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Master's Degree Thesis

A Study on the Purification of Flue Gas from Coal Power Plant for CO_2 Enrichment Cultivation in the Horticulture

Graduate School of Chosun University

Department of Environmental Engineering

Hok Chamroeun

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고농도 시설원예 재배를 위한 석탄발전소 배가스의 정제 연구

26th, August 2022

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Advisor: Professor Lee Inhwa

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Graduate School of Chosun University

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HOK CHAMROEUN, CHOSUN UNIVERSITY

Department of Environmental Engineering

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NOMENCLATURE

CO_2	: Carbon Dioxide
CCUS	: Carbon Dioxide Capture Utilization and Storage
PA	: Paris Agreement
°C	: Degree Celsius
SDGs	: Sustainable Development Goals
UNDP	: United Nations Development Programme
AR5	: Fifth Assessment Report
SR1.5	: Special Report on Global Warming 1.5 °C
CH_4	: Methane
CV1	: Cultivar 1
CV2	: Cultivar 2
FI	: Full Irrigation
DI	: Deficit Irrigation
HA	: Half Irrigation
PRD	: Partial Root-zone Drying
N_2O	: Nitrous Oxide
O_3	: Ozone
HFCs	: Hydrofluorocarbons
PFCs	: Perfluorocarbons
SF_6	: Sulfur hexafluoride
GWP	: Global Warming Potential
MF	: Microfiltration
UF	: Ultrafiltration
IE	: Ion-Exchange
RO	: Reverse Osmosis

CO	: Carbon Monoxide
NO	: Nitrogen Monoxide or Nitric Oxide
SO_2	: Sulfur Dioxide
H_2S	: Hydrogen Sulfide
RPM	: Revolutions Per Minute
H_2O_2	: Hydrogen Peroxide
Cl	: Chlorine
S	: Sulfur
P	: Phosphorus
K	: Potassium
Na	: Sodium
Ca	: Calcium
Mg	: Magnesium
Fe	: Iron
Mn	: Manganese
Zn	: Zinc
B	: Boron
Cu	: Copper
Mo	: Molybdenum
HP	: Hight Pressure
P&ID	: Piping and Instrument Diagram

ABSTRACT

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In the recent days, horticulture can use carbon dioxide (CO_2) enrichment in controlled environments has been shown to improve the development and yield of a wide range of crops. This study aims to utilize the CO_2 gas from coal power plant in horticulture to minimize global warming. Total 4 types of vegetables were selected as samples, namely tomato, green pumpkin, pepper and cucumber. The initial stage of this research understands the liquefaction technique of CO_2 gas. The main objectives of this study are to investigate the cultivation process of CO_2 from the flue gas of coal power plant using Post-Combustion Carbon Dioxide Capture Utilization and Storage (CCUS) technique and to inspect the most adequate level of CO_2 concentration for growth rate of agricultural products. Research findings has proven that CCUS is a reliable technique in facilitating CO_2 extraction in horticulture with extraction rate as high as 96%. Although result shows increase in the growth rate of vegetable leaves and stems, continuation of the current study should be developed considering economical factor.

Keywords: Horticulture, Post-Combustion Carbon Dioxide Capture (CCUS), Carbon Dioxide

한 글 요 약

고농도 시설원예 재배를 위한 석탄발전소 배가스의 정제 연구

Hok Chamroeun
Advisor: Prof. Lee Inhwa, Ph.D.
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최근 원예분야에서는 다양한 작물의 개발 및 수확량 증대를 위해 통제된 환경에서 이산화탄소 농축을 적용해왔다. 본 연구에서는 지구온난화를 최소화하기 위해, 석탄발전소에서 발생하는 이산화탄소를 원예에 활용하였다. 시료는 토마토, 청호박, 후추, 오이등 총 4종의 식물을 선정하였다. 연구 도입부에서는 CO_2 가스의 액화 기술에 대해 설명하였다. 본 연구의 주요목적은 석탄발전소 배기가스 중 CO_2 발생과정을 사후연소 이산화탄소 포집 이용 및 저장(CCUS) 기법을 이용하여 조사하고, 농산물 성장률을 고려한 최적의 CO_2 농도를 검토하는 것이다. 연구 결과에 따르면, CCUS는 96%의 높은 CO_2 추출 효율을 보이며 신뢰할 수 있는 기술임을 입증하였다. 또한, 식물의 잎과 줄기의 성장률이 증가함을 확인하였고 경제적 비용을 고려하여 이러한 연구개발은 지속될 필요성이 있다.

키워드: 원예, 연소 후 이산화탄소 포집(CCUS), 이산화탄소

1. INTRODUCTION

1.1. Background

Simply acknowledging that global temperature change is an ongoing issue, party leaders should recognize, focus on promoting, and take into account their various different responsibilities, including the right to life, indigenous peoples' privileges, local communities' rights, migrants' rights, children's rights, people with disabilities, and people in vulnerable situations' rights, and the right to development, as well as gender equality, women's empowerment, and intergenerational equity, when taking global warming action **[1]**. According to the PARIS AGREEMENT (PA) **[2]**, enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the sustainable development framework and possible to alleviate poverty, including by keeping global mean temperature increases well below 2 °C above pre-industrial levels and trying to pursue efforts to keep temperature increases to 1.5 °C above pre-industrial levels.

1.2. The Current State of Climate

In 2015, representatives across 193 countries gathered in New York to determine the implications. As a result, as shown in **Figure 1.1**, the Sustainable Development Goals (SDGs) plan was created by leaders from either of these countries. In just 15 years, this compilation of 17golas depicts a world free of starvation and disease, as well as impervious to some of the worst consequences of climate change. It's a long-term approach. The United Nations Development Programme is one of the primary institutions working to accomplish the SDGs by 2030. (UNDP). In approximately 170 countries worldwide, we help governments achieve the Goals. As a result of human activity, the environment, oceans, and earth have all been dramatically warmed. The atmosphere, oceans, cryosphere, and biosphere have all changed dramatically.

Figure 1.1 The global goals for sustainable development [3]

1.3. Limiting Future Climate Change

Since AR5, newer research, including the combination of insights from several lines of evidence have strengthened predictions of largest greenhouse gas budgets**[4]**. The effects of different parameters on environmental and air quality estimates are continually reviewed in scenarios that include a wide range of possible growing air emissions regulations. It's a major development to be able to anticipate when the climatic answer to cutting emissions will be seen above weather patterns, including climatic variation and responses to natural variables. According to theoretical physics, minimizing human-induced global climate change to a specific level implies restricting cumulative emissions of carbon dioxide to at least net zero, but also considerable declines in other greenhouse emissions. Strong, rapid, and long-term cuts in methane emission would also help alleviate the warming effect of reducing aerosol pollution while also benefiting the environment.

2. A LITERATURE REVIEW

2.1. CCUS Technologies

The primary CCUS technologies, such as CO_2 capture, sequestration (storage), consumption (direct use), and conversion into chemicals and/or fuels, are depicted in **Figure 2.1**.

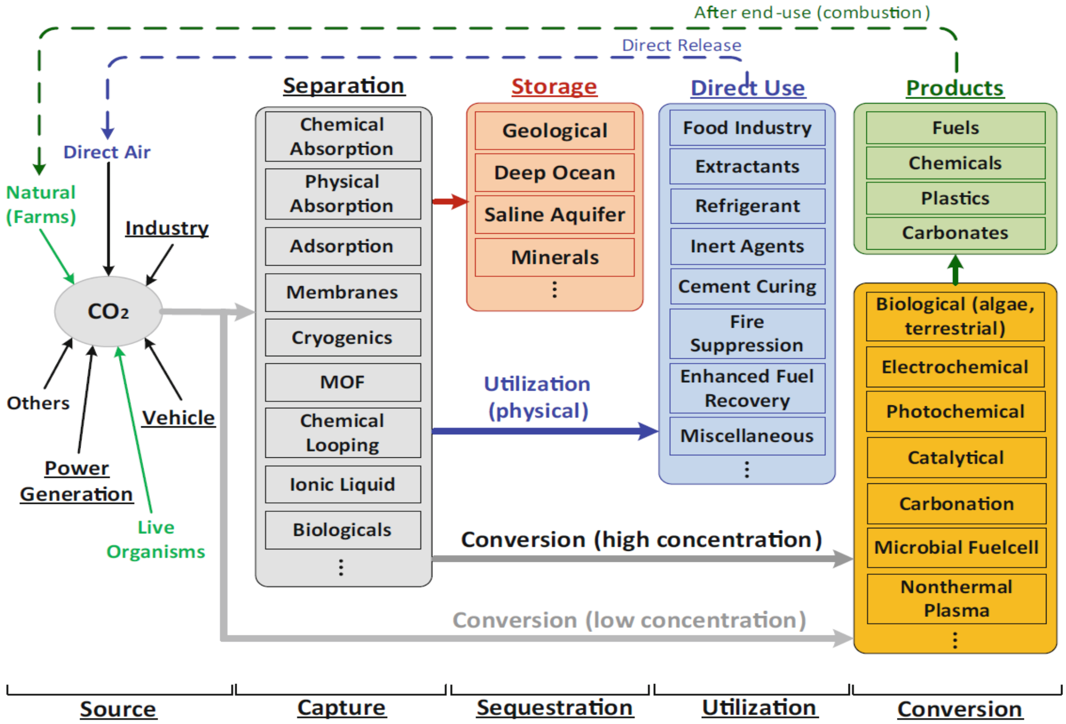


Figure 2.1 Technologies for CO_2 capture, use, and storage (CCUS) [5]

CCUS technology, for example, can successfully extract CO_2 from emission sources, transport it, and store it at suitable and long-term geological sites. Therefore, to study more deeply by using CCUS technology, should consider in many factors such as following:

- Necessity to develop CCUS technologies **[6]**
- Approaches to mitigate global climate change **[7]**
- CO_2 capture technologies (pre-combustion, post-combustion, oxyfuel combustion) **[8]**

- CO_2 separation technologies, transportation, utilization, geological storage **[9]**
- Life cycle greenhouse gas assessment and CO_2 leakage and monitoring **[10]**

2.2. Case Study by Utilizing CO_2 for Plant

2.2.1. Effects of CO_2 elevation on tomato

Global warming trends and the pathways that drive plant response to such change are critical for developing agricultural techniques and crops that are more suited to future growing circumstances **[11]**. CO_2 concentrations in the atmosphere are expected to rise to 550 ppm by the mid-century **[12]**. Short- and long-term anticipated changes in temperature and precipitation patterns, furthermore, reveal a considerable deal of regional and - in some cases - seasonal variability **[12]**. **[13]** looked examined how high CO_2 levels, different irrigation regimes, and their interactions affected leaf gas exchange, water relations, biomass output, and water usage efficiency in tomato plants. In spring 2014, 2 tomatoes cultivars (CV1, which is drought tolerant, and CV2, which is heat tolerant) were cultivated in two separate greenhouse cells at the experimental farm in Taastrup, Denmark, at CO_2 levels of 380 and 590 $\mu molL^{-1}$ (ppm). Plants were either watered to 18% of volumetric soil water content (FI, full irrigation) or irrigated with 70% of the water of the completely control, supplied to either the entire pot (DI, deficit irrigation) or even just half of the pot (HA, half irrigation) (PRD, partial root-zone drying). CO_2 enrichment increased flower number while having little effect on fruit number, resulting in reduced fruit set. Among both tomato cultivars, decreased irrigation combined with higher CO_2 resulted in a considerable enhancement in plant water usage efficiency.

2.2.2. Effect of CO_2 elevation on cucumber

Since industrialization, massive amounts of CO_2 have been emitted into the atmosphere because of anthropogenic such as fossil fuel emissions, reforestation, and land-use change **[14, 15]**. CO_2 enrichment, sometimes known as CO_2 fertilization, is a widely utilized procedure in the horticulture sector that promotes crop output. Plants, on the other hand, are more responsive to increased CO_2 (eCO_2) while they are young or when exposed to eCO_2 for a short period of time, but long-term exposure to eCO_2 causes photosynthetic acclimation or down-regulation of photosynthesis **[16-18]**. The investigators' interest in how to preserve sustainable agricultural yields in crops is piqued by photosynthetic acclimation under eCO_2 **[19, 20]**. **[21]** cucumber (Cucumis sativus L.) plants were hydroponically grown for two stages (the seedling stage and the initial fruit stage) in open-top chambers with 3 CO_2 concentrations [400 (aCO_2), 625 ($subeCO_2$), and 1200 (eCO_2), μmol mol^{-1}] and 3 NO_3^- concentrations [2 (low NO_3^-), 7 (moderate NO_3^-), and 14 (high NO_3^-), $mmol^{-1}$]. Cucumber revenue grew by 73 percent when exposed to eCO_2 in a high NO_3^- treatment, but not in a mild NO_3^- treatment.

