A STUDY ON THE UTILIZATION OF MICROALGAE FOR PRODUCING LIGHT AND BIOFUEL IN THE BUILT ENVIRONMENT

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ABSTRACT

A STUDY ON THE UTILIZATION OF MICROALGAE FOR PRODUCING LIGHT AND BIOFUEL IN THE BUILT ENVIRONMENT

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Microalgae utilization in the built environment can be a key way to develop sustainable urban environments. Microalgae have many potentials such as providing the raw material for biofuels, reducing greenhouse gas emissions, contributing to indoor air quality, treating wastewater, and illuminating spaces. Therefore, all these features offer the opportunity of symbiosis between the microalgae and the built environment. Although there are many studies on microalgae, more research is needed at the intersection of architecture and biotechnology to integrate them into the built environment. In this study, it is aimed to contribute to this new research topic by proposing integration designs to show the possibilities to produce biofuel and bioluminescent light from algae within a symbiosis between the microalgae and the built environment. In this context, a comprehensive literature review was conducted on microalgae and their characteristics, cultivation and harvesting methods, integration systems, processes to obtain bioenergy and bioluminescence. Microalgae utilized case studies in the built environment were reviewed. After having a fundamental knowledge, six microalgae species were defined for target use in the study: biodiesel and light production. Characteristics of selected species and requirements to cultivate them in buildings were presented and using this information, a conceptual study was prepared on Konya Provincial Directorate of National

Education Building's architectural project for microalgae integration. In the project, two different integrations were proposed: Utilization of microalgae on the building façade and inside the building. The proposal was based on the contribution that microalgae and the building could provide to each other. One of the conclusions of this study is the importance of architectural design process for integration studies. Microalgae become one of the building users as a result of integration, and like other living things, they can survive under certain conditions. In order to build a symbiotic relationship, the characteristics of the algae to be cultivated in the building should be well known and optimum conditions should be provided for them. Successful designs can create symbiosis and buildings can be productive components of sustainability.

Keywords: Sustainable Architecture, Productive Architecture, Microalgae in Architecture, Building-Integrated Photobioreactors, Bioluminescent Lighting

ÖZ

MİKROALGLERİN YAPILI ÇEVREDE IŞIK VE BİYOYAKIT ÜRETİMİ İÇİN KULLANIMI ÜZERİNE BİR ÇALIŞMA

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Mikroalglerin yapılı çevrede kullanımı sürdürülebilir kentsel çevreleri geliştirmek için anahtar yol olabilmektedir. Mikroalgler, biyoyakıtların hammaddesinin sağlanması, sera gazı emisyonlarının azaltılması, iç mekan hava kalitesinin arttırılması, atık suların iyileştirilmesi veya mekanların aydınlatılması gibi birçok potansiyele sahiptir. Dolayısıyla tüm bu özellikler mikroalgler ve yapılı çevre arasında simbiyosis imkanı sunmaktadır. Mikroalglerle ilgili birçok çalışma olmasına rağmen, mikroalglerin yapılı çevreye entegrasyonu için mimarlık ve biyoteknoloji alanlarının kesişiminde daha fazla araştırmanın yapılmasına ihtiyaç duyulmaktadır. Bu çalışmada, mikroalgler ve yapılı çevre arasındaki simbiyosis kapsamında alglerden biyoyakıt ve biyoluminesans ışığı üretme olanaklarını göstermeye yönelik entegre tasarımlar önerilmesi ile bu yeni araştırma konusuna katkıda bulunulması amaçlanmıştır. Bu kapsamda, mikroalgler ve özellikleri, kültivasyon ve hasat yöntemleri, entegrasyon sistemleri, biyoenerji elde etme işlemleri ve biyoluminesans konularında detaylı bir literatür taraması yapılmıştır. Yapılı çevrede mikroalglerin kullanıldığı örnekler incelenmiştir. Temel bilgiler edinildikten sonra bu çalışmada belirlenen kullanım amaçları olan biyodizel ve ışık üretimine yönelik altı mikroalg türü belirlenmiştir. Seçilen türlerin özellikleri ve yapılarda kültivasyonu için gereksinimleri sunulmuş, bu bilgiler kullanılarak Konya İl Milli Eğitim Müdürlüğü Binası mimari projesinde

mikroalg entegrasyonu üzerine konsept çalışma yapılmıştır. Projede iki farklı entegrasyon önerilmiştir: Mikroalglerin bina cephesinde ve bina içinde kullanımı. Önerinin temeli alglerin ve binanın birbirine sağlayabileceği katkıya dayanmaktadır. Bu çalışmada varılan sonuçlardan biri entegrasyon çalışmaları için mimari tasarım sürecinin önemidir. Mikroalgler entegrasyon sonucu bina kullanıcılarından biri olmaktadır, ve diğer canlılar gibi belli koşullar altında yaşamlarını sürdürebilirler. Simbiyotik bir ilişki kurulması için binada kültive edilecek algin özellikleri iyi bilinmeli ve onlar için en uygun koşulların sağlanması gerekmektedir. Başarılı tasarımlar sonucu simbiyosis oluşturulabilecek ve binalar sürdürülebilirliğin üretken öğeleri olabilecektir.

Anahtar Kelimeler: Sürdürülebilir Mimari, Üretken Mimari, Mimaride Mikroalgler, Bina Entegre Fotobiyoreaktörler, Biyoluminesans Aydınlatma

To my dear parents Pi-Yun Chen and Necati Örmeci,
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TABLE OF CONTENTS

ABSTRACT v

ÖZ vii

ACKNOWLEDGEMENTS x

TABLE OF CONTENTS xi

LIST OF TABLES xiv

LIST OF FIGURES xv

LIST OF ABBREVIATIONS xix

1. INTRODUCTION 1

1.1. Problem statement and argument 1

1.2. Objectives 3

1.3. Procedure 3

1.4. Disposition 4

2. LITERATURE REVIEW 7

2.1. Algae and current applications 7

2.2. Cultivation methods 9

2.2.1. Open systems 11

2.2.2. Closed systems 13

2.3. Requirements of microalgae and PBR Design parameters 18

2.3.1. Light 18

2.3.2. Nutrients supply 23

2.3.3. Culture conditions 23

2.3.4. Mixing 24
2.4. Harvesting Methods 24
2.5. Bioenergy 28
2.5.1. Conversion of biomass to biofuel 29
2.5.1.1. Biodiesel 30
2.5.1.2. Bioethanol 31
2.5.1.3. Biogas 31
2.5.2. Utilization of biofuels in buildings 32
2.5.3. Species selection for biodiesel production 32
2.5.4. Review of works conducted on selected species of Neochloris oleoabundans, Scenedesmus obliquus and Botryococcus braunii 34
2.6. Bioluminescence 37
2.6.1. Species selection for light production 43
2.6.2. Review of works conducted on selected species of Pyrocystis fusiformis, Pyrocystis noctiluca, and Ceratocorys horrida 44
2.7. Daylighting systems as a tool for microalgae cultivation in buildings 45
2.7.1. Light guiding systems 45
2.7.2. Light transport systems 47
2.8. Case studies 52
2.8.1. Applied Projects 52
2.8.2. Conceptual projects 63
2.8.3. Published research works 71
3. MATERIALS AND METHODS 75
3.1. Materials 75

3.1.1. Selected microalgae species for light production 76

3.1.2. Selected microalgae species for biodiesel production 80

3.1.3. Konya Provincial National Education Directorate Building Project 83

3.2. Method.....90

4. DISCUSSION OF THE KNOWLEDGE IN LITERATURE AND DESIGN PROPOSAL 93

4.1. The potentials of microalgae in the built environment.....93

4.2. Utilization of microalgae in the built environment 94

4.3. Microalgae integrated building's system components 95

4.4. Discussion on challenges in microalgae integrated building systems.....98

4.5. Process for designing.....101

4.6. Konya Provincial National Education Directorate Building Project: A conceptual study for integration of the selected microalgae species.....104

4.6.1. Façade integrated photobioreactors for biodiesel production.....109

4.6.2. Daylighting system integrated photobioreactors in building interiors for light production.....117

5. CONCLUSION.....127

REFERENCES.....133

APPENDIX 151

LIST OF TABLES

TABLES

Table 2.1 Comparison of different cultivation methods (Brennan & Owende, 2010). 17
Table 2.2 Comparison of different harvesting methods (Barros, Gonçalves, Simões, & Pires, 2015). 27
Table 2.3 Bioluminescent creatures in different environments (Widder, Marine bioluminescence, 2001). 38
Table 2.4 Energy indicators of PBRs (Lakenbrink, Petersen, & Roedel, 2013). 55
Table 3.1 Selected microalgae species for light production and their properties. 79
Table 3.2 Examples of microalgae species for biodiesel production and their properties. 82
Table 4.1 Characteristics of microalgae and their potential to use in built environment. 95
Table 4.2 Temperatures measured in Konya (Meteoroloji Genel Müdürlüğü, 2019). 106

LIST OF FIGURES

FIGURES

Figure 2.1 Open system cultivation methods (Borowitzka & Moheimani, 2013). 12
Figure 2.2 A Tubular photobioreactor in a greenhouse growing Spirulina (Farm1, 2019). 14
Figure 2.3 Flat panel photobioreactor (Lofgren, n.d.).....16
Figure 2.4 The solar radiation spectrum (Fondriest Environmental, 2019). 19
Figure 2.5 Schematic diagram of the flat panel PBR and its tilt angles studied by Qiang and his partners (Qiang, Faıman, & Richmond, 1998). 22
Figure 2.6 Diagram of microalgae harvesting techniques, adapted from (Barros, Gonçalves, Simões, & Pires, 2015), (Show & Lee, 2014).....25
Figure 2.7 Energy conversion processes from algal biomass (Tsukahara & Sawayama, 2005). 29
Figure 2.8 Light penetration in the ocean and spectrum of visible light (Manuel, 2017). 40
Figure 2.9 Left. The region a milky sea was spotted (box, color enhanced) by a merchant ship in the Indian Ocean near the horn of Africa in 1996. Right. Enlarged image of the same area (Therese & Hastings, 2013). 41
Figure 2.10 Light guiding systems: a) Light guiding shade, b) Louvers and blinds, c) Anidolic ceiling, d) Light shelf, e) Fish system louver, f) Laser cut panel, g) Prismatic panel, h) Sun-directing glass (Ruck, et al., 2000). 46
Figure 2.11 Semi-transparent double light shelves made out of reflective glass (Ruck, et al., 2000).....47
Figure 2.12 Heliostat above the Morgan Lewis Office Building (Boubekri, 2014). .48
Figure 2.13 Capturing the light by a heliostat configured with a mirror (Okutan, 2008). 49
Figure 2.14 Concentration and transportation of light (Okutan, 2008). 50

Figure 2.15 The illuminance in the room (Okutan, 2008). 50
Figure 2.16 Heliostats above Borusan Holding (Boubekri, 2014). 51
Figure 2.17 Borusan Holding's daylighting; Left: Section of the daylighting system, Right: The illuminance in the room (Boubekri, 2014). 52
Figure 2.18 Façade integrated flat panel PBRs in BIQ Building (Lakenbrink, Petersen, & Roedel, 2013). 53
Figure 2.19 Installation system of PBRs (Synthetic Design Biotopes, 2019). 54
Figure 2.20 The Urban Algae Folly (Ecologic Studio, 2019). 57
Figure 2.21 The Urban Algae Canopy (Ecologic Studio, 2019). 57
Figure 2.22 The Urban Algae Canopy (Ecologic Studio, 2019). 58
Figure 2.23 Algae curtain (Ecologic Studio, 2019). 58
Figure 2.24 Algae filling (Ecologic Studio, 2019). 59
Figure 2.25 The Algae Dome (Morris, 2019). 60
Figure 2.26 Algocultures in Pavillon de l'Arsenal (Pavillon de l'arsenal, 2019). 61
Figure 2.27 Microbial Home project by Philips (Koerner, 2019). 62
Figure 2.28 Bioluminescent Field Project installation in 2010 Luminale, Frankfurt: Left:glass vials with dinoflagellates installed on a reactive floor; Right: Bioluminescence response after the entrance of visitors (Burggraf, 2019). 63
Figure 2.29 Net zero retrofit solution for GSA office building by HOK and Vanderweil (Dexigner, 2019). 64
Figure 2.30 Design proposal of Marina City Towers by Influx Studio (Meinhold, 2019). 65
Figure 2.31 In Vivo project, the AlgoHouse (Legendre, 2019). 66
Figure 2.32 In Vivo project, the Tree House (Legendre, 2019). 67
Figure 2.33 Functional diagram of In Vivo project (Legendre, 2019). 67
Figure 2.34 French Dream Towers (Block, 2019). 68
Figure 2.35 Sustainable design strategies of French Dream Towers (Pinto, 2019). . 69
Figure 2.36 FSMA Tower (Chalcraft, 2019). 70
Figure 2.37 Algae Façade System (Kim K.-H. , 2013a). 71

Figure 2.38 Test set-up of the prototype for thermal performance analysis (Kim K.-H. , 2013a).....72
Figure 2.39 Test environment with flat panel PBRs (Decker, Hahn, & Harris, 2016). 73
Figure 2.40 Drawing of test environment (Decker, Hahn, & Harris, 2016). 73
Figure 3.1 Michael Latz stimulates bioluminescence of cultured dinoflagellates. True color image. Retrieved from (Latz, Glowing with the Flow, 2005). 76
Figure 3.2 Pyrocystis fusiformis (Widder, 2002).....78
Figure 3.3 Botryococcus braunii (UTEX, 2019).....81
Figure 3.4 3D rendering of Konya Provincial National Education Directorate Building.....83
Figure 3.5 Konya Provincial National Education Directorate Building project site plan.....85
Figure 3.6 Second basement floor plan of Konya Provincial National Education Directorate Building.....86
Figure 3.7 First basement floor plan of Konya Provincial National Education Directorate Building.....87
Figure 3.8 Ground floor plan of Konya Provincial National Education Directorate Building project.....88
Figure 3.9 Typical floor plan of Konya Provincial National Education Directorate Building.....89
Figure 3.10 Section A-A. 90
Figure 4.1 Integration of the microalgae production system in the building. 97
Figure 4.2 Microalgae integrated building's design process. 102
Figure 4.3 Solar irradiance potential of Konya. Meram, which is the region that project site is located, has 1650-1750 KWh/m2-year solar irradiance (Yenilebilir Enerji Genel Müdürlüğü, 2019). 105
Figure 4.4 Solar irradiance potential of Turkey. Dark blue color represents 1400-1450 KWh/m2-year and the dark red color represents 1800-2000 KWh/m2-year (Yenilebilir Enerji Genel Müdürlüğü, 2019). 108

Figure 4.5 Site plan showing the proposal for sunspace addition. 110
Figure 4.6 Ground floor plan showing the sunspace addition: PBRs are integrated to its façade. 111
Figure 4.7 South-East elevation of the building with PBR integrated sunspace addition. 113
Figure 4.8 Partial section B-B showing the PBR integrated sunspace and its relation with the building. 114
Figure 4.9 Detail from section B-B. 115
Figure 4.10 Partial roof plan showing the solar collector system where sunlight is captured..... 119
Figure 4.11 Partial typical plan showing the vertical light pipes where light is redirected into horizontal light pipe..... 120
Figure 4.12 Partial section C-C showing the solar collector and vertical light pipe connections. 121
Figure 4.13 Partial section D-D showing the vertical and horizontal light pipe connections. 122
Figure 4.14 Partial elevation detail showing the light introduced to flat plate PBRs with fiberoptics connection..... 123

LIST OF ABBREVIATIONS

GHG	Greenhouse gas
O_2	Oxygen
CO_2	Carbondioxide
PBR	Photobioreactor
UV	Ultraviolet
IR	Infrared
PAR	Photosynthetically active radiation
CHP	Combined heat and power systems
UTEX	Culture Collection of Algae, which is administrated as an Organized Research Unit of the University of Texas

CHAPTER 1

INTRODUCTION

This study presents the utilization of algae in the built environment mainly for biofuel and bioluminescent light production purposes. In this chapter, the concerns underlying this study, motivational background, argument, objectives, and methodology are introduced. The chapter ends with disposition, the brief information of which is given in the following chapters.

1.1. Problem statement and argument

Energy is one of the main indicators that present the potential for social and economic development. Over the decades, especially in developed countries, energy demand continues to increase. According to the International Energy Agency, there is a 3% growth in the buildings' floor area globally every year. Also, the buildings and building construction sectors consume 36% of total energy and are responsible for 40% of direct and indirect carbon dioxide (CO_2) emissions (The International Energy Agency, 2019). High demand and consumption of fossil fuels cause depletion of sources with increasing greenhouse gas emissions which lead many countries to plan energy policies for short and long term.

By 2020, the European Union aims to reduce greenhouse emissions by 20% compared to the 1990 year level, increase energy efficiency and to achieve a 20% reduction in primary energy consumption, to supply 20% of energy consumption from renewable sources. Regulated by the EU Energy Performance of Buildings Directive, all new buildings are required to be nearly zero-energy by the end of 2020, and all new public

buildings must be nearly zero-energy by 2018 (The European Parliament, 2010). The United States has a comprehensive multi-year program plan which requires buildings to achieve a 17% reduction in greenhouse gas emissions by 2020 (from 2005 levels) and 83% by 2050. Doubling energy productivity relative to 2010 by 2030 is also highlighted in national goals (U.S. Department of Energy, 2016).

Renewable sources and carbon neutral fuels are the key solutions to achieve a sustainable environment. Despite the global energy issues, scientists have been continuing to search for renewable energy sources, new alternatives, energy efficient designs, and technologies.

The climate and weather conditions have been a problem for constant energy production from commonly utilized renewable sources like solar and wind. One of the renewable energy alternatives, bioenergy, which is derived from biomass, receives attention worldwide. Biomass is mainly converted into biofuel types such as biodiesel, bioethanol, and biogas through different processes. Microorganisms which are defined as third generation bioenergy feedstock, are highly advantageous among first and second generation feedstocks like starch-rich crops and non-food crops (Pragya, Pandey, & Sahoo, 2013), (Chia, Ong, Chew, Show, Phang, Ling, Nagarajan, Lee, & Chang, 2018). The microalgae are photosynthetic aquatic organisms which are the primary producers in the marine environment (Chia, et al., 2018), (Spilling & Seppälä, 2012). Because of simple cell structure, they are more efficient converters of solar energy compared to other photosynthetic plants (Bajhaiya, Suseela, & Ramteke, 2012). They contribute to a significant amount of oxygen production and more than 40% of carbon is fixed by algae on a global scale (Ahmed, Li, & Schenk, 2012). As a third generation feedstock, microalgae have much more to offer like the potential of doubling their mass every few hours during the exponential growth period and the oleaginous cell structure which can be more efficient for biofuel production (Bajhaiya, Suseela, & Ramteke, 2012). Additionally, they don’t require large and arable lands like crop plants, and they can live in marginal water sources like non-potable water (Ozkan, Kinney, Katz, & Berberoglu, 2012).

Algae which are classified under the division dinophyta called the dinoflagellates can be both photosynthetic and bioluminescent. Bioluminescence, the light production by living organisms, is commonly observed on the surface ocean, and bioluminescent groups among dinoflagellates are mostly the source of "glowing" seas (Wynn, Behrens, Sundararajan, Hansen, & Apt, 2010), (Marcinko, Painter, Martin, & Allen, 2013), (Valiadi & Iglesias-Rodriguez, 2013).

All in all, considering the use of microalgae in built environment can be worthwhile. They can be cultivated in built environment and be feedstock supply for biofuels, reduce greenhouse gas (GHG) emissions and contribute to indoor air quality in terms of CO_2 absorption, treat wastewater, and illuminate our world. By these features, it is argued that microalgae have the potential to meet the built environment's requirements, and be cultivated within buildings in a symbiotic relationship.

1.2. Objectives

Recent studies show that microalgae are one of the renewable bioenergy sources to achieve a sustainable clean environment. There are many efforts to maximize the biomass production and obtaining end-products from algae but more studies are needed on building integrated microalgae cultivation and its effects on built environment. So here, it is aimed to contribute to this new research topic, by conducting a comprehensive literature review on microalgae and proposing integration designs on Konya Provincial Directorate of National Education Building's architectural project to show the possibilities to produce biofuel and bioluminescent light from algae within a symbiosis between the microalgae and the built environment.

1.3. Procedure

This study is majorly developed in 4 phases. In the first phase, microalgae utilization is examined within the framework of;

- Microalgae cultivation and harvesting methods
- Methods to obtain bioenergy from algal sources,
- Bioluminescence to define the potential for lighting,
- Microalgae utilized architectural applications.

In the second phase, suitable algae species for biodiesel and light production are reviewed. However, it is estimated that over 50.000 species of microalgae do exist, but nearly 30.000 of them have yet to be determined (Elcik & Çakmakcı, 2017). Depending on the desired function and the end product, determining the microalgae species becomes crucial as the efficiency of cultivation, harvesting and energy conversion methods depend on the strain's biological structure (Pragya, Pandey, & Sahoo, 2013). Besides, the chemical compositions and the growth rate of algae are affected by culture medium and environmental conditions, such as temperature, pH, light intensity, nutrient availability, salinity level, CO_2 levels, mixing rate (Chia, et al., 2018), (Elcik & Çakmakcı, 2017). Therefore, the most suitable algae species are identified among the commonly studied ones by scientists for biofuel production and bioluminescence research. Their characteristics are collected and optimal growth conditions are obtained from published data in the biological field. Microalgae requirements and photobioreactor design parameters are also reviewed.

In the third phase, the information is interpreted and the integration of microalgae into the built environment is discussed. A conceptual study has been prepared for Konya Provincial National Education Directorate building for the integration of microalgae to building façade for biodiesel production, and to building interiors with daylighting systems for bioluminescent light production.

In the last phase, the study is evaluated overall and conclusions are given.

1.4. Disposition

The report is composed of five chapters.

After the introduction, a literature review is presented for a better understanding of microalgae, its potential and possible applications in architectural design. In the section of the literature review, information about algae is given, common cultivation methods are explained, microalgae requirements and design criteria of photobioreactors are reviewed. In the following part, algae potential is examined under two main categories which are bioenergy and bioluminescence. Under bioenergy, harvesting algal biomass and conversion methods to bioethanol, biodiesel and biogas are presented. Bioluminescence category consists of different biologic lighting mechanisms with a highlight on bioluminescence phenomena, in which the chemistry and molecular biology, behavior and physiology, and functions are examined. According to research targets microalgae species are selected and their characteristics are given. In the last 2 sections of the literature review, daylighting systems as a tool for microalgae cultivation and examples of algae utilization in built environment are reviewed.

The third chapter presents the materials and the method of the study.

The fourth chapter presents discussion on the integration of microalgae into the built environment with a conceptual study a conceptual study prepared for Konya Provincial National Education Directorate building.

The final chapter gives the conclusion.

CHAPTER 2

LITERATURE REVIEW

In this chapter, literature is reviewed to know more about algae, its potential and possible implications in architectural design from different aspects. Algae cultivation methods, conversion of biomass to different types of energy, bioluminescence, and biologic lighting mechanisms are examined. Moreover, examples of algae utilized projects are presented at the end of this chapter.

2.1. Algae and current applications

Life has started on Earth with Cyanobacteria. These prokaryotic algae were the first colonizers, and through photosynthesis, carbon dioxide filled atmosphere was cleaned and oxygen was released which enabled other life forms to live (Demirbaş & Demirbaş, 2010), (Chu, 2012).

Algae are single-celled or multicellular simple organisms (Demirbaş & Demirbaş, 2010). They can be found everywhere on Earth but mainly in the marine environment; they are the most abundant of the primary producers in the ocean which have 71% of the footprint. Despite their mass size constitutes less than 1%, more than 40% of carbon is fixed by algae (Bast, 2012). It is reported that approximately 1.8 kg of CO_2 can be fixed by 1 kg of microalgae biomass (Sharma & Sharma, 2017).

Algae are an extremely diverse group. Despite their important role on the Earth, the knowledge of algal diversity remains limited due to geographically unexplored areas and lack of research. Biologists still discuss algal taxonomy and systematics; current classification of algae are mainly based on kinds of photosynthetic pigments, cellular

structure, and life cycle. Major groups of algae have been classified into divisions, which are; Cyanophyta (blue-green algae) and Prochlorophyta, Chlorophyta (green algae), Rhodophyta(red algae), Euglenophyta, Chlorarachniophyta, Glaucophyta, Heterokontophyta, Cryptophyta, Haptophyta, and the Dinophyta (Elnabris), (Bast, 2012).

In terms of size, they can be defined as the microscopic (microalgae) and macroscopic (macroalgae) forms including seaweeds in macroalgae (Chu, 2012). Microalgae are commonly photosynthetic; by using CO_2, they convert solar energy and produce valuable compounds by metabolic reactions. High surface to volume ratio cell body makes them capable to take more amount of nutrients and sunlight (Demirbaş & Demirbaş, 2010). Their structures are majorly designed to store and convert energy without development beyond the cells, the simplicity of their growth has made them more sustainable than other renewable bioenergy sources (Adeniyi, Azimov, & Burluka, 2018). Even the consideration of algae as a renewable energy source is not new, benefitting from microalgae by humans dates back 2.000 years to the Chinese (Spolaore, Joannis-Cassan, Duran, & Arsène, 2006). At the present time, they are many biotechnological applications:

- They are used in the food industry due to their high nutritional value, microalgae such as *Spirulina* and *Chlorella* are being mass cultured for dietary supplementary products (Chu, 2012).
- They have a significant contribution to the health industry. Microalgae are rich sources of bioactive metabolites which have applications in pharmaceutical industries. It is reported that most of the algae have anti-microbial, anti-viral, anti-coagulant anti-enzymatic, anti-oxidant, anti-fungal, anti-inflammatory, and anti-cancer activity compounds (Sigamani, Ramamurthy, & Natarajan, 2016).
- They contain many compounds that help to increase the fertility of soil besides acting as a biological protector against plant diseases. Nitrogen is one of the most important factors for the growth of plants while most

cyanobacteria are known to fix atmospheric nitrogen as an effective fertilizer (Sharma & Sharma, 2017).

- Environmental biotechnology is applied to remediate the wastewater hence algae can be used as a tool for assessment and monitoring of environmental pollutants (Chu, 2012),
- They are used as feed in aquaculture as well as for pets and farm animals (Carlsson, Beilen, Möller, & Clayton, 2007), (Spolaore, Joannis-Cassan, Duran, & Arsène, 2006), (Sharma & Sharma, 2017)
- They can be incorporated into cosmetics which microalgal extracts are used in anti-aging and rejuvenating care products, sun protectants and hair care products (Spolaore, Joannis-Cassan, Duran, & Arsène, 2006), (Sharma & Sharma, 2017).

Besides the applications, there are conducted researches on light production from the living organisms. Simply, bioluminescence is visible light produced by living creatures (Widder, Marine bioluminescence, 2001). Inspired by nature's phenomena, studies in architecture investigate the potential applications of microorganisms in spatial or material context (Manuel, 2017).

As a result, carbon capture, sequestration, light production features, rapid growth rate and ability to survive in severe conditions leads microalgae to be a potential for utilization in built environment. In this study, from many applications of algae explained previously, algae utilization will be evaluated mainly in terms of energy production, carbon capturing and lighting.

2.2. Cultivation methods

Strain selection and isolation of microalgae depend on the intended purpose of utilization. But in general, strain selection needs to be evaluated on certain parameters under resistivity to the environmental changes such as light, temperature, nutritional requirements, carbon supply, pH, and contamination. Also, a high growth rate is a

crucial factor as it reduces cultivation time and cost (Rashid, Rehman, Sadiq, Mahmood, & Han, 2014). Selected strain can be obtained from culture collections, but it is reported that cultured microalgae tend to lose their resistivity to environmental factors and reproduction capability in time due to the controlled environment. Therefore, it is suggested to isolate the selected microalgae strain from nature, which many methods exist such as single cell isolation, serial dilution, streak plate, density centrifugation. Commonly, the following steps are applied for isolation:

- Collection of microalgal samples and filtration of undesired microorganisms,
- Reducing the number of cells in a gradual manner by diluting the filtered sample,
- Determination of microalgae strain which is examined from diluted samples by microscope and cultivation in the agar media,
- Transportation of microalgae to liquid media (Elcik & Çakmakcı, 2017).

Algae basically need nutrients such as sunlight, CO_2 and water but the selection of cultivation and harvesting methods also depends on the desired end product (Adeniyi, Azimov, & Burluka, 2018). In the production of microalgae, biological, non-biological and many factors arising from operating parameters are effective. Light, temperature, nutrients, O_2, CO_2, pH, salinity and toxic chemicals are non-biological factors, whereas bacteria, viruses, and other algae species are among the biological factors. Besides, mixing, operational factors such as dilution rate, harvesting frequency are also effective in biomass production (Elcik & Çakmakcı, 2017).

At present, microalgae biomass for is harvested from natural habitats or obtained from controlled cultivation processes for commercial purposes. Natural ponds and lagoons, or artificial ponds such as raceway and circular ponds, photobioreactors and fermenters can be used to grow microalgae (Zittelli, Rodolfi, Bassi, Biondi, & Tredici, 2013). In general, cultivation methods can be categorized as open and closed systems. Hybrid systems and algal films also exist for biomass culturing but closed PBRs are the main focus within the scope of building integrated algae utilization.

2.2.1. Open systems

Open systems are commonly used for large-scale production. Microalgae cultivation takes place outdoors where the culture is directly exposed to the environment. These systems can be listed as; raceway ponds, mixed ponds, shallow lagoons and ponds, inclined systems, and circular central-pivot ponds (Borowitzka & Moheimani, Open Pond Culture Systems, 2013). Constructed ponds can be in excavated pits or raised above ground level, usually incorporated with a mixing system like paddlewheels, water jets or air pumps. Mixing plays an important role to achieve a homogenous culture circulation of algae, water, and nutrients as well as enabling algae to suspend in the water close to the surface for sunlight penetration and CO_2 absorption (Adeniyi, Azimov, & Burluka, 2018). Open systems are introduced below:

- Algae lagoons, ponds and ditches are used as natural systems of algae culture. These natural systems serve for wastewater treatment and biomass production in the food industry including aquaculture feed and human consumption.
- In inclined systems, algae culture flows down on an inclined surface and pumped back to the top level continuously during the day.
- Circular central-pivot ponds are one of the oldest types which are used for cultivation. These ponds which are made of concrete, can be 50 meters in diameter and mixed with rotating arm mounted at the center.
- Mixed ponds are commonly used on biomass production for aquaculture feed. These ponds or tanks can vary in mixing methods like aeration from the base or using drag boards (Borowitzka & Moheimani, Open Pond Culture Systems, 2013).
- Raceway ponds are generally preferred among artificial cultivation systems. The channels 20 -50 cm in depth comprise a closed loop, which can be built in concrete, or compacted earth and be lined with plastic. The paddlewheel, where the nutrients are supplied to culture in front of it, is operated to achieve continuous flow and to prevent sedimentation. CO_2 is supplied from the

surface air but aerators may be installed to enhance absorption (Brennan & Owende, 2010).

