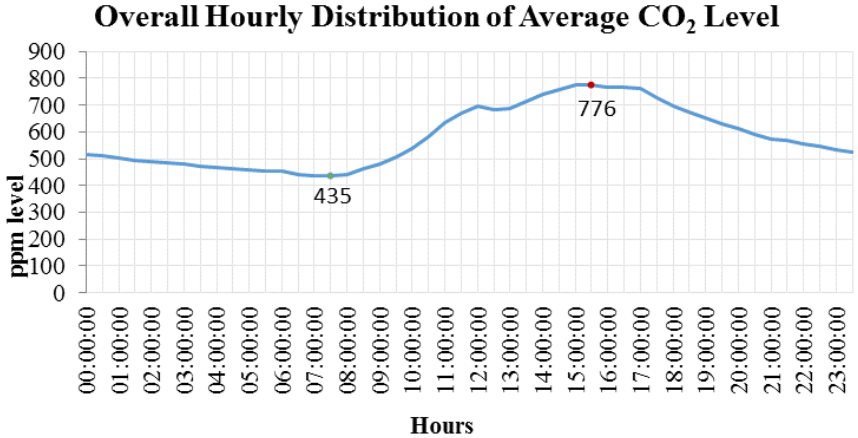

Figure 4.8 Hourly Distribution of Average CO_2 Level From November to April

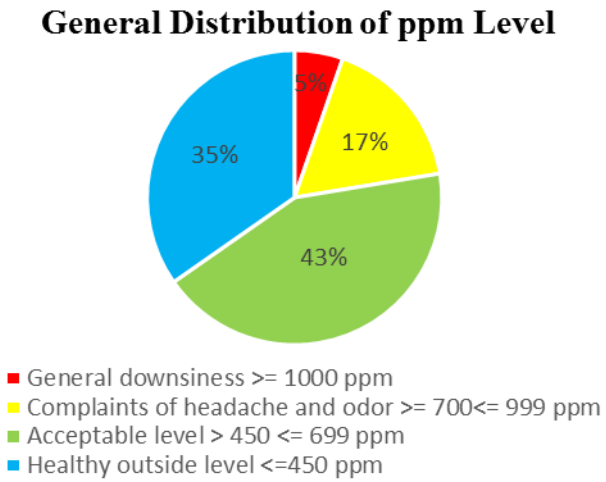

Figure 4.9 General Distribution of ppm Level

The total experiment composed of two parts. The experiment I and the experiment II. The experiment I was from November 6, 2018 to January 18, 2019. The experiment II was from February 1 to March 31, 2019. However, the since the data logger device continuously records the CO_2 level in the office area in between the experiments the data from the weekends were evaluated separately within the experiment I and experiment II and separated according to the change in the number of official users.

4.2.1. The Experiment I (November 6 – January 18)

The experiment I was conducted from November 6, 2018 to January 18, 2019. During the experiment I, the used microalgae specie was *Spirulina sp.*. *Spirulina sp.* is a blue-green freshwater algae, which uses Na_2CO_3 (Sodium Carbonate) as medium (De Morais & Costa, 2007).

Table 4.2 shows the characteristics and optimum requirements of this specie together with the office area's conditions. Also, during the experiment I, the office was officially used by five people. Between, 6th of November to 11th of December the PBR was filled with *Spirulina sp.* mixture and the occupancy pattern was not recorded. In December 12, a PIP camera was installed to record the occupancy pattern and the PBR was cleaned. From 12th of December to 18th of January, the experiment I was done with an empty PBR and recorded occupancy pattern. Table 4.3 indicates the chronological process of the experiment I.

Table 4.2 Characteristic of *Spirulina sp.* and Office Conditions

***Spirulina sp.* Growth Temperature (^{0}C)**	20-30 ^{0}C (Converti, Casazza, Ortiz, Perego, & Del Borghi, 2009)	**Office Temperature (^{0}C)**	Between 25-30 ^{0}C	
***Spirulina sp.* CO_2 level for maximum fixation**	0.07% (Kim, Park, Park, Lee, & Oh, 2004)	**Office CO_2 Level**	0.04%	
Illumination Levels for *Spirulina sp.*	370-11.100 lux (Sforza, Simionato, Giacometti, Bertucco, & Morosinotto, 2012)	**Office Illumination Levels (Lux) (tested by testo 435 measuring device)**	**Weekdays**	**Weekends**
			243 in general 228 around PBR*	8 in general 3 around PBR*

* Achieved values are mean of calculated measured illumination level during working hours.

Table 4.3 Chronological Process of Experiment I

6th of November	• IAQ measuring device (testo 160 IAQ) was placed in the office area. • 20 Liters of *Spirulina sp.* was obtained from Ege University, Faculty of Fisheries. • *Spirulina sp.* is mixed with 60 liters of clean water (pH 6.8). • PBR was filled with total of 80 liters of microalgae-water mixture. • Aquarium air pump (Angora XL-1000F) was placed in the PBR to provide even growing rate.
Every 10 days	• Mixture was fed by 16 grams of Sodium Carbonate (Na2CO3) for each liter as nutrition (16x80=1280 grams). • Clean water was added to keep the amount of microalgae mixture in the same level.
Until 11th of December	• CO_2 level in office was continuously data logged by IAQ measuring device.

12th of December	• PIP Camera was installed in office to record the number of the users inside (Occupancy of one person and door openings for less 15 minutes were ignored. Official total number of the users were5) • PBR with 80 liters of *Spirulina sp.* mixture was emptied and cleaned.
From 17th of December to 17th of January	• CO_2 level in office was continuously data logged by IAQ measuring device (testo 160 IAQ) (Empty PBR). • Number of the users inside was recorded for each half hour period.
18th of January	• End of the experiment I.

The experiment I, includes three parts: I) Increase in CO_2 level by one person, II) CO_2 level in the office area during the weekdays. III) CO_2 level in the office area during the weekends. In the first and the second parts of the experiment, artificial illumination by the florescent lamps in the office were used constantly during working (08.30- 17.30) hours because of the location of the office, it was quite dark to work sufficiently in the office without any external illumination source. The illumination level in the office averagely measured as 2-3 lux during the weekends and 243 lux in the weekdays with testo 435 measuring device.

The first part was done to understand the increase of carbon dioxide by a person within half an hour period when the office has started to use in the mornings during the weekdays. The weekends were not calculated within the average value. To evaluate this, they days are selected when the first user arrived to the office and stayed in the office alone for at least half hour period before the other users arrive. The CO_2 level recorded by the data logger at the time when the first user had arrived used as initial hour data, then the CO_2 level after half hour occupation was used as end hour data. All the CO_2 levels are averaged for the selected days as initial and end hours. In the experiment I, 30 days were fitting the requirements, 17 days with microalgae and 13 days without. During the period when there was 80 L of microalgae mixture, **the minimum initial hour ppm was measured as 409 ppm on 12.11.2018 and maximum was 693 ppm on 03.12.2018, during the same period, minimum end hour was 440 and maximum was 800 ppm. The lowest values are measured as 432 ppm on 26.12.2018 and for the initial hour and 506 for the end hour on 17.01.2019 when there were no microalgae in the office. The highest values**

measured as 746 and for 859 on 24.12.2018 both for initial and end hours. Table 4.4 indicates the average ppm levels for initial and end hour in terms of CO_2 increase by one person. **The average values were calculated as 563 for the initial and 628 for the end hour for the times without the microalgae in the office area. For the times with the microalgae the same values were calculated as 487 ad 560 with the same order.**

Table 4.4 Average Initial and End Hours of CO_2 level (November 6- January 18)

Average Initial Hour CO_2 ppm	Average End Hour CO_2 ppm	Microalgae Mixture Amount (L)
563	628	0
487	560	80

The second part of the experiment I, was done to understand average CO_2 level differences between the times with and without the microalgae in the weekdays. During the experiment I, the office used to use by five people officially. The PBR was filled with 80 liters of *Spirulina sp.* mixture from November 6 to December 12. Then from December 13 to January 18, data loggings were made to analyze the usual levels of the IAQ of the office area with the empty PBR and without any expectations of improvement in the CO_2 level. **From November 6 to January 18, the lowest measured value was 384 ppm on 19.11.2018 (Monday) at 07:00 AM, meanwhile the highest one was 1733 ppm on 28.11.2018 (Wednesday) at 17:00 PM.** The experiment was done in two parts *Spirulina sp.*1 and *Spirulina sp.*2 (S1 and S2). S1 was the period when the PBR was filled with microalgae and S2 was the period when the PBR was empty. The S1 was done from 6th of November to 12th of December. During the S1 there was 80 liters of *Spirulina sp.* mixture in the PBR. **The minimum and maximum CO_2 concentrations for S1 were 384 ppm on 19.11.2018 (Monday) at 07:00 AM and 1733 ppm on 28.11.2018 (Wednesday) at 17:00 PM, which was one of the busiest days in the office during the whole experiment. Moreover, daily average CO_2 concentrations were calculated for S1. The minimum and maximum average ppm levels were 531 on 23.11.2018 (Friday) and 902 on 28.11.2018 (Wednesday) as well as the overall daily average was 676 ppm.** Figure 4.10 indicates the daily average CO_2 level for S1.