2.2.3. Effect of CO_2 elevation on pepper

Under such a circumstance, net primary output could be limited, resulting in a lowering in both water supply quality, and global warming could exacerbate salinity stress, particularly in the Mediterranean region, where global warming projections show a significant increase in water scarcity **[22, 23]**. Pepper (*Capsicum annuum*) is a popular greenhouse crop in Europe, and its salt tolerant **[24]**. **[25]** investigates whether the anticipated CO_2-protective effects on saltwater stress-induced growth suppression, photosynthetic impairment, and nutritional imbalance are achieved by a sustainable outcomes of the plant hormone hormonal balance. Sweet pepper plants were cultivated with a nutrient solution containing o or 80 mM NaCl at ambient or high CO_2 (400 or 800 μmol mol^{-1}). When compared to ambient CO_2, elevated CO_2 enhanced plant dry weight, leaf area, leaf relative water content, and net photosynthesis in saline circumstances, although photosystem II's maximal theoretical quantum efficiency remained unchanged.

3. DESIGN OF SEPARATION MEMBRANE AND LIQUEFACTION DEVICE

3.1. Membranes for Gas Separation Introduction

Around the planet, a modern manufacturing revolution is taking place. To reduce raw material expenditure and waste output while increasing efficiency, rapid advances in equipment, control, and process configuration are being made. "Environmentally Friendly" and "Green" have become the new millennium's buzzwords. This increased environmental consciousness reflects not only a movement in public perception, but also a global acknowledgment that environmental impacts are now required. Much of the new understanding has centered on carbon dioxide emissions and their effects on overall climate change. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are examples of greenhouse gases **[26]**. CO_2, CH_4, and N_2O, among these gases, have become the focus of attempts to reduce environmental issues because they are set to release in massive amounts and have major impact on global warming (GWP), a measure of a species' effect on climate based on its capacity to absorb thermal light, the specific location of absorbance on the spectrum, and atmospheric lifetime.

3.2. Membrane Separation Procedures

Membrane technology technique is determined by the physical or chemical interaction of certain gases with the membrane material. Membrane processes, with their great efficiency, ease of operation, and cheap cost, are regarded visible and practical technology for the extraction of gaseous mixtures at the huge application. Membrane separations are frequently characterized according to the pore size and separation driving force. Microfiltration (MF), Ultrafiltration (UF), Ion-Exchange (IE), and Reverse Osmosis (RO) are examples of such classifications. **Figure 3.1**.

depicts the ideas of the four most common membrane device designs. Purification and sewage treatment applications frequently use tubular and plat-and-frame systems. In many cases, many tubes are crammed into a single cylindrical receptacle. A shell-and-tube design is what this is called. Polymer membrane innovation based on hollow fibers or flat sheets is currently used in all industrial gas separation membrane applications **[27]**.

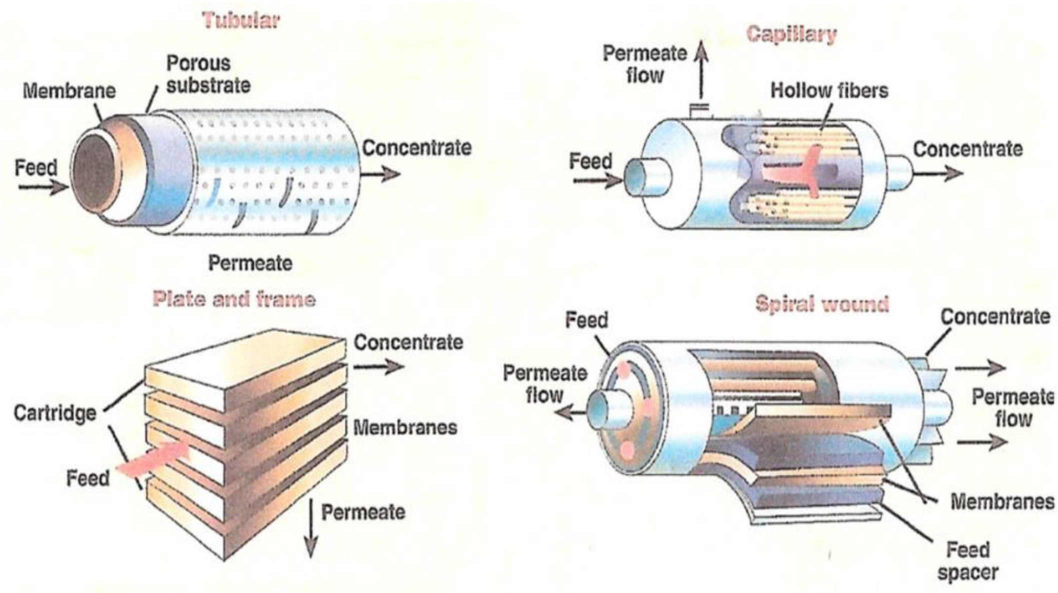


Figure 3.1 Common Membrane Module Designs

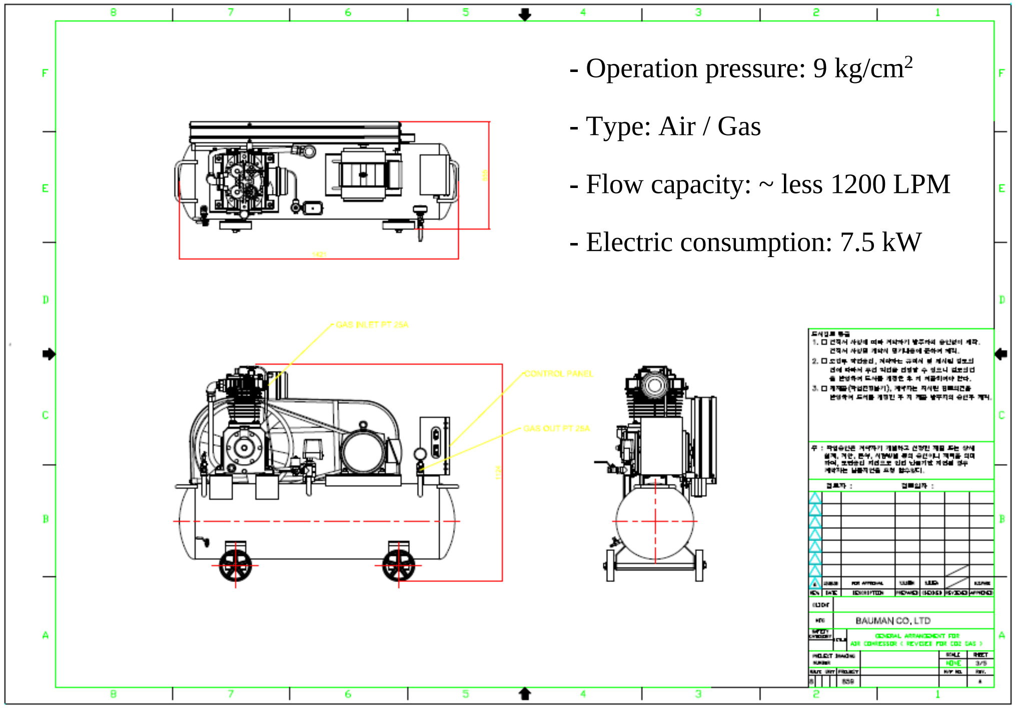


Figure 3.2 Gas compressor

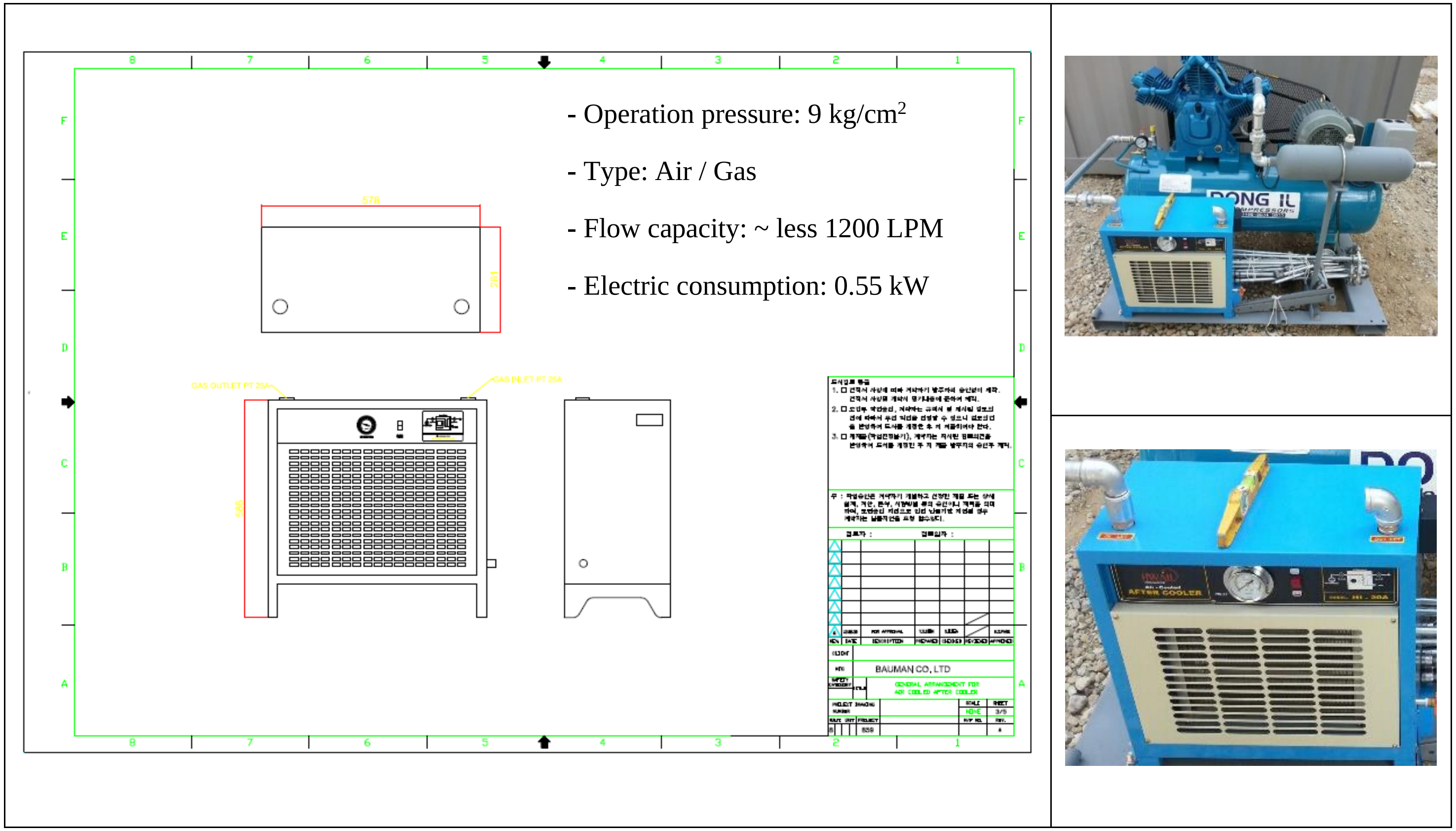
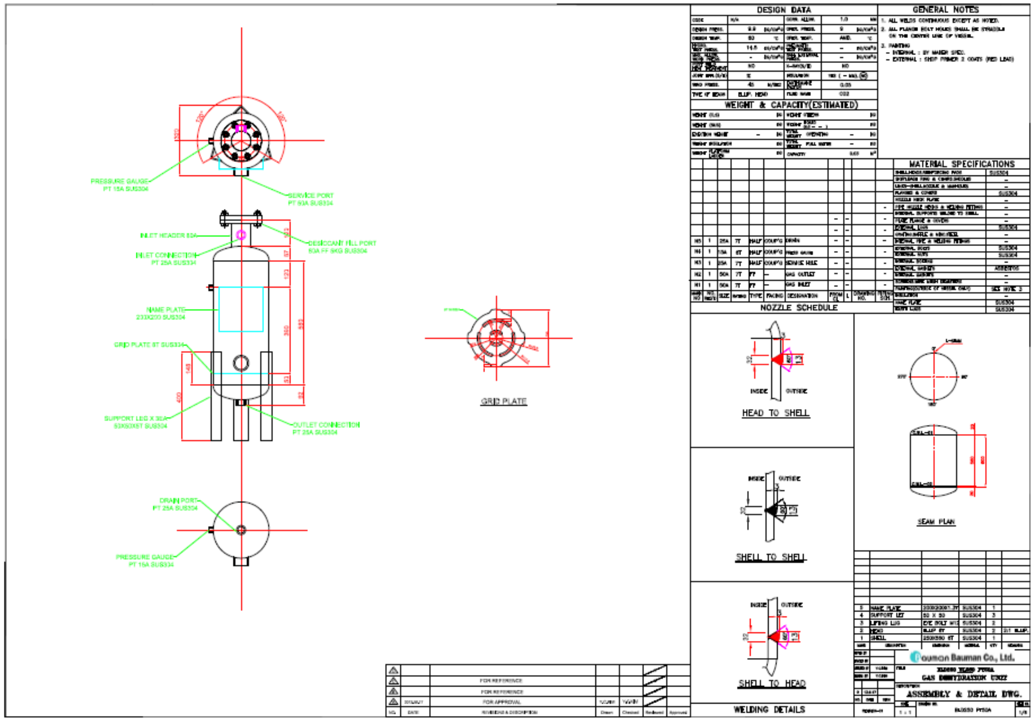
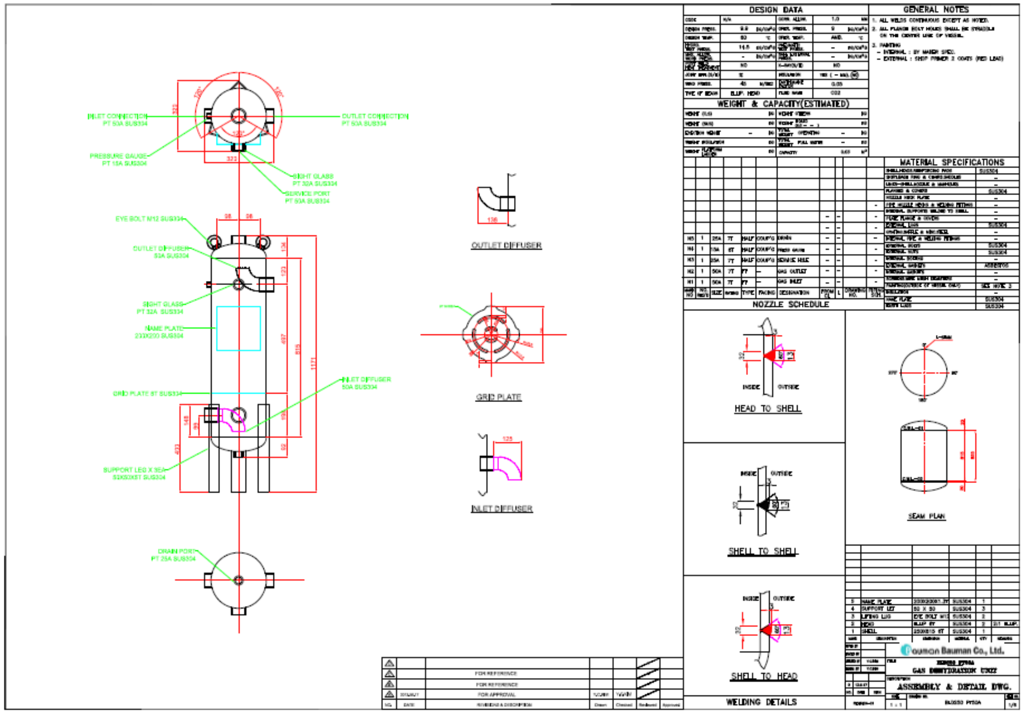