Some open systems can be seen in Figure 2.1. At the top left, a shallow pond is presented which is one of the largest commercial microalgae production plants in Australia. Mixing is ensured by wind, convection and water flow management through the system. The top right shows paddle wheel driven raceway ponds in USA, and the bottom left shows sloping shallow cascade system in Czech Republic. At the bottom right, water-jet circulated lined raceway-type pond in Australia is introduced (Borowitzka & Moheimani, 2013).

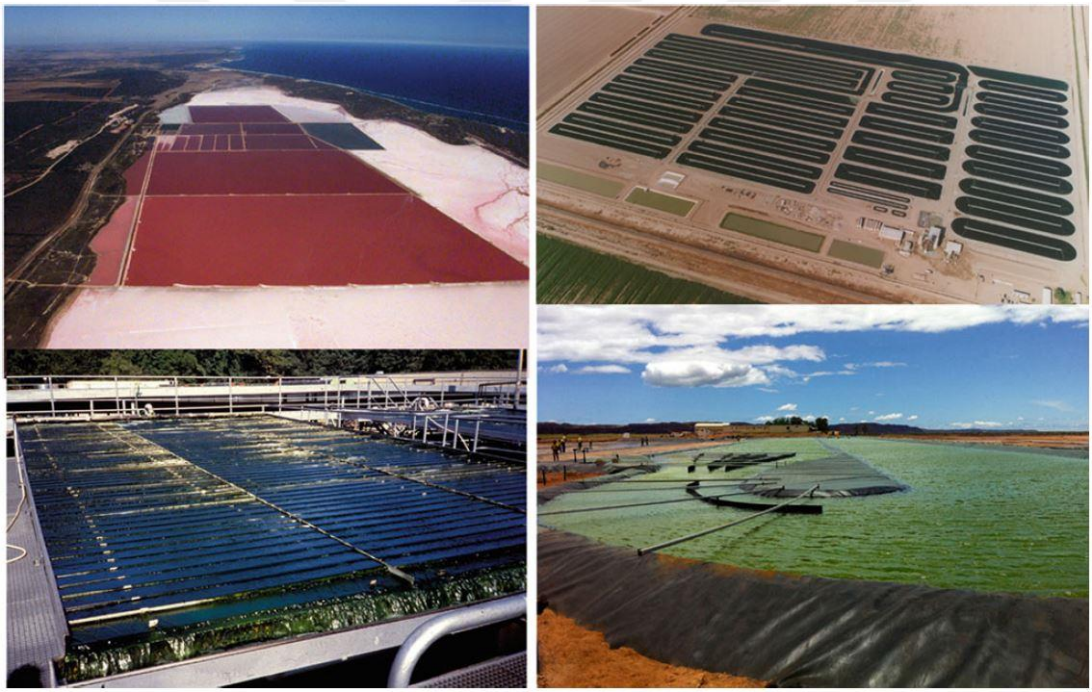


Figure 2.1 Open system cultivation methods (Borowitzka & Moheimani, 2013).

Open systems are more advantageous compared to closed systems in terms of installation and operation costs. They also have lower energy requirement, and maintenance and cleaning are easier. Despite disaccords, open systems are generally

reported to be less efficient on biomass productivity, which these affecting factors can be evaporation losses, temperature fluctuation in the growth media, CO_2 deficiencies, inefficient mixing, and light limitation. Moreover, open systems is limited to a few genera and they require highly selective environments due to contamination risk (Chia, et al., 2018), (Brennan & Owende, 2010).

2.2.2. Closed systems

Closed systems are different types of tanks or photobioreactors in which algae are cultivated. Water, necessary nutrients and carbon dioxide are provided in a controlled way, where monoculture or multicultural cultivations are possible (Carlsson, Beilen, Möller, & Clayton, 2007). Photobioreactor technology is designed to overcome the problems associated with open systems such as contamination and pollution risk (Brennan & Owende, 2010). Photobioreactors have higher efficiency on biomass production, shorter harvest time and higher surface-to-volume ratio compared to ponds. They consist of photo-limited central dark zone and peripheral zone with better lit close to the surface. Turbulent flow provided by air circulates microalgae between light and dark zones, also helping the mass transfer of carbon dioxide and oxygen gases (Demirbaş & Demirbaş, 2010). Closed systems are generally characterized by their shape and geometry. The design considerations for PBRs in common are efficient transport of light and diffusion of CO_2, O_2 gas removal and temperature and pH control. If solar light is used, transparent materials are needed to comprise the system; for plastics, the highest optical transparency in the red wavelength range between 590-670 nm is recommended. The reflective material coating on internal surfaces of PBRs can be preferred if an internal artificial light source is used. Medium culture is mixed through aeration or mechanically with the use of an impeller. Since homogenous diffusion of CO_2, nutrients and light access are important factors on productivity, the thickness of PBR and selection of mixing system have an effect on these parameters (Genin, Aitchison, & Allen, 2016). Closed systems are commonly in three geometries,

they include tubular, flat plate and column photobioreactors (Brennan & Owende, 2010).

Tubular photobioreactors are the most commonly used type in commercial algae production. They consist of tubes either made of glass or plastic in which the culture is circulated (Fig. 2.2) (Zittelli, Rodolfi, Bassi, Biondi, & Tredici, 2013). Transparent tubes range from 3 to 6 cm in diameter and 10 to 100 m in length and can be positioned in various ways (Janssen, Tramper, Mur, & Wijffels, 2003):

- In a horizontal plane, as straight tubes with U-bends
- Vertical, coiled as a cylinder
- In a vertical plane, positioned in a fence-like structure using U-bends or connected by manifolds
- Horizontal or inclined, parallel tubes connected by manifolds.

Figure 2.2 A Tubular photobioreactor in a greenhouse growing Spirulina (Farm1, 2019).

The culture is continuously circulated between the tubes and a reservoir. Biomass sedimentation is prevented by high turbulent flow which is produced by a mechanical pump or an airlift pump (Chisti, 2007). Smaller tube diameter increases biomass productivity and ensures optimal light regime. Extremely long tubular design effects photosynthesis inhibition caused by excessive O_2 production (Acien, et al., 2017).

Column PBRs are vertical elements aerated from the bottom which can be stirred tanks, bubble columns or airlifts. They can be illuminated through perimeter surface or internally (Brennan & Owende, 2010), (Eriksen, 2008). "Column PBR" terminology varies in many sources. (Carvalho, Meireles, & Malcata, 2006) defines airlift and bubble column reactors as types of vertical tubular reactors and (Yen, Hu, Chun-Yen, & Chang, 2014) categorizes them under vertical column PBRs, whereas (Duan & Shi, 2014) remarks them individually like main PBR types as flat or tubular PBR. Considering all with details, bubble columns and air-lifts can be categorized under column PBRs. Bubble column PBRs are vertically placed tubular PBRs and air-lift reactors can be defined as modified bubble column reactors which an internal structure is added. While gas flow is directed to the entire reactor in a bubble column, the volume is separated with a secondary internal column in order to create a circulating flow in the air-lift reactor. Rising bubbles in the internal structure cause the liquid to flow upwards than downwards to counteract forces. In terms of efficiency, it is reported that dimensions for bubble column and air-lift reactors should be limited by 0.2 m in diameter and 4 m in height (Duan & Shi, 2014), (Bitog, et al., 2011).

Flat panel reactors are transparent boxes with a depth ranging from 1 to 5 cm, they are designed to capture maximum solar energy. They are oriented according to the sun either vertically or inclined. Perforated tube at the bottom of the panels supply air and mix the culture (Fig. 2.3).

Overall, closed systems are advantageous for ensuring a controlled environment in terms of temperature, pH, mixing, contamination prevention, evaporation prevention and reduction of carbon dioxide losses (Adeniyi, Azimov, & Burluka, 2018).

However, the equipment and high-energy requirement of the systems impede them to be utilized widespread. Also, most regions of the world's climate conditions are not suitable for stable biomass production, therefore temperature control in culture medium come into prominence. As a result, designing new systems and new material selections with lower costs is crucial for further development (Yen, Hu, Chun-Yen, & Chang, 2014).

Figure 2.3 Flat panel photobioreactor (Lofgren, n.d.).

Comparison of PBR efficiency is theoretically possible, however, experiments conducting various PBRs using the same species under identical environmental conditions are needed for realistic results. A study concluded that vertical PBRs provide higher areal productivity due to lower incident photon flux density on the reactor surface. Flat PBRs found to have the highest average photosynthetic efficiency, areal and volumetric productivity (Acien, et al., 2017). According to a

different research, the maximum cell concentration of *Phaeodactylum tricornutum* was achieved through flat panel PBR among airlift and stirred tank (Guler, Deniz, Demirel, Oncel, & Imamoglu, 2019). In another study, it is reported that flat-plates are considered to be the most efficient design for PBRs (Genin, Aitchison, & Allen, 2016).

Table 2.1 Comparison of different cultivation methods (Brennan & Owende, 2010).

Production system	Advantages	Limitations
Raceway pond	Relatively cheap	Poor biomass productivity
	Easy to clean	Large area of land required
	Utilises non-agricultural land	Limited to a few strains of algae
	Low energy inputs	Poor mixing, light and CO_2 utilisation
	Easy maintenance	Cultures are easily contaminated
Tubular PBR	Large illumination surface area	Some degree of wall growth
	Suitable for outdoor cultures	Fouling
	Relatively cheap	Requires large land space
	Good biomass productivities	Gradients of pH, dissolved oxygen and CO_2 along the tubes
Flat plate PBR	High biomass productivities	Difficult scale-up
	Easy to sterilise	Difficult temperature control
	Low oxygen build-up	Small degree of hydrodynamic stress
	Readily tempered	Some degree of wall growth
	Good light path	
	Large illumination surface area	
	Suitable for outdoor cultures	
Column PBR	Compact	Small illumination area
	High mass transfer	Expensive compared to open ponds
	Low energy consumption	Shear stress
	Good mixing with low shear stress	Sophisticated construction
	Easy to sterilize	
	Reduced photoinhibition and photo-oxidation	

Table 2.1 shows the advantages and disadvantages of commonly used cultivation methods. In summary, the major advantage of raceway ponds is the feasibility in terms

of low construction costs, low power consumption and easy maintenance. In contrast, biomass productivity is low, and the cultivation is limited to a few strains of microalgae due to contamination risk. Also raceway ponds require large areas of lands. As the closed systems are designed to overcome the limitations of open systems, they have the advantage of reducing the risk of contamination thus giving the opportunity to produce monocultures of the selected microalgae species. Also, controlled culture conditions provide higher biomass productivity. On the other hand, fouling is one of the disadvantages. Fouling and dense biomass culture limits light penetration into the culture. Tubular and flat panel PBRs have larger illumination surface area compared to column PBRs, but high surface to volume proportion can result in difficulties to control culture conditions (Acien, et al., 2017), (Brennan & Owende, 2010).

2.3. Requirements of microalgae and PBR Design parameters

Information about the site, the building function and requirements often constitutes the fundamentals of initial architectural design. Parameters of cultivating microalgae take part in these design fundamentals since the environment can have a crucial effect on organisms. Therefore, the key way to create an efficient symbiosis between microalgae and built environment is to provide the optimal growth conditions for microalgae through PBRs in the first step. In the previous section, brief information about microalgae cultivation and common types of PBRs are presented. In this section, requirements of microalgae and design parameters of PBRs are reviewed in order to have the knowledge for integrating them in buildings.

2.3.1. Light

Light is the energy input for photosynthetic organisms; thus becoming the most important factor in algal growth and productivity. Therefore, knowledge about solar radiation is necessary to understand the primary requirement of microalgae. Solar

radiation is electromagnetic energy from the sun. It can be evaluated in 2 ways; as light quantity and light quality.

i. Light quality

Solar radiation spectrum includes bands between 100 nm and 1 mm, and this band is categorized into 3 ranges as ultraviolet, visible and infrared. As seen in Figure 2.4, ultraviolet radiation covers the range of 100-400 nm, visible light is between 400-700 nm, and infrared light contains wavelengths from 700 nm to over 1mm.

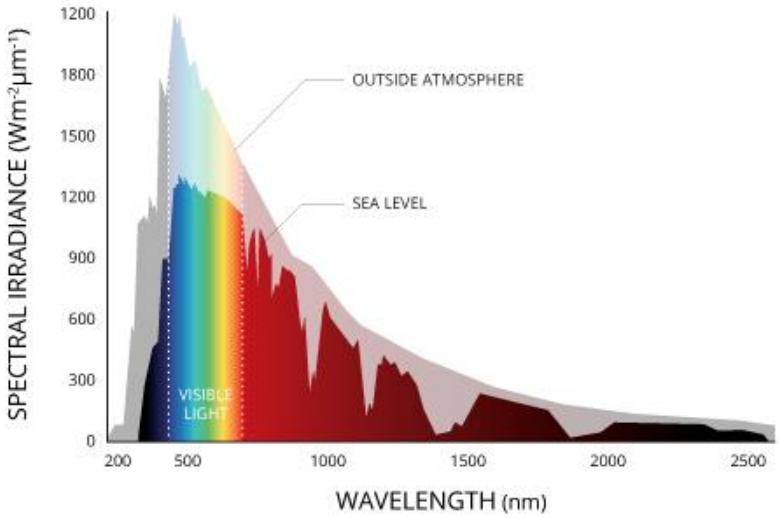


Figure 2.4 The solar radiation spectrum (Fondriest Environmental, 2019).

Shorter wavelengths are more energetic compared to longer ones, which tend to cause more harm. Ultraviolet (UV) light can damage DNA and other important cellular structures, and it is also known to inhibit photosynthesis in phytoplankton by over 8%.

Infrared light is on the opposite side of the spectrum and it is responsible for warming Earth. It is reflected more than UV or visible light due to its longer wavelengths and allows to transfer heat.

The visible light spectrum is the range that can be used for photosynthesis, which is also defined as photosynthetically active radiation (PAR). Different plants may respond to different wavelengths of PAR with different light levels. Similar to microalgae variety, sun plants require higher solar irradiance while shade plants conduct photosynthesis at lower light intensities (Fondriest Environmental, 2019).

ii. Light quantity

Radiation can be quantified in photometric, radiometric and quantum units. Watts, joules, and calories are radiometric units which quantify the amount of energy contained within the radiation. Photometry is a way of measuring light for humans, photometric units include candela, lux or lumens which are also used in architecture (Mattson, 2019). Quantum units express the number of light particles or photons delivered in between the PAR range (Korczynski, Logan, & Faust, 2002). For plants, instantaneous light incident upon a surface is commonly measured in units of micromoles per square meter per second (µmol/m^2/s), where 1 mole of photon is equal to 6.022 x 10^{23} photons. Accumulation of all the PAR received during one day is called daily light integral, and moles per square meter day (mol/m^2/day) is the unit.

The solar irradiance depends on the elevation of surface level, sun's angle and scattering elements like clouds (Fondriest Environmental, 2019). Greatly depending on season and weather conditions, sun can provide about 2000 µmol/m^2/s on a sunny summer day at noon and 65 mol/m^2/day over the course of the day, and 50 µmol/m^2/s on a cloudy winter day at noon and 1 mol m^2/day over the course of the day (Mattson, 2019). In the study conducted by Korczynski, Logan, and Faust (2002) mean daily light integral was presented for each month of the year in United States Provinces. The minimum daily light integral was measured as 5-10 mol m^{-2} d^{-1} at northern cities in December, and the maximum was measured as 55-60 mol m^{-2} d^{-1} at south-western cities in June (Korczynski, Logan, & Faust, 2002).

iii. Microalgae's light requirements

Microalgae can exploit solar irradiation within the PAR range. Approximately 50% of sunlight includes PAR, except PAR range most of the energy is lost due to reflection, fluorescence emission, and dissipation as heat in the light absorption process. At the final stage, the conversion of light energy to biomass efficiency decreases to 8-9%. During outdoor cultivation, light conditions are never constant and light intensity levels affect microalgae's photosynthetic efficiency. Although it is a known fact that algae have the ability to adapt various light intensities, an excessive amount of light can lead to photoinhibition and lack of light can cause photo limitation. For most species, photosynthesis is saturated at 200 µE m^{-2} s^{-1} and maximal productivity is established in the range of 50-100 µE m^{-2} s^{-1}, photoinhibition occurs at irradiances over 500 µE m^{-2} s^{-1} (Acien, et al., 2017), (García Cañedo & López Lizárraga, 2016), (Huang, Jiang, Wang, & Yang, 2017). In addition, it was reported that red light (600-700 nm) and blue light (400-500 nm) appears to be more suitable for cell growth (Chang, et al., 2017).

Correspondingly with light requirements of algae, the main design criteria for PBRs include geometry (surface to volume ratio), orientation and inclination. Generally, it is desired to have a high surface area per volume to maximize the light received. On the other hand, the same characteristic may cause PBRs to become inefficient systems when scaled up to industrial size due to control of frequent volumetric activities such as O_2 accumulation, CO_2 absorption, and nutrient depletion (Tredici, 2004). Also, the influence of orientation and inclination of PBRs on biomass productivity are studied by several authors:

Tredici (2004) stated that reactors placed in east west-direction with tilt angle result in higher productivity at high latitudes while the angle of inclination has no significant effect at low latitudes (Tredici, 2004).

A study was conducted to estimate the solar radiation of flat panel surfaces; horizontal, vertical north/south and vertical east/west in Almeria, Spain (36◦48'N; 2◦54'W). East/west oriented vertical PBRs maximized the solar radiation gathered over the year

for the location studied. The radiation intercepted in winter was increased while the culture was tended to be photo-limited, and in summer was decreased while culture was tended to be photo-inhibited. It was concluded that the east/west orientation is more appropriate for latitudes above 35º, and north/south oriented PBRs receive more radiation at latitudes below 35º (Sierra, et al., 2008).

The relationship between the optimal tilt angles of south facing flat panel PBR and productivity of *Spirulina platensis* under the climatic conditions of south Israel (latitude approximately 31º) was investigated (Fig. 2.5). Small tilt angles of 10-30º in summer and 60º in winter resulted in maximal productivities. For single adjustment, it was 30º for the entire year, besides it was highlighted that several adjustments throughout the year resulted in the highest overall annual productivity (Qiang, Faıman, & Richmond, 1998).

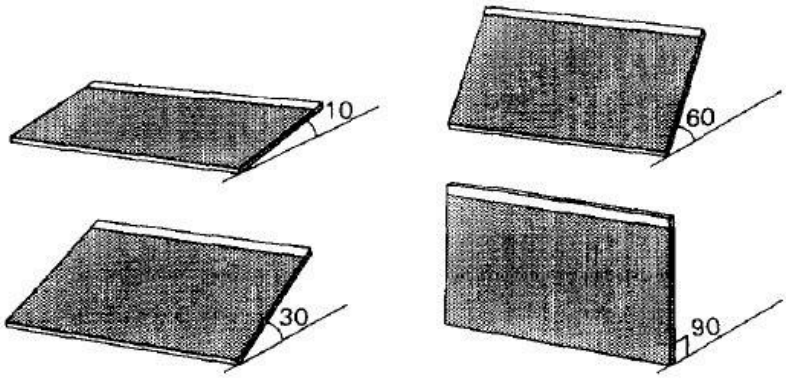


Figure 2.5 Schematic diagram of the flat panel PBR and its tilt angles studied by Qiang and his partners (Qiang, Faıman, & Richmond, 1998).

A theoretical modeling based investigation was made to define the effects of building integration conditions on PBR operation. Three scenarios of inclinations were evaluated on the south facing façade using green microalgae *Chlorella vulgaris*; vertical, horizontal and 45º. It was found that 45º inclination maximizes the yearly

amount of light energy intercepted for a fixed system in Nantes, France (47º 12N, 01º33W) (Pruvost, Le Gouic, Lepine, Legrand, & Le Borgne, 2016).

2.3.2. Nutrients supply

Microalgae are composed of carbon, oxygen, hydrogen, nitrogen, phosphorus, and minor amounts of other elements like sulfur, potassium, magnesium, and calcium. Maximal performance of culture depends on fulfilling these nutrients which comprise the biomass composition (Acien, et al., 2017). Besides light transfer the most important task of PBRs is to be the supply of CO_2 since carbon is the major constituent of algal cells (Posten, 2009), (Chang, et al., 2017).

2.3.3. Culture conditions

Microalgae require adequate culture conditions to grow, which pH and temperature are the major variables. The pH value is an important factor in cultivation since it affects biological mechanisms and especially determines the solubility of CO2 and other essential nutrients. Most of microalgae's optimal values range from neutral to slightly alkaline. Generally, the variations inside the culture medium's pH value occur from the reactions involved in the consumption of carbon and nitrogen. Additionally, the excess accumulation of O_2 has a toxic effect on algae and decreases PBR efficiency. Therefore aeration or degassing system for O_2 removal is necessary for cultivation in a PBR (Acien, et al., 2017), (Chang, et al., 2017).

Temperature control is another factor in establishing high biomass production. The optimal temperature for growth of the most microalgae species ranges from 20º to 35º. Below the optimal temperature the biomass yield can be decreased, but overheating of the cultures can become fatal for the cells. Shading, water spraying, immersion in a water bath, regulating the temperature feed and installing a heat exchanger are

methods to avoid overheating of PBRs (Tredici, 2004), (Huang, Jiang, Wang, & Yang, 2017), (Acien, et al., 2017).

2.3.4. Mixing

Agitation or mixing is essential in the cultivation of microalgae. One of the most important phenomena related to mixing is regulating light utilization. In PBRs with dense culture light gradients can be formed and several illuminated regions occur as saturated region, limited region, and photoinhibition region. In other words, incident light is absorbed by microalgae on PBR surface and light cannot penetrate deeper because of dense culture, which causes photic zones (high light intensity) and dark zones where fermentative growth occurs. Efficient mixing provides all cells to experience light and dark cycles and increase biomass productivity and PBR efficiency. Additionally, it provides uniform distribution of nutrients to the cells, facilitates heat transfer, ensures gas exchange, prevents sedimentation and maintains the cells in suspension. Excessive applications can damage cells and result in culture collapse. Mixing methods include air bubbling, stirring, or liquid circulation by pumps (García Cañedo & López Lizárraga, 2016), (Chang, et al., 2017), (Acien, et al., 2017).

2.4. Harvesting Methods

Harvesting is the recovery of biomass from the medium which requires one or more steps to achieve desired biomass concentration (Brennan & Owende, 2010). Harvesting costs may contribute 20 - 30% to the total cost of algal biomass depending on the cell size and culture volume (Carlsson, Beilen, Möller, & Clayton, 2007). Selection of harvesting technology depends on characteristics of microalgae such as cell size, density, and the value of the target products. Biomass is obtained from algal suspension by harvesting and drying.

Figure 2.6 shows the diagram of microalgae harvesting techniques. In general, harvesting consists of two stages: bulk harvesting or thickening, which the culture is concentrated; dewatering, which the slurry obtained by bulk harvesting is concentrated and dewatered to a cake. In other words, it is vital to reduce the water content of algae suspension to enable practical harvesting and obtain a thick algae slurry. The harvesting methods include flocculation, filtration, flotation, centrifugation, gravity sedimentation (Brennan & Owende, 2010), (Barros, Gonçalves, Simões, & Pires, 2015), (Show & Lee, 2014). At the present, harvesting technology involves mechanical, chemical, biological and electrical based methods. Combination of these methods is widely preferred in order to achieve a high separation rate at lower costs. In fact, flocculation-sedimentation with centrifugation combination can reduce the process costs (Barros, Gonçalves, Simões, & Pires, 2015).

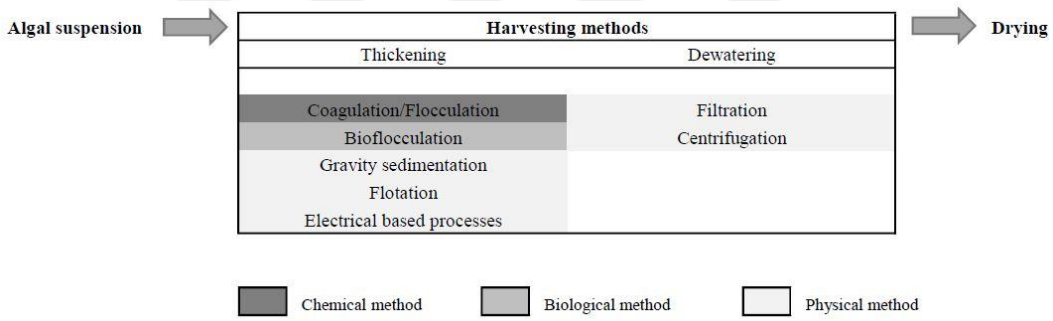


Figure 2.6 Diagram of microalgae harvesting techniques, adapted from (Barros, Gonçalves, Simões, & Pires, 2015), (Show & Lee, 2014).

Flocculation is a method that aggregates particles with each other forming flocs, causing them to sink as sediments by high density (Rashid, Rehman, Sadiq, Mahmood, & Han, 2014). Naturally, algal cells carry a negative charge that prevents aggregation. Addition of flocculants neutralizes or reduces the negative charge, providing aggregation for the harvest. Flocculation can be defined as a preparation stage for other harvesting methods like filtration and flotation, which mentioned as bulk

harvesting process above (Brennan & Owende, 2010). Chemical coagulation/flocculation is the main approach to optimize the harvesting costs (Brennan & Owende, 2010).

Filtration is a widely used technique which the microalgae suspension is passed through a porous medium. The pore size depends on species cell size which microfiltration or ultra-filtration can be used. The efficiency of 95% can be achieved by filtration (Rashid, Rehman, Sadiq, Mahmood, & Han, 2014).

In flotation, gas bubbles are introduced to the broth medium for particle transportation and separation by lifting force. This method can also be defined as an inverted sedimentation. Flotation method is advantageous in terms of low space requirements, short operation time and high flexibility with lower initial equipment costs (Barros, Gonçalves, Simões, & Pires, 2015). 80-90% harvesting efficiency is reported by this method (Rashid, Rehman, Sadiq, Mahmood, & Han, 2014).

In centrifugation, the centrifugal force separates microalgae biomass from the medium. The process is rapid and energy intensive, 80-90% of harvesting efficiency can be obtained within 2-5 min operation (Rashid, Rehman, Sadiq, Mahmood, & Han, 2014). Gravity and the centrifugation sedimentation are based on Stoke's Law, settling of suspended particles are determined by density and radius of algae cells. Gravity sedimentation is suggested for harvesting microalgae which will be obtained low-value products such as wastewater treatment or biofuels (Brennan & Owende, 2010), (Barros, Gonçalves, Simões, & Pires, 2015).

Table 2.2 shows the main advantages and disadvantages of different harvesting methods. Low-energy requirement is the advantage of chemical coagulation/flocculation, auto and bioflocculation, gravity sedimentation, and filtration methods. However, the use of chemicals and intervention in culture pH can be toxic or change the cellular composition of microalgae. As an electrical based process, centrifugation do not require additive chemicals, but they require high-energy compared to the others. Filtration is a simple method and it has no effect on

microalgae's cellular composition, but risk of clogging requires regular membrane cleaning that increases the operational costs.

Table 2.2 Comparison of different harvesting methods (Barros, Gonçalves, Simões, & Pires, 2015).

Harvesting method	Advantages	Disadvantages
Chemical coagulation/ flocculation	Simple and fast method	Chemical flocculants may be expensive and toxic to microalgal biomass
	No energy requirements	Recycling of culture medium is limited
Auto and bioflocculation	Inexpensive method	Changes in cellular composition
	Allows culture medium recycling	Possibility of microbiological contamination
	Non- toxic to microalgal biomass	
Gravity sedimentation	Simple and inexpensive method	Time-consuming
		Possibility of biomass deterioration
		Low concentration of the algal cake
Flotation	Feasible for large scale applications	Generally requires the use of chemical flocculants
	Low cost method	Unfeasible for marine microalgae harvesting
	Low space requirements	
	Short operation times	
Electrical based processes	Applicable to a wide variety of microalgal species	Poorly disseminated
	Do not require the addition of chemical flocculants	High energeticandequipmentcosts
Filtration	High recovery efficiencies.	The possibility of fouling/clogging increases operational costs
	Allows the separation of shear sensitive species	Membranes should be regularly cleaned
		Membrane replacement and pumping represent the major associated costs
Centrifugation	Fast method	Expensive method
	High recovery efficiencies	High energy requirements
	Suitable for almost all microalgal species	Suitable only for the recovery of high-valued products
		Possibility of cell damage due to high shear forces

2.5. Bioenergy

Depletion of fossil fuel sources and their negative environmental impacts has given cause for a common practice on using renewable energy sources hence reducing carbon dioxide emissions (Pragya, Pandey, & Sahoo, 2013). As a solution, bioenergy derived from renewable sources is considered to be one of the most sustainable alternatives. Also, it is argued to be advantageous because of its independence from climate and weather conditions which can be a problem for other renewable energy alternatives like solar and wind. Bioenergy is acquired from non-fossilized biological sources where biomass can be used directly as fuel or converted into liquid or gas form. The common types of biomass used for energy are firewood, plants, forest, animal waste which are burnt to obtain heat energy and defined as primary biofuels. Secondary biofuel types are mainly; biodiesel, bioethanol, and biogas, which grouped as in three generations. First generation biofuels are produced from human food stock like sugarcane, soybean, wheat, sugar beets and rapeseed. While starch-rich crops like sugarcane and wheat which contain a high amount of carbohydrates are commonly used as feedstock for bioethanol, biodiesel is produced from oleaginous biomass like soybean, coconut, and rapeseed. Unfortunately, it is reported that the usage of food crops has caused food shortage also affecting food prices negatively. The second generation feedstock are mainly non-food crops; but unsustainability, low-yield, expensive production processes make them infeasible. Therefore, the target of third generation biofuel's feedstock are microorganisms, which the algae strikes the most attention by researchers (Chia, et al., 2018), (Alam, Mobin, & Chowdhury, 2014).

Biofuel production technology consists of four basic stages as microalgae isolation and characterization, microalgal biomass production, harvesting and product processing. While there are many important factors in the development of biofuel production, cultivation process plays a key role among them (Elcik & Çakmakcı, 2017). Besides, it is reported that production of biofuels from microalgae through existing methods still cannot achieve a positive energy balance (Sevigne Itoiz, et al., 2012), (Pruvost, Le Gouic, Lepine, Legrand, & Le Borgne, 2016).

2.5.1. Conversion of biomass to biofuel

Microalgae can be used as a source of raw materials for many types of biofuels. Unlike fossil fuels, biofuel production is environmentally friendly and the processes do not entail the release of dangerous compounds. Biofuels can be in solid, liquid and gas form. For example, it is possible to produce methane by anaerobic degradation of microalgal biomass, biodiesel by microalgal oils and biohydrogen by photobiological reactions (Elcik & Çakmakcı, 2017), (Morone, 2016).