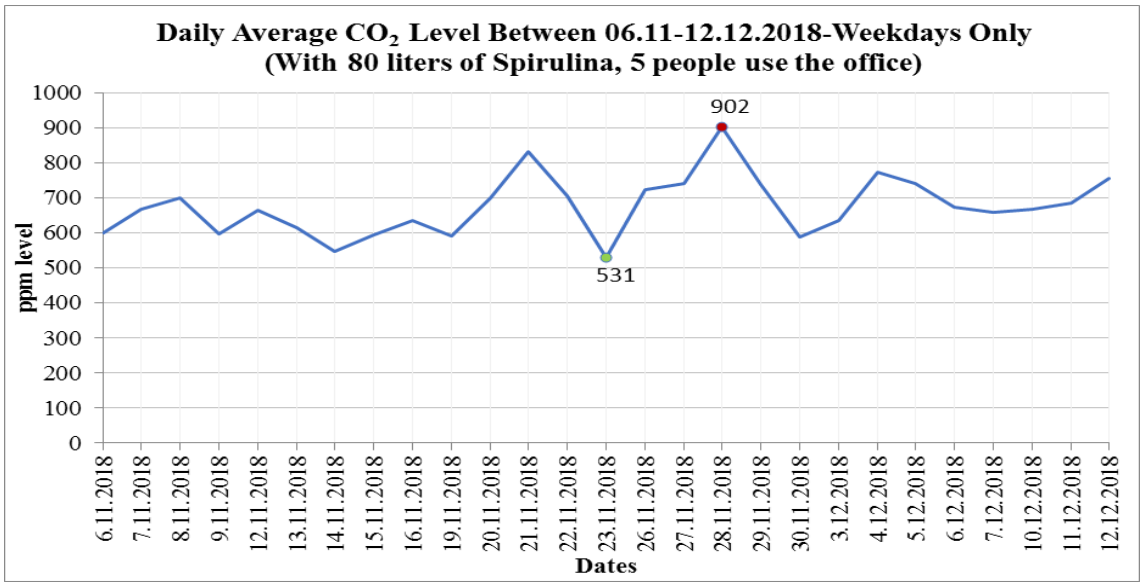

Figure 4.10 Daily Average CO_2 Level for S1.

The S2 was observed from 13th of December 2018 to 18th of January 2019. During the, S2 the PBR was inactive. **The lowest and highest CO_2 levels of S2 were 390 ppm on 07.01.2019 (Monday) at 07:00 AM and 1451 on 04.01.2019 (Friday) at 16:30 PM. The highest and lowest daily CO_2 average levels for S2 calculated as 407 ppm on 01.01.2019 (Tuesday) and 887 ppm on 28.12.2018 (Friday). The lowest daily average was 407 ppm on 02.01.2019 (Wednesday) and highest one was 887 ppm on 28.12.2019 (Friday) were shown in Figure 4.11. Also, the overall average was calculated as 683 ppm.**

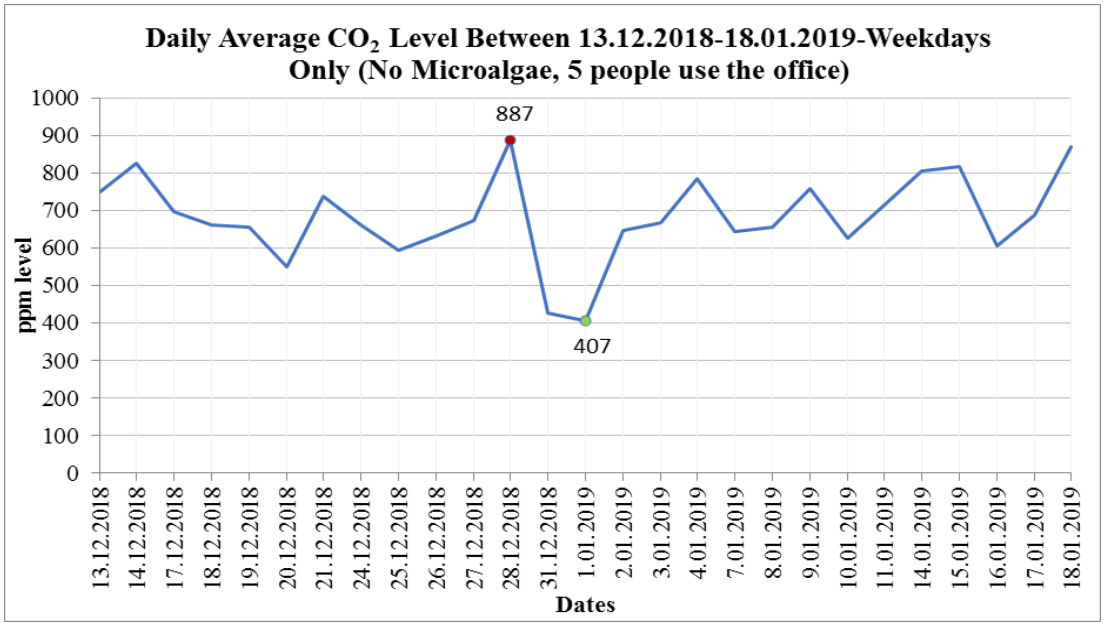

Figure 4.11 Daily Average CO_2 Level for S2.

Furthermore, hourly averages were calculated both for S1 and for S2. For S1 the lowest average values were measured at 07:30 PM as 430 ppm before the occupancy hours

and the maximum level was 985 ppm at 17:00 PM. Figure 4.12 indicates the hourly distribution of the average CO_2 level during S1. **The overall hourly distribution average was founded as 676 ppm. The minimum average for S2 calculated as 436 ppm within the same hour with S1 and the maximum value was 1035 ppm at 15:30 PM. In addition, hourly average was calculated as 683 for S2.** Figure 4.13 demonstrates the hourly distribution of the S2 that is highly similar to S1 with some slight changes.

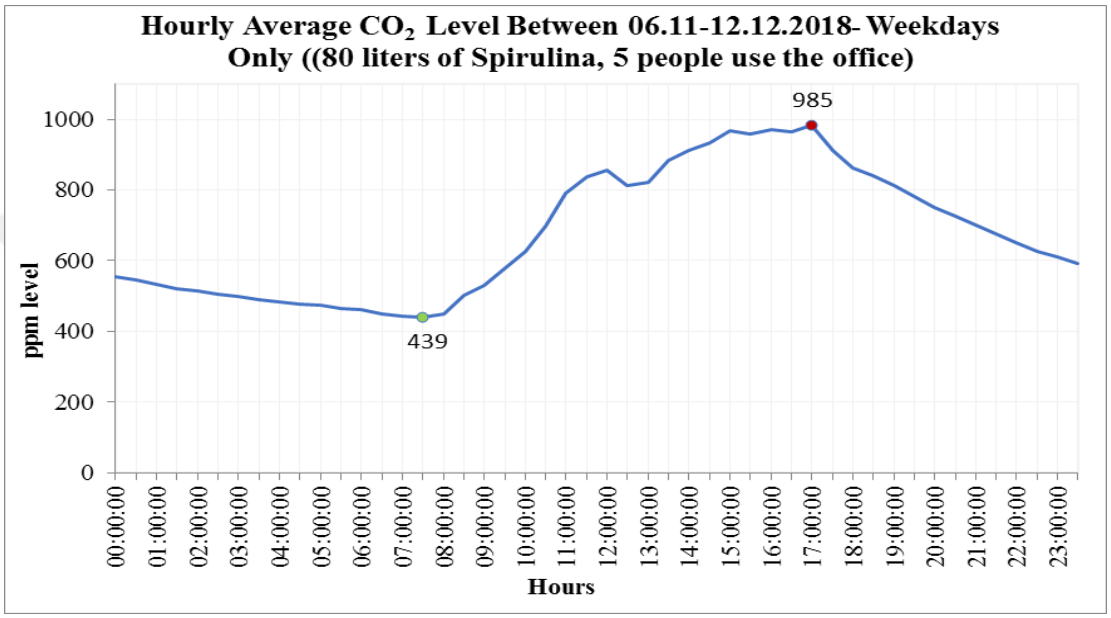

Figure 4.12 Hourly Average CO_2 Level for S1.