Figure 3.3 Chiller



- Operation pressure: 9 kg/cm^2
- Type: Air / Gas
- Flow capacity: ~ less 1200 LPM
- Deliquescent type

Figure 3.4 Gas dehydration unit_1



- Operation pressure: 9 kg/cm^2
- Type: Air / Gas
- Flow capacity: ~ less 1200 LPM
- Activated carbon (2 mm)

Figure 3.5 Gas dehydration unit_2

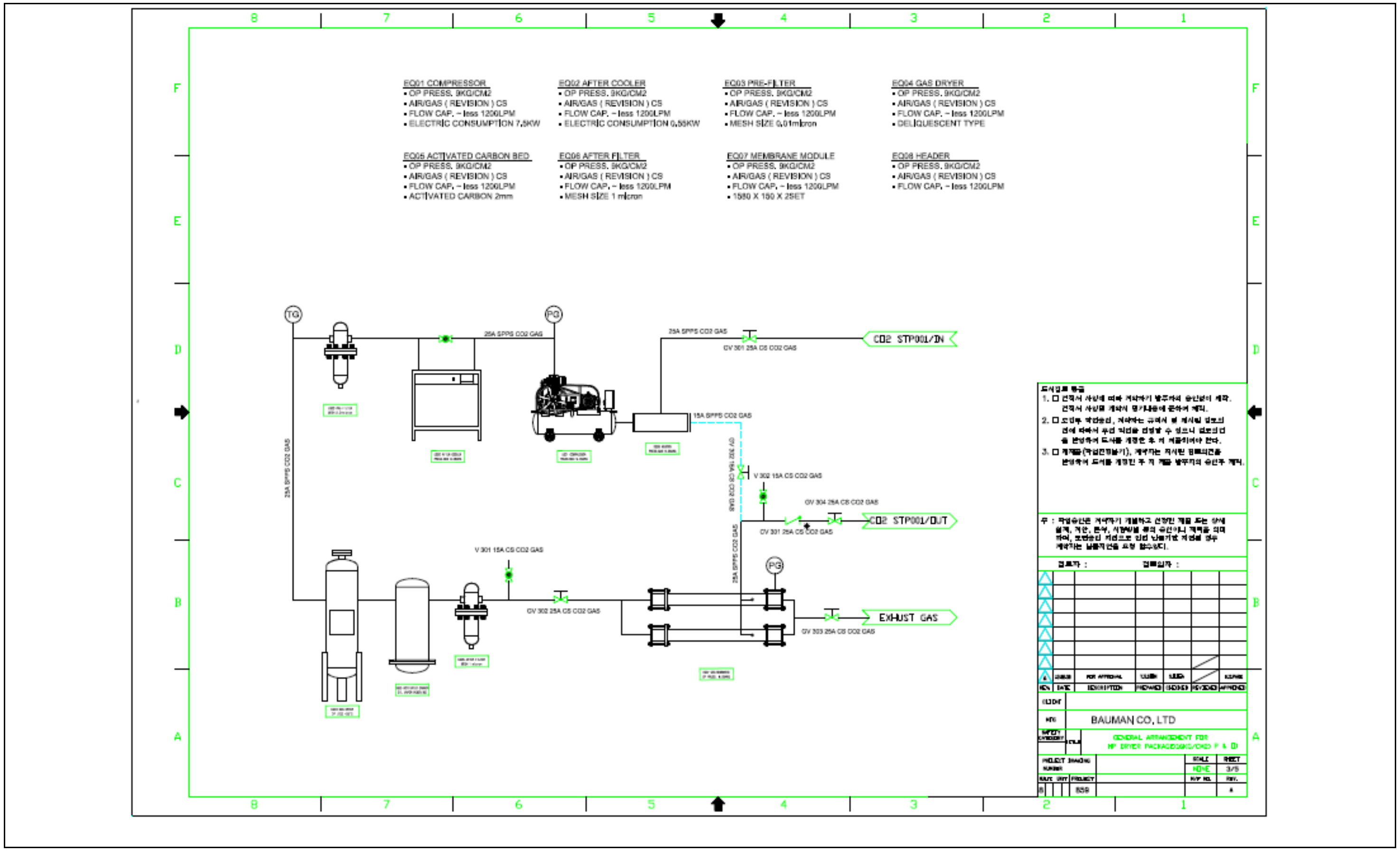
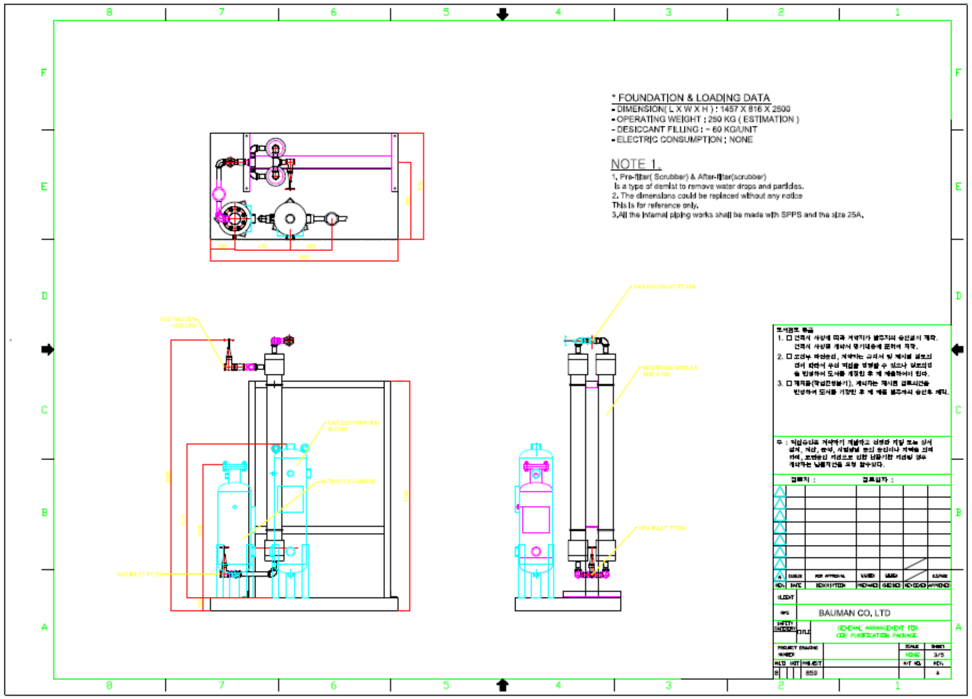


Figure 3.6 General arrangement for HP dryer package P&ID



- Dimension (L*W*H):1457*816*2500
- Operation weight: 250 kg
- Desiccant filling: ~ 60 kg
- Electric consumption: none
- All the internal piping works shall be made with SPPS and the size 25A