Figure 2.7 shows the energy conversion processes from biomass. The conversion technologies to process microalgae biomass can be categorized as thermochemical and biochemical conversion. Selection of conversion process mostly depends on the type and quantity of biomass feedstock, desired form of energy and economic aspect (Brennan & Owende, 2010). Thermochemical conversion processes include gasification, direct combustion, pyrolysis, and liquefaction. These methods are the thermal decomposition of organic components in biomass to obtain biofuel. Biochemical conversion processes can be given as anaerobic digestion, alcoholic fermentation, and photobiological hydrogen production (Tsukahara & Sawayama, 2005).

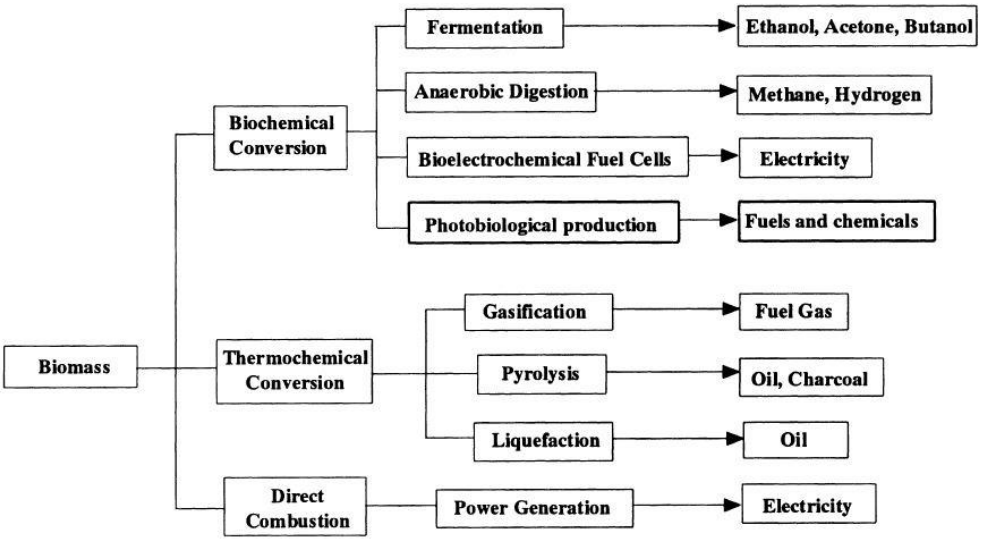


Figure 2.7 Energy conversion processes from algal biomass (Tsukahara & Sawayama, 2005).

2.5.1.1. Biodiesel

Biodiesel is a sustainable fuel type that is obtained from biologic sources of oil and fats which contain long-chain esters. Transesterification is a chemical reaction between triglycerides and alcohol in the presence of a catalyst. Triacylglycerol (oil) is processed through transesterification to produce biodiesel which contains long-chain fatty acid methyl ester and glycerol as a byproduct (Morone, 2016), (Du, et al., 2016), (Brennan & Owende, 2010).

Microalgae are composed of carbohydrates, lipids, and protein, which lipids that can be used to produce biodiesel. Therefore, oleaginous algae strains, which are rich in oil content, are desirable for biodiesel production (Sun, Liu, & Zhou, 2016). Usually, lipid rates are between 1-70%, but under certain conditions, specific strains can reach up to 90% of dry weight (Mata, Martins, & Caetano, 2010). Lipid quality and quantity can vary relatively with nutrients conditions in the cultivation media; for example, lipid rate can be increased in the absence of nitrogen and silicon. On the other hand, growth rate and lipid production are inversely correlated; while an increment of 15-30% in lipid rate, the growth rate decreases up to 50%. A study has shown that 22% of nutrients are used for biomass production and the rest is supplied for oil production in plants.

As a result, the selection of algae strain and cultivation mode are the key aspects of microalgae cultivation before harvesting. After harvesting the processes for converting biomass to biodiesel involve sequential post-harvesting steps: drying, cell disruption, oil extraction, and transesterification, followed by the characterization of the fuel (Mohan, Devi, Subhash, & Chandra, 2014). Besides, all the applied processes may have a significant effect on oil quality and quantity. For example, an increment of lipid extraction from *Chlorella sp.* was reported by using glass microparticles as disruption enhancer (Derakhshandeh, Atici, & Un, 2019).

2.5.1.2. Bioethanol

Carbohydrate is an important component of interest in biofuel production. Algae's energy reserves can consist of starch, cellulose, paramylon, and laminarin which are formed by carbohydrates. Bioethanol and biobutanol are biofuel types which algae can provide, sugar-containing starch/cellulose in algae acts as a substrate for fermentation. After harvesting algae biomass, bioethanol can be produced in three general steps; pre-treatment to release fermentable sugars, fermentation of the sugars to ethanol, and the separation and purification of ethanol (Chia, et al., 2018).

Currently, bioethanol is the major biofuel in the global market. The studies found out the use of ethanol addition to gasoline increases the efficiency of engines, reduces gasoline consumptions and CO_2 emissions (Chia, et al., 2018). Bioethanol fermentation has lower energy consumption compared to biodiesel production. Furthermore, the undesired byproduct CO_2 can be used for cultivation process (Bahadar & Khan, 2013).

2.5.1.3. Biogas

Biogas is a mixture consisting of primarily methane (55-75%), carbon dioxide (25-45%) and other gases like hydrogen sulphide which can be obtained through anaerobic digestion (Brennan & Owende, 2010), (Harun, Singh, Forde, & Danquah, 2010). It is a complex biochemical process that a group of microorganisms metabolize the organic compounds into biogas. Methane can be used directly for the production of heat, electricity, and transportation, also supplied for a natural gas network. The final digestate is utilized as fertilizer (Kiran, Stamatelatou, Antonopoulou, & Lyberatos, 2016). Anaerobic digestion is suitable for highly moist organic wastes (80-90%), therefore it eliminates biomass drying process and provides better energy efficiency compared to other methods used for biofuel production (Brennan & Owende, 2010), (Adeniyi, Azimov, & Burluka, 2018), (Prajapati & Malik, 2015). Production of biogas by anaerobic digestion process is affected by factors like temperature, pH, but long

retention time and high organic loading rate provides better methane yield (Harun, Singh, Forde, & Danquah, 2010).

2.5.2. Utilization of biofuels in buildings

Biofuels have been used since ancient times as a source of heat and light. However, increasing energy needs lead fossil fuels to be the focus of interest and provided development in refining and supply chain management of fossil fuels. Recent political, economic, environmental, and security concerns have brought biofuel utilization forward. Currently, the attention is focused on biofuel utilization in the transportation sector. Considering the energy consumption of buildings, biofuel becomes one of the alternatives to reduce the environmental impact of building operations and the carbon footprint.

Biodiesel and biogas variants may be used in fuel oil and natural gas boilers and water heaters. In general, manufacturers have developed the performance of systems compared to conventional ones regardless of fuel type, only the energy density of utilized biofuel can create noticeable changes.

Biofuels can also be used in reciprocating engine, turbine or fuel cell, which can be grouped as prime movers, to generate electricity and heat. Another alternative is to pair prime movers with heat recovery systems to form combined heat and power (CHP) systems, which are also known as cogeneration systems. CHP systems can recover the energy losses which stems from conversion, transmission, and distribution of energy from grid power (Betz, 2012).

2.5.3. Species selection for biodiesel production

Obtaining energy from algae is not a new subject, however, researchers encounter with countless possibilities since there too many microalgae species. Therefore, the selection of suitable microalgae species for the target product is no easy task. Even

there can be great variations in terms of cell composition and response to growth conditions between strains (Borowitzka, Species and Strain Selection, 2013).

In this part, a review of microalgae species which are suitable for obtaining biodiesel as an end-product is made. The energy content of biodiesel is higher with 41 MJ kg^{-1}, compared to biogas with 9.36 MJ kg^{-1}, and it is more convenient to store (Patel, Tamburic, Zemichael, Dechatiwongse, & Hellgardt, 2012). There are many studies in the literature and some species that are suitable for biodiesel production come into prominence. High lipid productivity, which means both high oil content and high growth rate, is desired among other characteristics for biodiesel production (Chisti, 2007), (Borowitzka, Species and Strain Selection, 2013). It is reported that smaller microalgae grow faster and tend to have higher lipid productivity. Relatively, the high growth rate may depend on different factors:

- Non-sticky small-size cells easily suspend in the water column, therefore the diffusion of nutrients and CO_2, and contact with light from all directions would be easier, consequently leading to better photosynthetic efficiency and higher growth rate.
- The ability of toleration to high irradiances is another feature that reduces photoinhibition and photodamage at high light intensities which can also increase productivity.
- Large-size and heavy cells can be harvested with low-cost methods like filtration but it is hard to keep them in suspension in the culture system and they generally grow slower.
- The culture system and its geographical location determine the temperature that microalgae may be exposed. It is essential that the selected strain has the ability to tolerate the temperature range to avoid cell damage or culture loss.

Apart from these, photosynthetic activity, CO_2 sinking capacity, respiration rate, lipid composition and quality, pH and oxygen tolerance, salinity, shear tolerance to forces of mixing system, competitiveness to contaminating organisms in the culture are other

desirable characteristics of microalgae for energy production (Borowitzka, Species and Strain Selection, 2013), (Brennan & Owende, 2010). Overall, it is unlikely to have all the characteristics in one strain. It can be concluded that, selection of species having the strongest characteristics for the desired end product and which also can tolerate the environmental conditions are both the key for a reliable production at the lowest cost.

Neochloris oleoabundans, Scenedesmus obliquus, and *Botryococcus braunii* are examples of suitable microalgae species for biodiesel production. They are selected due to their high lipid productivity. Review of research papers which guided the species selection process is as follows. The characteristics of the selected microalgae species were collected in Chapter 3, Table 3.2, and some of the information were referenced from these papers.

2.5.4. Review of works conducted on selected species of Neochloris oleoabundans, Scenedesmus obliquus and Botryococcus braunii

i. *Botryococcus braunii*, *Chlorella vulgaris*, and *Scenedesmus sp.* were examined under high levels of CO_2 for lipid production. Growth rate, carbon fixation ability, total lipid content, and fatty acid profile of three species were evaluated. Microalgae were cultivated at 25 ± 1 ºC with continuous illumination of 150 µmol m^{-2} s^{-1} with a high level of CO_2 similar to flue gas for 2 weeks. In result, *Scenedesmus sp.* was appropriate for mitigating CO_2, due to its high biomass productivity and carbon fixation ability, and *B. braunii* was suitable for biodiesel production, due to its lipid quantity and quality (Yoo, Jun, Lee, Ahn, & Oh, 2010).

ii. *Botryococcus braunii* strain CHN 357 was examined in terms of lipid content and growth at different temperatures, light intensities, and salinities. Overall, the results indicate that the optimum culture conditions of this strain are 23 ºC and 30-60 W m^{-2} (Qin & Li, 2006).

iii. Microalgae species of *Chlorella vulgaris*, *Spirulina maxima*, *Nannochloropsis sp.*, *Neochloris oleabundans*, *Scenedesmus obliquus*, and *Dunaliella tertiolecta* was screened in order to find the most adequate one(s) for biofuel production in terms of oil quantity and quality. The aim was identifying the strains with the highest growth rates and appropriate composition of oil content. Firstly, all the microalgae were cultured in airlift bioreactors, and then in polyethylene bags with bubbling air under 150 µE m^{-2} s^{-1} lighting conditions, at the optimal temperature for each microalga (indoors), and finally in outdoor raceways mixed by paddle wheels, during 4 months from May to August. As a result, *Neochloris oleabundans* and *Nannochloropsis sp.* had the highest oil content, 29%, and 28.7% respectively, and they were found to be suitable as feedstock for biofuel production. Both microalgae can reach up to 56% oil content under Nitrogen deficient culture medium. Besides, *Scenedesmus obliquus* presented the most adequate fatty acid profile, which makes it a good option for biodiesel production (Gouveia & Oliveira, 2009).

iv. In Li, Mark, Wang, Wu, and Q. Lan's (2008) study, *Neochloris oleabundans* was selected for examining the effects of nitrogen on cell growth and lipid accumulation. In literature; *Chlorella*, *Dunaliella*, *Nannochloris sp.*, *Parietochloris Incisa*, *Neochloris oleoabundans*, *Botryococcus braunii* have been reported to have the ability to accumulate large quantities of lipids. Among these, marine species of *Dunaliella* and *Nannochloris* were reported to be unsuitable for freshwater cultivation. *Parietochloris Incisa*'s lipid composition was found to be less desirable for biodiesel production due to its lipid composition and *Botryococcus braunii* was approved to be appropriate for liquid biofuel production but not biodiesel, regarding the energy conversion processes from biomass (Li, Mark, Wang, Wu, & Q. Lan, 2008).

v. A comprehensive review was made on *Neochloris oleoabundans* strain for biofuel production by (Abu Hajar, Riefler, & Stuart, 2017). The optimum temperature and light intensity for growth vary in literature according to

different studies. Nevertheless, the growth conditions of 180-220 µmol/m^2/s range for light intensity and 25-30 ºC range for temperature is widely accepted.

vi. The effect of light intensity on *Scenedesmus Obliquus* culture was examined in terms of growth rate, lipid content and photosynthetic performances, both in batch and continuous systems. In batch reactors, the species showed a maximum growth rate at 150 µmol m^{-2} s^{-1} light intensity. At higher intensities growth was inhibited but microalgae exploited light with lower efficiency, therefore biomass accumulation was substantial. In continuous flow experiment, a higher biomass density was obtained and the photo saturation point was found to be increased to more than at 300 µmol m^{-2} s^{-1}. The results show that *Scenedesmus Obliquus* has the property of adaptation to various lighting conditions which is advantageous to reduce operating conditions of reactor systems for controlling (Sforza, Gris, Silva, Morosinotto, & Bertucco, 2014).

vii. Hodaifa, Martinez, & Sanchez (2010) studied on the influence of temperature on growth of *Scenedesmus Obliquus* in diluted olive mill wastewater as culture medium. They examined the effect of temperature changes with a range of 14.85-34.85 ºC on algal growth and concluded that 29.55 ºC was the ideal value for maximum growth rate (Hodaifa, Martinez, & Sanchez, 2010).

viii. *Botryococcus braunii* was grown in flat panel PBR under different light intensities. Flat panel dimensions were 0.75 m × 0.59 m × 0.068 m, and the experiments were conducted in a controlled environment, in 27 ºC with %1 CO_2. Biomass concentration and specific growth rate were maximum at a light intensity of 800 µmol m^{-2} s^{-1}, and lipid content and lipid yield were maximum at a light intensity of 450 µmol m^{-2} s^{-1}. The results were used in mathematical modeling in order to predict and optimize light transport in PBRs for biomass and lipid accumulation. Based on the modeling, the optimal conditions for lipid production were found to be 450 µmol m^{-2} s^{-1} light intensity which allows maximizing the use of light energy. Also, it was reported effective light

penetration decreases beyond 3 cm width of the PBR irrespective of the incident light at high biomass concentration (Khichi, Anis, & Ghosh, 2018).

2.6. Bioluminescence

Light is one of the prime movers of the evolution process and it has always been an integral part of living systems. Regardless of the evolutionary hierarchy, all living organisms emit ultraweak light spontaneously that is not detectable by the human eye, which the phenomena is called as biophoton emission. Different from biophoton emission, bioluminescence is the emission of visible light by living organisms. From time immemorial, natural light sources like sun, moon, stars, and biologically originated systems, in other words, bioluminescent organisms have fascinated and captured the attention of many people (Devaraj, Usa, & lnaba, 1997). Since the ancient era, there are many written records of bioluminescence. Observations date back roughly from 1500 to 1000 B.C. in China, referring to fireflies and glow-worms. Marine bioluminescence has been recorded firstly by Greek philosopher Anaximenes (585-528 BCE). Aristotle (384-322 BCE) who wrote the first detailed bioluminescence observations, also identified cold light that bioluminescent organisms was not accompanied by heat. During the renaissance period, before the end of the 15th century, the explorers brought back reports of “burning seas”, the phenomenon which is known as milky seas at the present time, suggested being due to the bioluminescent marine bacteria. In 1885 the chemical reaction of bioluminescence was verified by the French scientist Raphael Dubois. In addition, regarding the cold light spectrum, bioluminescence was advertised as a source of illumination, “the cheapest form of light”. Therefore, it can be said that bioluminescence played a role in the development of the modern theory of light. By the end of the 19th century, the advancements of ocean-going vessels and deepwater trawling provided to describe most of the bioluminescent species, revealing that all marine species below 200 fathom are bioluminescent (Roda, 2011), (Lee J. , 2017).

Bioluminescence is a widespread phenomenon in nature, a broad range of organisms from single-celled to large vertebrates can produce light (Table 2.3). In the table, bioluminescent creatures are categorized according to their living environments as marine, freshwater and terrestrial. As seen, a major part of the bioluminescent organisms resides in the ocean, in a diverse range of habitats, from polar to tropical waters at different depths (Widder, 2010). Emission of light serves for different functions, with different chemistries in different species, and the process has changed or perhaps lost many times during evolution (Therese & Hastings, 2013).

Table 2.3 Bioluminescent creatures in different environments (Widder, Marine bioluminescence, 2001).

MARINE
Bacteria
Dinoflagellates
Radiolarians
Sponges
Coelenterates Scyphozoa (Jellyfish); Hydrozoa: Hydroids, Hydromedusae; Siphonophores; Anthozoa: Sea fans, Soft corals, Sea pens, Sea pansies.
Ctenophores (Comb jellies)
Nermerteans (Ribbon worms)
Molluscs Sea slugs, Boring bivalves, Cuttle fish, Squid, Vampire squid, Octopods
Annelids Polychaeta (Bristle worms), Parchment tube worms, Scale worms, Fireworms
Arthropods Pycnogonids (Sea spiders), Copepods, Ostracods (Sea fireflies), Malacostraca, Opossum shrimp, Amphipods, Euphausiids (Krill), Decapod shrimp
Bryozoa (Sea mats)
Chaetognaths (Arrow worms)
Echinoderms Crinoids (Sea lilies), Holothurians (Sea cucumbers), Asteroids (Starfish), Ophiuroids (Brittle stars)
Hemichordates (Acorn worms)
Chordates Tunicates: Sea squirts; Pyrosomes (Fire cylinders); Larvaceans
Vertebrates Sharks, Anchovies, Gulper eels, Spookfish, Slickheads, Shining tube shoulders, Bristlemouths, Hatchetfish, Viperfish, Dragonfish, Snagglетooth fish, Loosejaws, Pearleye fish, Lanternfish, Morid cod, Merluccid hake, Rat-tails, Midshipman fish, Anglerfish, Pinecone fish, Flashlight fish, Ponyfish, Drums
TERRESTRIAL
Bacteria
Fungi
Molluscs Snails
Annelids Earthworms
Arthropods Insects, Springtails, Fireflies, Click beetles, Railroad worms, Glow-worms, Centipedes, Millipedes
FRESHWATER
Molluscs Limpet (*Latia*)

Bioluminescent light is produced as a result of energy released during a chemical reaction. Without exceptions in all bioluminescence mechanisms, molecules specific to a group of organisms are oxidized and catalyzed by specific enzymes. The chemical reaction consists of two main components; a light emitting molecule - luciferin, which is highly conserved across phyla, and a catalyzing enzyme – either luciferase or photoprotein. In the marine environment, four different luciferins are commonly seen. Different from luciferins, luciferases and photoproteins are unique and derived from many evolutionary lineages (Haddock, Moline, Case, & F., 2010), (Therese & Hastings, 2013).

Fluorescence and phosphorescence are different natural optical phenomena than bioluminescence. Fluorescence is the emission of light derived from the energy of an absorbed photon which happens in less than a second like a bioluminescent flash. The distinction between two mechanisms may be blur because of some luciferins are fluorescent and rarely the excitation energy is passed along to fluorescent proteins. Phosphorescence is the delayed emission of light over a long period of time from the optically excited source, which glow in the dark paints can be example (Haddock, Moline, Case, & F., 2010), (Widder, 2001).

Light production in creatures occurs in diverse forms of morphology and it is controlled by chemical and neurological mechanisms. While some animals have complicated light organs, single-celled organisms also contain all needed apparatus for light production (Shimomura, 2012). Bioluminescence reflects the characteristics of the environment in which the living organisms have evolved. In the ocean, sunlight decreases approximately 10 times at every 75 m until the depth of 1000 m, where sunlight cannot reach further. Light is a way of communication in the deep ocean and it frequently serves multiple functions for a single organism. Visible light is in the blue-green spectrum after a particular depth, so the majority of marine organisms are sensitive to blue light. Figure 2.8 shows the light penetration and light spectrum in the ocean. The wavelength is centered around 470 nm, which the light travels farthest through seawater. A bioluminescent flash can be seen from tens to hundreds of meters

away, even a single-celled dinoflagellates flash can reach 5 m away. Additionally, creatures can control their light like adjusting the intensity, color, and angular distribution, and have the ability to turn their photophores on and off. The functions of bioluminescence include:

- Defense,
- Counter-illumination,
- Burglar alarm,
- Aposematism,
- Offense and prey attraction,
- Illumination,
- Intraspecific communication (Widder, 2010), (Haddock, Moline, Case, & F., 2010).

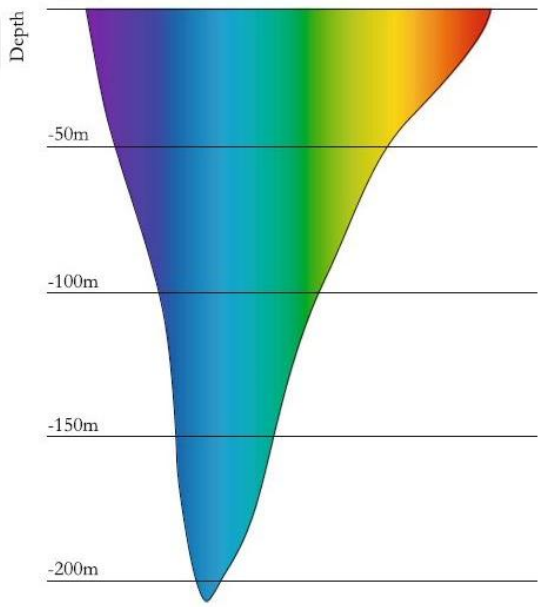


Figure 2.8 Light penetration in the ocean and spectrum of visible light (Manuel, 2017).

Luminous bacteria are widely distributed in the marine environment, which glows continuously and forms bioluminescent surface phenomenon “milky seas” as they reach sufficiently high concentrations to initiate quorum sensing in the presence of oxygen. Figure 2.9 shows the region a milky sea was spotted by a merchant ship in the Indian Ocean near the horn of Africa in 1996. The light intensity is weak, but the continuous emission can make them to be visually distinguished from dinoflagellates. Commonly, marine living bacteria are in the genera *Photobacterium*, *Beneckea,* and *Vibrio*, while non-marine forms are in *Vibrio* and *Xenorhabdus*. Some of them correlate symbiosis with certain marine fishes and squid, while bacteria produce light, the host provides the optimum growth environment. Generally accepted hypothesis for luminous free-living bacteria is that the continuous light production serves for attraction, which causes them to be consumed and thereby living in nutrient-rich gut (Haddock, Moline, Case, & F., 2010), (Shimomura, 2012), (Widder, 2010).

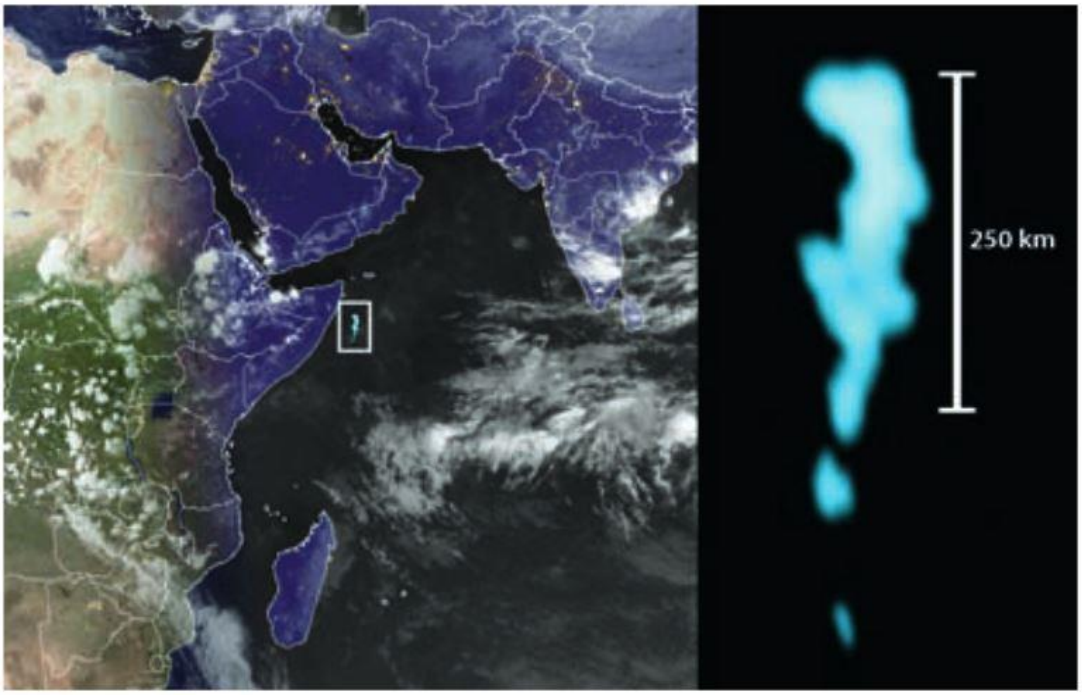


Figure 2.9 Left. The region a milky sea was spotted (box, color enhanced) by a merchant ship in the Indian Ocean near the horn of Africa in 1996. Right. Enlarged image of the same area (Therese & Hastings, 2013).

Dinoflagellates are single-celled algae, which are abundant in the surface water of the marine environment. They comprise of thousands of species which are mostly marine, within the only members of phytoplankton community with the ability of bioluminescence. These microscopic organisms emit light in short flashes when disturbed at night, forming beautiful sparkles that attract people, for example, bioluminescent bays in Puerto Rico and Jamaica are one of the tourist destinations. “Red tides”, which are colored patches formed by some species of dinoflagellates, can be seen due to excessive growth. (Therese & Hastings, 2013), (Haddock, Moline, Case, & F., 2010), (Marcinko, Painter, Martin, & Allen, 2013).

The cell size of the dinoflagellates varies between 30 µm - 1 mm and the wavelength of the light produced can reach 474 nm. The light production process takes less than 20 ms, as it makes bioluminescence one of the fastest cellular processes has known. Each cell can produce more than one flash, light production can continue until the whole luciferin is oxidized and the cell is depleted. The light intensity changes between 10^8-10^{10} photons/s/flash and it can be detected by the human eye. (Latz, 2005).

Bioluminescence is prior for dinoflagellates, light production comes first after the ability to swim rather than growth. Results of previously done works show that dinoflagellates invest in bioluminescence even more than the reproduction system in terms of energy utilization. Generally, the emission of light is a response to mechanical stimulation, which is activated by deformation of the cell wall. Mechanical stimulation can be in fluid shear stress form or direct physical contact. Experiments also have shown that different stimuli like rapid temperature changes, chemical, pH, electrical and osmotic shock can also induce bioluminescence. Intensity and decay rate of flashes are mainly mechanical stimulation-dependent, and other affecting factors include sensitivity of cells to mechanical stimulation, nutritional state of the cell and light (Haddock, Moline, Case, & F., 2010), (Marcinko, Painter, Martin, & Allen, 2013), (Valiadi & Iglesias-Rodriguez, 2013), (Deane & Stokes, 2005).

The change in the hydrodynamic environment is known to stimulate bioluminescence, but there are no accurate statements about its causes and functions. Besides, it is known that bioluminescence changes the feeding behavior of the predator. One of the theory is the utilization of light as a defense tool, which is known as “burglar alarm”. The prey attracts other larger predators to distract the organism which threatens (Latz, 2005). The origins and causes of bioluminescence are still being investigated and many experiments have been conducted to investigate the effect of different fluid flow mechanics on the cellular mechanism (Cussatlegras & Le Gal, 2004), (Widder, 2010), (Latz, 2005).

2.6.1. Species selection for light production

Bioluminescence has been reported in 81 dinoflagellates species (Marcinko, Painter, Martin, & Allen, 2013). The level of bioluminescence may vary according to the morphological structure, physiological state, diurnal rhythm and mechanical stimulation of the cell; different species and even each cell under the same strain may react differently (Valiadi & Iglesias-Rodriguez, 2013). The light intensity and length vary according to the species, but it is known that large cell species give more light. *Pyrocystis* species were found to produce bioluminescence 1000-fold more per cell than *Lingulodinium*, and 100-fold than *Ceratium fusus*, *Peridinium pentagonium*, and *Pyrodinium bahamense* (Lee R. E., 2018). *Pyrocystis* and *Dissodinium* species reach the maximum population at depths of 60-100 m, although they can be found below 200 m (Bhovichitra & Swift, 1977). Therefore, high population densities and cell division rates can be associated with low light intensities for the growth of *Pyrocystis* (Rivkin, Seliger, Swift, & Biggley, 1982).

Pyrocystis fusiformis, *Pyrocystis noctiluca*, and *Ceratocorys horrida* are selected as examples of suitable microalgae species for light production. *Pyrocystis fusiformis*, *Pyrocystis noctiluca* has high light intensity and *Ceratocorys horrida* has high bioluminescence response level. Review of research papers which guided the species selection process is as follows. The characteristics of the selected bioluminescent

microalgae species were collected in Chapter 3, Table 3.1, and some of the information were referenced from these papers.

2.6.2. Review of works conducted on selected species of Pyrocystis fusiformis, Pyrocystis noctiluca, and Ceratocorys horrida

i. Latz, Nauen, and Rohr (2004) conducted a study to compare flow sensitivity of morphologically diverse species of *Ceratium fusus*, *Ceratocorys horrida*, *Lingulodinium polyedrum* and *Pyrocystis fusiformis* using fully developed laminar and turbulent pipe flow. Laboratory cultures of dinoflagellates were grown in seawater with f/2 additions on a 12:12 light/dark cycle. Bioluminescence response thresholds were occurred in laminar flows, depending on species, ranged from 0.02 – 0.3 N m^{-2}. It was found that *C. horrida* showed the highest response rate, while *P. fusiformis* had the brightest flashes. As a result, species were ranked in order of decreasing sensitivity as *C. horrida* > *P. fusiformis* > *C. fusus* > *L. polyedrum* of bioluminescence response in laminar flow. The response was not significantly changed in turbulent flow (Latz, Nauen, & Rohr, 2004).

ii. Bioluminescence of *Pyrocystis noctiluca* was examined by different flow regimes using Couette chamber. Laboratory cultures of dinoflagellates were grown in enriched f/2 media and maintained in a culture chamber at 20 ± 2 ºC on a 12:12 light/dark cycle. It was concluded that stationary homogeneous laminar shear flow was unable to excite the bioluminescence reaction in *Pyrocystis noctiluca*. It was suggested that temporal changes are required such as turbulence with accelerated flows to stimulate massive bioluminescence. In the experiment, total light emission was $3x10^{14}$ for the amount of $25x10^{3}$ cells (Cussatlegras & Le Gal, 2004).

iii. Swift and Meunier (2008) studied the effects of light intensity on division rate, stimulable bioluminescence and cell size of the oceanic dinoflagellates *Dissodinium lunula*, *Pyrocystis fusiformis* and *P. Noctiluca*. Cultures were

grown on a 12:12 light/dark cycle at different light intensities under cool-white fluorescent lamps. Cell numbers did not increase above an intensity of 5-10 µEin m^{-2} s^{-1} for all species and division rate was saturated at 30, 60 and 60 µEin m^{-2} s^{-1} for *Pyrocystis fusiformis, P. Noctiluca,* and *Dissodinium lunula* respectively (Swift & Meunier, 2008).