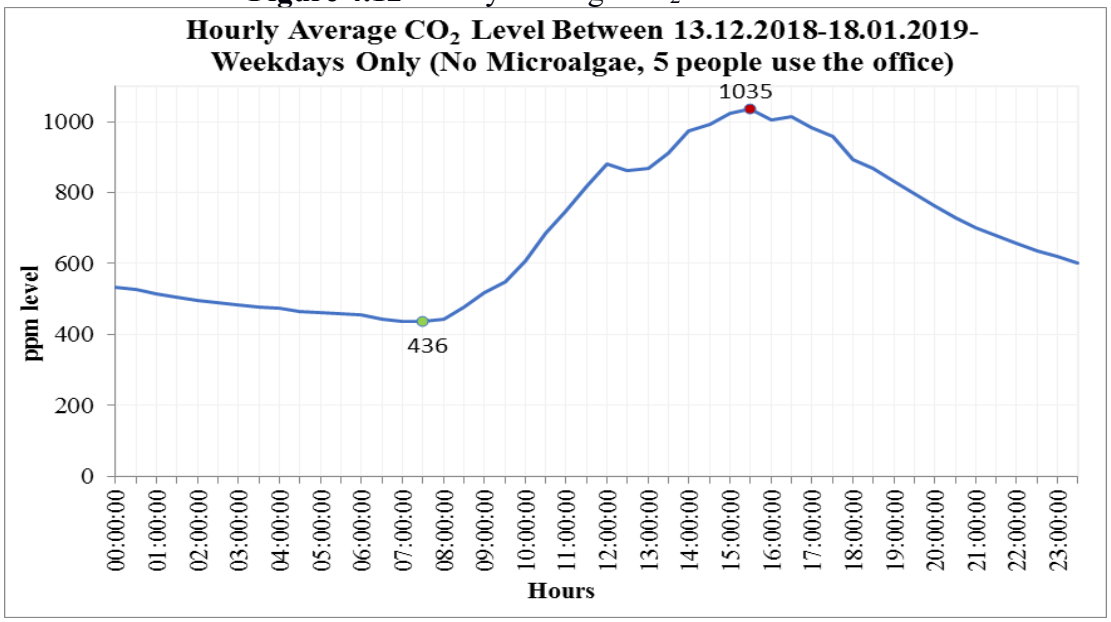

Figure 4.13 Hourly Average CO_2 Level for S2.

The last part of the experiment I, was done to evaluate the CO_2 levels during the weekends. Since the experiment was done in the winter time the illumination level in the office area was very limited especially for the weekends. The illumination time

was almost from 08:00 AM to 18:00 PM. However, the location of the office was not very fortunate to use the sunlight for the microalgae to make photosynthesis. The illumination level was 2-3 lux averagely during the weekends in the office. From 6th of November to 12th of December 5 weekends were evaluated when the PBR were actively in use. Then 5 weekends were evaluated when the PBR was empty from 13th of December to 18th of January. The observations were done in two parts *Spirulina sp.*Weeknd1 and *Spirulina sp.*Weekend2 (SW1 and SW2). **In SW1 the lowest data measured as 383 ppm on 11.11.2018 at 20:30 PM. The highest value was 614 on 17.11.2018 at 14:00 PM. The lowest daily average was 397 on 18.11.2018 and the highest one was 463 on 17.11.2018.** Figure 4.14 indicates the daily average CO_2 level for SW1. **Overall average CO_2 level for SW1 calculated as 419 ppm.**

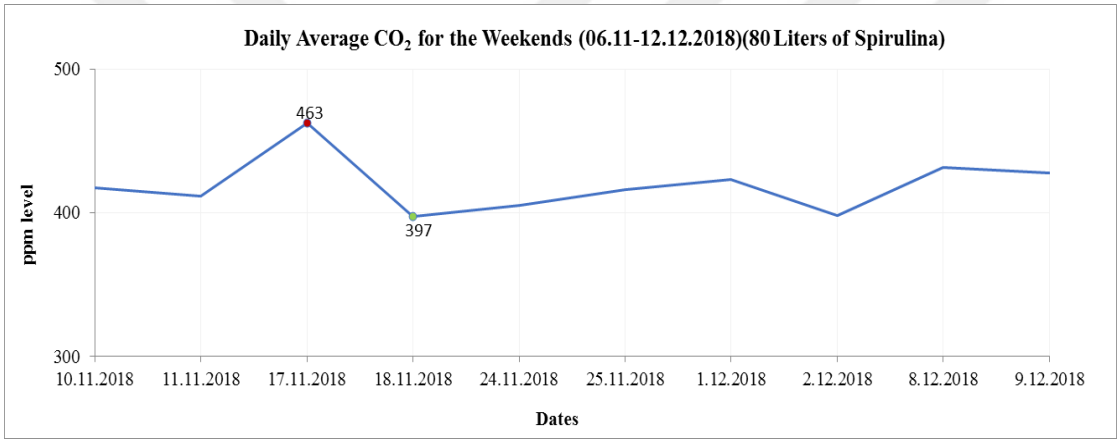

Figure 4.14 Daily Average CO_2 Level for SW1.

In SW2 5 weekends from 15th of December to 13th of January are evaluated similarly with SW1. **In SW2 the lowest CO_2 level measured as 395 ppm on 30.12.2018(Sunday) at 18:30 PM and the highest one was 767 ppm on 29.12.2018(Saturday) at 00:00 AM.** Figure 4.15 daily average CO2 levels were indicated. The lowest daily average was 416 ppm on 06.01.2019 and the highest one was 520 ppm on 22.12.2018. **The overall average calculated as 461 ppm.**

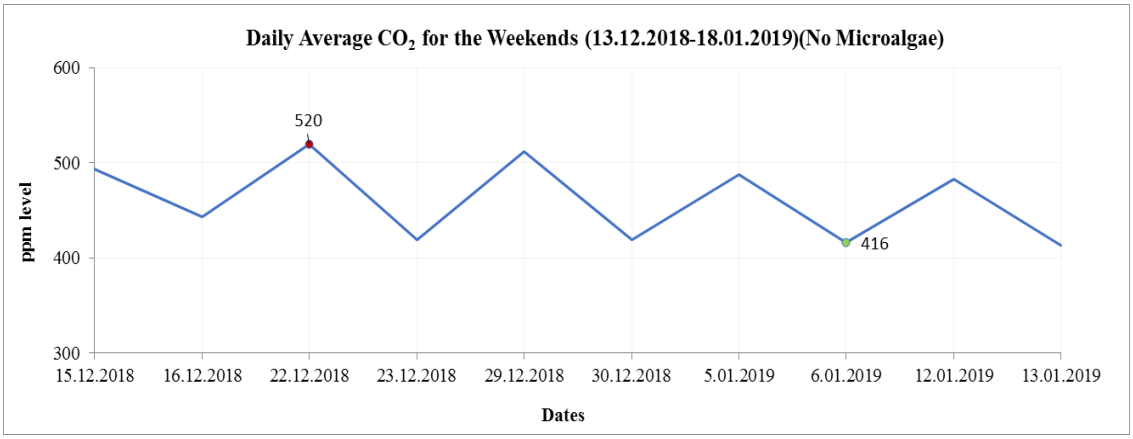

Figure 4.15 Daily Average CO_2 Level for SW2.

4.2.2. The Experiment II (February 1 - March 31)

After the experiment I, the experiment II was done from 1st of February to 31st of March. In the experiment II, *Chlorella vulgaris* was used as an experimental microalgae specie which is a fresh water green algae and uses Bristol medium as nutrition source (De Morais & Costa, 2007). Table 4.5 indicates the characteristics and requirements of *Chlorella vulgaris* as well as the office conditions. Since just before the experiment II, 4 people moved out from the office and the official number of the users in the office dropped into 1. Moreover, Table 4.6 shows the chorological process of the experiment II.

Table 4.5 Characteristics of *Chlorella vulgaris* and Office Conditions.