Figure 3.7 Membrane gas separator

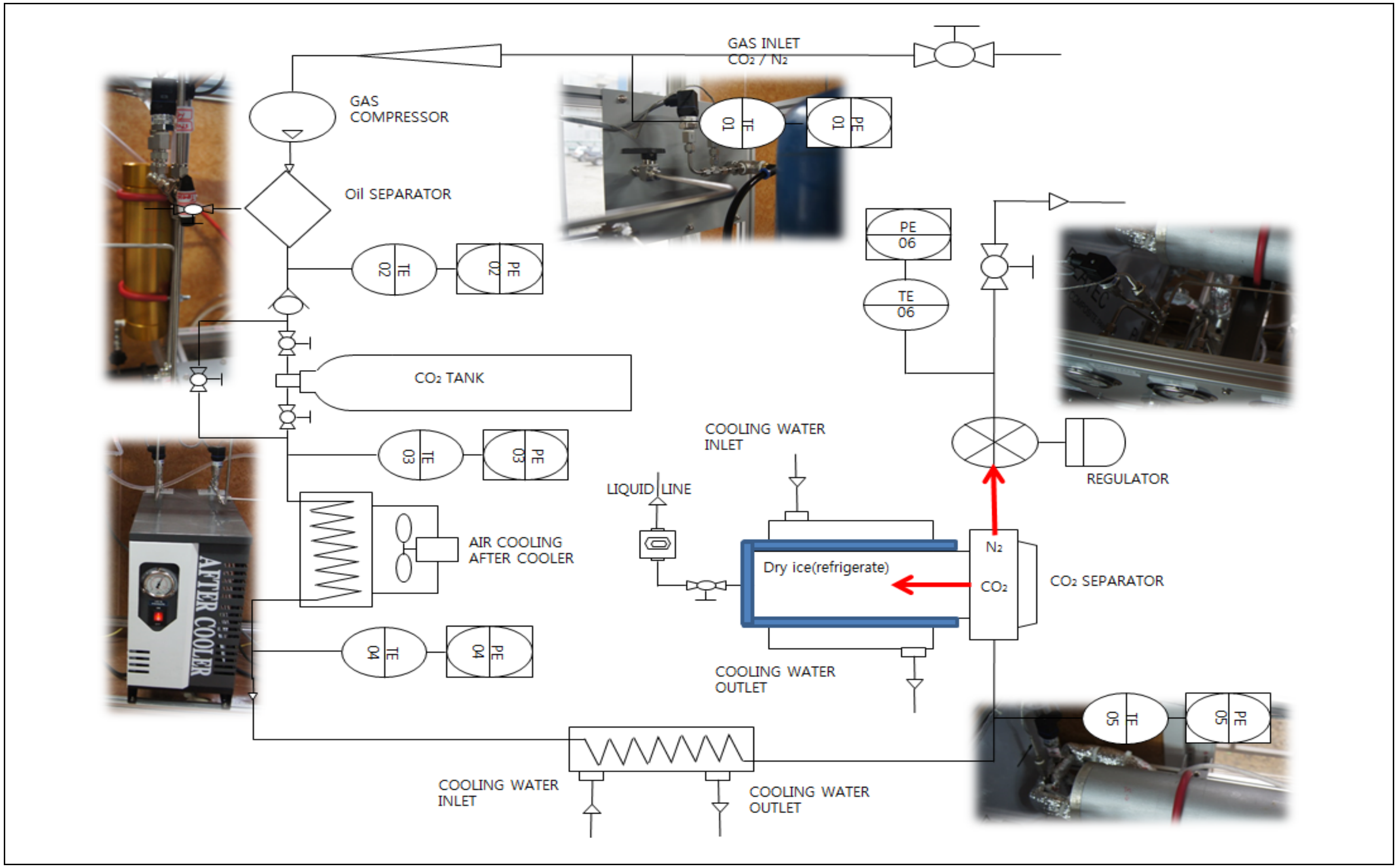


Figure 3.8 P&ID of CO_2 liquefication equipment

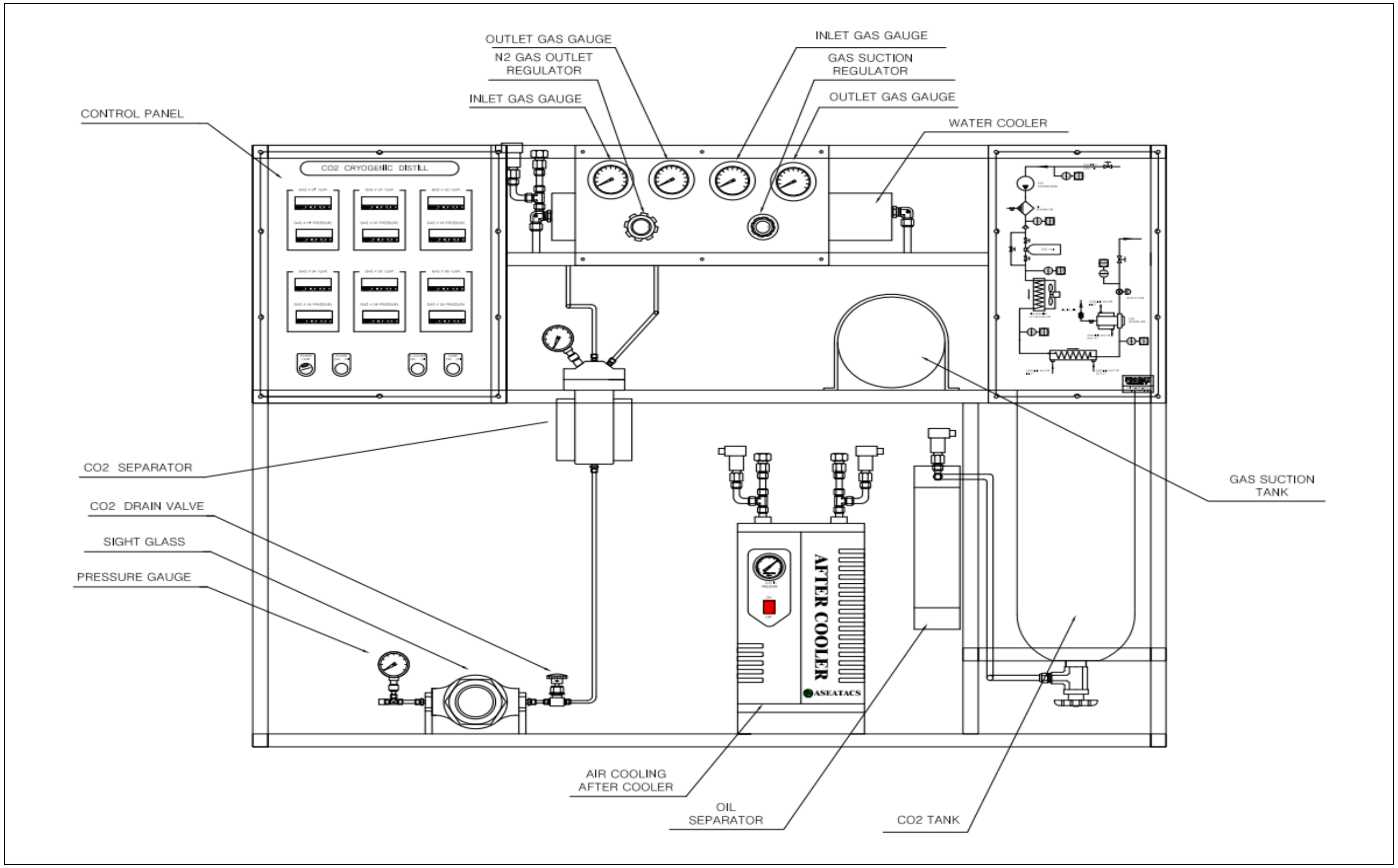
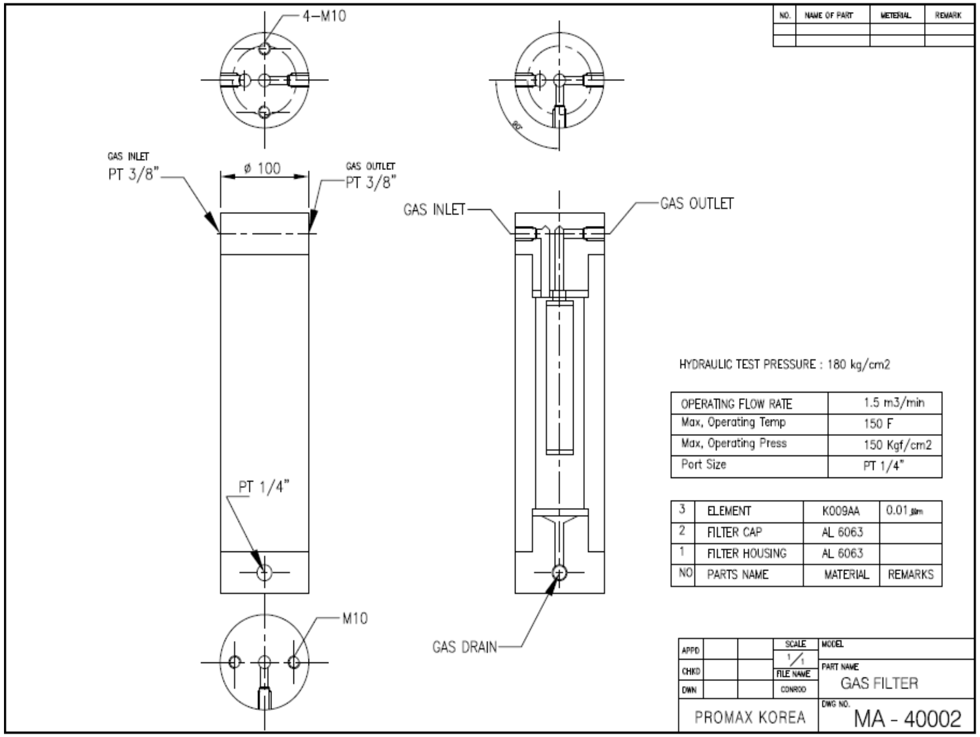
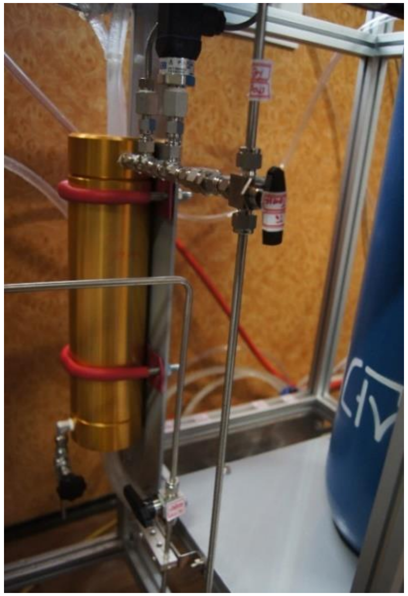


Figure 3.9 CO_2 liquefication equipment deign plan

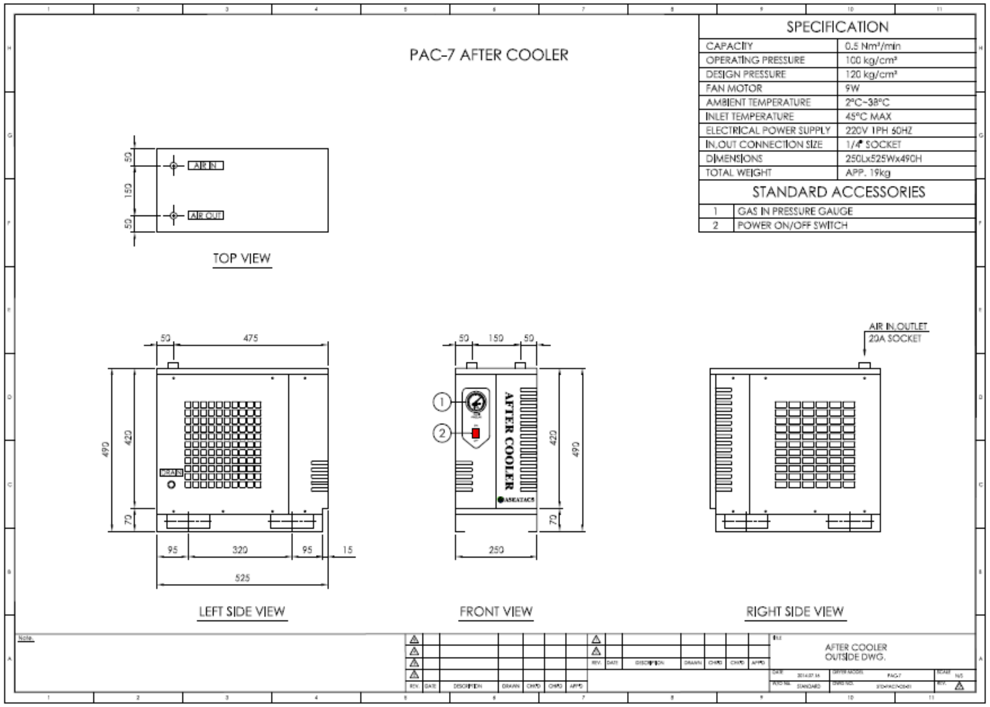
Figure 3.10 Photograph for CO_2 liquefication equipment





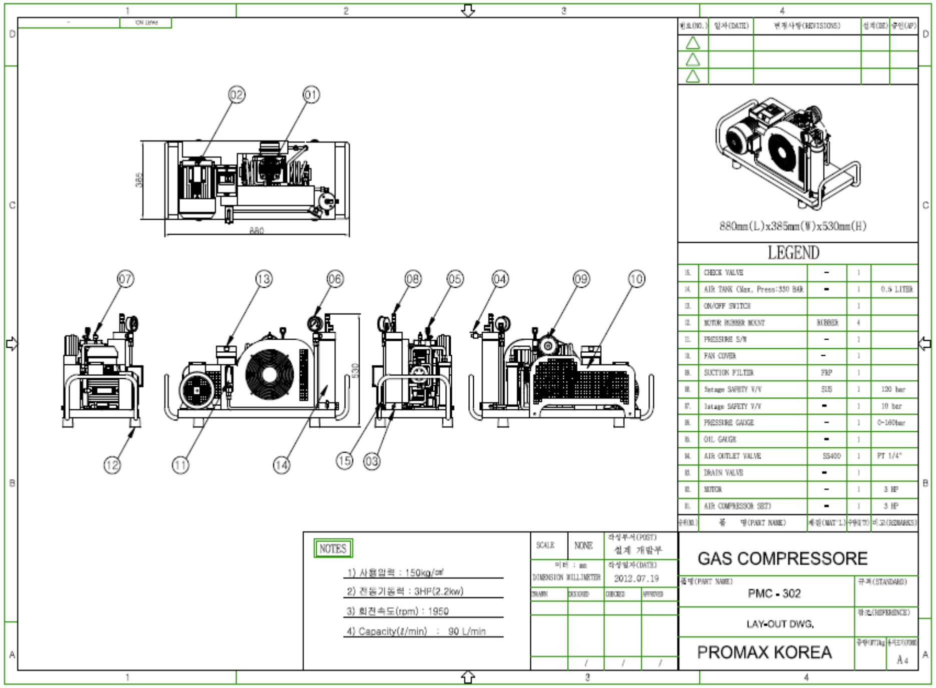
- Operation flow rate: 1.5 m^3/min
- Operation temperature (max): 150 F
- Operation pressure: 150 kgf/cm^3
- Port size: PT ¼”