2.7. Daylighting systems as a tool for microalgae cultivation in buildings

Diffused skylight and direct sunlight are the components of the term "daylight" (Alrubaih, ve diğerleri, 2013). Daylight provides high illuminance and color discrimination for good vision and affects human health positively. Researches on daylighting are still developing since the systems can improve building occupant's life quality, increase energy efficiency and reduce environmental pollution. Daylight systems are used to improve the daylight while adjusting the illuminance of regions as desired, provide sun-shading and eliminate glare (Ruck, et al., 2000). In this section, daylighting systems are introduced focusing on the light transport methods since they are a way to provide light for microalgae in building cores.

Due to the fact that some of the systems do not fall precisely into a single category, different classifications of daylighting systems exist in literature. In here, they are considered as 2 main groups: light guiding and light transport systems.

2.7.1. Light guiding systems

Light guiding systems enables the light to reach 8-10 m further from its entrance by reflection, refraction or deflection (Garcia Hansen & Edmonds, 2003). Either direct sunlight or diffuse light can be used, but generally, systems which are designed for direct sunlight also provide shading. These systems include light shelves laser cut panels, prismatic panels, louvers systems, sun-directing glasses, holographic optical elements, and anidolic ceilings. Some light guiding systems are presented in Figure

2.10. The working principle of the system (a), and d is the redirection of the light to the room ceiling. Figure 2.11 shows an example of a light shelf application. The systems which are shown in Fig. 2.10 (b), (e), and (h) are different types of louvers that give opportunity to block the direct sunlight that causes glare, allow the penetration of daylight at desired angle or redirect the light to the desired area. Laser cut panels and prismatic panels shown in (f) and (g) are made of transparent materials that redirect light. Prismatic panels can be either used as a shading device but they also transmit diffuse skylight. Sun directing glass (Fig. 2.10 h) is made of concave acrylic elements stacked within a double-glazed unit. It is usually placed in the window area above the eye level, the system redirects direct sunlight onto the ceiling. Anidolic ceiling is shown in (c), the diffuse light is concentrated with parabolic concentrators and the light is transported with a light duct to the back of the room. Anidolic ceilings provide adequate light to room interiors under overcast sky conditions (Ruck, et al., 2000).

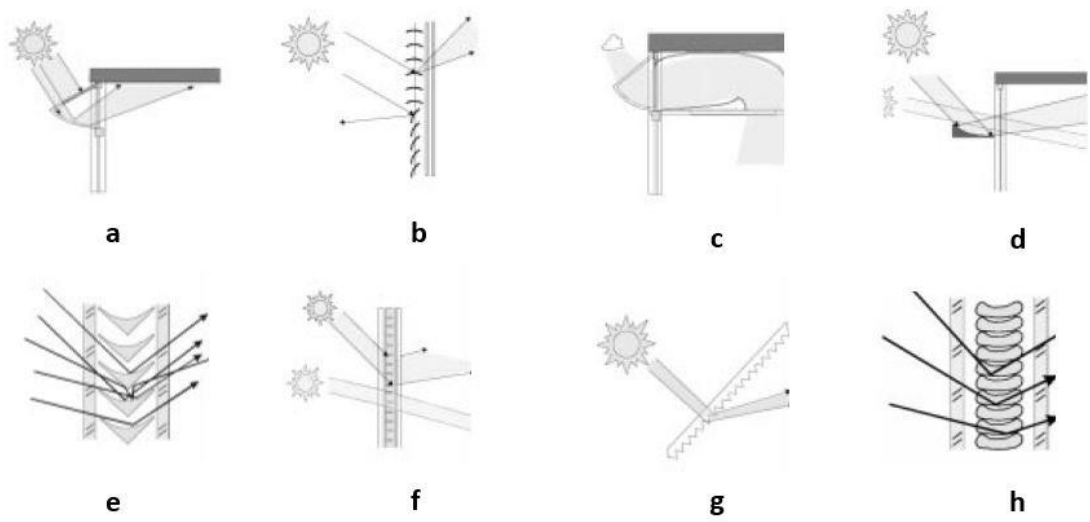


Figure 2.10 Light guiding systems: a) Light guiding shade, b) Louvers and blinds, c) Anidolic ceiling, d) Light shelf, e) Fish system louver, f) Laser cut panel, g) Prismatic panel, h) Sun-directing glass (Ruck, et al., 2000).

Figure 2.11 Semi-transparent double light shelves made out of reflective glass (Ruck, et al., 2000).

2.7.2. Light transport systems

Light transport systems channel the collected sunlight to building interiors, the majority of them depend on direct light. The systems details are given below as they can transmit light to further distances than guiding systems, and they have the potential to provide sufficient sunlight for microalgae in the building core. Light transport systems consist of 3 major components: a collector, light guides for transportation, and distributors (Garcia Hansen & Edmonds, 2003), (Nair, Ramamurthy, & Ganesan, 2014). Transport elements deliver light from the collector to the place where it will be distributed, although some types can also act as emitters (Carter, 2004).

Laser cut panels, anidolic concentrators can be given examples as passive light collectors. They are able to capture sunlight only at a certain angle due to fixed applications, so they require a large area to collect. Active light collectors are coupled

with a sun-tracking device (Nair, Ramamurthy, & Ganesan, 2014). Heliostat is one of the active light collectors, which is a sun-tracking mirror. Figure 2.12 shows the heliostats above the Morgan Lewis Office Building. As shown, usually, two mirrors are seen in configurations, the second fixed mirror is used to redirect sunlight to the desired direction. Honeycomb system and Fresnel lenses are other light collectors and combination of systems can be used to capture and concentrate the light. In the Himawari system, small hexagonal Fresnel lenses are attached to heliostat to concentrate sunlight and eliminate UV and IR light. Than collimated beams are received by 1 mm diameter of glass fibers, which can transport light up to 200 m. (Nair, Ramamurthy, & Ganesan, 2014), (Tsangrassoulis, 2008).

Figure 2.12 Heliostat above the Morgan Lewis Office Building (Boubekri, 2014).

Light transport methods can be named differently in literature such as; tubular guidance systems (Carter, 2004), light pipes (Boubekri, 2014), or light transportation guides (Nair, Ramamurthy, & Ganesan, 2014). These methods include lens systems,

hollow mirrored guides, hollow prismatic light guides, and fiber optics. Classification of transport elements may depend on materials or physics of light transmittance like multiple specular reflection and total internal reflection (Garcia Hansen & Edmonds, 2003), (Nair, Ramamurthy, & Ganesan, 2014), (Boubekri, 2014). In general, light transport systems have benefits of:

- Integration possibility with artificial lighting,
- Providing centralized lighting without electrical fixtures and cables,
- Eliminating UV, IR radiation, and heat (Garcia Hansen & Edmonds, 2003).

Figure 2.13, 2.14 and 2.15 presents an applied light transport system in Austria. A heliostat configured with a mirror redirects light to a concentrator (Fig. 2.13). The concentration of captured sunlight is increased by two adjustable Fresnel lenses to be transported in 30 cm diameter tubular prismatic hollow guide (Fig. 2.14). As seen in Figure 2.15, diffuse ambient light is provided to the task area. Users can adjust the mirror to provide light directly on the task area and to have visual contact with outdoors. The working plane illuminance is reported between 100 and 1200 lux in sunny conditions with a 30% overall system efficiency. Artificial lighting is also incorporated in the system, which can be adjusted according to sky conditions. Power savings of 40-60% were recorded compared with a conventional system (Carter, 2004).

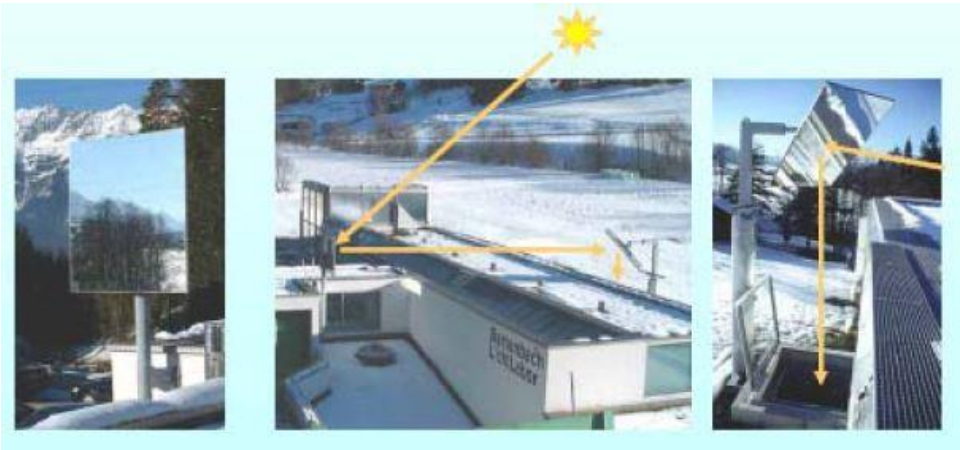


Figure 2.13 Capturing the light by a heliostat configured with a mirror (Okutan, 2008).

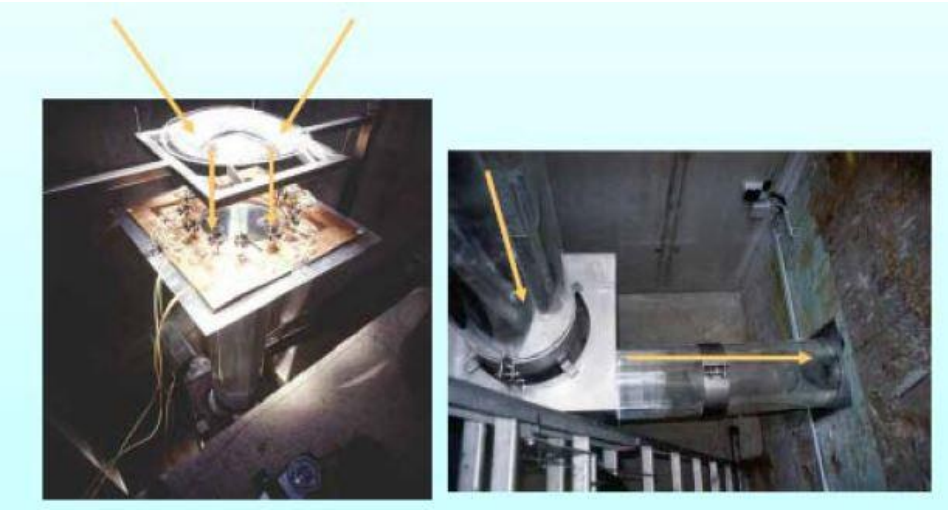


Figure 2.14 Concentration and transportation of light (Okutan, 2008).

Figure 2.15 The illuminance in the room (Okutan, 2008).

Another example of applied the light transport system is in Borusan Holding Building, İstanbul. Light is collected with heliostats and redirected to prismatic light guide (Fig. 2.16).

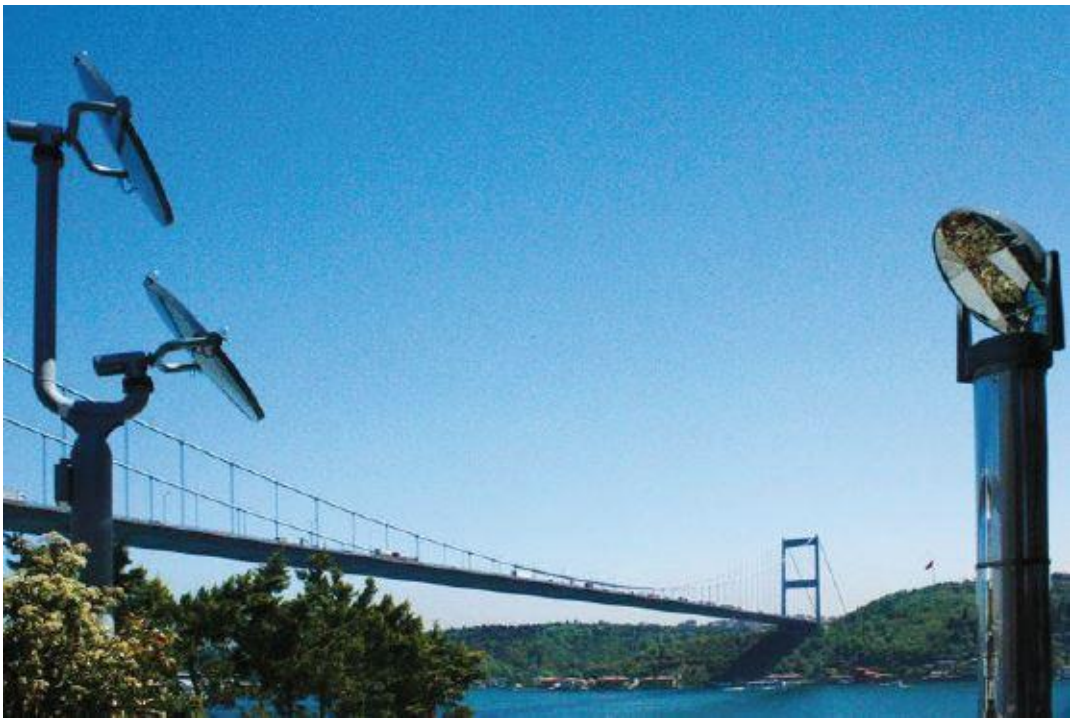


Figure 2.16 Heliostats above Borusan Holding (Boubekri, 2014).

In Figure 2.17, the light transportation is shown on the building section. The prismatic light guide has a length of 8 m at outside, and it continues for 24 m across four floors inside the building. The illuminance is reported as 400 lux on the upper floor and 150 lux on the lower floor in sunny sky conditions (Boubekri, 2014).

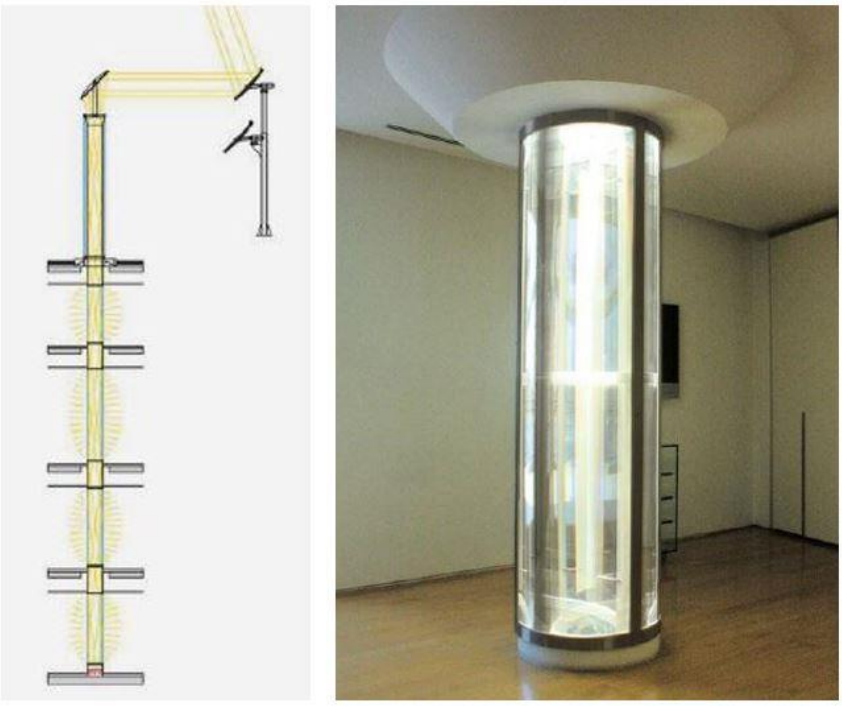


Figure 2.17 Borusan Holding's daylighting; Left: Section of the daylighting system, Right: The illuminance in the room (Boubekri, 2014).

2.8. Case studies

Forms and functions of natural systems have always influenced architects, designers, and scientists. Unfortunately, the complexity and the requirements of living organisms limit their use in construction. In this context, there are many conceptual and theoretical works at the present time, some of them have experimented and few of them have been put into practice.

2.8.1. Applied Projects

i. BIQ Building

BIQ (Bio Intelligent Quotient) is the world's first algae integrated building in Hamburg, designed by Splitterwerk Architects in collaboration with Arup. The four-

story building has a 1.600 m^2 of gross floor area with 15 apartments, and the construction cost is approximately 5 million euro funded by Hamburg Climate Protection Concept. Figure 2.18 shows the building picture from south. Flat panel PBRs are used on the southeast and southwest sides of the façade which are 200 m^2 in total, consisting 129 modules of 70 cm wide, 170 cm high and 8 cm thick, rotatable sun-tracking panels. Laminated safety glass is used as PBR material and without supports they are 1.7 cm wide filled with the culture medium (Lakenbrink, Petersen, & Roedel, 2013).

Figure 2.18 Façade integrated flat panel PBRs in BIQ Building (Lakenbrink, Petersen, & Roedel, 2013).

The bio-reactive facade serves for different functions, it generates energy from algal biomass and solar thermal heat and provides a second exterior layer as well, which can function as shading, thermal insulation or noise abatement. PBRs are mounted on a steel frame, approximately 35 cm apart from the building envelope, integrated with installation system for the requirements of algae such as nutrients, CO_2 and air (Fig. 2.19).

Figure 2.19 Installation system of PBRs (Synthetic Design Biotopes, 2019).

Panels are filled with drinking water enriched with nutrients for the cultivation of algae, which are connected in series and to building services center for circulation. Each of them has an inlet and outlet connection to the water system and the circuit is separated for each story. The temperature of the culture medium is constantly kept below 40 ºC in the summer and above 5 ºC in the winter. High flow velocities along the inner surfaces of PBRs and scrapers inhibit sedimentation and keep algae in suspension. Air injection is controlled by magnetic valves and is provided every 4 seconds. CO_2 is supplied from flue gas which is saturated before introducing algae. It is reported that BIQ building can reduce CO_2 emissions by six tons per year.

Since algae absorb sunlight, the produced heat can be used for different functions after harvesting, either for the heating system or hot water system. The associated heat is reintroduced to the system with integration of heat pumps or excess energy can be stored in geothermal boreholes or transferred to the district energy network for later use. Flotation is used to harvest algae and the biomass is converted into biogas in an external biogas plant and supply energy to the city.

Overall, the integration of different systems and utilization of algae composes the energy concept of BIQ building. The whole system is tracked in a central building management system (BMS) called Rockwell SPS. Energy indicators of PBRs are presented in Table 2.4. Photobioreactor façade can produce 4500 kWh of electricity or generate heat of 6000 kWh per year. According to these data, one apartment's electricity consumption or four apartment's heat requirement can be covered by algae façade. The results are provisional forecast for the annual energy balance. Even the exact energy consumption rates of the building are not provided, yet it exemplifies a good practice for architecture (Lakenbrink, Petersen, & Roedel, 2013), (Fondazione Eni Enrico Mattei), (Fytrou-Moschopoulou, 2019).

Table 2.4 Energy indicators of PBRs (Lakenbrink, Petersen, & Roedel, 2013).

Basic data per m² bioreactor area	
Biomass production	15 g TS/m²/day (900 kg/year)
Energy production in biomass	345 kJ/m²/day
Biogas production from biomass	10.20 L methane/m²/day
Energy indicators for 200 m² bioreactor area with 300 days of production per year	
Biomethane production	612 m³ methane /year
Energy in methane	6487 kWh/year
Energy loss (auxiliary power, etc.)	30 per cent of production
Net energy as methane	approx. 4541 kWh/year
Net energy from heat	approx. 6000 kWh/year

ii. Urban Algae Folly, Canopy, and Algaecurtain

A cladding system with the use of engineered algae was proposed by the architecture firm Ecologic Studio with their partners. Cushions made of ETFE are filled with a tailor-bred strain, *Nannochloropsis gaditana*, which compose a PBR. The integration of microalgae in ETFE façade creates a bio farm to obtain fuel, biological fertilizer and food supplement from algae. The dynamic façade also provides shading which reduces the energy requirements for cooling and increases urban air quality. Utilization of microalgae contributes to citizens' wellbeing and educates society by addressing environmental and energy issues. It is stated that ETFE cladding requires less structural support compared to an equivalent system in glass, and its carbon footprint is claimed to be 80 times lower. The fabrication process of ETFE PBR is still being worked, but the Urban Algae Folly installations are handmade mock-up demonstrations of this technology (Ecologic Studio, Photo.Synth.Etica, 2019).

The Urban Algae Folly is an interactive pavilion integrating microalgae, which is built for EXPO Milano 2015 Future Food District (Fig.2.20). Microalgae are cultivated in the ETFE architectural skin system and it approximately produces 2 kg of O2 per day, the equivalent oxygen that 3 adults need to survive; which normally 25 large trees can provide. *Spirulina* is being known as the food of the future which is selected to be cultivated. The folly can produce the equivalent in proteins of 2 kg of meat per day, enough for 12 adults, with no animals being killed and no methane being released, as well as capturing 4 kg of CO_2 per day. Placed sensors read visitors' presence and speed which control the flow of microalgae for algal oxygenation, solar insolation, and growth (Ecologic Studio, Photo.Synth.Etica, 2019).

Figure 2.20 The Urban Algae Folly (Ecologic Studio, 2019).

The Urban Algae Canopy was also presented as other microalgae integrated ETFE architectural cladding system in the Expo Milano 2015 Future Food District (Fig. 2.21 and Fig. 2.22) Figure 2.22 shows the structural elements holding the ETFE cladding and detached pipes for supplying algae nutrients and CO_2 (Ecologic Studio, 2019).

Figure 2.21 The Urban Algae Canopy (Ecologic Studio, 2019).

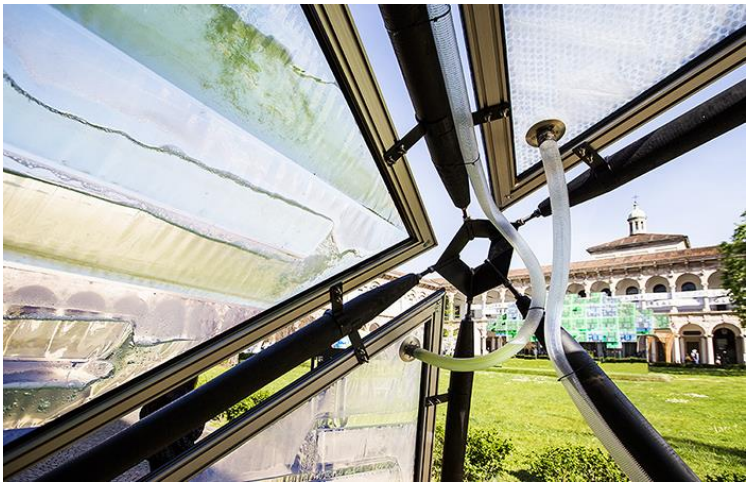


Figure 2.22 The Urban Algae Canopy (Ecologic Studio, 2019).

Algae curtain is designed to be integrated into both existing and new buildings. It was presented in Dublin during the week of Climate Innovation Summit 2018 (Fig. 2.23 and Fig. 2.24). The curtain is a custom made bio-plastic container, which is 16.2x7 m in size. Unfiltered urban air is captured from the bottom and air bubbles rise through the watery medium within the container. Oxygen is released from the top of each module. Sun feeds microalgae and releases luminescent shades at night (Ecologic Studio, 2019).

Figure 2.23 Algae curtain (Ecologic Studio, 2019).

Figure 2.24 Algae filling (Ecologic Studio, 2019).

iii. The Algae Dome

Four-meter-high bioreactor dome is designed by IKEA's external lab Space10 and architects Aleksander Wadas, Rafal Wroblewski, Anna Stempniewicz, which was installed at Copenhagen's Chart Art Fair to show the potential of algae as a super crop of future (Fig. 2.25). It was chosen to be exhibited in the 2017 event after winning an architecture competition run by the fair. The dome is wrapped with 320 meters of coiled tubing filled with microalgae. It is pointed out that the different species of microalgae could be used for animal feed, the development of biofuels and as a way to reduce CO2 and GHG, as a method of treating industrial wastewater (Morris, 2019).

Figure 2.25 The Algae Dome (Morris, 2019).

iv. Algocultures

SymBIO2 is an industrial research and development project which aims to develop hybrid façade systems that optimize the symbiosis between building and microalgae cultivation. Project participants are XTU architects, National Center for Scientific Research (University of Nantes) and engineering consulting firms. The first prototype of this operational façade was introduced in Pavillon de l'Arsenal, which was exhibited and studied on at the same time (Fig. 2.26). During the exposure time, the engineers and the researchers measured the culture conditions and various parameters

on the prototype (Pruvost, Le Gouic, Lepine, Legrand, & Le Borgne, 2016), (Pavillon de l'arsenal, 2019).

Figure 2.26 Algocultures in Pavillon de l'Arsenal (Pavillon de l'arsenal, 2019).

v. Philips Biolight

Manufacturer Philips presented the Microbial Home in 2011, a domestic eco-system project which proposes a lighting fixture by using household waste. Wall-mounted glass cells were filled with bioluminescent bacteria solution which are fed with methane and composted materials. A soft green light was emitted by the bacteria in a sustainable cycle (Fig.2.27) (Manuel, 2017), (Koerner, 2019).

Figure 2.27 Microbial Home project by Philips (Koerner, 2019).

vi. Bioluminescent Field and Interference projects

The German designer Nicola Burggraf has conducted research using *Pyrocystis lunula*. Different types of stimulations to induce bioluminescence were explored, ranging from tilting, shaking, stirring, pouring and rotating. It is reported that 200 ml of dinoflagellates showed 0.6 lux of illuminance. As an extension of preceding experiments “Bioluminescent Field” and “Interference” projects were exhibited publicly to test the response of dinoflagellates to motion and sound. In Bioluminescent

Field project, eighty thin poles carrying dinoflagellates filled glass vial was connected with a reactive floor. After the visitors' entrance, algae was responded to movement by flashes. Researcher indicates that every cell was acted as a motion sensor to visitors which could be seen as intruders (Fig. 2.28). In Interference, the effect of acoustic waves on algae was explored. It was found that specific frequencies stimulate algae and induce bioluminescence (Burggraf, Bioluminescence: Toward Design with Living Light, 2014).

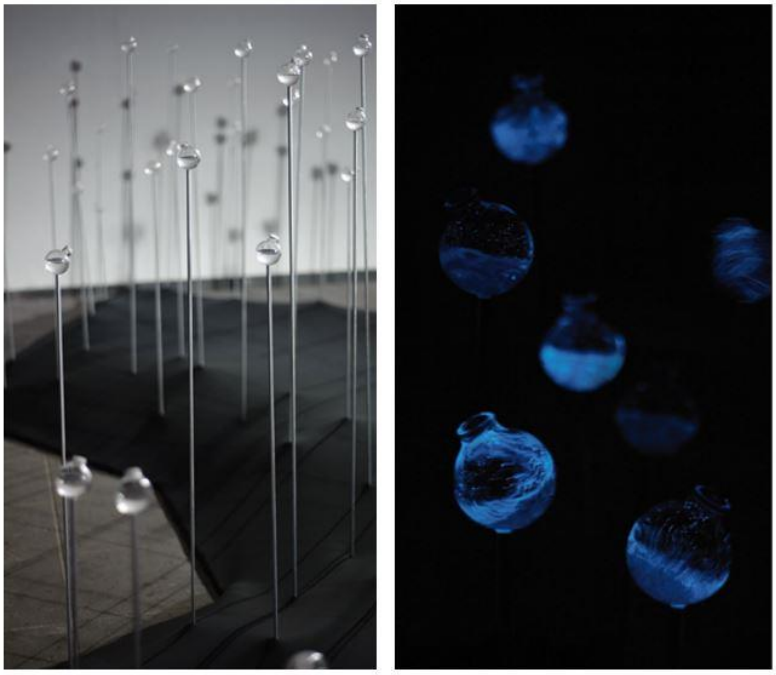


Figure 2.28 Bioluminescent Field Project installation in 2010 Luminale, Frankfurt: Left:glass vials with dinoflagellates installed on a reactive floor; Right: Bioluminescence response after the entrance of visitors (Burggraf, 2019).

2.8.2. Conceptual projects

ii. Los Angeles Federal Office Building

Architects and engineers from HOK and Vanderweil won the Metropolis Magazine's Next Generation Design Competition with "net zero building retrofit" submission proposed for the 46-year-old federal office building in Los Angeles (Fig. 2.29). The

design uses mixed energy conservation and renewal strategies like integrated louvers for passive ventilation, phase changing materials for insulation, photovoltaic films, rooftop solar collectors and cloud computing system. Additionally, a modular network of tubular PBRs wrap the building, also providing sun shading for interior offices spaces. Microalgae contribute to renewable energy production on site by 9%. The PBRs are covered with a thin photovoltaic film to protect the tubes and avoid overexposure to the sun. CO_2 is captured from the nearby freeway, it enters a central vessel with building's wastewater and additional nutrients that are derived from building's black water and supplied to feed the system. Reclaimed water can be reintroduced to the system and generated O_2 is released into the building. Overall, it is given 84% of reduction in building's energy demand while generating 16% on site with achieving the goal of net-zero design (HOK, 2019), (Elrayies, 2018).

Figure 2.29 Net zero retrofit solution for GSA office building by HOK and Vanderweil (Dexigner, 2019).

iii. Marina City Towers

Marina City Towers are icons of Chicago City, which were originally built in 1962. A design proposal was made by Influx Studio to achieve zero environmental footprint by the integration of different systems which algae come into prominence among others (Fig.2.30). The project, named The Green Loop, was the winner of the Abundance Prize of the 2011 International Algae Competition. Wind turbines at the top of the towers enhance airflow and carbon scrubbing plants capture CO_2 and filter it be used in algae bioreactors to produce biofuel. Algae tubes wrap around the circumference of the towers. The phytoremediation garden recycles water for irrigation of the vertical gardens cladding the façade and allows building occupants to farm. Exterior surface of balconies is covered with photovoltaic and solar thermal panels to provide additional energy and light for the plants. The bridge between towers is used as algae showroom and bazaar, brings people together to promote farming (Meinhold, 2019), (Kim E. , 2019), (Elrayies, 2018).