***Chlorella vulgaris* Growth Temperature (^{0}C)**	30 ^{0}C (Hernandez, De-Bashan, Rodriguez, Rodriguez, & Bashan, 2009)	**Office Temperature (^{0}C)**	Between 25-30 ^{0}C
CO_2 level for maximum fixation for *Chlorella vulgaris*	2.5% (Chiu et al., 2008)	**Office CO_2 Level**	0.04%

Illumination Levels for *Chlorella vulgaris*	370-11.100 lux (Sforza et al., 2012)	**Office Illumination Levels (Lux) (tested by testo 435 measuring device)**	**Weekdays**	**Weekends**
			243 in general 228 around PBR*	8 in general 3 around PBR*

* Achieved values are mean of calculated measured illumination level during working hours.

Table 4.6 Chronological Process of Experiment II

31st of January	• 4 users moved out from the office.
From 1st to 21st of February	• CO_2 level in office was continuously data logged by IAQ measuring device. (PBR empty) • Number of the users inside was recorded for each half hour period.
21st of February	• 4 Liters of *Chlorella vulgaris* was obtained from Ege University, Faculty of Fisheries. • *Chlorella vulgaris* was mixed with 46 liters of clean water (pH 6.8). • PBR was filled with total of 50 liters of microalgae-water mixture. • Two aquarium air stones (35 cm each) were placed in the PBR to provide even growing rate (less sound than the previous air pump)
From 22nd of February	• CO_2 level in office was continuously data logged by IAQ measuring device (PBR was filled with *Chlorella vulgaris* mixture). • Number of the users inside was recorded for each half hour period.
Every 10 days.	• Mixture was fed by 50 milliliters of *Chlorella vulgaris* nutrition mixture (Bristol Medium). • Clean water was added to keep the amount of microalgae mixture in the same level.
Until 22nd of March	• CO_2 level in office was continuously data logged by IAQ measuring device (PBR was filled with *Chlorella vulgaris* mixture).

	• Number of the users inside was recorded for each half hour period.
31st of March	• End of the experiment II.

Similarly the experiment II, has three sections: I) Increase in CO_2 level by one person, II) CO_2 level in the office area during the weekdays. III) CO_2 level in the office area during the weekends. The illumination levels were also the same with the experiment I, since the office does not have any openings to the ambient air, and use of artificial lighting is a must. In the first two parts of the experiment II, artificial illumination by the florescent lamps in the office were also used constantly. The illumination level in the office averagely measured as 243 lux with the testo 435 measuring device.

The first section of experiment II was done to understand the increase of carbon dioxide by a person within half an hour period when the office has started to use in the mornings during the weekdays since the microalgae specie was changed. The weekends were not calculated within the average value. To evaluate this, they days are selected when the only user arrived to the office and stayed in the office alone for at least half hour period before the other users arrive. The CO_2 level recorded by the data logger at the time when the first user had arrived used as initial hour data, then the CO_2 level after half hour occupation was used as end hour data. All the CO_2 levels are averaged for the selected days as initial and end hours. In the experiment II, 23 days were fitting the requirements, 6 days without microalgae and 15 days with microalgae. As a contrast, CO_2 concentration in the office was slightly higher in the second case when the PBR was filled with microalgae. Table 4.7 demonstrates the average levels from January 1 to March 31. **The lowest values are measured as 487 ppm and for the initial hour and 528 ppm on 14.02.2019 (Thursday) and the highest values are measured as 660 ppm for the initial hour on 21.02.2019(Thursday) and 774 on 01.02.2019 (Friday) for the end hours when the PBR was inactive. After the filling 50 L of *Chlorella vulgaris* mixture to the PBR, the lowest initial hour measured as 537 ppm on and for the end hour 575 on 27.03.2019 (Wednesday) for both values. The maximum values were measured as, 738 ppm and 789 on 13.03.2019 (Wednesday) both for initial and end hours. The average values were calculated as 578 for the initial and 642 for the end hour for the times without the microalgae, and for the times with the microalgae the same values were calculated as 593 ad 661 with the same order.**

Table 4.7 Average Initial and End Hours of CO_2 level (January 1-March 31)

Average Initial Hour CO_2 ppm	Average End Hour CO_2 ppm	Microalgae Mixture Amount (L)
578	642	0
593	661	50

In the second part of the experiment II, from 1st to 21st of February, there were no microalgae in the office area. Then from 22nd of February to March 31 where were 50L of *Chlorella vulgaris* mixture in the PBR. The second part of the experiment II, was done to by aiming the same with experiment I and also composed of two parts; *Chlorella vulgaris*I and *Chlorella vulgaris*II (C1 and C2). From 01.02.2019 to 21.02.2019 (C1) the CO_2 level was measured without any algae in the PBR and the occupancy pattern was recorded. **The minimum measured value was 390 ppm on 18.02.2019 (Monday) at 05:00 AM and the maximum value was 1040 ppm on 01.02.2019 (Friday) at 11:30 AM because of the moving out occasion in the office.** Therefore, the extreme value of 1040 ppm was ignored while calculating the average CO_2 level. **Figure 4.16 shows the daily CO_2 average level in C1, with the maximum 650 ppm on 01.02.2019 (Friday) and minimum 483 ppm on 07.02.2019 (Thursday). The overall average value was calculated as 555 ppm.**

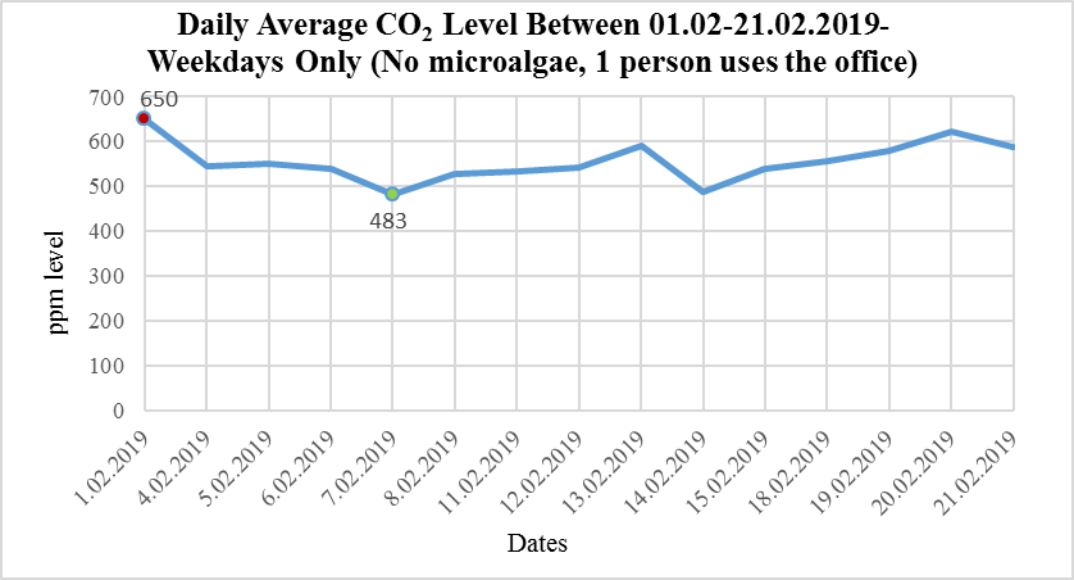

Figure 4.16 Daily Average CO_2 Level for C1.

From 21.02 to 31.03.2019 (C2) the measurements were done, when the PBR is filled with 50 liters of *Chlorella vulgaris* mixture. **The lowest value was 382 ppm on 25.02.2019 (Monday) at 04:00 AM meanwhile the highest value was 1094 on 01.03.2019 (Friday) at 14:00 PM after a busy occupation. Figure 4.17**

demonstrates the daily CO_2 average level in C2. The minimum daily average was 502 ppm on 25.02.2019 (Monday) and the maximum number was 699 on 12.03.2019 (Tuesday). The overall CO_2 average was calculated as 581 ppm.