Figure 3.11 Gas filter design plan



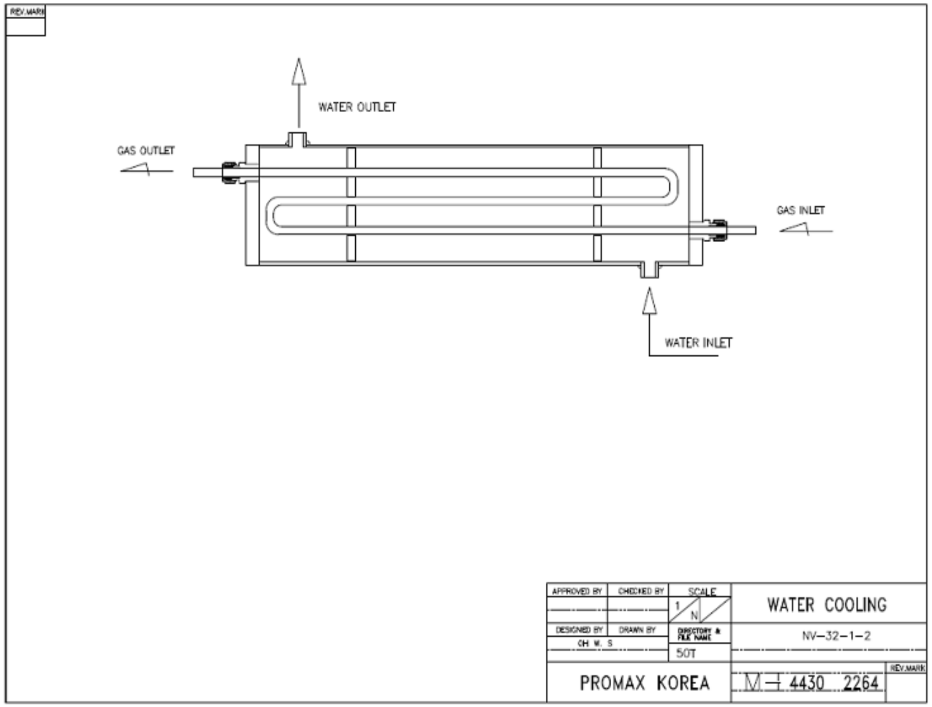
- Capacity: 0.5 Nm^3/min
- Operating pressure: 150 kgf/cm^2
- Fan motor: 9 W
- Ambient temperature: 2°C ~ 38°C
- Dimensions: 250L*525W*490H

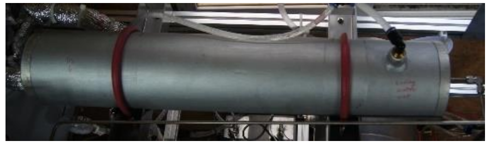
Figure 3.12 After cooler design plan



- Operating pressure: 150 kgf/cm^2
- Electric power mobility: 3 HP (2.2kW)
- Revolution per minute: 1950 rpm
- Capacity: 90 L/min

Figure 3.13 Gas compressor design plan





- Operation flow rate: 200L/min
- Operation temperature (max): 150F
- Operating pressure: 150 kgf/cm^2
- Port size: PT ¼’’

Figure 3.14 Water cooler design plan

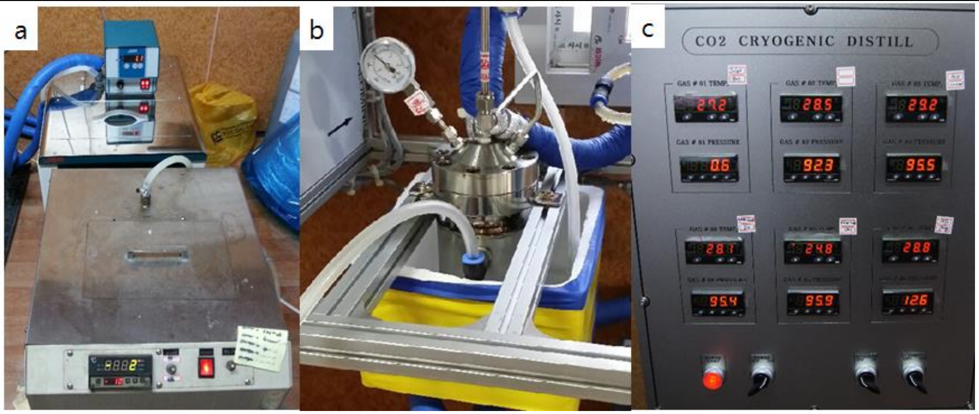


Figure 3.15 Photograph for liquefaction equipment (a: Chiller, b: Gas separator, c: Temperature and pressure signal panel)

Figure 3.16 Photograph for liquefaction equipment (pressure control panel)

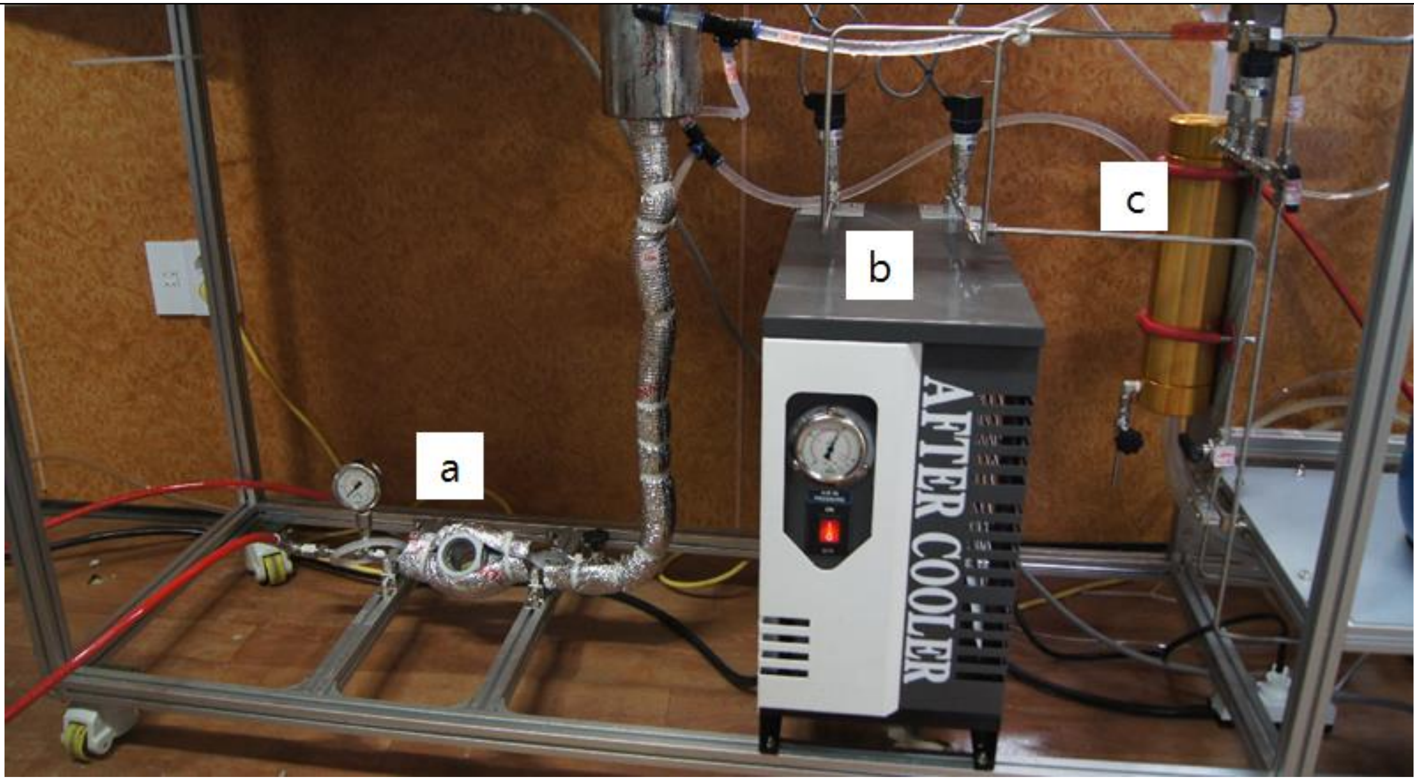


Figure 3.17 Photograph for liquefaction equipment (a: sight glass, b: after cooler, c: oil separator)

4. OBJECTIVES OF STUDY

By capturing CO_2 from the coal power plant and transfer it through the conversion process to supply it for the agriculture usage, so the purpose of this study in including in the following objective:

i. To study the conversion process of CO_2 from gas state into liquid state.

ii. To investigate the extraction of CO_2 using CCUS method and its usage on agriculture.

iii. To examine the effect of CO_2 concentration level on the rate of agricultural growth.

5. METHODOLOGY

Figure 5.1 depicts the suggested framework, which proposes the post-combustion approach to sequence the process of measuring the CO_2 footprint in an industrial park. By establishing the right CO_2 fixing industry for the industrial location, CO_2 is captured, distributed, and utilized. The CO_2 from the flue gases of a selected power plant gas stack from an industrial site after combustion collection, use, and use of technology. To obtain the recommended CO_2 purity, flue gas is purified using various scrubbing and filtration procedures to eliminate contaminants. If the CO_2 does not meet the quality standards, it is recycled through the CO_2 purification process. The conversion of captured CO_2 into resources for reuse inside an industrial site has not been widely investigated as a technique of lowering an industrial site's CO_2 footprint. The CO_2 resources for CO_2 fixing plants produced for horticulture as vaporization are caught and cleansed. Furthermore, in the future, an economic analysis of the CO_2 chemical fixation techniques' cost of carbon capture, raw material costs, and energy and power costs will need to be considered.