Figure 2.30 Design proposal of Marina City Towers by Influx Studio (Meinhold, 2019).

iv. In Vivo

In Vivo is another microalgae utilized project which is designed by XTU architects, MU architecture and SymBIO2 consortium (Fig.2.31 and 2.32) (Legendre, 2019). In the project, it is aimed for urban integration of nature and living matter with using urban greenhouses, vertical forests and building integrated microalgae. The project consists of 3 buildings; the Tree House which the trees and bushes are placed on balconies, the Plant House which is dedicated to small scale urban agriculture, and the AlgoHouse which the microalgae is used within building's façade (Fig. 2.33). Also, there is another house for earthworms to allow the vermicomposting of organic waste and culture conditioning. Named "biofaçade" is developed by XTU architects and the SymBIO2 consortium under a research program for bio-based medicines. The heat collected by PBRs will be used for domestic hot water and heating systems.

Figure 2.31 In Vivo project, the AlgoHouse (Legendre, 2019).

Figure 2.32 In Vivo project, the Tree House (Legendre, 2019).

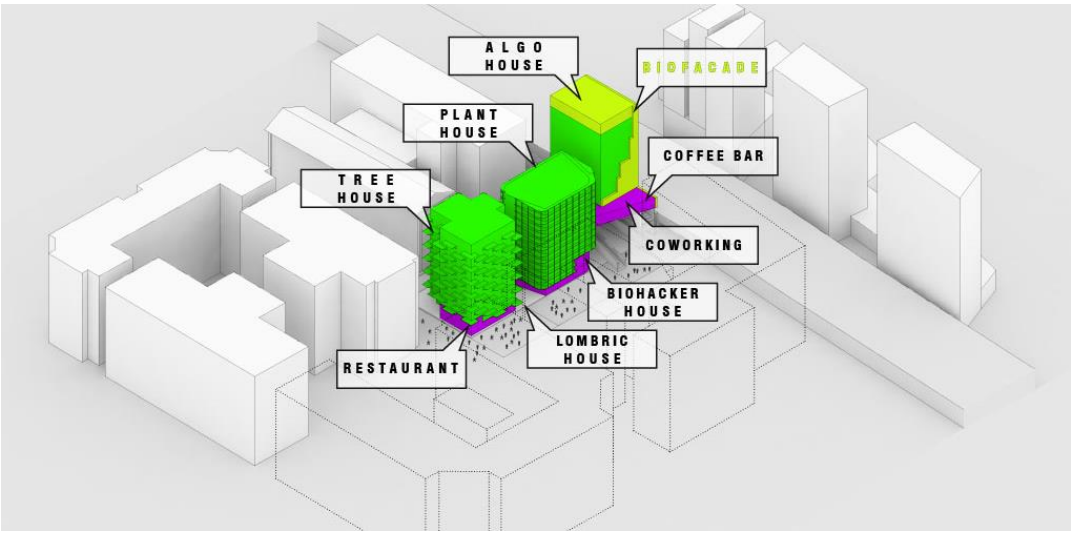


Figure 2.33 Functional diagram of In Vivo project (Legendre, 2019).

v. French Dream Towers

XTU Architects had a design proposal for high-rise French Dream Towers in Hangzhou called French Dream Towers (Fig. 2.34), which many sustainable strategies are utilized in the project including microalgae integration (Fig. 2.35). The French architecture studio has influenced from various sources of Chinese history, haute-couture fashion and nature in the design.

Figure 2.34 French Dream Towers (Block, 2019).

The algae are introduced as a layer to provide natural insulation, also the building's heat is used to regulate the culture temperature of algae. As can be seen in Figure 2.35, organic building form and sloped façades help facilitate rainwater collection, the rainwater flows naturally to basins on the roof and ground. Through the phytoremediation process, flora growing near the basins cleans air and rain and aquaponics system allow for the cultivation of vegetables, flowers, and fish (Block, 2019), (Pinto, 2019).

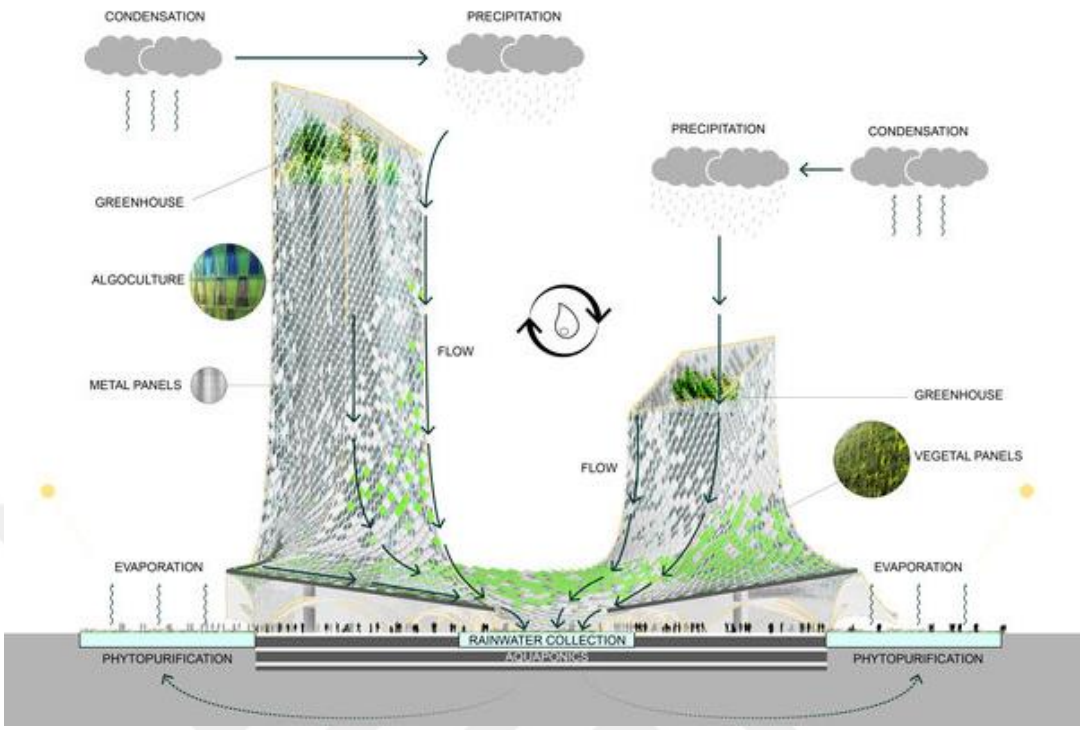


Figure 2.35 Sustainable design strategies of French Dream Towers (Pinto, 2019).

vi. FSMA Tower

The architect Dave Edwards proposed a skyscraper design for London which focuses on algae (Fig. 2.36). The building envelope was considered as a green wall that improves air quality, produces food and biofuel. The waste biomass feeds the building skin and wastewater can be recycled through microalgae. A ground source heat pump allows to store the excess heat and to be reused (Chalcraft, 2019).

Figure 2.36 FSMA Tower (Chalcraft, 2019).

vii. Developments in synthetic biology

Developments in synthetic biology have accelerated for the new forms of architecture that incorporate the dynamic properties of living structures. Recent studies show that different species of bacteria can be adapted for detecting pollutants, maintaining indoor quality and used for producing bioluminescent trees (Armstrong & Spiller, 2010). “Glowing Plant Project” was an open source initiative which was funded by many people on Kickstarter and exceeded its financial goals. It was aimed that trees could replace street lamps and serve as a sustainable lighting source in the long period (Manuel, 2017).

2.8.3. Published research works

i. Kim (2013) performed a study on algae integrated façade system which structural, thermal and environmental performances were analyzed using computer software and experimentation. The idea was to replace an algae bioreactor system between two glazing systems to provide thermal and structural performance, daylight transmission, shading capability and improve indoor air quality. The façade system consists of algae zone, which is a flat panel PBR, vision zone and a mechanical system for growth and maintenance of algae, the panels are made of ½ inch acrylic sheet 12ft tall by 5 ft wide with a 1-inch water gap (Fig. 2.37).

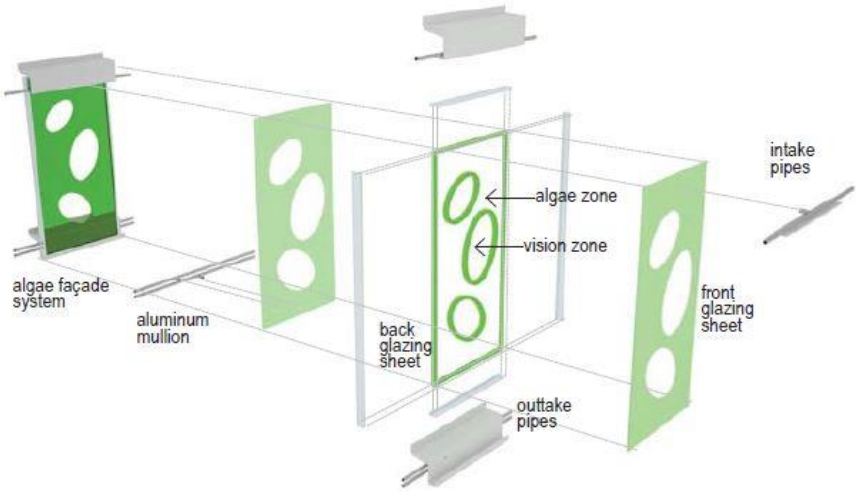


Figure 2.37 Algae Façade System (Kim K.-H. , 2013a).

A series of prototyping was carried out in School of Architecture at UNC Charlotte in order to assess fabrication methods, cost analysis, daylighting and thermal performances, which were made of acrylic panels 2 ft by 2 ft in size (Fig. 2.38). High dynamic range photogrammetric techniques are used to evaluate the daylighting performance and space color created by the algae zone. It was found that algae zone

needs solutions from the interior side to minimize color transmission, and film application was suggested to overcome the problem. The preliminary thermal assessment indicated that U-factor of algae façade is comparable to low-e coated insulated glass unit although double layers of acrylic panels are needed to provide thermal comfort. Based on published data, O_2 generation and biofuel production per panel with 5ft by 12ft are calculated. The initial value of preliminary assessment is assumed as 70 liters of oxygen per hour, 2.12-21.2 g/panel/day in biomass and 1.2-4.2 g/panel/day of lipids for *Chlorella vulgaris* (Kim K.-H. , 2013a) (Kim K.-H. , 2013b).

Figure 2.38 Test set-up of the prototype for thermal performance analysis (Kim K.-H. , 2013a).

ii. Kim and Patel (2018) worked on a simulation project of an existing office building in New York City. Two models were studied in order to carry out an energy analysis; the original building and its copy with a different window system. The results demonstrated that it was possible to reduce a building's energy consumption and environmental impact by retrofitting to microalgae façade. The retrofitted building could reduce CO2 emissions by 200 tons and also could have more than $10M over a 30-year period (Kim & Patel, 2018).

iii. In a study, it was indicated that algae façade integration has a great impact on the overall translucency and transparency of building skin. A design

experiment was conducted to investigate the use of flat panel reactors applied in a double skin façade. A test environment was built with a couple of rotating flat panel PBRs, which give the opportunity to measure light levels on the surface of PBRs as well as the interior space of the test environment (Fig. 2.39, 2.40).

Figure 2.39 Test environment with flat panel PBRs (Decker, Hahn, & Harris, 2016).

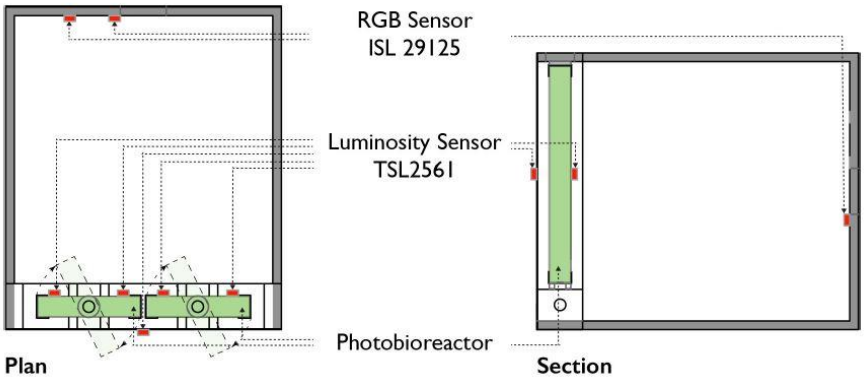


Figure 2.40 Drawing of test environment (Decker, Hahn, & Harris, 2016).

It was stated that the rotation of panels from the direction of an ideal relationship with the light source to other directions decreased the light levels within the reactor due to reactor geometry. The factors affecting light levels were reactor geometry, frame details, panel rotations, and culture density. In conclusion, they found that there was a relationship with the density of algae culture with the light levels inside the test environment (Decker, Hahn, & Harris, 2016).

iv. An empirical study was conducted to define the relationship between culture density and light quality. The negative correlation of culture density and light transmittance was also confirmed by Elnokaly and Keeling (2015). Although, a weak relationship was found between culture density and shading efficiency; shading co-efficient was decreased within increased density (Elnokaly & Keeling, 2015).

v. In a study, the potential of dinoflagellates was discussed within the scope of architectural lighting. Based on the morphological and bioluminescence characteristics of *Ceratium*, *Ceratocorys*, *Gymnodinium*, *Lingulodinium* (*Gonyaulax*) *Pyrocystis and Pyrodinium,* units of emitted light by each kind of cell were converted to lumens from photons. In conclusion, it was suggested that algae light is an option where no point illumination is needed such as public lighting or decorative lighting (Veron, Ibarria, & López, 2013).

CHAPTER 3

MATERIALS AND METHODS

In this chapter, the materials and method of the study are presented. Source of information and selected microalgae to be integrated in built environment are given in the materials section. In the methodology part, steps of this study are explained.

3.1. Materials

This research is based on a comprehensive literature review. The materials of this study include related books, articles, conference proceedings, and websites. Additionally, literature review was supported by the information gained from 11 biologists (the contact list is given in Appendix A), and 1 laboratory observation.

Microalgae are the subject matter of this study. The characteristics of algae can vary significantly between the species and strains. For this reason, it is vital to define the subject materials in detail in order to propose an appropriate habitat for them in the built environment. Based on their characteristics, six species of microalgae are selected in view of the research target; to obtain light and biodiesel as end products, and benefitting from other features of microalgae during cultivation such as thermal buffering and sunlight filtration.

The information collected from literature were interpreted and used to propose design ideas to integrate microalgae in the buildings specifically for Konya Provincial National Education Directorate Building project.

3.1.1. Selected microalgae species for light production

Pyrocystis fusiformis, *Pyrocystis noctiluca*, and *Ceratocorys horrida* are examples of suitable microalgae species for light production. They have been frequently mentioned on their high bioluminescence levels in the literature and on the web. The selection criteria of species was bioluminescence level. These bioluminescent dinoflagellates classified in Dinophycea which Figure 3.1 shows the light produced by them.

Figure 3.1 Michael Latz stimulates bioluminescence of cultured dinoflagellates. True color image. Retrieved from (Latz, Glowing with the Flow, 2005).

Species are morphologically diverse and their cell size differs approximately from 70 µm to 1 mm (Latz, Nauen, & Rohr, 2004). All of the selected species are photosynthetic, and they present bioluminescence on a diurnal rhythm controlled by an endogenous circadian clock. The light level is tuned according to the external environment and minimize energy expenditure (Marcinko, Allen, Poulton, Painter, & Martin, 2013), (Valiadi & Iglesias-Rodriguez, 2013). Some dinoflagellate species are toxic and they are responsible for red tides in the seas, but information on toxicity of

the selected species could not be obtained, hence, they can be accepted as harmless for utilization in the built environment.

Pyrocystis fusiformis and *Pyrocystis noctiluca* are large, autotrophic and slow-growing dinoflagellates which mostly can found in calm tropical or subtropical oceans. Both *Pyrocystis* species are capable of emitting highest intensities of light among dinoflagellates and they are abundant at depths of 60-100 m (Bhovichitra & Swift, 1977), (Behrmann, Hardeland, Stickan, & Siebert, 2002). *Pyrocystis fusiformis* cells are fusiform shaped, elongated with tapered ends, and large enough to be seen under a dissecting microscope. (Fig. 3.2). Cell division occurs in the night phase and takes minimum 5 to 6 days (Sweeney, 1982). *Pyrocystis noctiluca* has a spherical shape with an approximate size of 500 µm in diameter (Cussatlegras & Le Gal, 2004). They are reported as the dominant luminescent dinoflagellate in the Sargasso Sea contributing to bioluminescence potential (Latz, Case, & Gran, 1994). Vertical migration occurs commonly in dinoflagellates during specific life stages, mature cells remain in the upper water column, whereas newly divided cells sink down to deeper. The behavioral strategy is related to overcome source limitation, and maximize the nutritional uptake, also the photosynthesis rate. This phenomenon is called "once in a generation" for *Pyrocystis noctiluca*. Asexual reproduction may take several days to complete in mature cells. The maximum division rate in laboratory cultures and nature are determined as 0.11 to 0.13 d^{-1} (Seo & Fritz, 2000), (Rivkin & Swift, 1985).

Ceratocorys horrida are in spherical form with six distinctive spines, and relatively smaller than Pyrocystis species with 70 µm cell size in diameter. They have a doubling time of approximately 11-12 days. They have a wide distribution; are found in tropical waters of the Mediterranean Sea and Indian, Atlantic, and Pacific Oceans with a low abundance. It is reported that it has no significant contribution to levels of in situ stimulated bioluminescence. The luminescent capacity of *Pyrocystis fusiformis* and *Pyrocystis noctiluca* are higher than *Ceratocorys horrida* (Latz & Lee, 1995). On the other hand, it is one of the most shear sensitive organisms that spines are thought to act as levers to increase the shear force (Zirbel, Veron, & Latz, 2000). Additionally,

Ceratocorys horrida is one of only 2 species in which spontaneous bioluminescence exhibits circadian rhythm in both flashing and glowing (Latz & Lee, 1995).

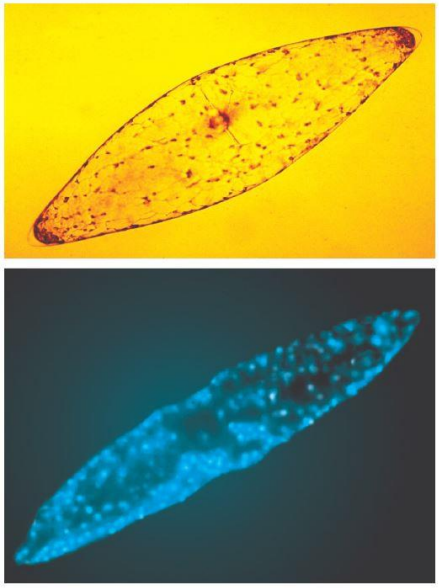


Figure 3.2 Pyrocystis fusiformis (Widder, 2002).

All the selected microalgae's characteristics were collected in Table 3.1 in order to understand their potentials and limitations, and to integrate them in the built environment. Optimum light intensity and temperature values of microalgae determine the fundamentals of integrated building design. Photobioreactor location, orientation, or the requirement of heating and cooling systems of PBRs depend on the limits of microalgae.

Light is the flow of photons; einsteins or moles are the units used for measuring quantum (photon) flux density. Number of flashes per cell, flash duration and maximum flash intensity indicate the bioluminescence light level for species, which means the higher value is higher level of light. Cell size is another important parameter to be evaluated. Larger cells produce more light. Also, the size information is necessary for deciding the harvesting method, and the decision guides the design of building integration system.

Table 3.1 Selected microalgae species for light production and their properties.

Examples of suitable algae strains	Class	Cell shape and size	Number of flashes $cell^{-1}$	Flash duration (ms)	Maximum flash intensity	Optimum light intensity for growth or maintenance	Optimum temperature for growth or maintenance
Pyrocystis fusiformis	Dinophyceae	Fusiform shaped, elongated with tapered ends/970 x 163 µm (Latz, Nauen, & Rohr, 2004)	23-62 (Latz, Nauen, & Rohr, 2004)	210 (Latz, Nauen, & Rohr, 2004)	690 x 10^9 photons s^{-1} (Latz, Nauen, & Rohr, 2004)	42 µEin m^{-2} s^{-1} (Bhovichitra & Swift, 1977), 30 µEin m^{-2} s^{-1} (Swift & Meunier, 2008)	22° C (Hackteria, 2019)
Pyrocystis noctiluca		Spherical shaped, 500 µm in diameter (Cussatlegras & Le Gal, 2004)	-	-	1.1 x 10^8 photons s^{-1} cell $-^1$ (Cussatlegras & Le Gal, 2004)	42 µEin m^{-2} s^{-1} (Bhovichitra & Swift, 1977), 60 µEin m^{-2} s^{-1} (Swift & Meunier, 2008), 10 W m^{-2} with cool-white fluorescent lamps for maintanence (Cussatlegras & Le Gal, 2004)	20° C for maintenance (Cussatlegras & Le Gal, 2004)
Ceratocorys horrida		Spherical shaped, 70 µm in diameter (Latz, Nauen, & Rohr, 2004)	7 (Latz, Nauen, & Rohr, 2004)	184 (Latz, Nauen, & Rohr, 2004)	9.2 x 10^9 photons s^{-1} (Latz, Nauen, & Rohr, 2004)	120 µmol of photons m^{-2} s^{-1} with cool-white fluorescent lamps for maintanence (Latz & Lee, 1995)	20° C for maintenance (Latz & Lee, 1995)

3.1.2. Selected microalgae species for biodiesel production

Neochloris oleoabundans, Scenedesmus obliquus, and *Botryococcus braunii* are examples of suitable microalgae species for biodiesel production. They have been commonly studied on due to their oleaginous cell composition and high growth rate. In Table 3.2 their characteristics are given. Within the context of the study, the risk of selected microalgae for the human health has not been investigated and none were encountered during the literature review of various sources.

Neochloris oleoabundans is one of the freshwater microalgae species showing promising results for biodiesel production. It has a spherical cell shape with an average size of 3-3.5 µm in diameter, and it can be cultivated in saline media similar to seawater. This microalga has received attention since 1980s due to its high growth rates and lipid accumulation (Abu Hajar, Riefler, & Stuart, 2017). It has been proved that its oil content can reach up to 40% under nitrate starvation conditions (Li, Mark, Wang, Wu, & Q. Lan, 2008).

Scenedesmus obliquus is widespread species which is dominant in freshwater lakes and rivers, normally in forms of four-celled colonies (Mansouri & Hajizadeh, 2018), (Huang, et al., 2018). It has been defined as a versatile and fast-growing alga that can be easily cultivated in different wastewaters and different environmental conditions. It efficiently fixes CO_2 and presents an adequate fatty acid profile, which makes it a good option for biodiesel production (Gouveia & Oliveira, 2009), (Sforza, Gris, Silva, Morosinotto, & Bertucco, 2014).

The green colonial algae, *Botryococcus braunii* is widespread in freshwaters, they can live in reservoirs at temperate, tropical and arctic latitudes, and exist in the form of blooms (Fig. 3.3). Clusters of elliptical cells form colonies vary between 30 µm to 2 mm in size. This alga has been recognized for the potential of producing liquid hydrocarbons due to their rich hydrocarbon content. (Ashokkumar & Rengasamy, 2012) (Pérez-Mora, Matsudo, Cezare-Gomes, & CM Carvalho, 2016). Based on the chemical structure of synthesized hydrocarbons the species is differentiated in four distinct races (Blifernez-Klassen, et al., 2018). It can produce up to 85% of its dry

weight in hydrocarbons, which are chemically similar to petroleum oil (Qin & Li, 2006). Its lipid content and the oleic acid proportion is appropriate for biodiesel production (Yoo, Jun, Lee, Ahn, & Oh, 2010).

Figure 3.3 Botryococcus braunii (UTEX, 2019).

All the selected microalgae's characteristics were collected in Table 3.2. Optimum light intensity and temperature values are given to ensure them the appropriate conditions in building design. The cell size of the species were also evaluated as it is a determinant factor for the selection of harvesting and processing methods. The oil content of the selected species, maximum biomass concentration and total lipid productivity provide information about the quantity of the biofuel that will be obtained. Maximum biomass concentration is the weight of the biomass in one liter of liquid and the lipid productivity shows the total oil amount in biomass per liter per day.

In the table, each parameter value is given as a result of the relevant study, therefore it should be noted that these results may vary in different cases, as many factors such as light, temperature, pH of the medium culture, etc. affects microalgae.

Table 3.2 Examples of microalgae species for biodiesel production and their properties.

Examples of suitable algae strains	Class	Cell shape and size	Oil content	Maximum biomass concentration / Biomass productivity	Total lipid productivity	Optimum light intensity for growth or maintenance	Optimum temperature for growth or maintenance
Neochloris oleoabundans (Gouveia & Oliveira, 2009)	Chlorophyceae	Spherical shaped, 3–3.5 µm (Abu Hajar, Riefler, & Stuart, 2017)	29% (Gouveia & Oliveira, 2009)	2 g L^{-1} (maximum biomass concentration) (Gouveia & Oliveira, 2009)	0.09 g L^{-1} d^{-1} (Gouveia & Oliveira, 2009)	150 µE m^{-2} s^{-1} (Gouveia & Oliveira, 2009), 180–220 µmol/m^2/s (Abu Hajar, Riefler, & Stuart, 2017)	25–30°C (Abu Hajar, Riefler, & Stuart, 2017)
Scenedesmus obliquus (Gouveia & Oliveira, 2009)		10 x 4 µm (Akgül, Kizilkaya, & Erduğan, 2017)	17.7% (Gouveia & Oliveira, 2009)	2 g L^{-1} (maximum biomass concentration) (Gouveia & Oliveira, 2009)	0.09 g L^{-1} d^{-1} (Gouveia & Oliveira, 2009)	150 µE m^{-2} s^{-1} (Gouveia & Oliveira, 2009), 150 µmol of photons m^{-2} s^{-1} (Sforza, Gris, Silva, Morosinotto, & Bertucco, 2014)	29.55 °C (Hodaifa, Martinez, & Sanchez, 2010)
Botryococcus braunii (Yoo, Jun, Lee, Ahn, & Oh, 2010)		Spherical shaped, 400-120 µm in diameter (Ashokkumar & Rengasamy, 2012)	25.79 % (Yoo, Jun, Lee, Ahn, & Oh, 2010)	26.55 ± 7.66 mg dw L^{-1} d^{-1} (Biomass productivity) (Yoo, Jun, Lee, Ahn, & Oh, 2010)	5.51 ± 1.53 mg L^{-1} d^{-1} (Yoo, Jun, Lee, Ahn, & Oh, 2010)	150 µmol of photons m^{-2} s^{-1} (Yoo, Jun, Lee, Ahn, & Oh, 2010), 30-60 W m^{-2} (Qin & Li, 2006), 450 µmol of photons m^{-2} s^{-1} (for lipid production) (Khichi, Anis, & Ghosh, 2018)	23 °C (Qin & Li, 2006)

Annotation on units: An Einstein is defined as a mole of photons (Apogee Instruments, 2019). *To be expressive, the units in Einstein is expressed as* ***µmoles*** *on data collected from literature review.*

3.1.3. Konya Provincial National Education Directorate Building Project

In this section, Konya Provincial National Education Directorate Building project designed by the author is introduced, and in Chapter 4, integration designs are proposed for utilization of the selected microalgae species *Pyrocystis fusiformis* and *Neochloris oleoabundans*.

The project won the architectural design tender (which also included a design competition) in 2015 organized by Konya Metropolitan Municipality. During the designing process, the project was revised for a traditional appearance due to approving authority's request (Fig. 3.4). This project was selected for conceptual study because it represents a typical state institution building design that can be commonly encountered in Turkey. Therefore, the proposal design can show that the integration of microalgae cannot only be applied in new projects, but also in existing buildings, and it can lead to new ideas for architects.

Figure 3.4 3D rendering of Konya Provincial National Education Directorate Building.

The building has a total construction area of 6229 m^2 and consists of 2 basements and five normal floors. Projects site is located in Meram, the old town of Konya City and the lot is identified as educational zoning. As shown in the site plan (Fig. 3.5), there was a historical and a contemporary educational building on the project site, so the available construction area defined by the Konya metropolitan municipality was very limited. In the construction area there were surrounding buildings and also occupying ones located. Demolishment of the existing structures built within the borders of the construction site was planned for the new project.

The functional use of building storeys' are listed below:

- 2nd basement floor (Fig. 3.6): Technical rooms and an areaway for ventilation of these rooms, seminar room, shelter
- 1st basement floor (Fig. 3.7): Parking Area
- Ground floor (Fig. 3.8): Offices
- 1st, 2nd, 3rd floors (shown as typical floor plan in Fig. 3.9): Offices
- 4th floor: Refectory, kitchen, Multi-use hall

The offices were designed around the perimeter of the building to achieve the maximum use of daylight, corridors and core spaces remained at the center. In order to benefit from daylight as much as possible, interior walls of the offices were designed as glazing for illuminating building's core spaces.

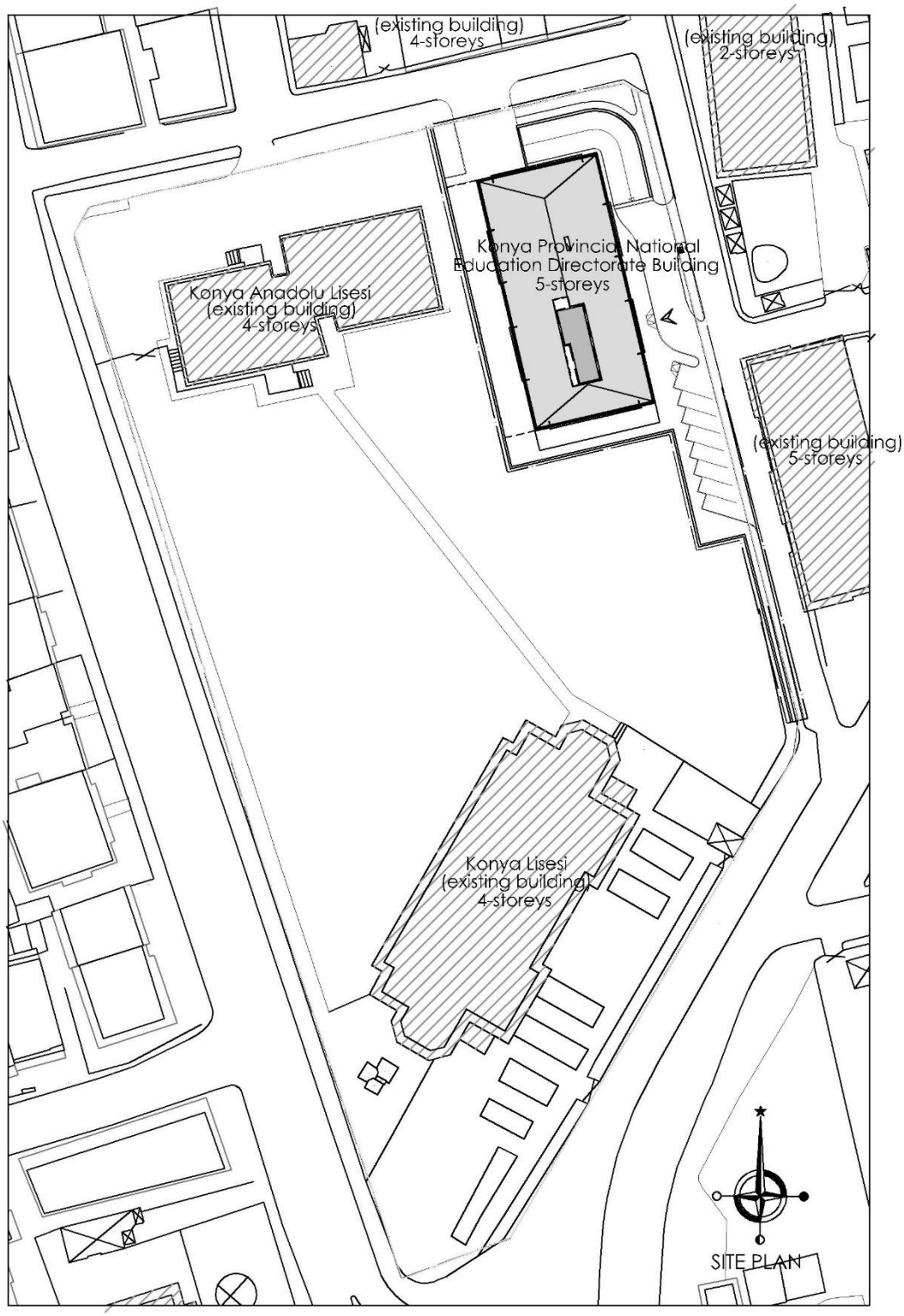


Figure 3.5 Konya Provincial National Education Directorate Building project site plan.