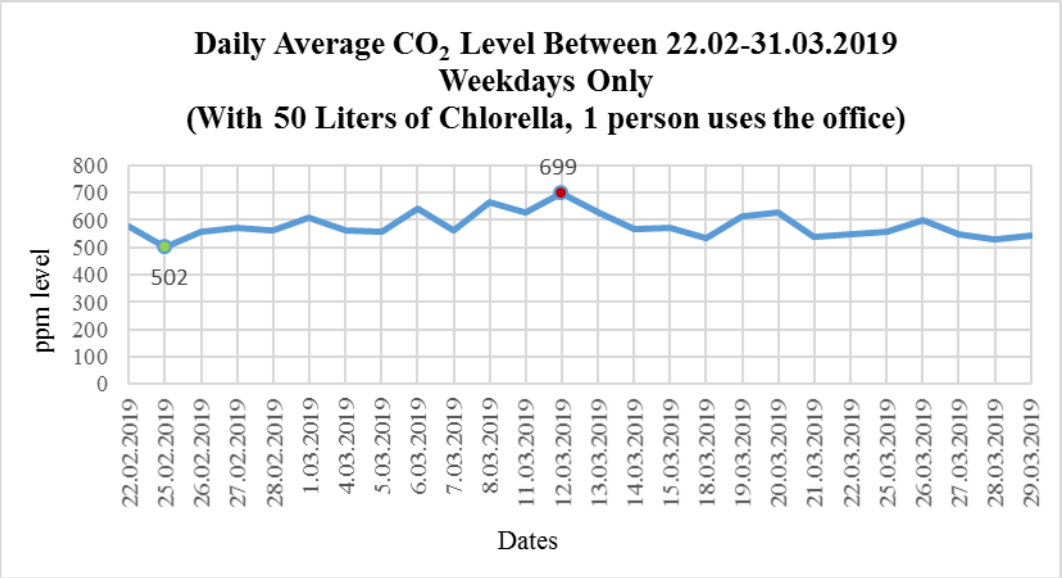

Figure 4.17 Daily Average CO_2 Level for C2.

In addition to the daily averages, hourly average CO_2 levels were calculated both for C1 and for C2. **In C1 lowest value was measured as 441 ppm at 07:30 AM and highest value was 778 ppm at 15:30 PM which is one of the most occupied hours with the occupancy pattern. In C2 the lowest ppm value was 421 and highest one was 749 ppm at the same hours with C1. The hourly distribution of C1 and C2 indicated in Figure 4.18 and Figure 4.19. Also, average levels were calculated as 555 ppm and 581 with a respective order.**

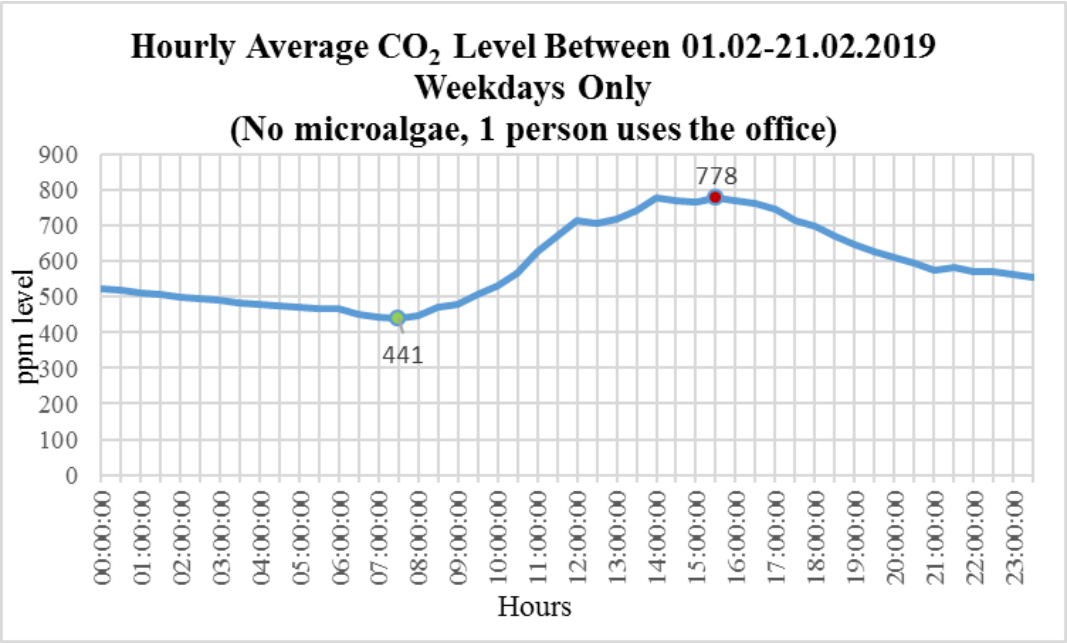

Figure 4.18 Hourly CO_2 Average Level in C1.

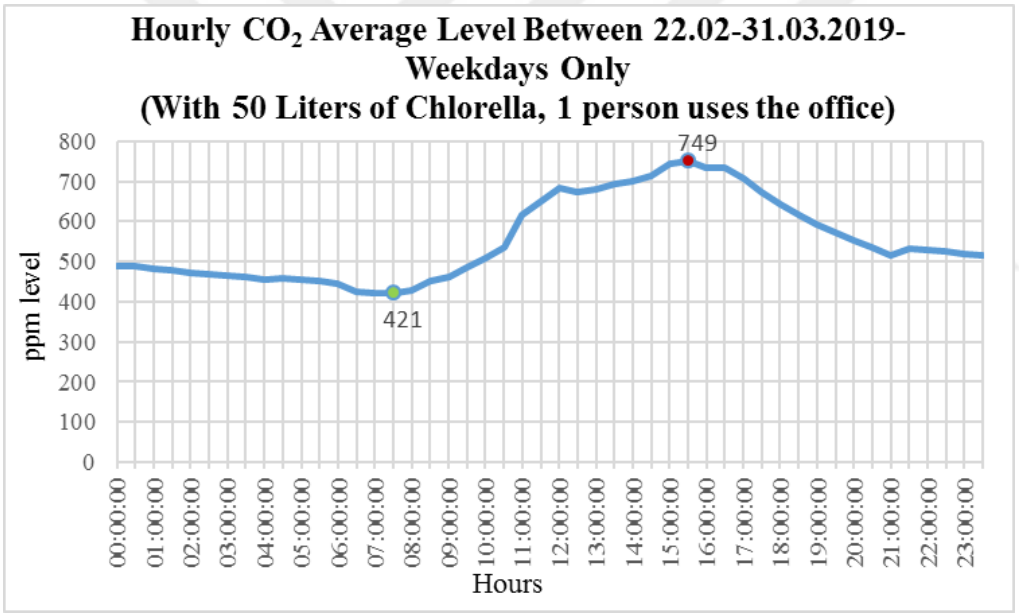

Figure 4.19 Hourly CO_2 Average Level in C2.

The third part of the experiment II, was done to evaluate the CO_2 levels during the weekends like the experiment I. From February 1st to March 31 the day times used get longer and the sun started to rise around at 08:17 and at 07:00 at the end of the experiment II. Also the sun used to set around 18:30 and 19:30 at the end. The illumination level was 2-3 lux around the PBR and 7-8 lux general in the office lux averagely during the weekends. From 1st to 21st of February, 3 weekends were evaluated when the PBR was empty. Then 6 weekends were evaluated when the PBR was filled with 50 liters of *Chlorella vulgaris* mixture until the end of the experiment II. The observations were done in two parts *Chlorella vulgaris*Weeknd1 and *Chlorella*

*vulgaris*Weekend2 (CW1 and CW2). **In CW1 the lowest data measured as 381 ppm on 10.02.2019 at 13:30 PM. The highest value was 527 on 02.02.2019 at 00:00 AM. The lowest daily average was 395 on 17.02.2019 and the highest one was 450 on 02.02.2019. Figure 4.20 indicates the daily average CO_2 level for CW1. Overall average CO_2 level for CW1 calculated as 413 ppm.** For CW2, 6 weekends from 22nd of February to 31st of March were evaluated. **In SW2 the lowest CO_2 level measured as 379 ppm on 24.03.2019 (Sunday) at 17:30 PM. The highest one was 868 ppm on 16.03.2019 (Saturday) at 12:30 AM due to the occupancy in the office. In Figure 4.21 daily average CO_2 levels were indicated. The lowest daily average was 383 ppm on 31.03.2019 and the highest one was 589 ppm on 09.03.2019. The overall average calculated for CW2 as 444 ppm.**