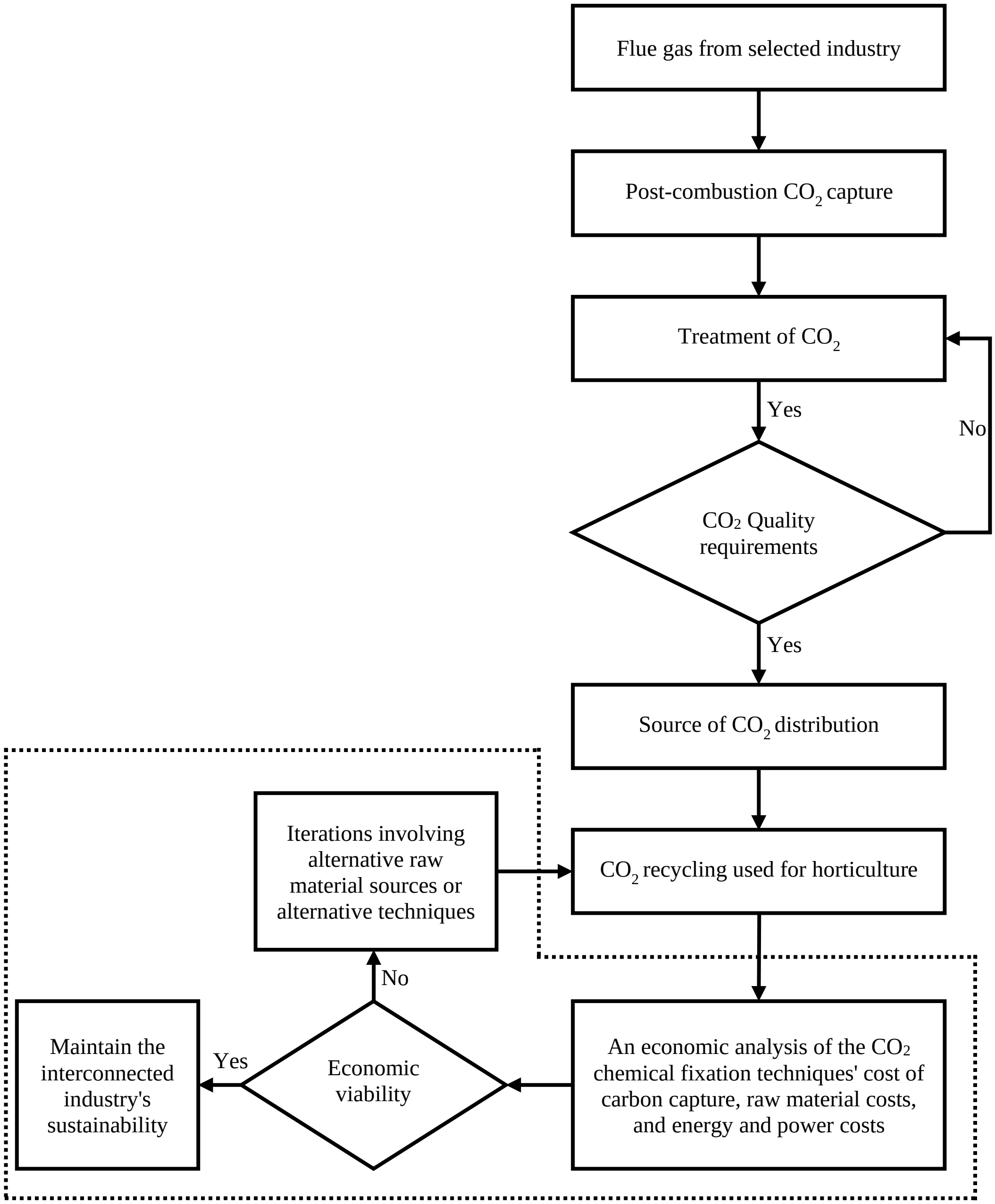


Figure 5.1 Framework for the capture, distribution, and usage of CO_2 from flue gases

6. RESULTS AND DISCUSSIONS

6.1. Exhaust Gas Analysis

6.1.1. Reactor inlet gas measurement

The removal efficiency of CO, NO and SO_2 from the internal circulating multi-plate bubble tower reaction device, silica gel tower, and activated carbon tower was initially determined by measuring the reactor incoming gas. The average value was calculated after measuring for 30 minutes with the ecosystem's NOVA 9K. The average CO_2 concentration value was 17.31%, the average CO concentration value was 15.28 ppm, the average NO concentration value was 34.00 ppm, and the average SO_2 concentration value was 26.67 ppm as a result of the measurement. CO exhibited a discrepancy of roughly 5 ppm between the measurement data and the TMS data, whereas sulfur oxide and nitrogen oxide showed a difference of about 4 ppm. The reason for this is that it is thought that a minor inaccuracy occurred as a result of the different measuring points **Figure 6.1**.

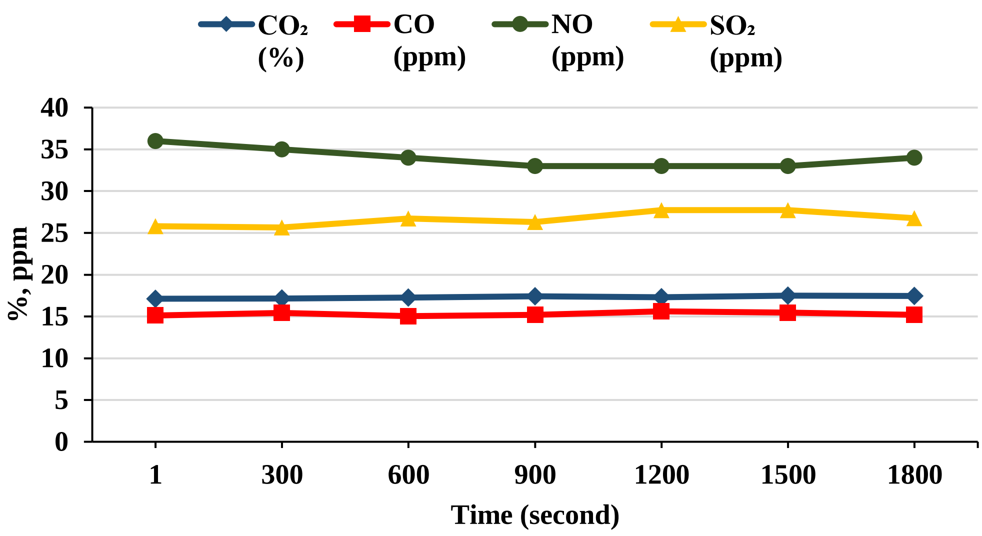


Figure 6.1 Emission gas concentrations of the input gas with analysis time

6.1.2. Reactor outlet gas measurement

CO_2, CO, NO and SO_2 in the emission gas were dissolved in the catalyst reaction tower as a result of the reactor outlet gas measurement, and the CO_2 concentration was 16.60 % about 4.1%, the CO concentration was 8.07 ppm about 47.19 %, the NO concentration was 29.83 ppm about 12.26 %, and the SO_2 concentration was 0 ppm about 100 percent were reduced **Figure 6.2**.

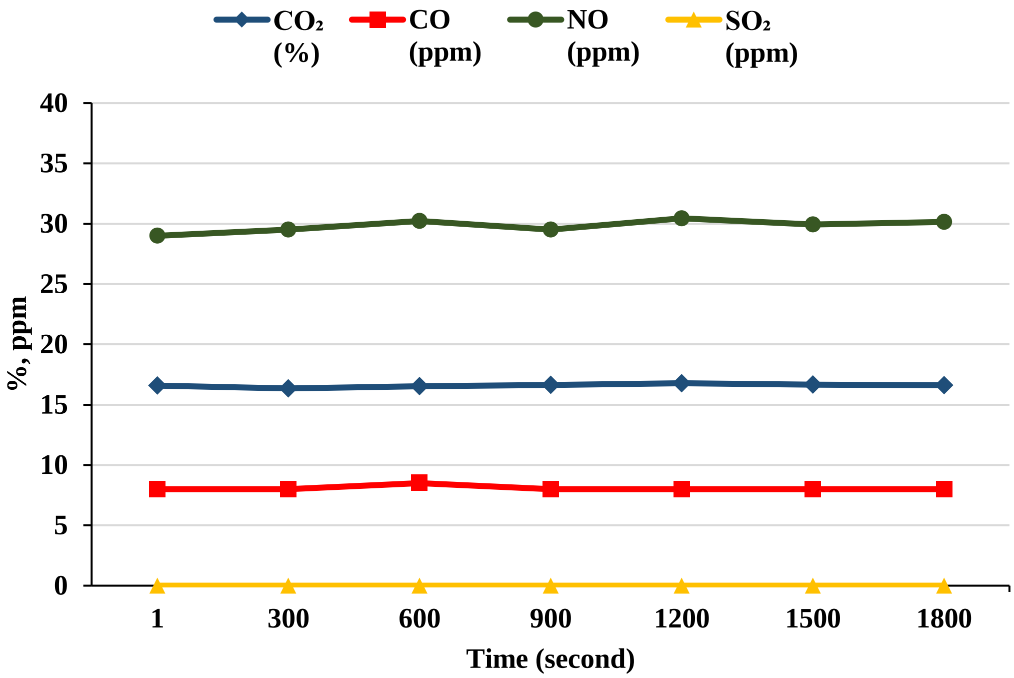


Figure 6.2 Emission gas concentrations of the output gas with analysis time

6.1.3. Silica-gel tower gas measurement

CO_2, CO, NO and SO_2 among the emitted gases passed from the catalyst reaction tower were adsorbed with silica gel as a result of the gas passing through the silica gel tower being measured and the CO_2 concentration was 15.83 % about 8.5%, CO concentration was 7.62 ppm about 50.13%, NO concentration was 18.32 ppm about 46.32%, and SO_2 concentration was 0 ppm about 100 percent was decreased **Figure 6.3**.

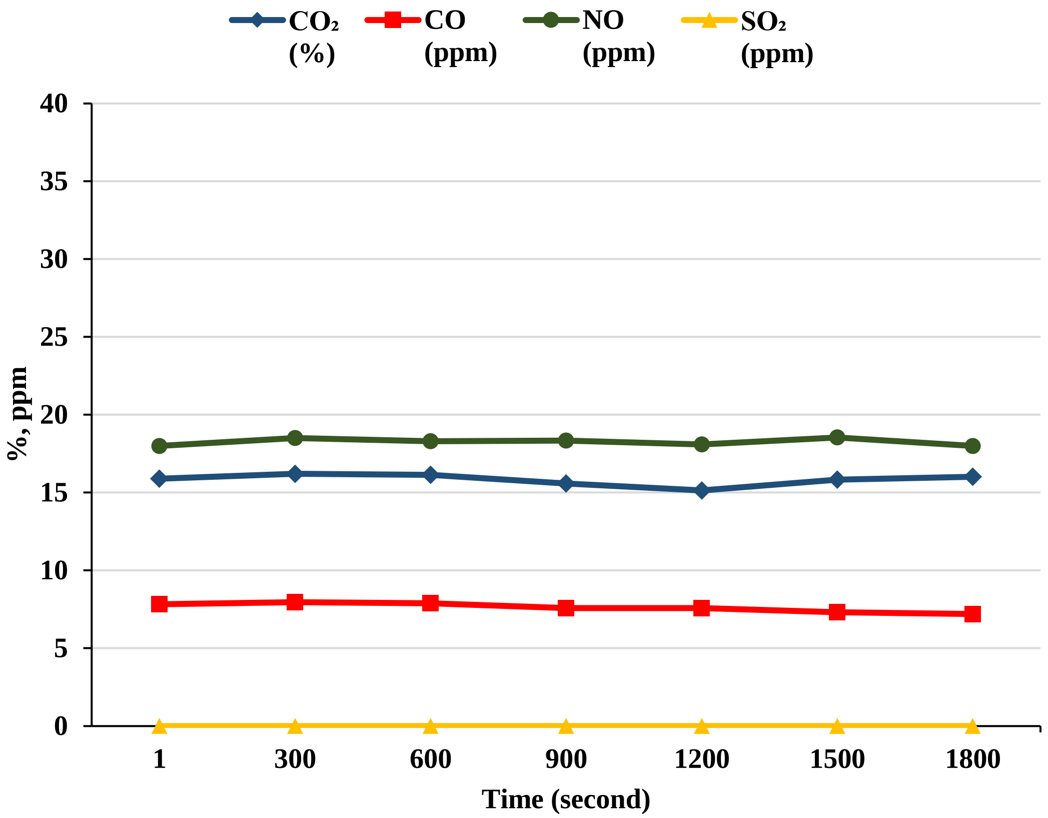


Figure 6.3 Emission gas concentrations of the output Silica-gel tower gas

6.1.4. Manganese-deposited activated carbon tower gas measurement

CO_2, CO, NO and SO_2 in the emission gas passing through the catalyst reaction tower were adsorbed to the deposited activated carbon in the manganese deposition activated carbon tower as a result of measuring the gas passing through the manganese deposition activated carbon tower, and the average CO_2 concentration was 17.60 percent about 1.6% was increased while the CO concentration was 4.42 part per million about 71.1%, NO concentration was 0 ppm about 100%, and SO_2 concentration was 0 ppm about 100 % was decreased. CO was adsorbed on manganese-deposited activated carbon to form CO_2 via a chemical reaction ($CO + O^{2-} + 2Mn^{4+/3+} \rightarrow CO_2 + 2Mn^{3+/2+}$), resulting in a modest increase in CO_2 concentration relative to the emission source gas **Figure 6.4**.