Figure 3.6 Second basement floor plan of Konya Provincial National Education Directorate Building.

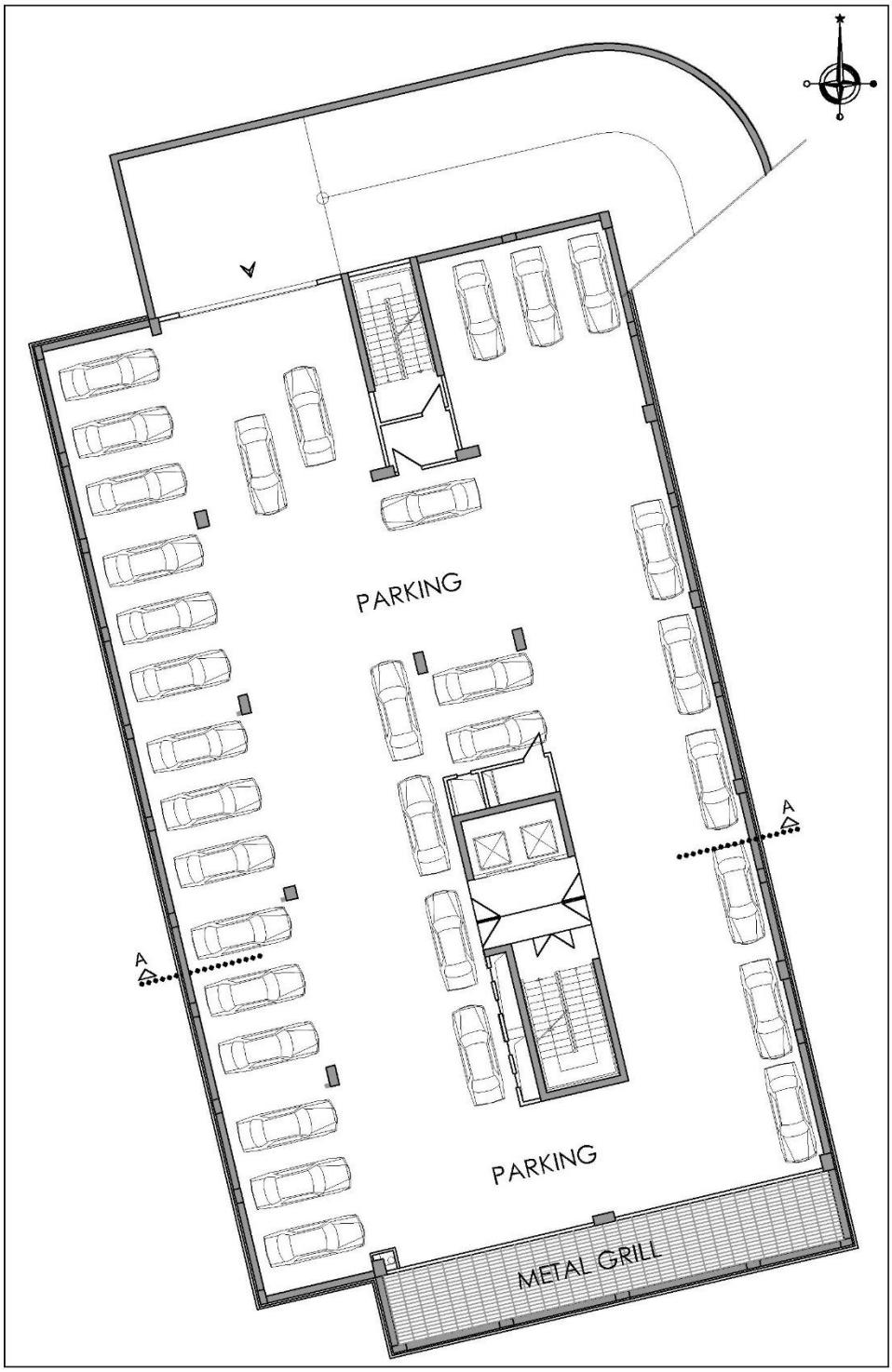


Figure 3.7 First basement floor plan of Konya Provincial National Education Directorate Building.

Figure 3.8 Ground floor plan of Konya Provincial National Education Directorate Building project.

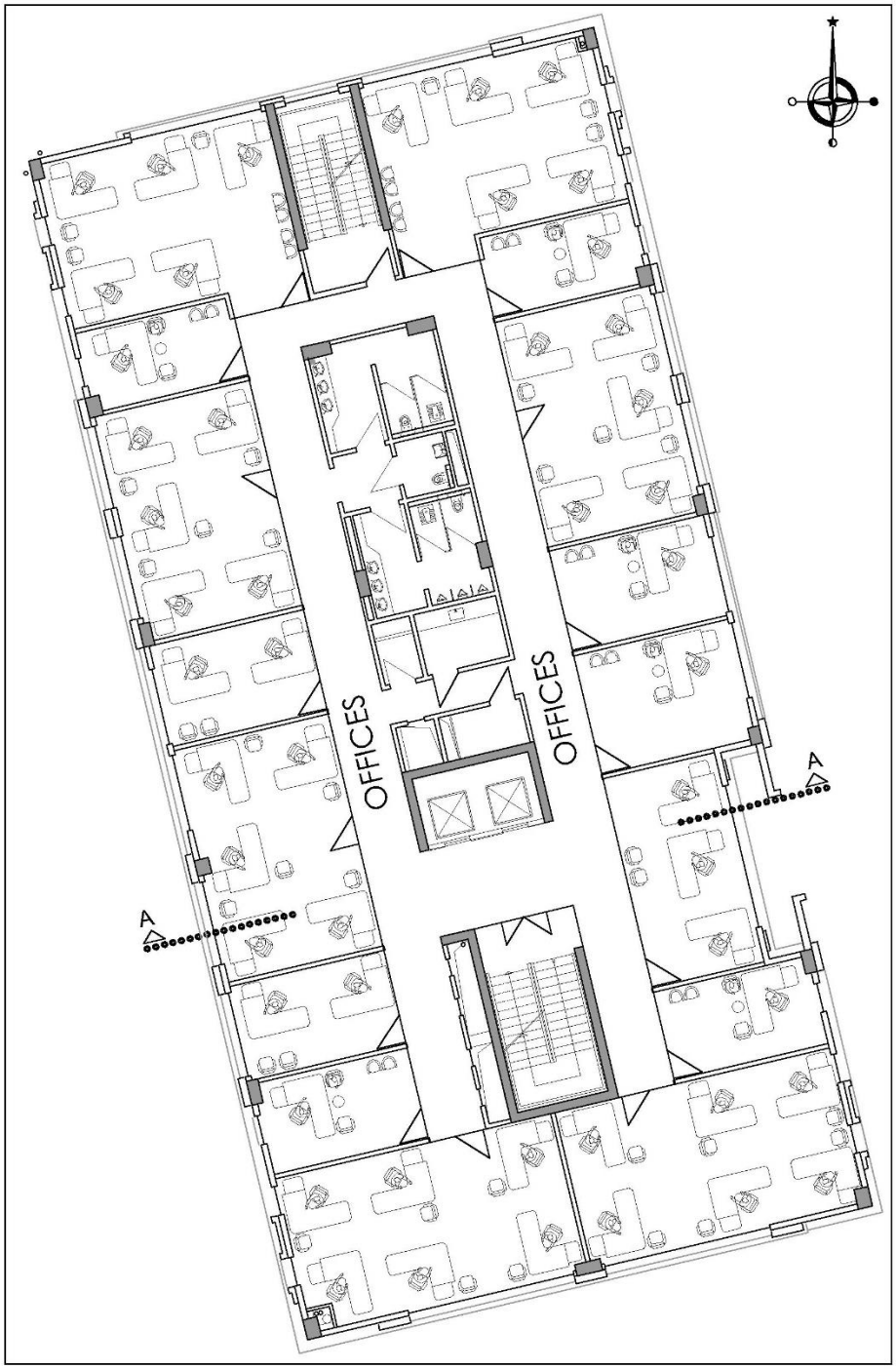


Figure 3.9 Typical floor plan of Konya Provincial National Education Directorate Building.

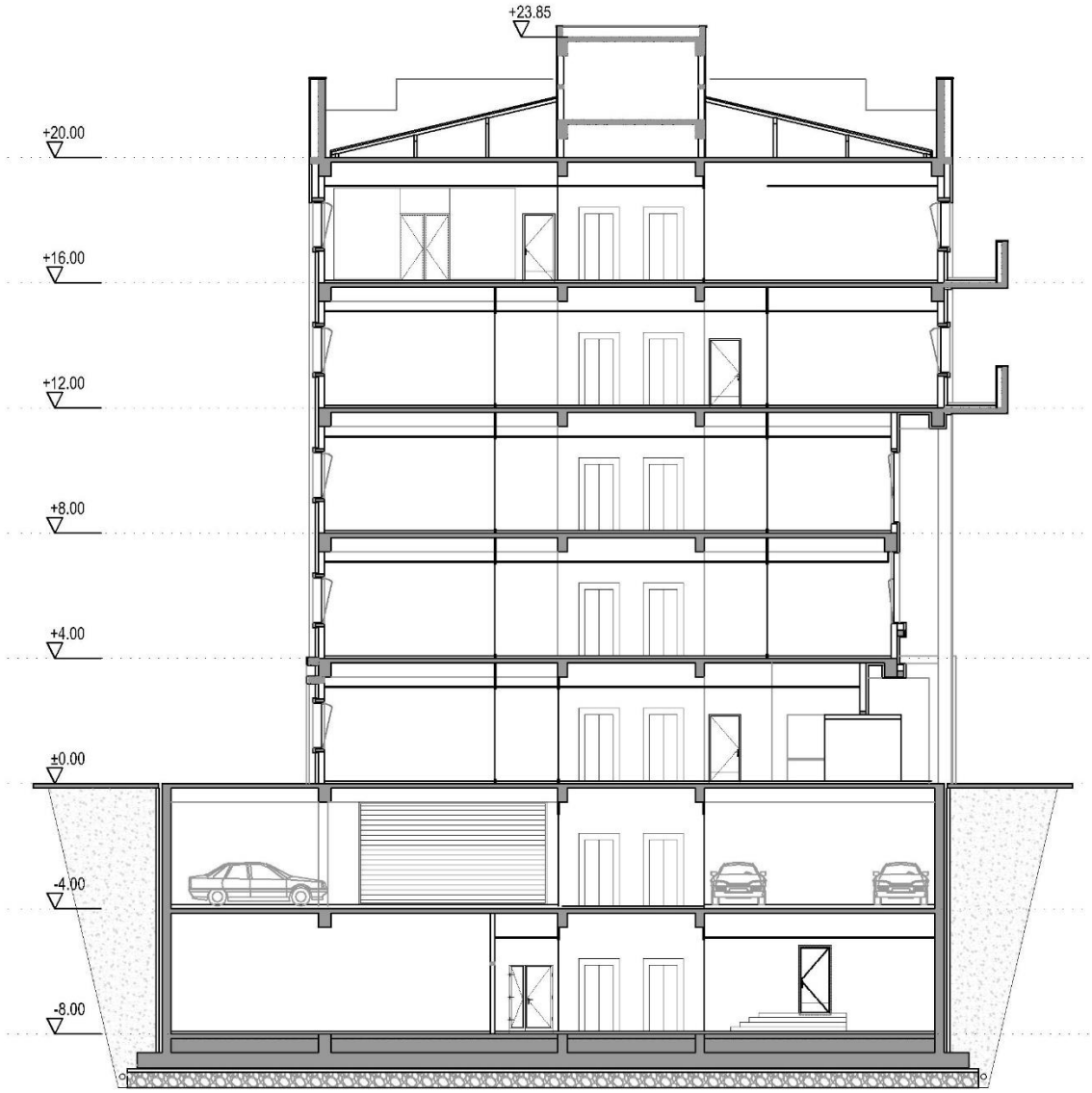


Figure 3.10 Section A-A.

3.2. Method

In this study, the methodology is based on the review of microalgae's characteristics and its requirements, cultivation and harvesting systems, and processes for obtaining biofuel products to benefit them in the built environment by an architectural approach. The knowledge gained from books, articles and journals, interviews with experts and

laboratory observation provided the basis for interpreting it for integration in architectural design.

This study was developed with the following steps:

- Investigation of algal potential and determination of target products to be used in built environment

Firstly, after examining the features that can be benefitted from algae, bioluminescence light and bioenergy production were determined as the main potentials that algae can provide to architectural environment. In the context of bioluminescence, bioluminescent organisms, the evolutionary origins, functions, chemistry, and light producing reactions were studied. In the field of bioenergy, the types of biofuels and the processes carried out in the production of biofuels were examined.

- The methods for growing microalgae in buildings

In this stage, cultivation methods, PBR types, harvesting methods were reviewed, and the cultivation systems were assessed according to microalgae requirements in order to understand what algae needs and how to benefit them in the built environment. Afterward, it was researched for the appropriate species for the defined target products in the study.

- The selection criteria of the microalgae species

The species which have high lipid productivity are suitable to obtain biofuels. It has been observed the species which are reported to have high lipid productivity in literature are also commonly studied by biologists and chemical engineers for biofuel production. The selection of the species in this research is based on the studies of these experts.

There are experimental studies on dinoflagellates to measure their bioluminescence response. Unlike the examination of species for biofuels, there are no comprehensive lists on the light capacity of the organisms as the issue of bioenergy production is an

area where researchers show more interest than bioluminescent lighting. Species selection for light production was made with the information in the literature and supported by interviews.

Three algae species were selected for bioenergy production and bioluminescent light production. Information on their requirements in terms of light and temperature, and the quantity of products that can be provided by algae were compiled from various studies. This information formed the design criteria to ensure the suitable conditions for microalgae cultivation.

- Interpretation of the literature review and design proposal

Cultivating microalgae in outdoor conditions is a challenge. Therefore, it was concluded that establishing a symbiotic relationship was mainly based on meeting the requirements of microalgae. Case studies on microalgae integrated buildings designs were examined. Overall, all the information was interpreted for the utilization of microalgae in the built environment. The ways to create suitable conditions for algae while benefitting from the products of the cultivation process were discussed. In this context;

i. Microalgae integrated building system was described,
ii. The potentials of microalgae in the built environment and system challenges were examined,
iii. Design methodology for a possible microalgae integration was proposed, the general design criteria to be considered in architectural design were presented,
iv. The design proposal was given using the Konya Provincial Directorate of National Education Project for microalgae integration. The proposal shows examples of integration to façade for biofuel production, and to building interiors for bioluminescent lighting.

CHAPTER 4

DISCUSSION OF THE KNOWLEDGE IN LITERATURE AND DESIGN PROPOSAL

In this chapter, microalgae integration to the built environment are discussed. In this context, the potentials of microalgae and the purposes for utilization are presented. The microalgae integrated building system is described and it is discussed on the challenges. At the end, a design proposal is given for Konya Provincial Directorate of National Education Project.

4.1. The potentials of microalgae in the built environment

Despite there is a great variety of living species, all microalgae present a common important feature which is photosynthesis, and which can be done more efficiently than terrestrial plants.

They grow, produce O_2, fix CO_2 naturally just by using sunlight. Consumption of CO_2 and liberation of O_2 as a byproduct of photosynthesis can improve life quality in a dense urban environment and help to keep the ecological balance.

Other species dependent characteristics of microalgae include light production, rapid growth, oleaginous morphology, and wastewater treatment. It means in suitable conditions, different species offer a variety of opportunities: they can produce light, biofuels can be obtained, dense culture can provide sunlight filtering and act as an additional insulation layer on building façade as a result of rapid growth characteristic, and specific microalgae species can treat wastewater by feeding components within. Also, after processing the residue can be used for soil fertilization or biogas production.

All these features point out to a sustainable cycle in an environment. Thus the idea is not new, it can be associated with the ecologic life support system, which the fundamentals of this concept was developed by NASA for space research. The ecologic life support system was designed to meet the essential requirements of human in a sustainable way for long duration space flights. The system uses living organisms, which microalgae takes the stage as a primary component. Therefore, to reduce the negative environmental impacts of the built environment, and to minimize the inputs and outputs of the buildings, renewable energy sources should be used and living organisms should be incorporated in the system.

4.2. Utilization of microalgae in the built environment

The basic characteristics of microalgae and the fields where they can contribute were defined in order to see how microalgae can be utilized in the built environment. As can be seen in Table 4.1, many of the features that contribute to the architecture are actually the regular metabolic activities of microalgae in their life cycle, which is expressed as cultivation under required processes.

In the table, basic characteristics of algae and their potentials for use in the built environment are listed. Except bioluminescence, all the microalgae species have characteristics like photosynthesis, feeding or reproducing, but potentials for use that are listed in the table depend on the right species selection. Besides all, high growth rate or reproduction rate is a desirable property for utilizing algae. As the number of cells increases they can provide more biofuels, more O_2 or more light, and dense culture can filter sunlight and stabilize the interior temperature if they are cultivated on building envelope. Therefore, possible locations of microalgae have been defined based on the characteristics on the last column of Table 4.1.

Target locations of microalgae cultivation are given as examples that suit to end products to be obtained from, but it should be noted that microalgae can be cultivated everywhere with presence of any sunlight or artificial light, CO_2 and nutrients they

need. Architectural design has no limits, location of microalgae cultivation can be defined different in a seaside building, a skyscraper or a desert house.

Table 4.1 Characteristics of microalgae and their potential to use in built environment.

Characteristics of microalgae	**Potentials for use in the built environment**	**Required processes**	**End product**	**Possible locations of microalgae cultivation**
Molecular composition	Biofuel production	Cultivation, harvesting and biofuel production processes	Biofuel	Façade, roof, landscape area
Bioluminescence	Light production	Cultivation	Light	Façade, interiors, landscape area
Photosynthesis	CO_2 Sequestering, Indoor air quality	Cultivation	O_2	Façade, roof, landscape area
Nutrition	Wastewater treatment	Cultivation	Clean water	Tanks or isolated landscape area
Reproduction	Sunlight filtering	Cultivation	Sunlight filtering element	Façade
Reproduction	Thermal comfort	Cultivation	-	Façade, roof
Molecular composition	Soil fertilization and biogas production	-	Biomass residual	Landscape area

4.3. Microalgae integrated building's system components

Microalgae can be cultivated in open or closed systems. Open cultivation systems can be integrated into flat roofs, terraces and landscape area. This study focuses on closed system integration because they provide high biomass productivity and they have low risk of contamination. Also, vertical cultivation requires less space in the building.

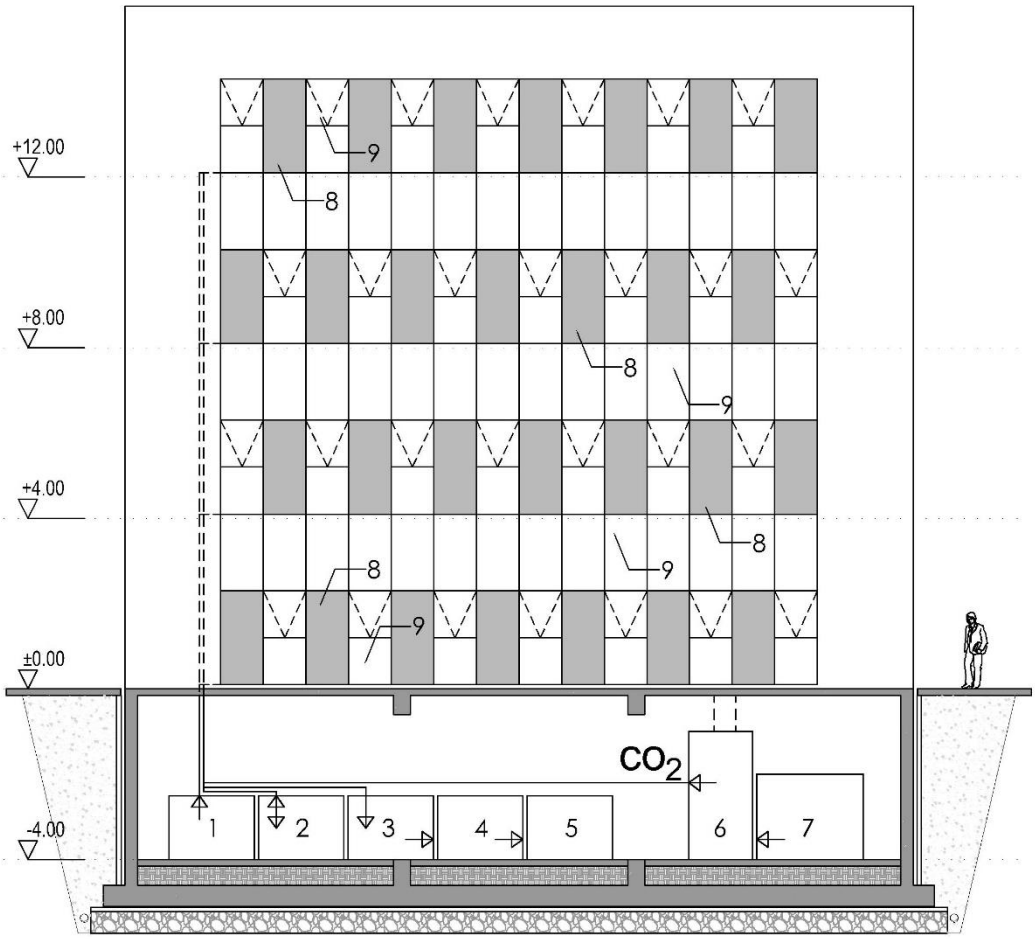
The design criteria to be considered for the integration of microalgae into the environment will vary according to various situations. The design approach for a new design project or a renovation project will be different; the geographic location,

building function, height, and construction area will affect the design considerations in terms of choosing the PBR type, specifying the quantity of integration area, and determining PBR's orientation and inclination. Since the water volume and algae density depend on the PBR sizes and numbers to be used, the building services like the selection of equipment and tank capacities, and mechanical and electrical systems should be designed accordingly. As the system also involves operation and control, the integration of microalgae in the built environment requires a multi-disciplinary work.

Fundamentally, the design of the building integrated microalgae system should be based on two criteria: meeting the microalgae requirements and the use of products obtained from the cultivation process in the building. Microalgae requirements are the suitable conditions for cultivation and harvesting. They grow under sufficient light, and the necessary nutrients and CO_2 should be provided, and the culture should be in the optimum temperature and pH range. Harvesting is required at the end of the each growth cycle as it can be short as several days. The whole system should be monitored and controlled to maintain the culture and to ensure the continuity of the operation. The components of this complex system can simply be grouped into photobioreactors, equipment to feed and cycle microalgae, harvesting unit, and the control unit which all the system is connected.

Figure 4.1 is given to describe the integration of the microalgae production system in the building. Microalgae is cultivated in flat panel PBRs (#8). Photobioreactors are integrated into the glazed curtain wall and they have dimensions of 100 x 220 x 2 cm. All the PBRs are connected to the building services in the basement of the building. In this system, after the algae is harvested, the culture liquid is sent to the PBRs for re-use and nutritional supplement is made from the new culture tank #1 when necessary. During the cultivation process, the flue gas from the boiler (#7) is pumped to the purification system for CO_2 sequestration (#6), and provided to algae. If the external temperature condition is not suitable, the culture temperature is compensated by the heat exchanger (#2). When the growth cycle of microalgae is completed, the

culture is collected in tank #3, harvested in tank #4, and the obtained algae sludge is kept in tank #5 to be taken for processing. The temperature and pH are measured at particular intervals to track the culture conditions and necessary interventions can be done from the building services center where the system is connected.



1: new medium tank 2: heat exchanger 3: collected medium tank
4: harvesting tank 5: algae slurry storage tank
6: flue gas purification system 7: boiler 8: flat panel PBR 9: glazed façade

Figure 4.1 Integration of the microalgae production system in the building.

4.4. Discussion on challenges in microalgae integrated building systems

- Environmental factors

The purpose of the utilization of microalgae in the built environment is based on the exchange of inputs and outputs between buildings and algae. Biomass production using the sunlight will be the most feasible option that microalgae will not be a burden to building in terms of energy consumption.

Solar irradiation and outdoor temperature are among the factors that affect algae. As reported in literature, microalgae are living organisms which can survive and be productive in certain range of temperature, and use the light in certain spectrum (which is called PAR) and quantity range for photosynthesis. Since the outdoor conditions are variable, keeping the culture under control is one of the most important challenges. The key to take precautions for maintenance of microalgae at outdoor conditions is to know the solar irradiation. To compare with microalgae's light requirement and to determine PBR's orientation and inclination angle at designing process, it is necessary to know the available sunlight in PAR at the building site, especially for all directions. The challenge is the difference of expression units which are given in radiometric and quantum units. To decide PBRs' location in the project based on accurate information, light can be measured in quantum units specifically at the site.

The design proposal in section 4.6 provide recommendations on how environmental factors can be controlled in microalgae utilized buildings.

- Energy consumption of the system

Building integrated microalgae cultivation has a complex system. As mentioned in the literature, the energy of the fuel produced from microalgae cannot meet the energy consumed by cultivation process, harvesting and biofuel production processes. Also, the light produced by the dinoflagellates which are cultivated for illumination may be weak and there may be imbalances between the inputs and the outputs of the whole system. Consequently, the cultivation process products should be used in the building

such as O_2 production, CO_2 sequestration, thermal buffering and sunlight filtering, and the system should be supported with other renewable energy sources.

Since harvesting and processing can consume a significant amount of energy, this issue can be evaluated separately in microalgae integrated buildings. Facilities can be designed in the urban environment to provide services for many buildings. In these facilities, large-scale harvesting and processing can be optimized to reduce the overall energy consumption.

- Aesthetics

As the biomass concentration increases, view can be obstructed in buildings in which PBRs are integrated into façade. At the same time the color of the microalgae will prevail the appearance of the façade, and the interior space's color will be affected as well. For user comfort, façade segmentation can be designed in a way that does not obstruct the view. In order to reduce the visual interaction between the culture and the building users, the PBRs can be used as a second façade layer such as integrating them in front of or beyond a solid wall. Second layer of a flat panel PBR's material can be made of stainless steel plate, or a double glazed PBR unit can be coated with film from the building interior. The architect may choose the color for the façade design among the species which are suitable for the end-product, as different algae species may have different colors.

- Structure

A flat panel PBR in 100 x 220 x 2 cm dimensions will hold 44 liters of water, which equals to approximately 44 kg in weight. Façade integrated flat panel PBRs will consist of steel, aluminum profiles and glass. As the PBR size increases, it should be considered that the liquid weight and internal pressure in the PBR will increase. The thickness of the glass and structural profiles should be selected according to engineering calculations.

The effect of PBR system's structural load on the building was evaluated by comparing the weight of the stone cladding system. Natural stone can be used widely in building cladding, and the weight of 1 m^2 (100 x 100 x 2 cm) is approximately 60 kg / m^2 without its structural profiles. The weight of the liquid in the PBR was about 22 kg / m^2, so the PBR system is lighter than the stone. The PBR system's impact on the structure will be insignificant unless the building is not a high-rise. However, since the PBRs will be located in specific directions due to incoming solar radiation, the gravity center of the building may need to be balanced in structural design.

- Fire and earthquake

The fire can spread very quickly on the building façade depending on the materials used. During the fire, glazing explodes under high heat and pressure which create a serious safety risk. If the PBRs are components of the glazed curtain wall system, the design precautions of the glazed curtain wall can be adapted for safety to reduce the risks of damage caused by fire and earthquake hazards.

- Wastewater treatment

Some microalgae species do not require clean water for cultivation and they can be used for wastewater treatment. On the other hand, water quality may not be stable for the use of algae, variable amount of heavy metals or inorganic substances may be present in wastewater. Besides, using gray water for cultivation in building interior may cause problems such as appearance, smell, and hygiene. Therefore, wastewater treatment system should be considered outside the building and water quality should be monitored regularly.

- Contamination

It can be difficult to keep the risk of contamination completely under control during cultivation and harvesting processes. Accordingly, designing an isolated space for microalgae's equipment and keeping the space sterile can reduce the risks. In addition, using genetically modified species resistant to contamination can be another option.

4.5. Process for designing

The designing process of microalgae integrated building has many stages. Architectural design is limitless, but fundamentally the purpose of utilization of microalgae is based on the beneficial exchange between the microalgae and the building.

As seen in Figure 4.2, microalgae integrated building design requires the determination of the final product to be obtained from microalgae in the first stage. Secondly, species selection should be made considering the final product and the building site where the cultivation will take place. Algae are an extremely diverse group, they can be found even on the poles or in the tropical waters. Since the temperature and light tolerance of alga species can vary, target-oriented species which is also suitable for cultivation at the geographical location of the building site should be selected. Species that can grow with minimum effort in the built environment would be an appropriate selection. The determination of geometry and the number of PBRs, and their location, orientation, inclination angle mainly compose the architectural work for integration. To build a symbiotic relationship between microalgae and the building, it is essential to provide optimal growth conditions for microalgae. In this context, microalgae's characteristics should be reviewed in detail, building site conditions should be analyzed, and the environmental data should be compared with algae's requirements. In parallel, the opportunities that can be provided by algae for the building should be considered according to algae's characteristics. Finally, the whole data can be combined to decide the location of cultivation for the highest biomass yield with multiple benefits for the building. At the same time, precautions should be considered in design for maintaining the culture under extreme environmental conditions. Subsequent to major design decisions, the structural project of the building should be reviewed. Operational planning should be made according to the number of PBRs, their liquid capacity and biomass capacity, and the mechanical and electrical projects of the building should be reviewed.