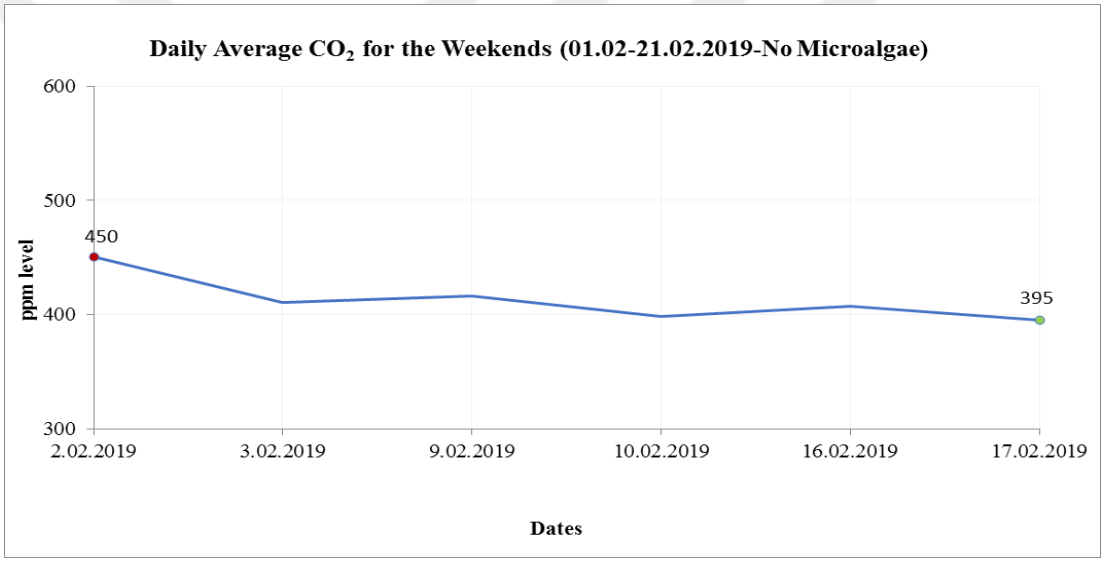

Figure 4.20 Daily Average CO_2 Level for CW1.

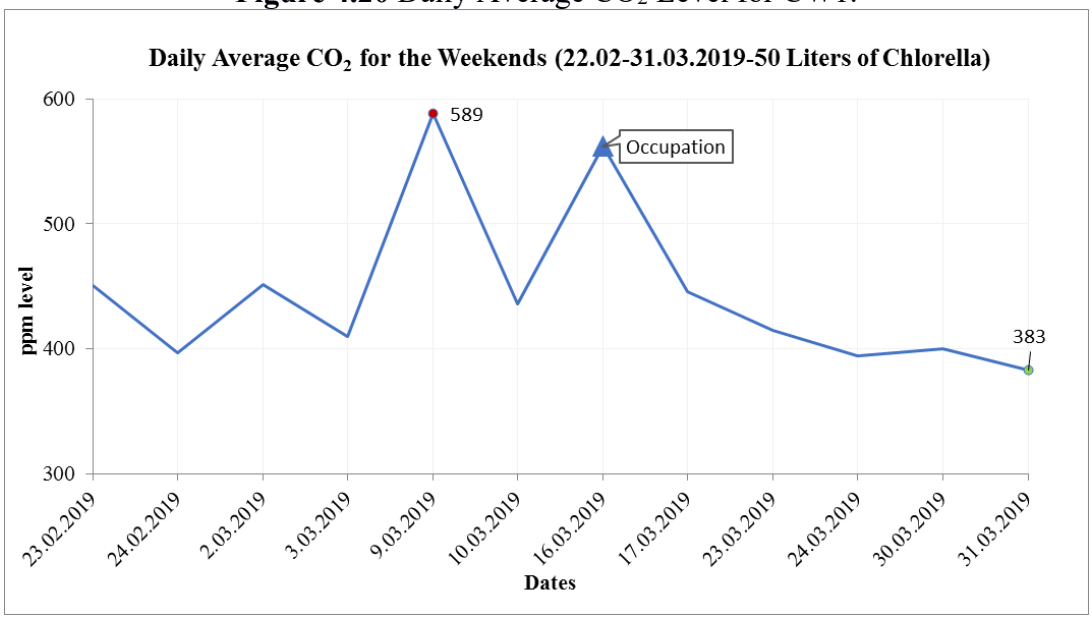

Figure 4.21 Daily Average CO_2 Level for CW2.

4.3. Results and Discussions

The data indicates different results and discussions according to the experiment I and II. The evaluations of the experiment results were given separately in this sub chapter.

4.3.1. The Experiment I (November 6 – January 18)

The results of the first part of the experiment I demonstrates that, the average ppm levels were lower both at initial and end hours when the PBR is actively in use (80 Liters of *Spirulina sp.*) than there is no microalgae in the office area. Moreover, it had been understood from the CO_2 changes and camera records, during the experiment I, the office was generally started to be used around 08:30 - 09:00 AM in the morning. **The average initial hours were considerably lower (487 ppm) when in PBR was in use then the times with no microalgae in the office (563) and also the end hours lower than when the PBR is empty (560 ppm (80 L), 628 (0 L)).** After the half hour period, the increase was 16% for the times with 80 Liters of microalgae and 12% for the times without the microalgae. This shows that microalgae did not make the increase of the CO_2 in the office slower, but still provided a better air quality by lowering the CO_2 levels especially during the non-occupied times for a fresher start of the day.

The second part of the experiment I results show that, **from November 6 to December 12, 2018 (S1) the overall daily CO_2 level is calculated as 676 ppm when the PBR was filled with 80 liters of *Spirulina sp.* mixture and from December 13 2018 to January 18 2019 (S2) the average value calculated as 683 ppm while the PBR was inactive.** Also, the comparison of the results of the hourly distributions of S1 and S2 based on the average ppm levels and standard deviation indicated in Figure 4.22 where the 0% is equal to the average CO_2 rate. The results showed that, the trend line is mostly similar, however, it can be still deduced from the trend lines percentage increase during the day time is lower when the PBR was actively in use and slightly higher during the night time. Also, according to bar chart the mostly visible changes both for the increase and decrease happens in nearly three hours of period as an expected result of the similar study (Dhokalia, Parsons, & Anderson, 1998). **To summarize total mean ppm levels calculated 1% lower when the PBR was actively in use as comparison of periods (with and without microalgae) with the five occupants.**

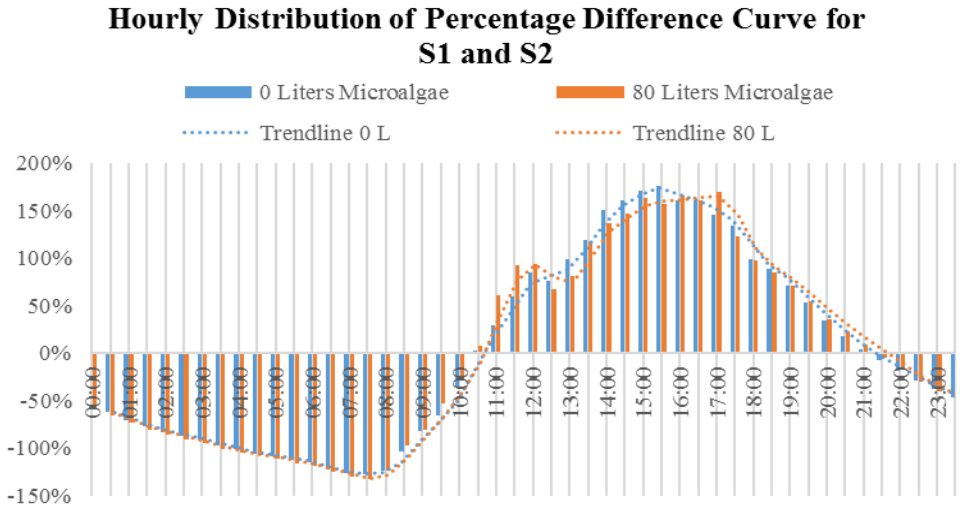

Figure 4.22 Hourly Distribution of Percentage Difference Curve for S1 and S2.

Moreover, pie charts of the ppm levels in a general range given in Figure 4.23. As Figure 4.23 indicates, during the experiment when there were microalgae in the room, the danger level was lower in a total range and healthy air level range was wider. On the other hand, measurement without the microalgae demonstrates that the danger level was somehow higher and healthy range slightly narrower. **The danger range calculated as 7% and 9% for S1 and S2 with a respective order. Also, the healthy air range is calculated as 35% and 34% for S1 and S2.** As shown at the pie chart during the times with the microalgae, the air in the office area was healthier and the danger levels were less in terms of percentage.