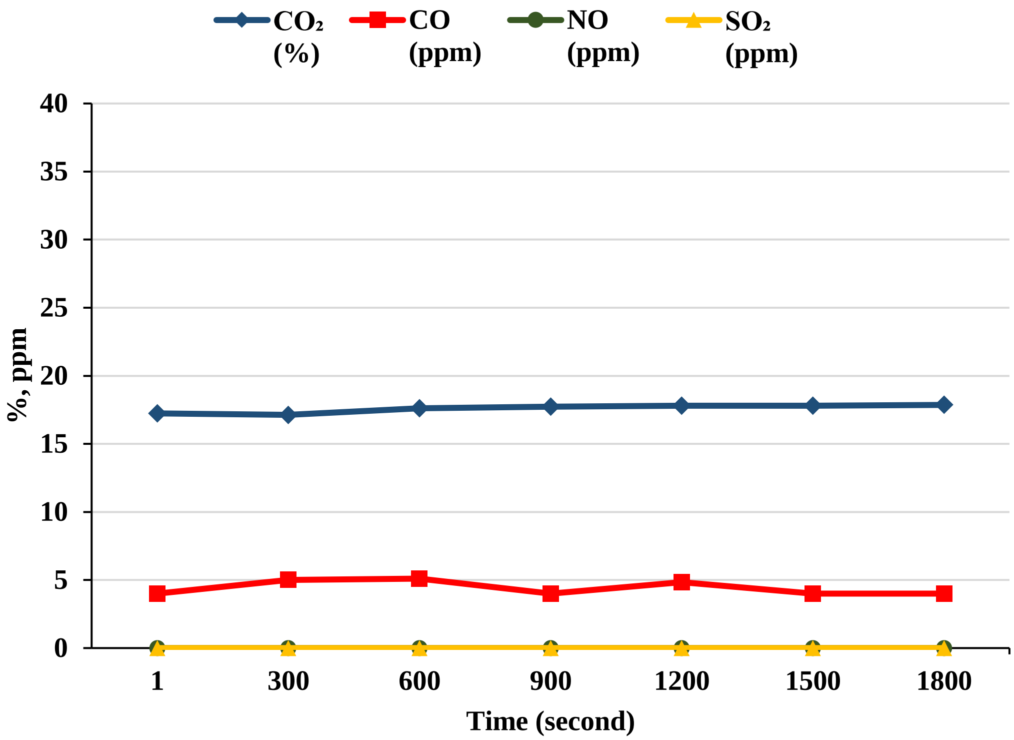


Figure 6.4 Emission gas concentrations of the output gas with analysis time

6.2. Changes in NO, CO, SO_x, CO_2 Gas Concentration

6.2.1. NO gas concentration depending on flow rates

By modifying the RPM of the blower, the gas flow rate was adjusted to 2,100 m^3/h, 2,300 m^3/h, 2,500 m^3/h, and 2,600 m^3/h, and the concentration of the reactor inlet and exit gas was slightly raised as the flow rate increased. The reason for this is that when the flow velocity increases, the contact period between the exhaust gas and the catalyst in the catalyst reaction tower decreases, resulting in a higher concentration. Furthermore, the deposited activated carbon tower adsorbed 100 %t of the NO in the exhaust stream, and NO was not found at the rear end of the deposited activated carbon adsorption tower as depicted in **Figure 6.5**.

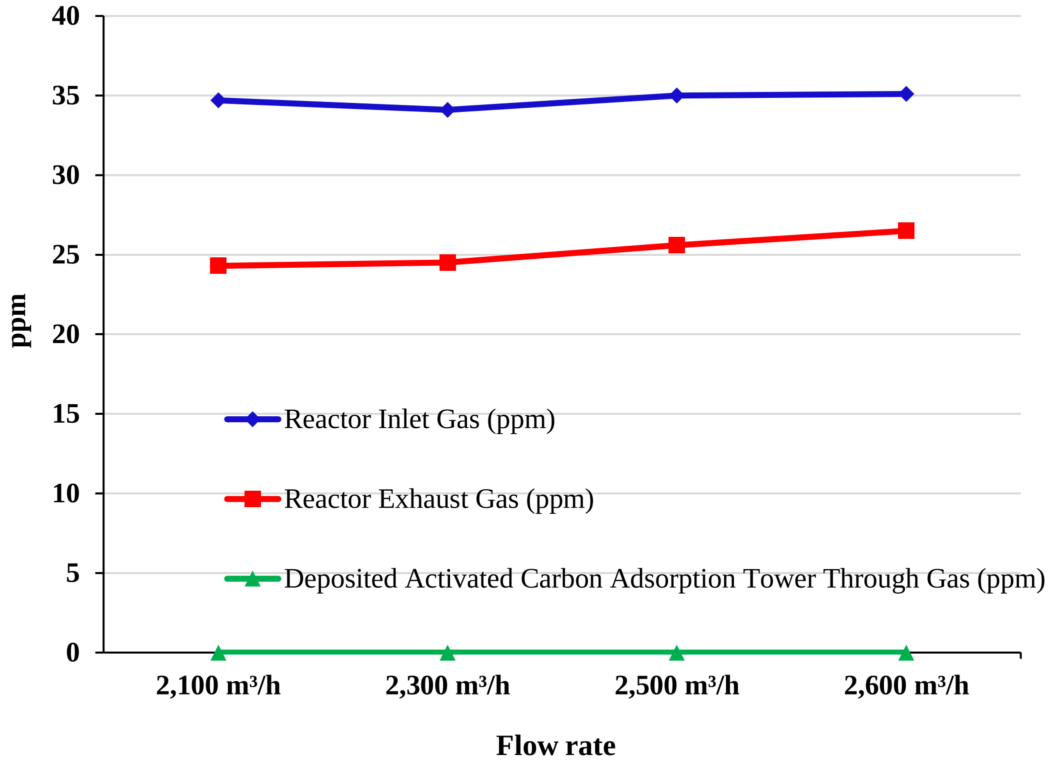


Figure 6.5 Emission gas concentrations of the output gas with analysis time

6.2.2. CO gas concentration depending on flow rates

By modifying the RPM of the blower, the gas flow rate was adjusted to 2,100 m^3/h, 2,300 m^3/h, 2,500 m^3/h, and 2,600 m^3/h, and the concentration of the reactor inlet and exit gas was slightly raised as the flow rate increased **Figure 6.6**. The reason for this is that when the flow velocity increases, the contact period between the exhaust gas and the catalyst in the catalyst reaction tower decreases, resulting in a higher concentration.

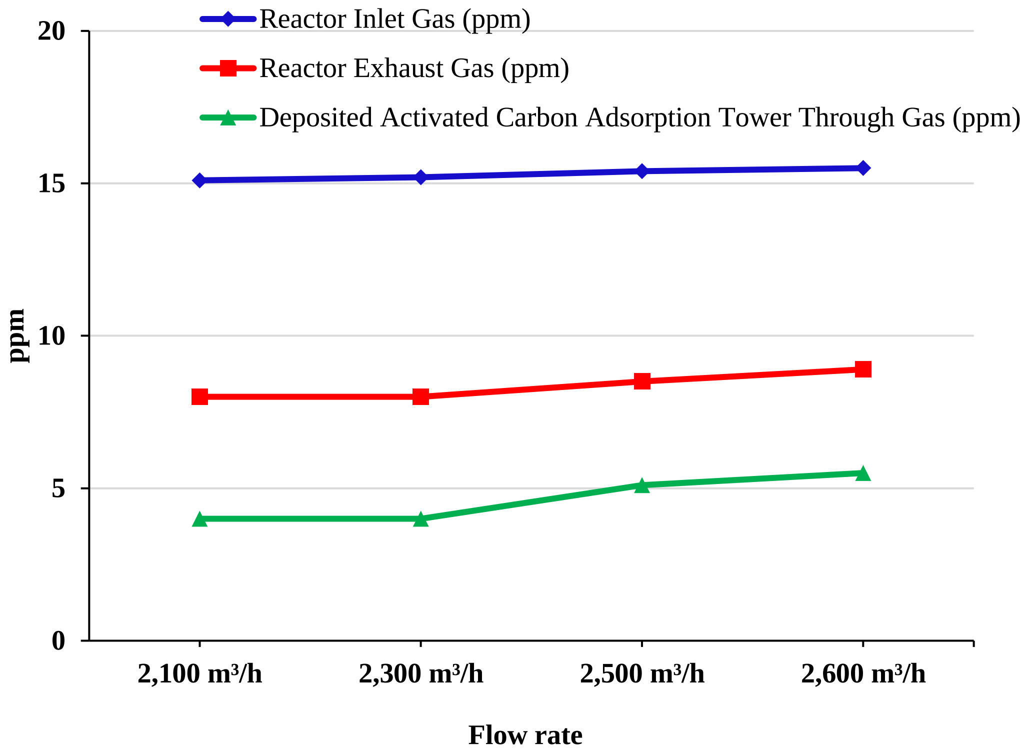


Figure 6.6 Change in concentration of gas according to the flow rate (CO)

6.2.3. SO_2 gas concentration depending on flow rates

By increasing the rpm of the blower, the gas flow rate was adjusted to 2,100 m^3/h, 2,300 m^3/h, 2,500 m^3/h, and 2,600 m^3/h, and the SO_2 gas concentration was slightly raised as the flow rate increased. The reason for this is that when the flow velocity increases, the contact period between the exhaust gas and the catalyst in the catalyst reaction tower decreases in **Figure 6.7**, resulting in a higher concentration. SO_2 was completely dissolved in the catalyst reaction tower, and no SO_2 was discovered at the reactor exit or in the passing gas from the deposit-activated carbon tower.

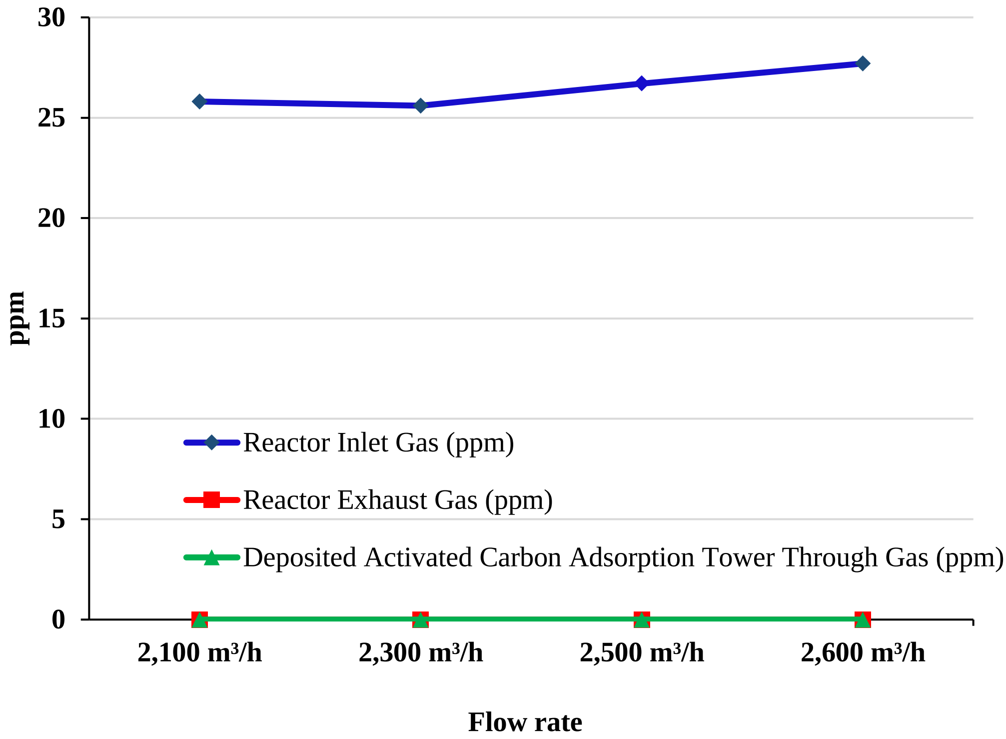


Figure 6.7 Change in concentration of gas according to the flow rate (SO_2)

6.2.4. CO_2 gas concentration depending on flow rates

By modifying the rpm of the blower, the gas flow rate was adjusted to 2,100 m^3/h, 2,300 m^3/h, 2,500 m^3/h, and 2,600 m^3/h, and the concentration of the reactor inlet and exit gas was slightly raised as the flow rate increased. The reason for this is that when the flow velocity increases, the contact period between the exhaust gas and the catalyst in the catalyst reaction tower decreases, resulting in a higher concentration as depicted in **Figure 6.8**. Furthermore, CO is adsorbed to the deposition activated carbon to form CO_2, which is why the CO_2 concentration of the gas passing through the deposition activated carbon is somewhat greater than the concentration of the reactor exit gas ($CO + O^{2-} + 2Mn^{4+/3+} \rightarrow CO_2 + 2Mn^{3+/2+}$).