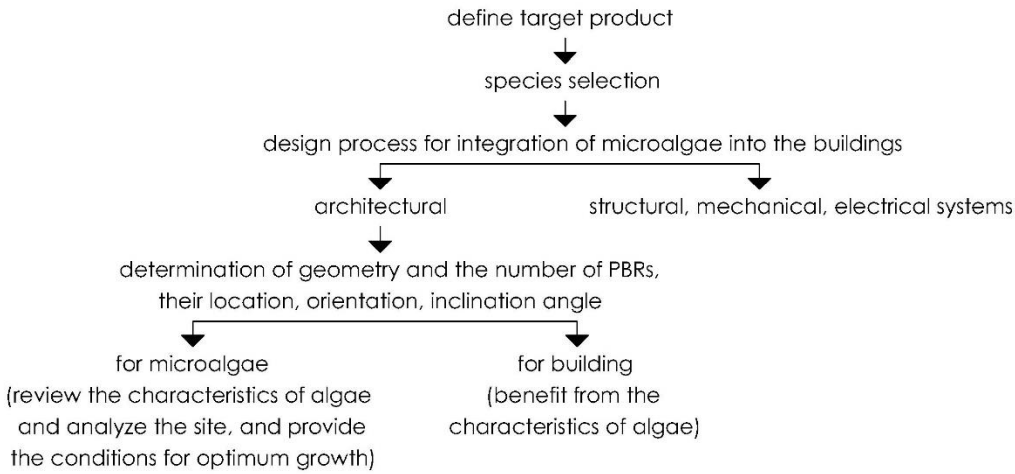


Figure 4.2 Microalgae integrated building's design process.

The criteria are listed below to give further details about analyzing the building site and comparing the environmental data with microalgae's light requirements. The correct decision for the location, orientation and inclination angle of the PBRs and appropriate geometry and material selection can provide optimal growth conditions for microalgae.

- **Geographical location and daily light integral**

The first criterion to be considered in the design phase is the location where the microalgae will be grown. The location provides information about the presence and intensity of light, which is the basic requirement of microalgae. High latitudes have different seasonal conditions and light levels show a significant change, whereas in the lower latitudes this difference is less. To achieve maximum biomass productivity, PBR orientation should be oriented to exploit sunlight in the most efficient way and prevent photo limitation where the solar irradiance levels are low. On the other hand, strategies should be developed to keep microalgae in the optimum light range and at desired temperature levels and prevent photoinhibition at low latitudes where solar irradiation levels are constantly high.

Microalgal productivity depends not only on the location of the building but also on the orientation and inclination of PBRs. As detailed in the previous chapter, it was stated that PBR orientation is more effective on the south direction at lower latitudes less than 35º, and on the east-west direction at higher latitudes. In the city of Hamburg (53º) BIQ Building's PBR orientation is south-east and south-west. According to studies examining the optimum PBR angle, 30º on south direction throughout the year in Israel (31º), and 45º on the south direction in France (47º) obtained the best results for microalgae productivity.

Although the risk of photoinhibition is mentioned commonly in literature, PBRs are widely considered in southern façades. For PBR orientation, the southern direction which has the longest exposure time to sunlight is logical. However, if it is accepted that about 2000 µmol/m^2/s of light hits on PBR's surface on a sunny summer day, it can be seen that this amount exceeds the light requirement of microalgae in most species. Also, heat is a result of high sunlight levels which creates lethal risk for microalgae if not controlled. Therefore, precautions are necessary for high solar irradiance conditions in the design of building integrated PBRs.

- **The building site and obstructions**

The construction site in an urban environment can be obstructed with surrounding buildings or either with plants. Besides, laws and regulations may effect architectural design significantly. Floor area indexes defined by zoning regulations and the aim of maximizing construction area may result in high-density urban environment which can be a problem against exploiting natural light in buildings. At the design phase, the architect should analyze the obstructions to shape the building in the most efficient way. For heavily obstructed façades, daylight redirecting systems can be used to improve interior space quality and microalgae productivity.

- **Selection of photobioreactor geometry and materials**

One of the important features required in the selection of PBR type is the high surface to volume ratio. Flat panel PBRs provide high biomass productivity due to this

property. In different cases where sunlight is transported to building interiors such as with light pipes or fiber optics, PBR geometry can be varied.

In terms of light transmittance and durability, glass will be the most adequate PBR material choice, also its life will be parallel to the building's life. Plastics, man-made fibers, acrylic materials are used either for PBRs and greenhouse cladding. However, plastic-based materials and man-made fiber panels are non-resistant to UV rays as color changes can occur and light transmittance can be reduced in time. Preservative additives to the material can prevent the permeability of UV and infrared rays, but this application is likely to adversely affect the transmission of PAR either.

4.6. Konya Provincial National Education Directorate Building Project: A conceptual study for integration of the selected microalgae species

In this section, microalgae integration is proposed for Konya Provincial National Education Directorate Building Project. Integration is implemented following the design process stages mentioned in the previous section.

Step 1: Defining the target products and species selection

Integration of microalgae into the built environment requires the selection of target product at the first stage. Subsequently, species selection should be done among the ones appropriate for the target product that can be cultivated with minimum effort at the construction site at outdoor conditions. Three species are selected for each light and biofuel production purposes after a comprehensive literature survey in this study. The species *Neochloris oleoabundans, Scenedesmus obliquus, Botryococcus braunii* are suitable for biofuel production and *Pyrocystis fusiformis, Pyrocystis noctiluca,* and *Ceratocorys horrida* are suitable for light production. Most regions of Turkey have mild climate and sufficient amount of solar irradiance. Depending on the seasons, conditions are within the optimum range for cultivation of algae in terms of light and

temperature. Still, during a real application project local species can be investigated for the specific target product to achieve easier cultivation process and reduce the overall energy consumption.

Step 2: Analyzing site conditions

Konya is located at 37.8º latitude (Konya İl Kültür ve Turizm Müdürlüğü, 2019). The city has a continental climate which shows a significant annual variation in temperature. According to the map of solar irradiance potential of Turkey (Fig. 4.3), Konya has annual solar irradiance level of 1600-1750 KWh/m2 in total. The project site is located at Meram, which has 1650-1750 KWh/m2-year solar irradiance (Fig. 4.3). The daily average insolation hours are 11.43 hours in June and 4.02 hours in December (Yenilebilir Enerji Genel Müdürlüğü, 2019).

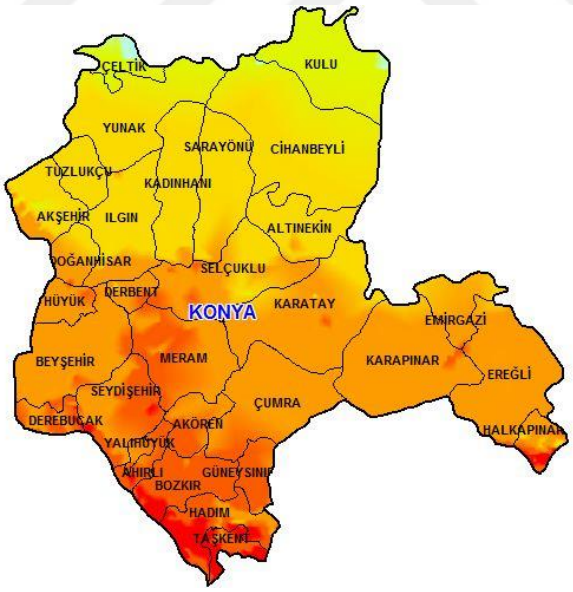


Figure 4.3 Solar irradiance potential of Konya. Meram, which is the region that project site is located, has 1650-1750 KWh/m2-year solar irradiance (Yenilebilir Enerji Genel Müdürlüğü, 2019).

According to temperature measurements from 1981 to 2010, the maximum and minimum values are reported as 37.2 ºC / 1.8 ºC in June and 21.8 ºC / -26 ºC in December. Average maximum and minimum temperature are 27.1 ºC / 13.1 ºC in June and 6.3 ºC / -2.4 ºC in December (Meteoroloji Genel Müdürlüğü, 2019). Monthly average temperatures are given in Table 4.2.

Table 4.2 Temperatures measured in Konya (Meteoroloji Genel Müdürlüğü, 2019).

Extreme Maximum, Minimum and Average Temperatures Measured in Long Period (°C)												
KONYA	January	February	March	April	May	June	July	August	September	October	November	December
Maximum Temp.	17.6	23.8	28.9	31.5	34.4	37.2	40.6	39.0	36.1	31.6	25.4	21.8
Minimum Temp.	-28.2	-26.5	-16.4	-8.6	-1.2	1.8	6.0	5.3	-3.0	-8.4	-20.0	-26.0
Average Temp. (1981-2010)	-0.2	0.8	5.5	11.0	15.7	20.4	23.6	23.4	18.9	12.7	5.8	1.6
Average Max. Temp.(1981-2010)	4.8	6.5	12.0	17.6	22.4	27.1	30.4	30.4	26.5	20.0	12.3	6.3
Average Min. Temp.(1981-2010)	-4.2	-3.8	-0.3	4.5	8.7	13.1	16.5	16.3	11.6	6.4	0.7	-2.4

Although temperature differences between the seasons, solar irradiation levels are high enough to utilize microalgae in Konya. General conditions of the city indicate that the cultivation of microalgae on building envelope is possible; also, in summer sky is mostly sunny and the utilization of daylighting systems becomes a practical option to integrate microalgae in building interiors.

Step 3: Analyzing the light and temperature requirements of the selected species

Solutions in architectural design are made according to user needs, comfort and activities. From the same point of view, algae are living organisms and it is necessary to provide them the suitable environment. Thus, a system design can be made in which the algae and the building can provide mutual benefits. Microalgae can survive in a certain temperature range in the presence of light, CO_2 and nutrients. The most variable criterion for outdoor cultivation is the temperature and the amount of light.

Therefore, the requirements of the selected species in terms of light and temperature are analyzed to determine the suitable location for cultivation in the building and the necessary building systems.

The optimum light level for growth of *Neochloris oleoabundans, Scenedesmus obliquus, Botryococcus braunii* species for biodiesel production is reported as 150 μmol/m^2/s. If ten hours of sunlight presence is considered in June than these algae need 5.4 mol/m^2/day (150 x 3600 seconds x 10 hours / 1000000). If it is assumed that 50% of this light will be lost due to PBR orientation, inclination angle, and material, it would be sufficient to have a daily light integral of about 10 mol/m^2/day. This value is even lower for selected bioluminescent species, it is stated in the literature that dinoflagellates reach the maximum population at depths of 60-100 m in the ocean. 42 μmol/m^2/s light requirement of selected dinoflagellates species is equal to 1.5 mol/ m^2/day. It is reported that in the most microalgae species photoinhibition occurs at irradiances over 500 μE m^{-2} s^{-1}, which equals to 18 mol/ m^2/day. Considering that 50% of light is dissipated, solar irradiance levels can be problem for microalgae culture in the regions that have daily light integral of more than 36 mol/ m^2/day.

In this study, the solar irradiation quantity on site and light requirements of the selected microalgae species could not be compared because of different unit expressions that are given in the literature. KWh is an energy derived unit, it quantifies the amount of energy contained within radiation. On the other hand, quantum units express the number of light particles or photons delivered in between the PAR range, which is a specific wavelength range, and it is neither energy nor power. Since radiometric and quantum units could not be converted to each other in this study, it is accepted that solar irradiance levels are high enough for microalgae cultivation in Konya City, which is located at mid-south part of Turkey (Fig. 4.4). All things considered, for an accurate decision of PBR orientation, the daily light integral which hits on each surface of all directions should be measured and compared with microalgae's light requirement that will be utilized in the building.

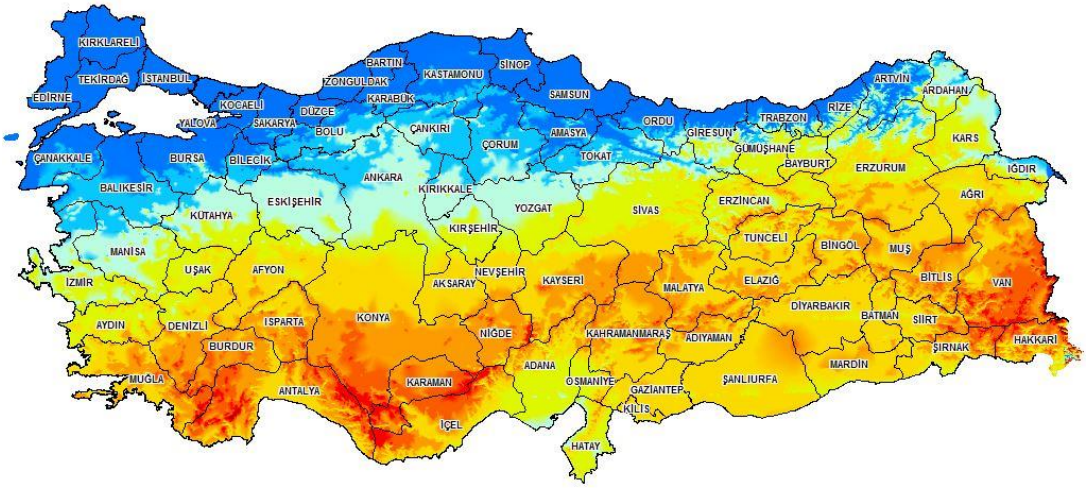


Figure 4.4 Solar irradiance potential of Turkey. Dark blue color represents 1400-1450 KWh/m2-year and the dark red color represents 1800-2000 KWh/m2-year (Yenilebilir Enerji Genel Müdürlüğü, 2019).

The optimum temperature varies from 23°C to 30°C for the species *Neochloris oleoabundans*, *Scenedesmus obliquus*, *Botryococcus braunii*, and 20°C to 22°C for the species *Pyrocystis fusiformis*, *Pyrocystis noctiluca*, and *Ceratocorys horrida*. According to the data retrieved from Turkish State Meteorological Service, temperature can differ significantly between the seasons and even it can drop by half during the day. The comparison of outdoor environment's temperature and the optimum range that is required for the selected species' medium culture indicates a requirement for a mechanical device to stabilize the temperature.

Step 4: Defining PBRs' location, orientation and inclination

The studies in the literature shows that there are efforts ongoing to obtain higher biomass. Orientation and inclination are two significant factors which directly affects biomass productivity. Many studies have been examined to decide for the right orientation and optimum angle of PBRs. According to one study, the geographical location of Konya requires east-west orientation of PBRs. On the other hand, PBR orientation was implemented to south direction in many other cases, even at different

latitudes/locations. As a result, it is interpreted that the focus should be to provide algae sunlight between its photo-limitation and saturation level range as long as possible.

Based on the information collected, microalgae species selected for biofuel production have higher light requirement than bioluminescent species. Also, according to the information that dinoflagellates reach the maximum population at depths of 60-100 m in the ocean, it can be understood that these organisms need a more stabilized environment, less light and cooler temperature compared to the microalgae species selected for biofuel production. So, integration of *Neochloris oleoabundans, Scenedesmus obliquus, Botryococcus braunii* is considered at the southern façade, and *Pyrocystis fusiformis, Pyrocystis noctiluca,* and *Ceratocorys horrida* are proposed to be cultivated in building interiors with using daylighting systems in the project. Inclination of southern-faced PBRs is considered with the same angle that PV panels are mounted. Additionally, control of environmental factors for outdoor cultivation are considered to maintain the microalgae culture and to obtain higher biomass yield.

4.6.1. Façade integrated photobioreactors for biodiesel production

For the proposal, it is intended to implement the integration design to the Konya Provincial National Education Directorate Building in the most practical way like a retrofitting project, with any requirement of major revisions. In the beginning, it was considered to integrate PBRs into the façade directly. But the building has many details on its façade like decorative protrusions, traditional motif covers and combination use of different materials. Therefore, façade integration was not preferred because of possible detail problems and aesthetically inappropriate appearance.

Then with a different approach, a sunspace addition is considered at the southern part as seen on the site plan (Fig. 4.5). The sunspace is added as the extension of the building, it has dimensions of 8 x 20 m. The original project consists of the metal grill shown on the ground floor plan (Fig. 4.6) which covers the areaway, the remaining

available space is considered for vegetation. PBRs are integrated into the façade of the sunspace; to the wall and the roof of the sunspace. The roof's tilt angle is 38º, and the value is calculated by reviewing the chapter on determining the optimum tilt angle of solar panels in renewable energy technologies document of the Ministry of Education. The aim here is to benefit from sunlight for microalgae in the most efficient way.

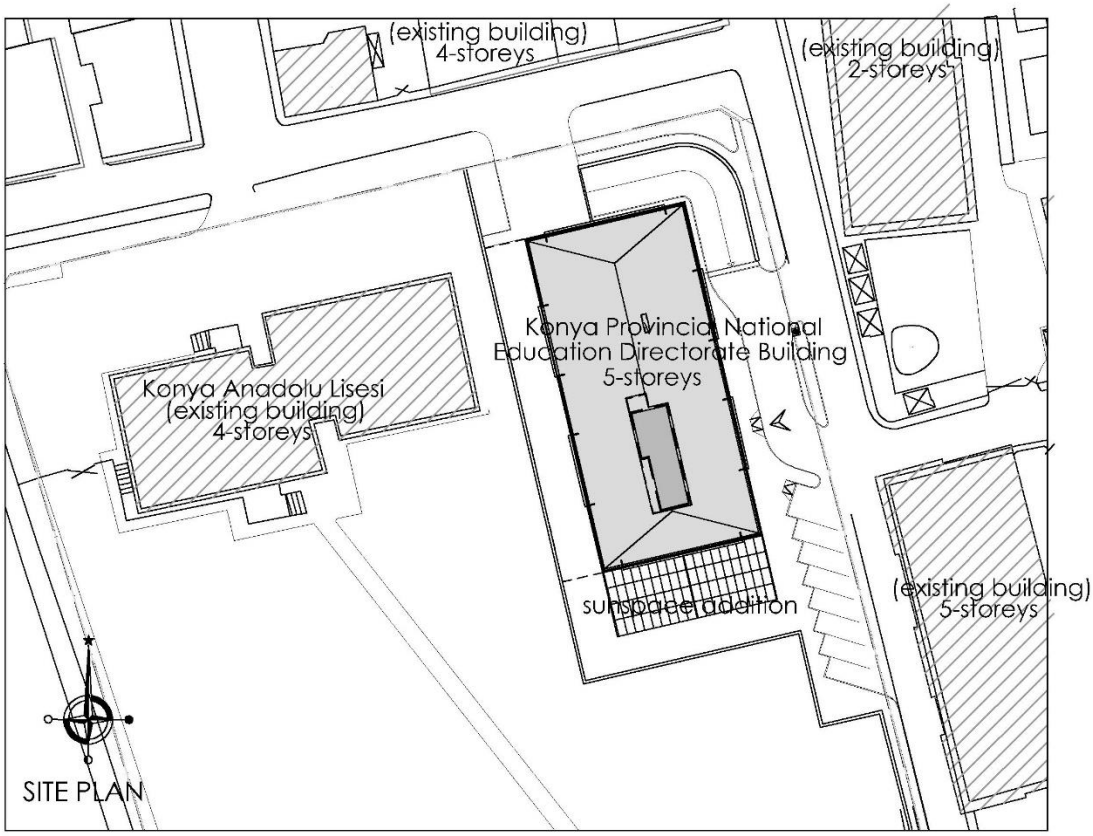


Figure 4.5 Site plan showing the proposal for sunspace addition.

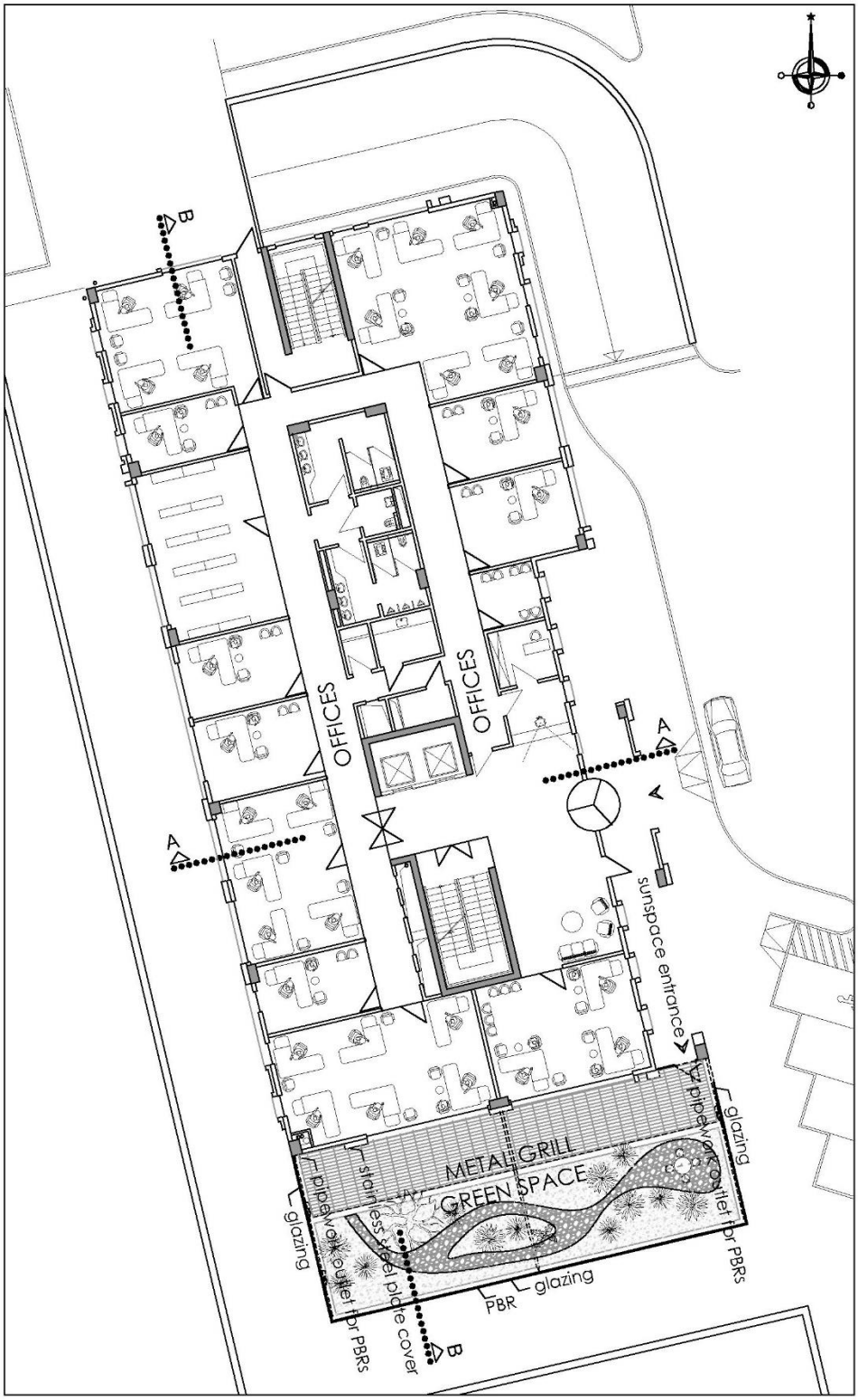


Figure 4.6 Ground floor plan showing the sunspace addition: PBRs are integrated to its façade.

Sunspace will be used for microalgae cultivation and leisure farming as well, so it will be an O_2 production center in the urban context and help to increase social awareness on green built environment concept. There are 63 units of 110 x 220 x 2 cm fixed flat plate PBRs on the façade of the sunspace. The total PBR area is 152 m^2. The offices adjacent to the sunspace required façade segmentation in order not to obstruct the visual interaction of the building occupants to outdoors. Therefore, PBR units are located according to user comfort as can be seen in Figure 4.7. The south-east elevation of the building shows that a series of one unit of PBR and one unit of glazing sequence is planned at the window level, and the floor slab levels are entirely covered with PBR units.

The advantages that proposal design offers:

In the original project, the technical rooms are located on the south side of the building at the second basement floor with an areaway for ventilation. These technical rooms consist of boiler, generator, server, and ups rooms. Parking space at the first basement floor is also adjacent to areaway, and its semi-open design provides natural ventilation. The areaway is covered with metal grill at the first basement and the ground level for safety reasons. In the proposal, the sunspace addition encloses the areaway which offers multiple advantages (Fig. 4.8):

- The CO_2 requirement of microalgae can be obtained by purifying the flue gas released in the boiler and generator room.
- The exhaust gas accumulated in the parking space will rise into the sunspace because of pressure difference and the polluted air can be cleaned naturally with the help of plants grown inside.
- The adjacent settlement of the sunspace and the technical rooms simplifies the installation design and reduces the energy consumption of PBRs.

As another advantage, the transmitted sunlight through the glazing walls of the sunspace will be stored as heat in thermal masses which are the architectural elements,

the materials in the sunspace and the PBRs. As seen in the section B-B (Fig. 4.8), there are four levels of openings to the sunspace that allows airflow and heat recycling into the building. In winter conditions the absorbed heat will help to maintain the building's and the PBRs' temperature and reduce the overall heating loads.

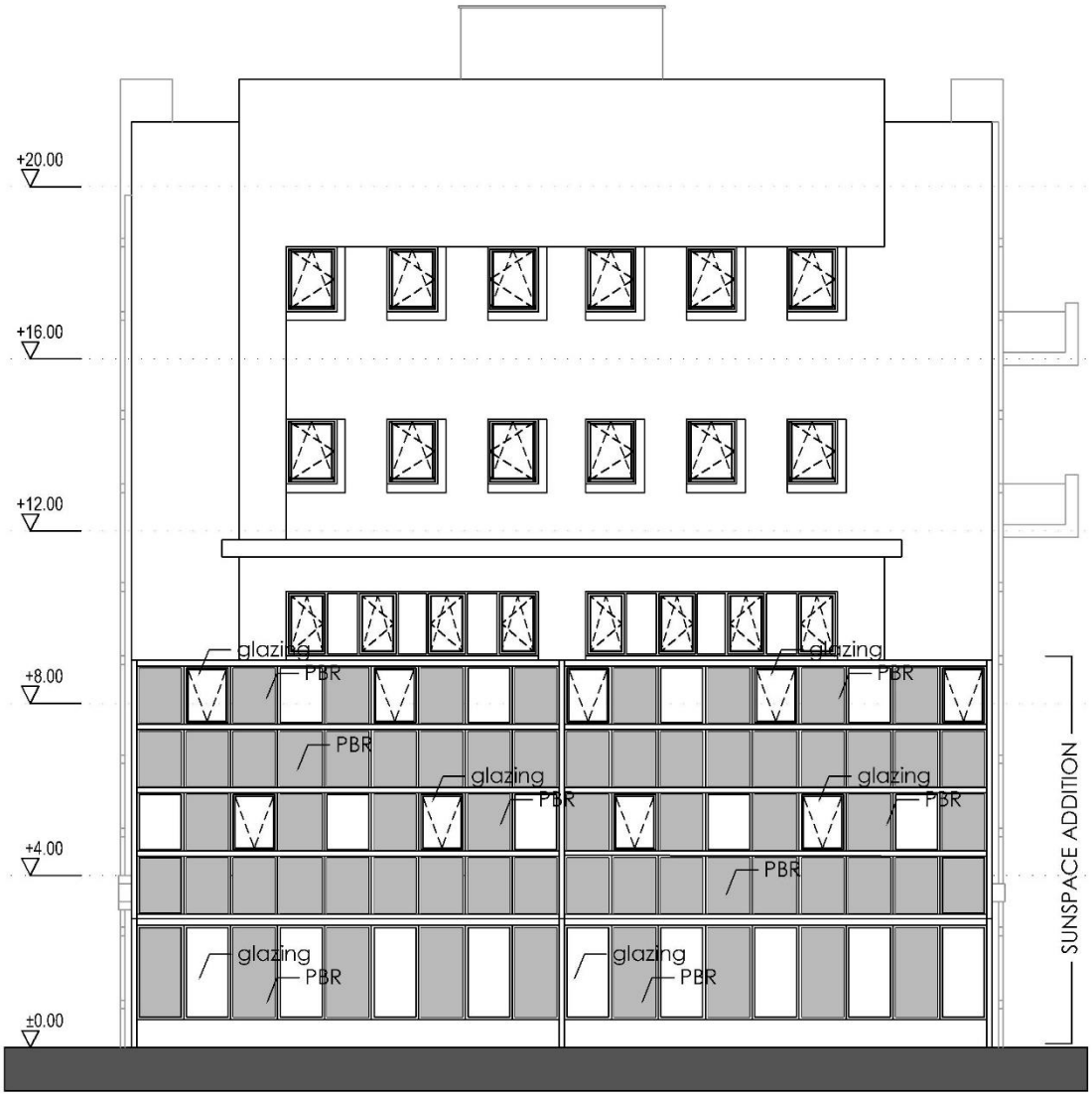


Figure 4.7 South-East elevation of the building with PBR integrated sunspace addition.

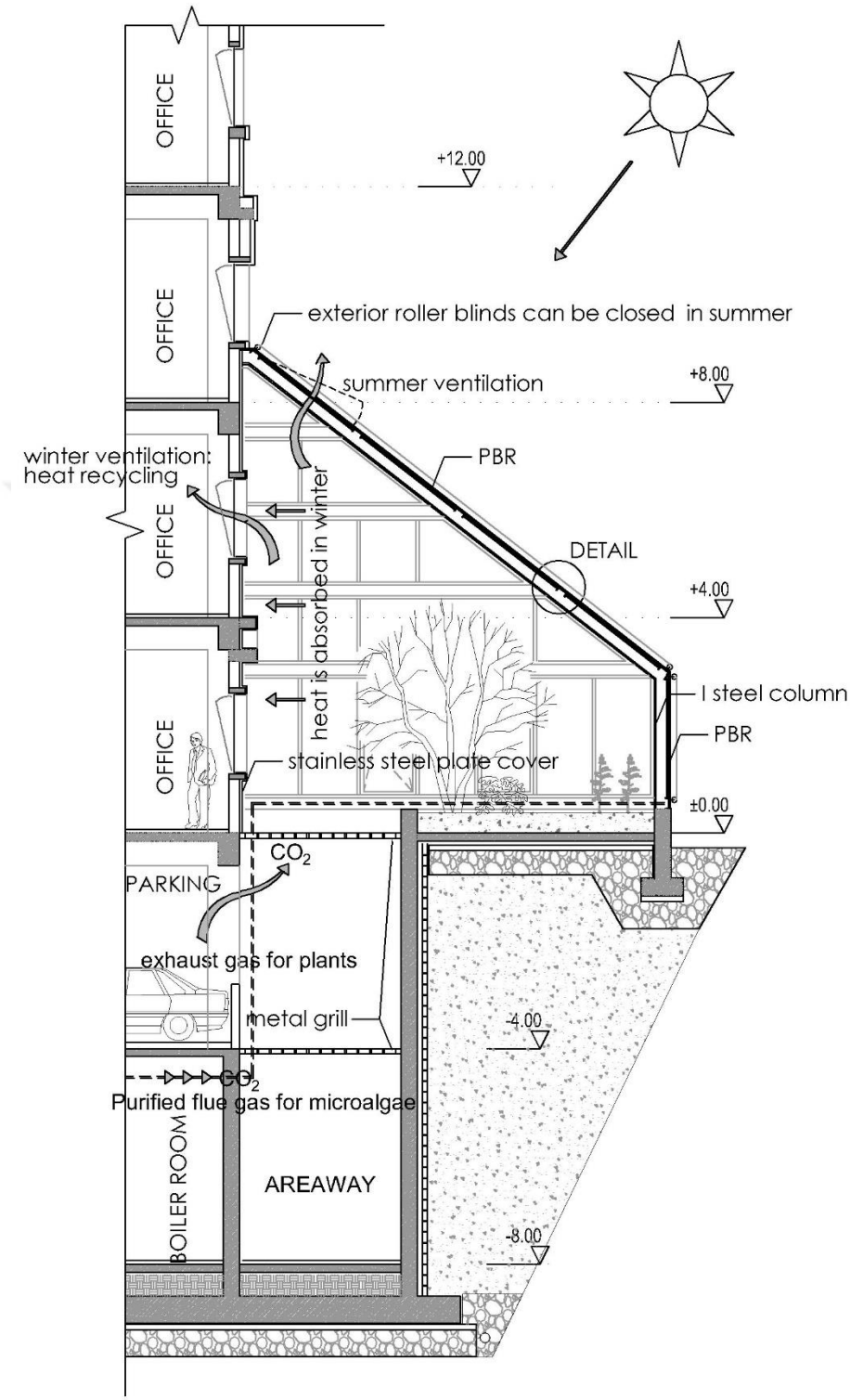


Figure 4.8 Partial section B-B showing the PBR integrated sunspace and its relation with the building.