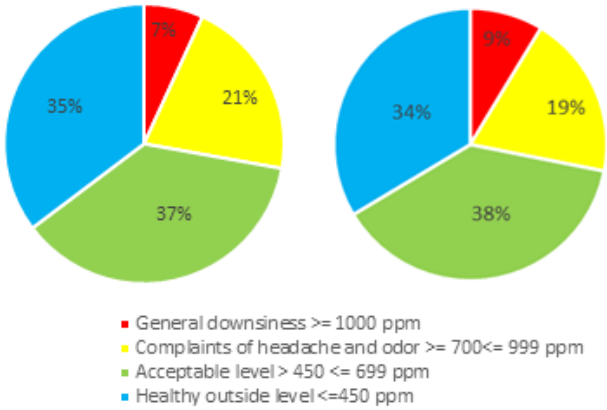

Figure 4.23 General Distribution of ppm Level in S1 and S2.

Finally but importantly, the results of the final part of the experiment I, shows that the daily averages were visibly lower especially on Sundays when the PBR was empty. However, Figure 4.24 clearly shows that the ppm levels were more stable and lower in the SW1 than the SW2. Therefore according to the Figure 4.24 *Spirulina sp.* was successful to keep the ppm levels lower in the weekends. Also, another assumption

that can be made depending on the figure is, the microalgae was successful to ameliorate the ppm levels in the weekdays, since the ppm levels on Saturday in SW1, which caused by having lower ppm levels during the whole week.

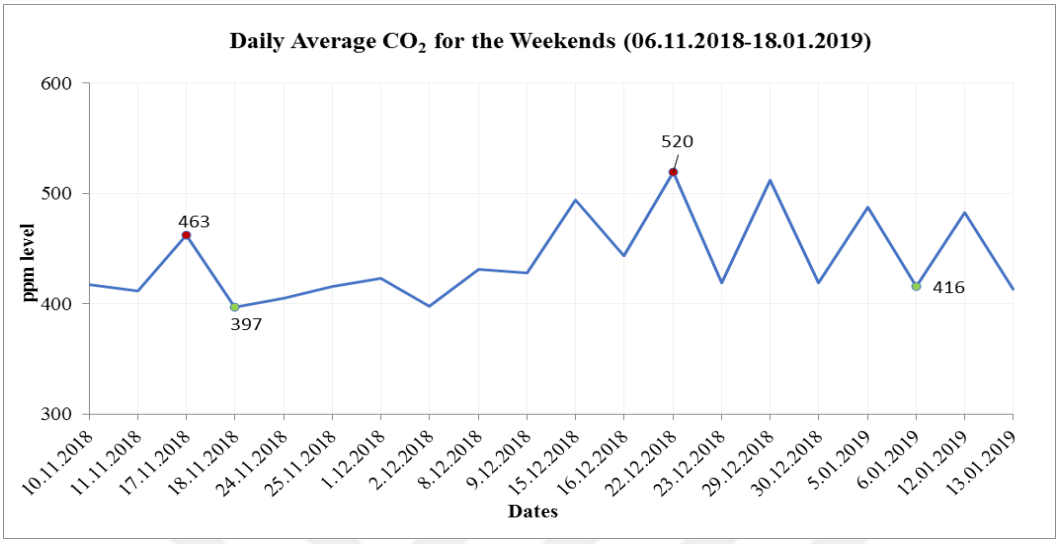

Figure 4.24 Daily Average ppm Levels for the Weekends(SW1-SW2)

In addition, distribution of ppm level is a general range indicated in Figure 4.25 for the weekends and the times of S1 and S2. **According to Figure 4.25 healthy level range increased noticeably from 62% to 86% when the PBR is actively in use, as the danger and complain levels remains nearly 0%.**

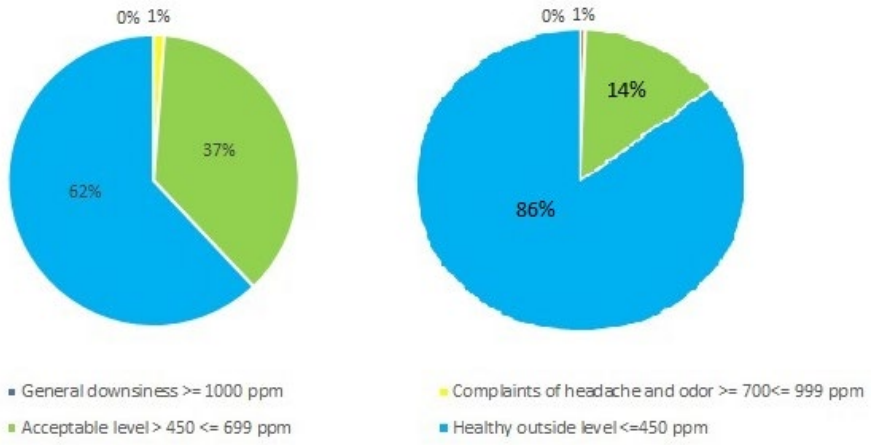

Figure 4.25 General Distribution of ppm Levels for the Weekends. (Left:S1, Right:S2)

4.3.2. The Experiment II (February 1 - March 31)

The outcomes of the experiment II indicates that, the general ppm levels were higher when the PBR was filled with 50 Liters of *Chlorella vulgaris* mixture.

In the first part, when there were no microalgae in the office the average ppm levels were calculated as 578 ppm at the initial hour and 642 ppm at the end hour

for half hour period when the office was used for the first time in each weekday. As a contrast, the average CO_2 levels were calculated as 593 and 661 from initial to end hour when the PBR was filled with 50 liters of microalgae mixture. Therefore, in order to understand the reason of the higher CO_2 levels in the second period the occupancy pattern was evaluated. Since the occupant is one person, the arrival times of the occupant to the office were observed and it had been noted that the occupant arrives the office later in most of the mornings in the experiment II (around 10:00-11:00). Therefore, even the office was not used, the use of the building in general rises the indoor CO_2 level from under the door CO_2 leakage as well as the mockup models which are stored in the office area during March as an extra source of indoor air pollutant (J. Singh, 1996).

In the second part of the experiment II the result show that, in **C1 (PBR empty) from February 1 to 21, the daily average ppm levels calculated as 555 ppm, then after in C2 (PBR filled with *Chlorella vulgaris*) from February 22 to March 31, the same value calculated as 581 ppm.** In addition, hourly distribution of the C1 and C2 compared to understand the reduction and increase level during the day and nighttime, depending on the average level and standard deviation. Figure 4.26 indicates the comparison of C1 and C2 where the 0% is equal to the average CO_2 level.

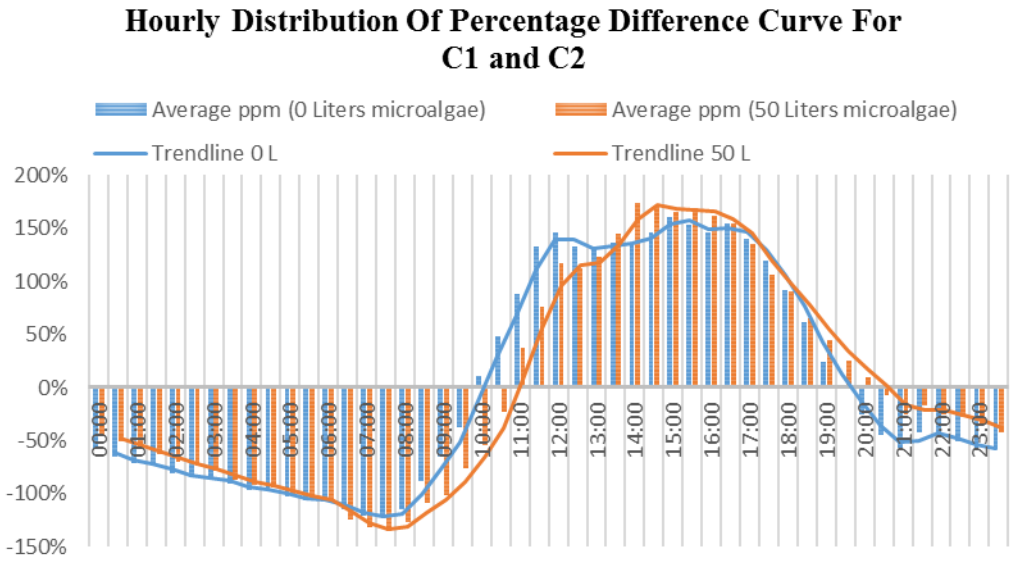

Figure 4.26 Hourly Distribution of Percentage Difference Curve for C1 and C2.