The roof integrated PBR detail is shown as in the Figure 4.9. The structural system of the sunspace consists of main steel I profiles and steel U profiles connecting them. The specific types of profiles are selected for the installation and the passage of pipework underneath the PBRs. Thus, the structural elements provide guide lines for the mechanical system. Four lines are planned for PBR's installation. Three of these are considered for culture medium inlet, outlet and gas inlet. The line above the PBR is for degassing.

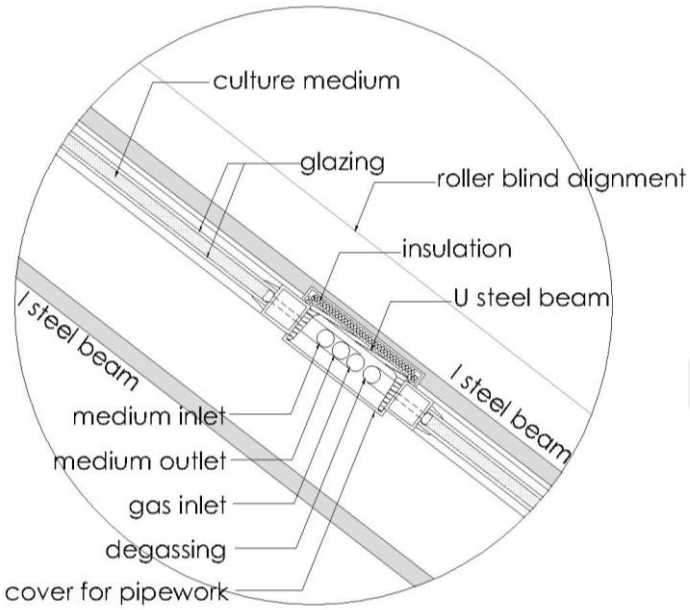


Figure 4.9 Detail from section B-B.

Precautions to control environmental factors:

The sunspace provides an advantage on sunny days of winter to maintain the heat of the building and PBRs, but the glazing enclosed space may be a problem in summer. Therefore, it is necessary to remove the heat inside the space to reduce overheating risk. Multiple strategies are considered to control the effects of environment as seen in the section B-B and the detail (Fig. 4.8, Fig. 4.9):

- The structural profiles are insulated and argon gas filled double glazed units are used for façade to protect the sunspace and the PBRs from the extreme conditions.
- The excess heat can be removed with roof windows, and building openings at different levels can provide cross-ventilation, and cool the sunspace and the building as well.
- Roller blind is used to control sunlight. External shading can prevent the increase of culture medium's and sunspace's temperature in summer when the sun's rays reach the steepest.
- The surface of the main building inside the sunspace is covered with a stainless steel plate that can help to increase the daylight level. The penetrated sunlight will be redirected into the sunspace and hit the back surface of PBRs. In this way, microalgae can benefit more from light and photo limitation risk of microalgae can be reduced in conditions where solar irradiation is insufficient.

In addition to the passive strategies mentioned, the use of heat exchanger can keep the culture medium temperature within the optimum range.

Biodiesel production potential of the system:

The criteria required for microalgae cultivation in the building are included in the proposal to achieve an efficient biomass production. Among the selected species for biodiesel production, cultivation of *Neochloris oleoabundans* can be more suitable due to its high oil content. According to the data obtained from the literature, Neochloris oleoabundans' productivity is 0.09 grams per liter per day (Table 3.2).

In the proposed project, there are 63 units of 110 x 220 x 2 cm flat plate PBRs. The maximum capacity of culture medium volume is 3.04 m^3 which equals to 3,040 liters.

The total biomass in PBRs can reach up to 273.6 grams per day (3,040 liters x 0.09 grams = 273.6 grams), and 99,864 grams per year. Almost 100 kg of microalgae (99.8

kg) can be obtained for commercial products by the integration of *Neochloris oleoabundans* to the project.

The oil content of the species is reported as 29%, so it can be said that 99.8 kg of biomass consists of 28.9 kg of oil. The oil can be used as feedstock for biodiesel production which the final quantity depends on the efficiency of biodiesel production processes like transesterification.

4.6.2. Daylighting system integrated photobioreactors in building interiors for light production

In this section, another integration is proposed for the same project (Konya Provincial National Education Directorate Building). The species *Pyrocystis fusiformis, Pyrocystis noctiluca,* and *Ceratocorys horrida* can be cultivated in building interiors with the natural light transported by daylighting systems.

Partial plans and sections show the proposed daylighting system integration. The system works in 4 phases; light collection, transportation of light in the vertical axis, and transportation and emission in the horizontal axis. At the last phase, the light is supplied to PBRs.

As seen in the partial roof plan (Fig. 4.10) and the partial section C-C (Fig. 12) and D-D (Fig. 13), the main staircase, the elevators and the installation shaft constitutes the building's top level. Installation of light collection system on top of this level was considered because:

- The surrounding buildings at the construction site can obstruct the sunlight falling onto the building. Top-lighting strategy provide the advantage to benefit from the available sunlight at maximum levels.
- Building shaft can also be used as a light distribution center. In the original project, the shaft ends at the building's top level which gives the opportunity

to install light collection system on and connect the vertical light pipes underneath.

The partial roof plan in Figure 4.10 shows the solar collector system for transporting the light to building interiors. A rectangular heliostat (120 x 105 cm) coupling with redirection mirror (120 x 105 cm) captures the sunlight at the top of the building. Fresnel lenses connected with heliostat system concentrate the light and direct the collimated beams to vertical closed prismatic light guides 20 cm in diameter (mentioned as vertical light pipes in the drawings). As seen in the partial plan (Fig. 11) and the partial section C-C (Fig. 13) the light is distributed at every floor to horizontal light pipes.

These horizontal light pipes are transparent and they are considered to function as emitters as well. At the last phase, the daylight is introduced to PBRs with fiberoptics connection as seen in detail drawing (Fig. 4.14). Fiberoptics is considered as a useful lighting tool for flat panel PBRs due to suitable dimensions in diameter. Regularly installed cables inside the panels can provide homogeneous internal lighting for microalgae.

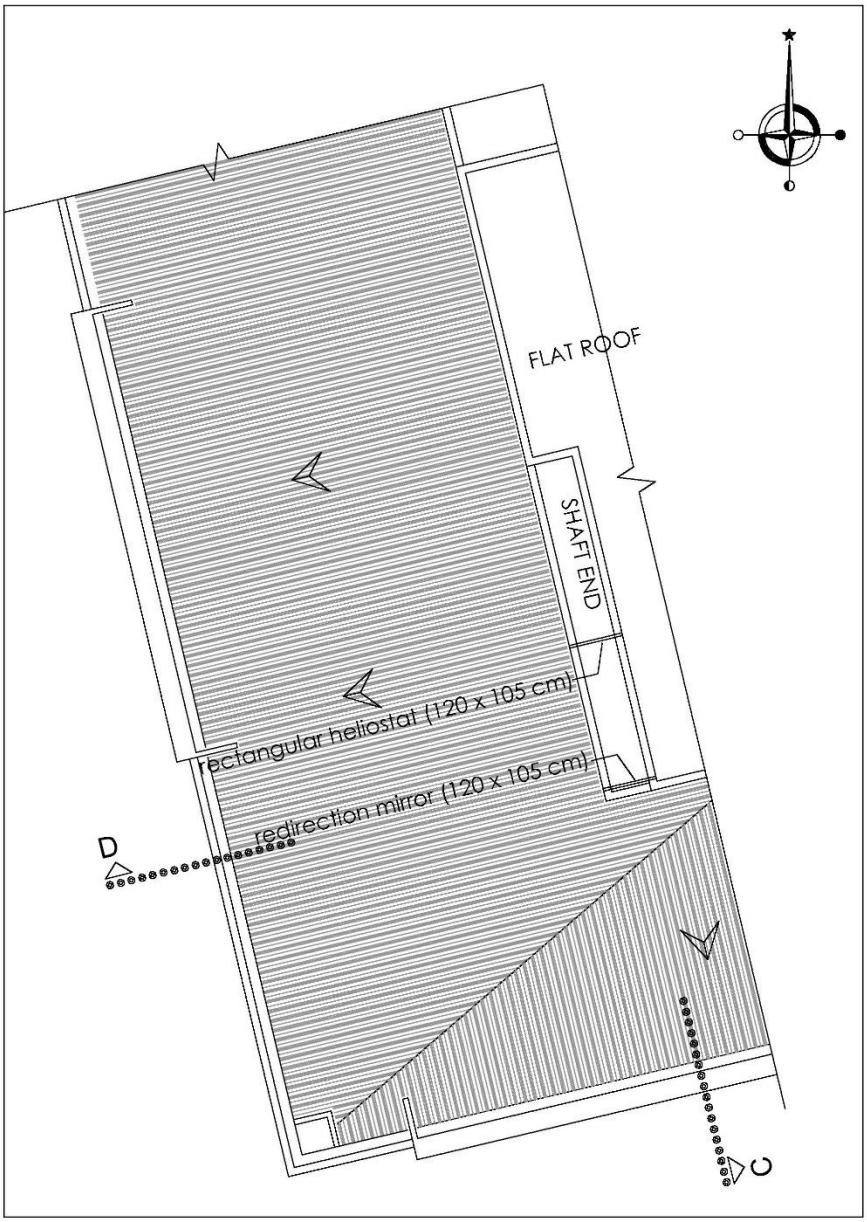


Figure 4.10 Partial roof plan showing the solar collector system where sunlight is captured.

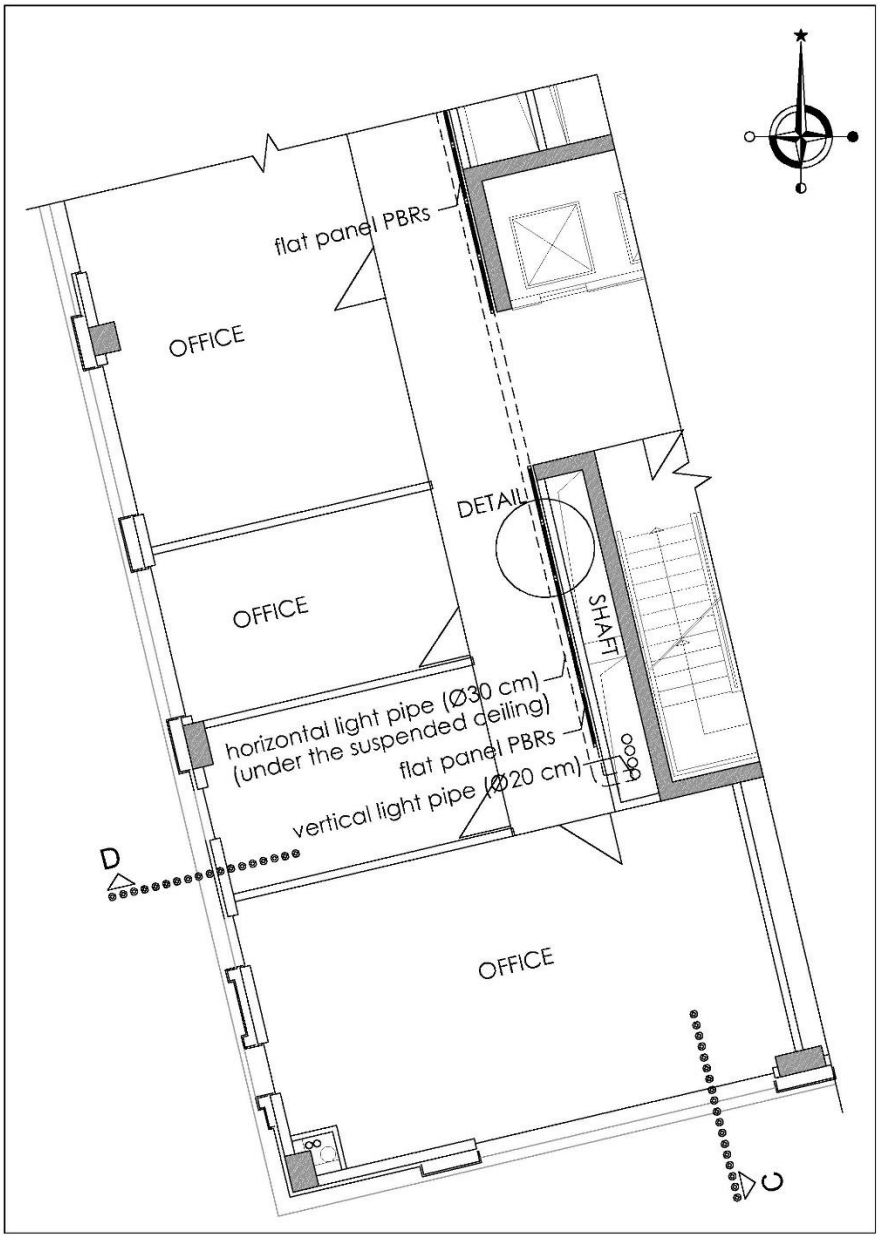


Figure 4.11 Partial typical plan showing the vertical light pipes where light is redirected into horizontal light pipe.

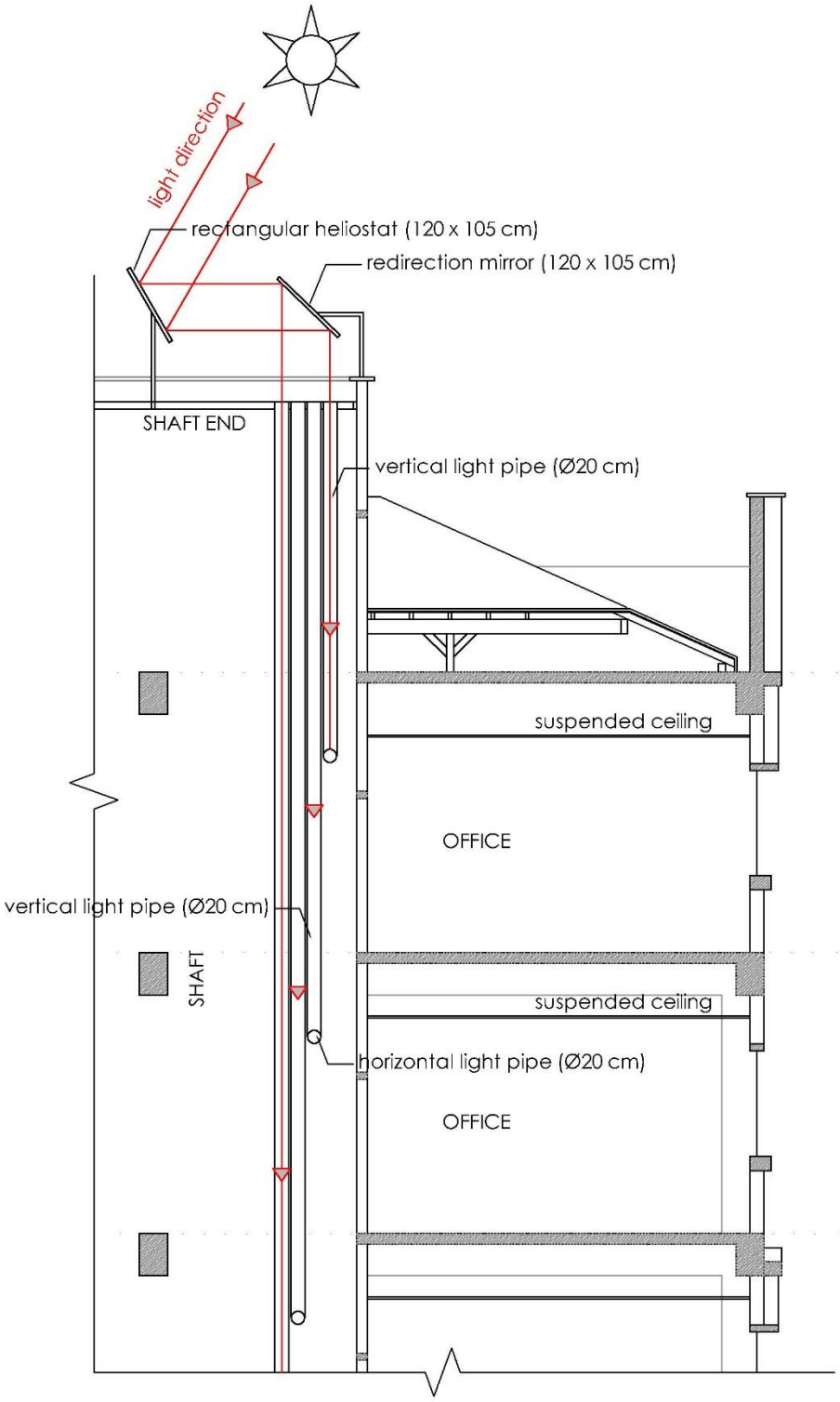


Figure 4.12 Partial section C-C showing the solar collector and vertical light pipe connections.

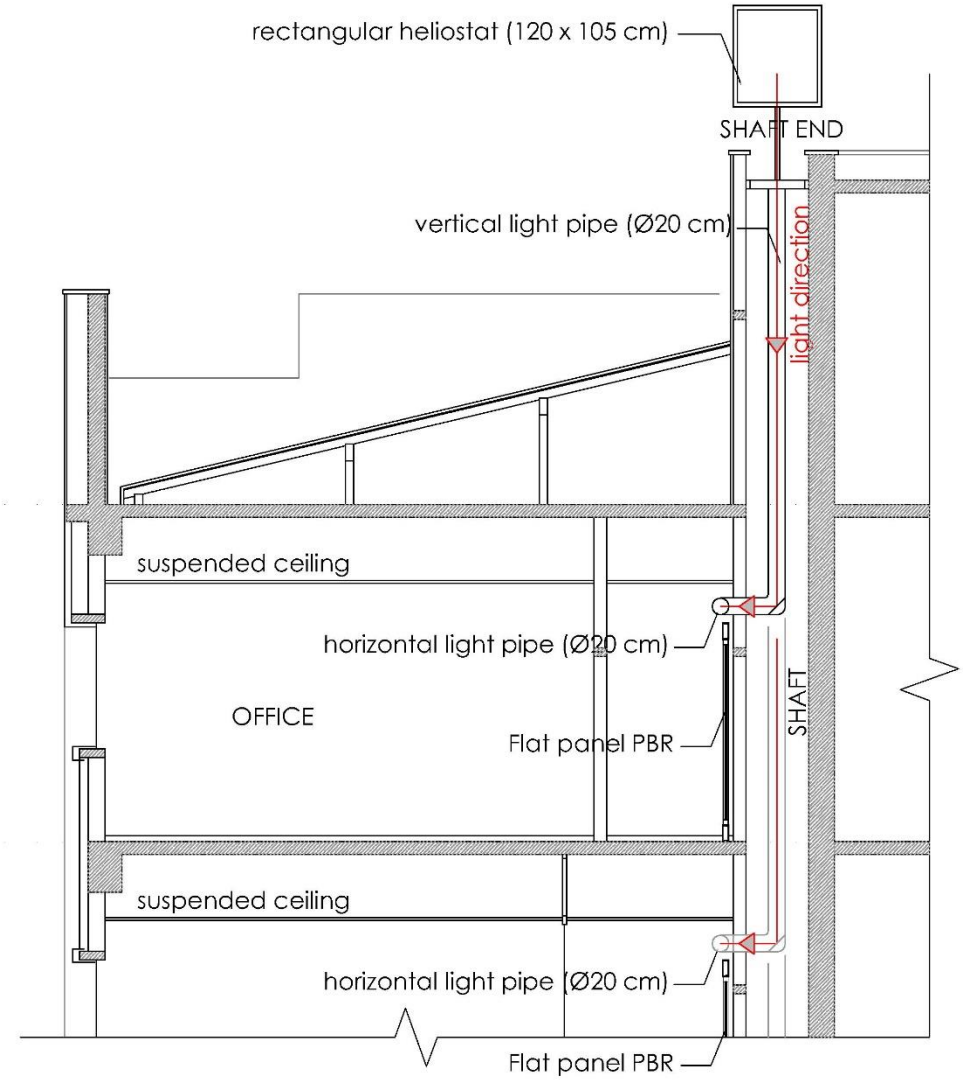


Figure 4.13 Partial section D-D showing the vertical and horizontal light pipe connections.

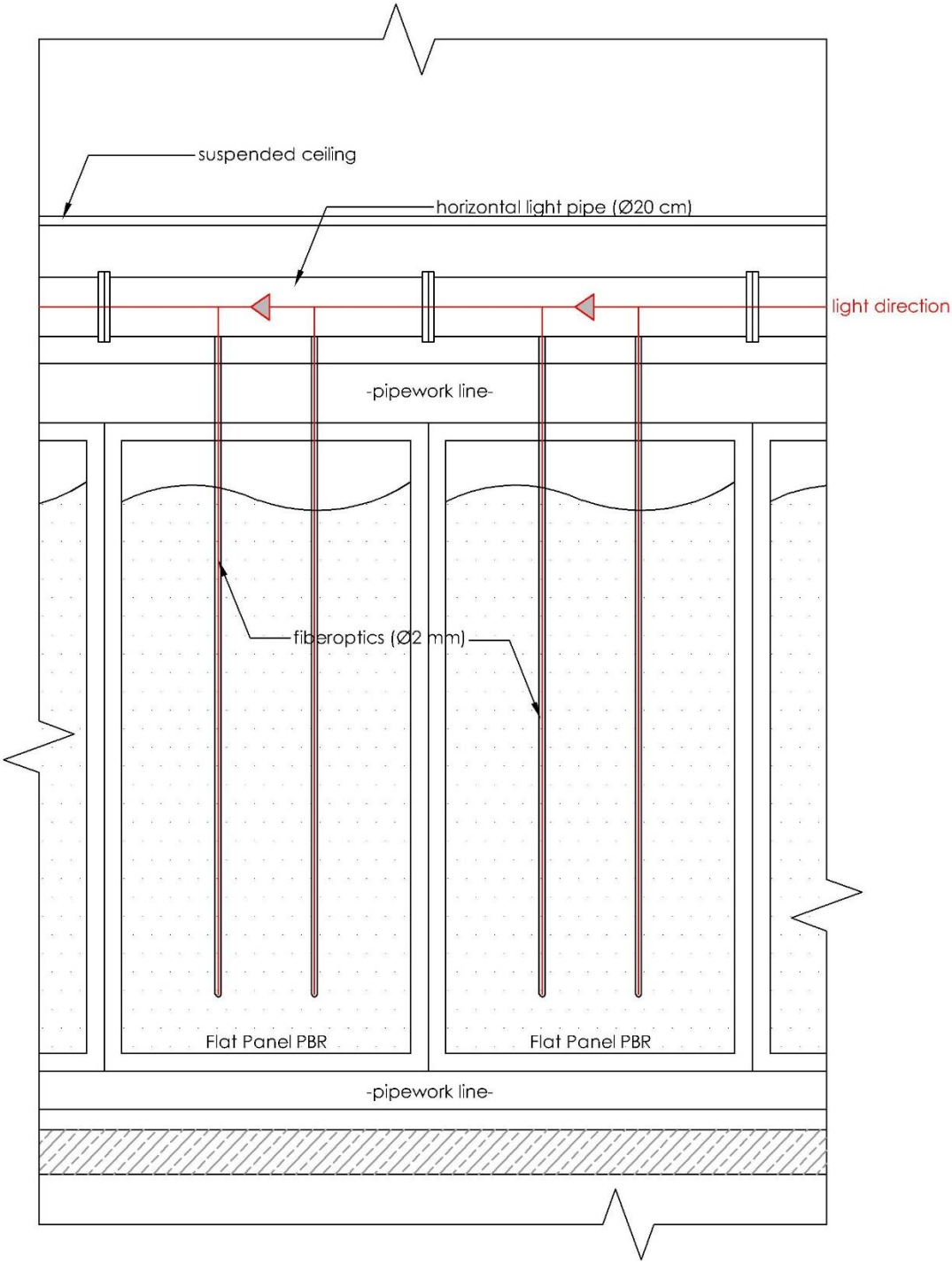


Figure 4.14 Partial elevation detail showing the light introduced to flat plate PBRs with fiberoptics connection.

The advantages that proposal design offers:

In the original project, the office units are 5.45 meters in width which causes the building core and circulation area not to get enough daylight. Using a daylighting system can reduce the dependency on the artificial lighting, ensure user-friendly building environment and provide the light needed for microalgae cultivation in the meantime. The dinoflagellates *Pyrocystis fusiformis, Pyrocystis noctiluca,* and *Ceratocorys horrida* can benefit from the daylight emitted by fiberoptics in PBRs and the horizontal light pipes. In particular, transported daylight can be very efficient for the cultivation, because daylighting systems consist of devices (like lenses) that can filter UV and IR rays that cannot be used for photosynthesis. Moreover, the dinoflagellates can use artificial lighting as well at the time the daylight quantity is insufficient. In return, they can provide O_2 and contribute to indoor air quality, and exhibit bioluminescence in the dark.

In conclusion, the whole system can be considered as a symbiosis. Light transport systems improve the daylight in building interiors, and dinoflagellates can benefit from the UV and IR filtered sunlight for photosynthesis, and provide blue light and fresh air for building occupants.

Precautions to control environmental factors:

The precautions to control the environmental factors for algae depend on the place where the cultivation takes place. The building interiors will have a constant temperature for building users' comfort, so unlike cultivation at outdoor conditions, an extra effort for maintaining PBRs' temperature may not be necessary. On the other hand, light levels can be insufficient in the building for algae. The quantity of daylight can decrease at every particular length, and at the end, algae may require additional light for photosynthesis. For similar projects, photo limitation of microalgae can be prevented by increasing the light quantity by installing additional solar collectors, coupling the daylighting system with artificial lighting that can be used by microalgae

like cool-white fluorescent lamps, and covering architectural elements with reflective materials that can redirect the diffused light on PBRs surface.

Light production potential of the system:

Light production potential of the system cannot be calculated since there are too many unknowns. Firstly, the light quantity transported to building interior is unknown, but the only data reached is a similar daylighting system applied in Borusan Holding Building which is located in İstanbul. Illuminance level of 400 lux was reported for the daylight levels obtained by the system. On the other hand, İstanbul's annual total solar irradiance is far lower from Konya, so it can be inferred that the light levels obtained by the daylighting system in the proposal project will be higher than 400 lux.

But yet, the quantity of light that can be produced by the dinoflagellates cannot be calculated because it is unknown if the light (assumption of light quantity higher than 400 lux) for photosynthesis will be sufficient. The light requirements of microalgae are given in moles, and it cannot be converted into lux for comparison. The complexity of conversions of photometric and quantum units is a major challenge to reach accurate results. If the dinoflagellates cannot store energy from light, they can be unable to make bioluminescence, therefore no conclusions were drawn.

CHAPTER 5

CONCLUSION

In this study, the optimized integration systems to maximize symbiosis between microalgae and built environment was discussed. Design strategies were proposed for utilization of microalgae species which were selected for light and biodiesel production. Proposed design approaches for integration were based on the reason that the utilization of microalgae and building a symbiotic relationship with the built environment requires optimum growth conditions to be provided for microalgae. Similar to greenhouses which are perfectly designed for plant growth, microalgae's requirements – primarily light, should also be considered in building design. In the literature, most of the studies on microalgae were conducted in a laboratory environment. Architects have started to show more interest in PBR integrated buildings, but more research is needed at the intersection of architecture and biotechnology, and especially in outdoor conditions, in order to present more realistic designs.

Determinations have been made in accordance with what has been learned from the literature. It is inferred that in the conceptual design phase of an integration project, species selection and review of species characteristics have to be completed. The site should be analyzed and the environmental data should be compared with microalgae's requirements. Comparison of available solar irradiation at the building site and the microalgae's light requirement is a challenge; because the information can be expressed in photometric, radiometric and quantum units which can be very complicated to convert to each other. After accurate light measurements at the site, comparison can be done and the decision of PBR orientation and inclination angle can

be given. Thus, precautions can be taken in the design to protect microalgae from extreme environmental conditions. Than at the final, a symbiosis can be expected after meeting the conditions for microalgae's cultivation. Overall, it can be already said that microalgae have high potential to benefit the built environment, and the scope of symbiosis yields the following results:

- PBRs can act as an additional insulation layer on the envelope. As culture density increases, microalgae can provide sunlight filtering and thermal buffering that controls the light and heat transmission.
- Building temperature can help to keep culture temperature under control, microalgae share the heating and cooling loads of the building.
- Curtain wall glazing is widely used to cover buildings and forms the envelope. Façade integrated PBRs as a part of glazed curtain wall will reduce the necessary materials used for the PBRs.
- Microalgae will be able to provide clean water and O_2 from the outputs of buildings such as greywater and flue gas.
- Bioluminescent lighting can be provided in built environment.
- They can be processed into end products for what they are cultivated for.
- Process residue can be used in the production of fertilizers or biogas.

It is obvious that a façade without PBR or a stand-alone PBR will be simpler than an integrated system. The processes to obtain biofuel is reported to have a negative energy balance, and with considering the operation of PBRs, the use of microalgae for commercial purposes may not be feasible. Therefore, the aim should be maximizing the symbiosis between microalgae and built environment. Thus, the cultivation process of microalgae comes into prominence more than the value of obtained end-product (like biodiesel). In other words, end-product can be considered as one of the tools to benefit from microalgae, and the building integrated cultivation systems can provide many advantages as listed above, which can also lead to re-question the overall energy balance.

In conclusion, all results indicate that microalgae have the potential to give more than it takes. Thanks to plants and microalgae, buildings can be productive components of sustainability.

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