In order to understand why the ppm levels are higher even the PBR was actively in use, the occupancy pattern was analyzed in a detailed way. According to the occupancy pattern analysis, in C1 the office was used maximum by 5/4 people only half an hour

and used by 1 people only for two and a half hours in total. However, in C2, three people used the office for one and a half hour, two people for seven hours in total for the 20 days of period in the weekdays. Thus, one reason of the higher CO_2 levels in the C2 is the busier occupancy in the office. Table 4.8 shows the comparison of total hours of occupancy in C1 and C2.

Table 4.8 Comparison of Occupancy Load for C1 and C2.

Number of Users (person/hour)	Total Hours of Occupancy	
	C1	C2
0	425	431.5
1/4	7.5	11
1/2	40.5	38
3/4	1	1
1	2.5	7
5/4	0.5	-
6/4	-	1.5

The other possible reason could be the amount of microalgae is not enough to reduce the CO_2 concentration since the occupancy hours are longer in C2. Also, the optimal growing conditions for *Chlorella vulgaris* may not be provided enough such as light penetration and intensity as well as constant source of CO_2 (Biłos, Patyna, Płaczek, & Witczak, 2016).

Finally, the results of the third part of the experiment II demonstrated in Figure 4.27. According to the results, **Overall average CO_2 level for CW1 calculated as 413 and as 444 ppm for CW2.** The probable reasons for higher CO_2 levels in CW2 was the occupation on 16.03.2019 and the unknown reason of high average on 09.03.2019. Also, since the occupancy load was more during the CW2 the results in the weekends are more changeable then the CW1, such as visibly higher on Saturdays than the Sundays. However, the last 3 weekends of the CW2 also shows that, if there was no occupancy in the office, the PBR filled with 50 Liters of *Chlorella vulgaris*, still can show a similar results with the experiment I.

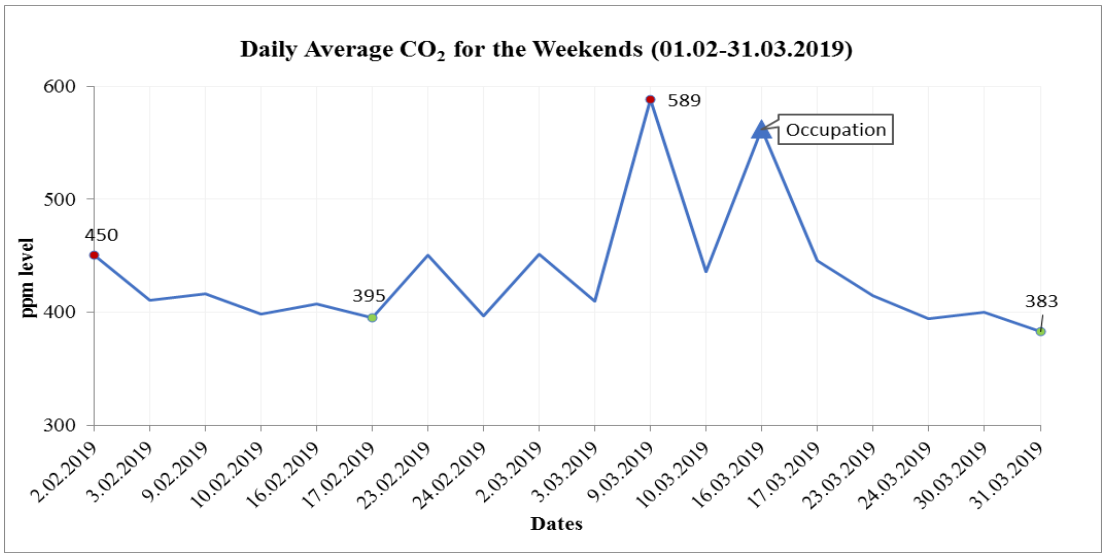

Figure 4.27 Daily Average ppm Levels for the Weekends (CW1-CW2)

CHAPTER 5
CONCLUSION

Considering the facts that people spend quite a lot of time in interiors and provision of a high quality indoor air is a necessity. This research of the thesis is to measure the effect of *Spirulina sp.* and *Chlorella vulgaris* species of microalgae on the indoor CO2 concentration by using photosynthesis in the selected office space as well as a cure for a sick building syndrome.

Therefore, standards and literature about the CO_2 level in the indoor areas and ways to improve IAQ in terms of CO_2 level were analyzed. Thus, some studies found that IAQ might be improved by using photosynthesis which is an ability that microalgae also have. Secondly, studies on the microalgae, depending on their bio-mitigation capacity of CO_2, ways to grow microalgae and their usage in the architecture and design were evaluated. Based on the research about IAQ and microalga, a gap in the literature has been found in terms of using microalgae in a real-life case study to measure their effect to bio-mitigate the indoor CO_2 levels. Yet, most of the studies about microalgae are either in the laboratory environments or in large scale outdoor environments. Also the studies and ideas about microalgae as an application to the design or to contribute IAQ, are aesthetically eye pleasing yet lack offering scientific data. Therefore, this study is a unique one, by using a real life case study and using smaller scale indoor PBR.

In order to contribute to fulfill the gap in the literature, two different experiments total of four months had been done in the office in Yaşar University and its results evaluated. The first experiment (experiment I) was conducted from November 6 (2018) to January 18 (2019) both with the empty PBR and PBR filled with 80 liters of *Spirulina sp.* mixture. The highlight results of the experiment I are listed in below:

- In the first part, CO_2 levels were measured lower when the PBR was filled with 80 liters of *Spirulina sp.* mixture than the times with the empty PBR in the morning times.
- In the second part, similarly daily averages were %1 lower in S1 than the S2,

meaning that microalgal photosynthesis lowered the CO_2 levels in the office area.

- In the third part, during the weekends, the results with the active PBR (SW1) were noticeably lower and more constant than the times with inactive PBR (SW2). Although in the weekends there were no extra source of CO_2, there were no illumination source in the office area and the illumination levels were around 2-3 lux. Which is highly beneficial yet an interesting result at the same time.

The second experiment (experiment II) was done after the first one from February 1 to March 31 both with 50 Liters of *Chlorella vulgaris* mixture and empty PBR. The results of the experiment II is summarized in below:

- In the first part, the CO_2 levels were detected higher in the mornings when the PBR was active. The reason of this situation was, later the arrival time of the user to the office which was the CO_2 level in the office was already higher due to occupancy in the building in general.
- In the second part, during the weekdays the CO_2 levels were almost the same in C1 and C2. The probable reasons of why the CO_2 levels in C1 were almost as high as C2 are might be due to the higher occupancy load in C2 and the interior conditions of the office may not be suitable for the selected type of microalgae to grow successfully. Moreover the initial density and amount of microalgae may not be enough to ameliorate the CO_2 levels.
- Finally in the third part, CO_2 level for CW1 calculated as 413 and as 444 ppm for CW2 in the weekends.

The general results of the experiment demonstrated the CO_2 level in the office area were higher than 1000 ppm, which is general guideline upper value, only 5% of the total time and mostly in the acceptable level. Also, the experiment I was more successful than the experiment II in order to mitigate the indoor CO_2 level. The effect of *Spirulina sp.* mixture in general, detected as 1% decrease on CO_2 levels with the five occupants. However, the measurements with the *Chlorella vulgaris* showed no improvement during the occupancy times. The most visible improving effects of the microalgae were observed during the weekends, which was lowering the CO_2 levels 5% with the *Spirulina sp.* mixture. Also, noticeable increases detected in the range of

ppm distribution during the weekends with the times with 80 liters of microalgae. The range which is less than 450 ppm increase from 62% to 86% with the 80 liters of *Spirulina sp.* mixture.

The aim for finding a cure related with sick building syndrome by using micro algae has been researched by these two experiments.

The results shows that:

- *Spirulina sp.* has decreasing effect on CO_2 level, but for better effect on the indoor usage the amount must be more than 80 L with a better microalgae concentration.
- 50 L *Chlorella vulgaris* is not enough for a 75 m^3 office room to mitigate the CO_2 level.
- The results of weekends show that both species has decreasing and promising effect on indoor CO_2 level.

As the further studies, the design of the experimental PBR can be improved and the noise problem, which is caused by the pumping system inside the PBR, measured as around 60 decibel with a "Sound Meter" app and that level might considered as constant conversation in office area can be solved. As well as more suitable light source and more controlled CO_2 source can be integrated with the PBR to obtain better results.

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