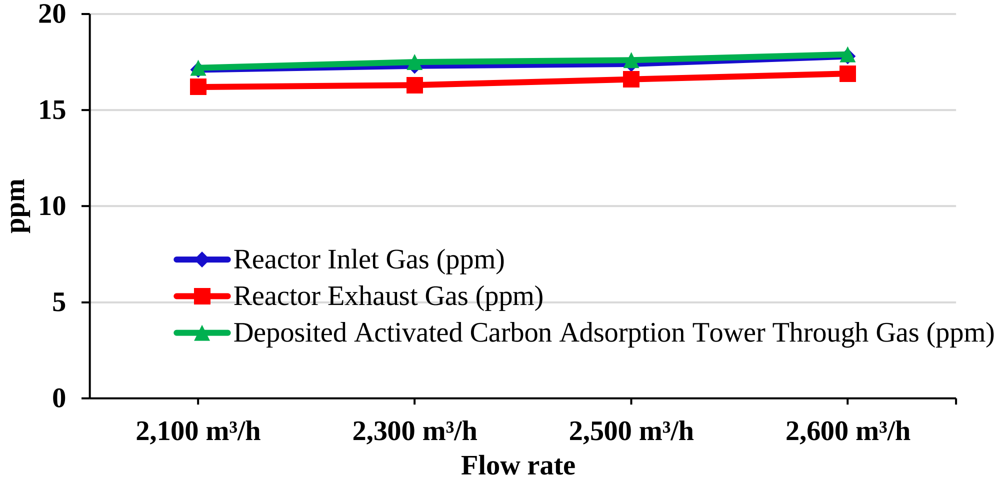


Figure 6.8 Change in concentration of gas according to the flow rate (CO_2)

6.3. Changes in Gas Properties depending on the Amount of Hydrogen Peroxide (H_2O_2) Injected

After hydrogen peroxide was introduced to the catalyst reaction tower from 20 to 120 L, the concentration of nitrogen monoxide to the catalyst and hydrogen peroxide fell from 120 L to 13 ppm.

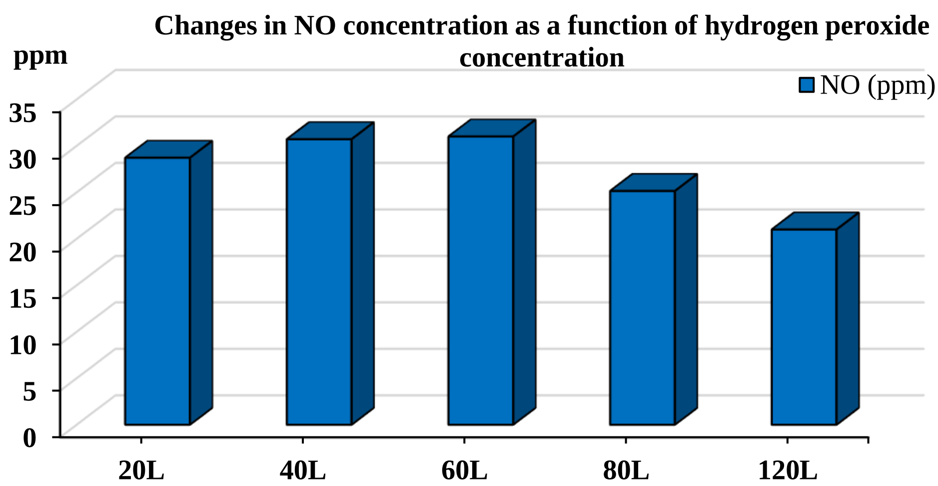


Figure 6.9 Gas properties change with the amount of hydrogen peroxide (H_2O_2)

6.4. Verification of Plant Growth Impact

In Atmospheric Cultivation Rooms, **Table 6.1** shows the average leaves and stems development rates for each crop grown in an atmospheric growing environment without CO_2 concentration control.

Table 6.1 Changes of numbers of leaves and plant length (greenhouse-atmosphere)

Classification		Atmospheric Cultivation			
		07th April		15th April	
		Leaf	Stem (cm)	Leaf	Stem (cm)
Cucumber	1	4	8	6	12
	2	3	8	5	11
	3	5	8	8	20
Pumpkin	4	10	10	13	12
	5	14	10	23	12.5
	6	10	12	18	20.5
	7	10	13	19	17
	8	6	14	11	22.5
Pepper	9	12	20	21	30
	10	15	17	16	21
	11	14	18	14	18.5
	12	11	18	12	19.5
	13	14	18	15	19
Tomato	14	5	29	9	40
	15	4	28	6	30
	16	4	28	5	29
	17	4	30	5	35
	18	5	29	5	34

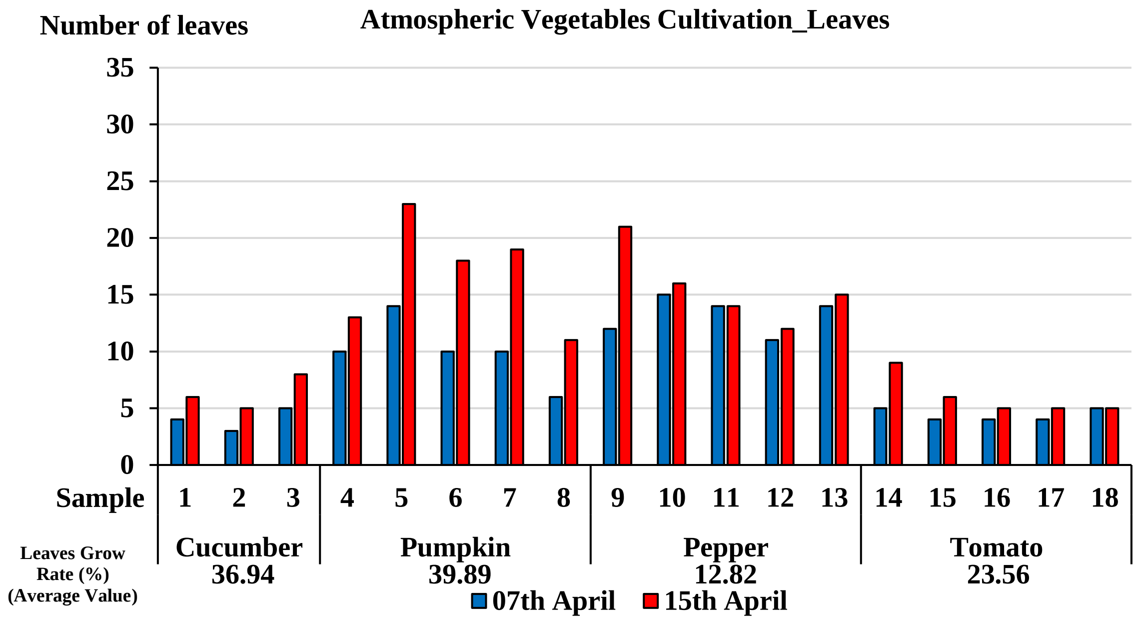


Figure 6.10 Growth rate of leaves numbers (greenhouse-atmosphere)

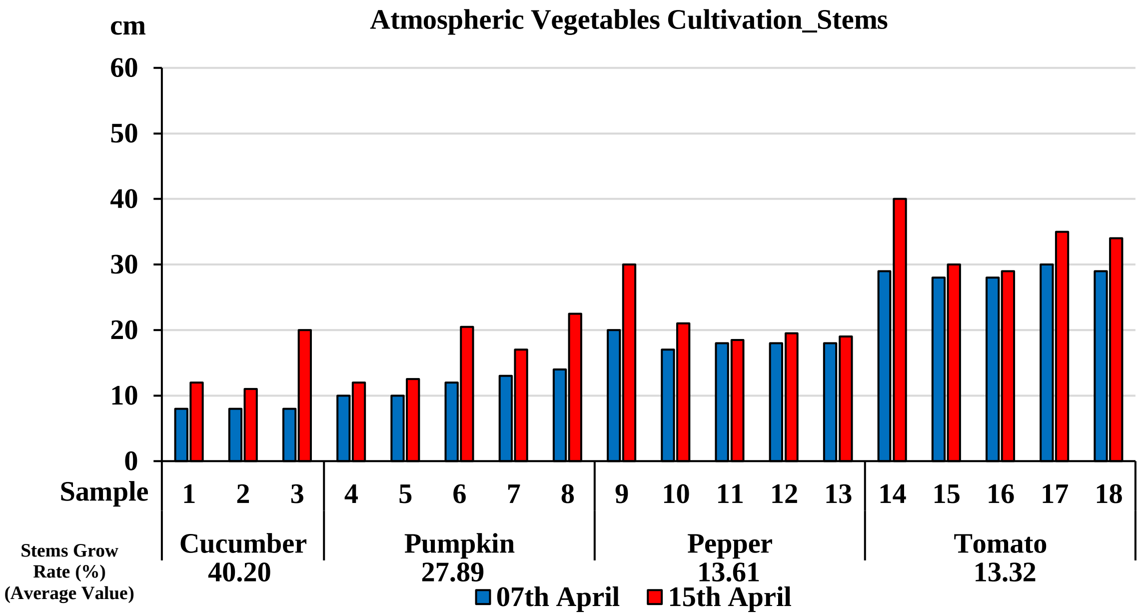


Figure 6.11 Growth rate of total length (cm) (greenhouse-atmosphere)

In CO_2 Cultivation Rooms, **Table 6.2** shows the average leaflet and soy sauce growth rates for each crop cultivated in a glass greenhouse with a controlled CO_2 concentration of 800 to 1200 ppm.

Table 6.2 Changes of numbers of leaves and plant length (greenhouse-CO_2)

Classification		CO_2 Enrichment Cultivation			
		07th April		15th April	
		Leaf	Stem (cm)	Leaf	Stem (cm)
Cucumber	1	6	8	7	18
	2	6	8	8	23
	3	7	8	8	26
Pumpkin	4	11	10	20	19.5
	5	14	14	23	24.5
	6	7	12	7	13
	7	13	11	21	23
	8	10	11	16	15
Pepper	9	16	17	24	20
	10	19	18	30	29
	11	17	13	22	18
	12	15	17	22	21
	13	18	18	23	28
Tomato	14	7	27	11	4
	15	5	31	11	50
	16	6	30	16	40
	17	6	33	16	51
	18	5	22	12	30

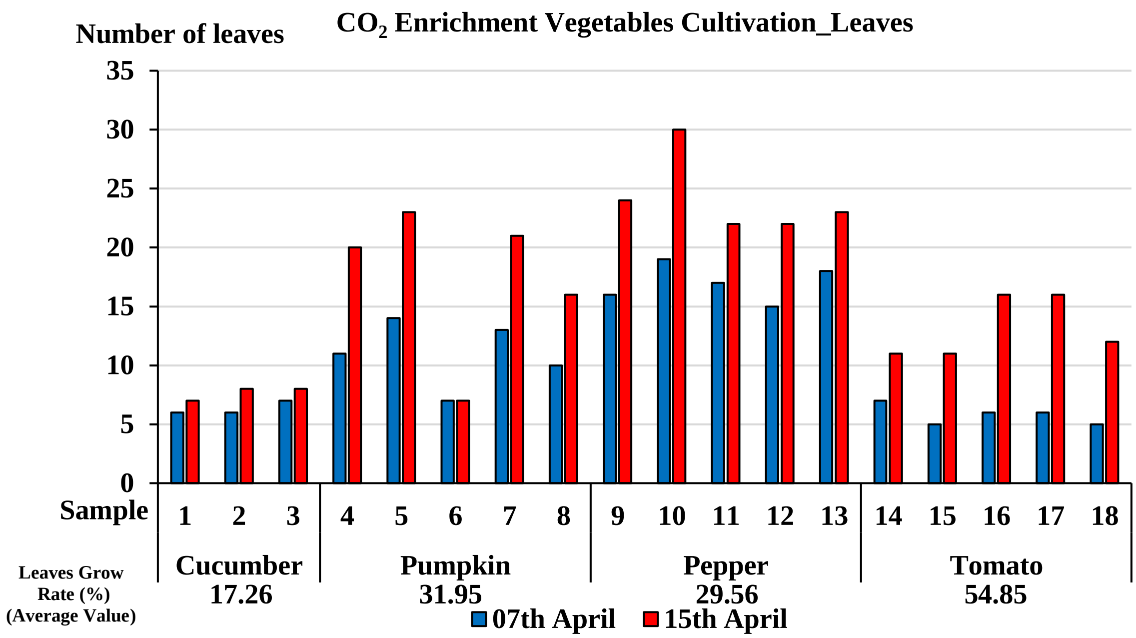


Figure 6.12 Growth rate of leaves numbers (greenhouse-CO_2)

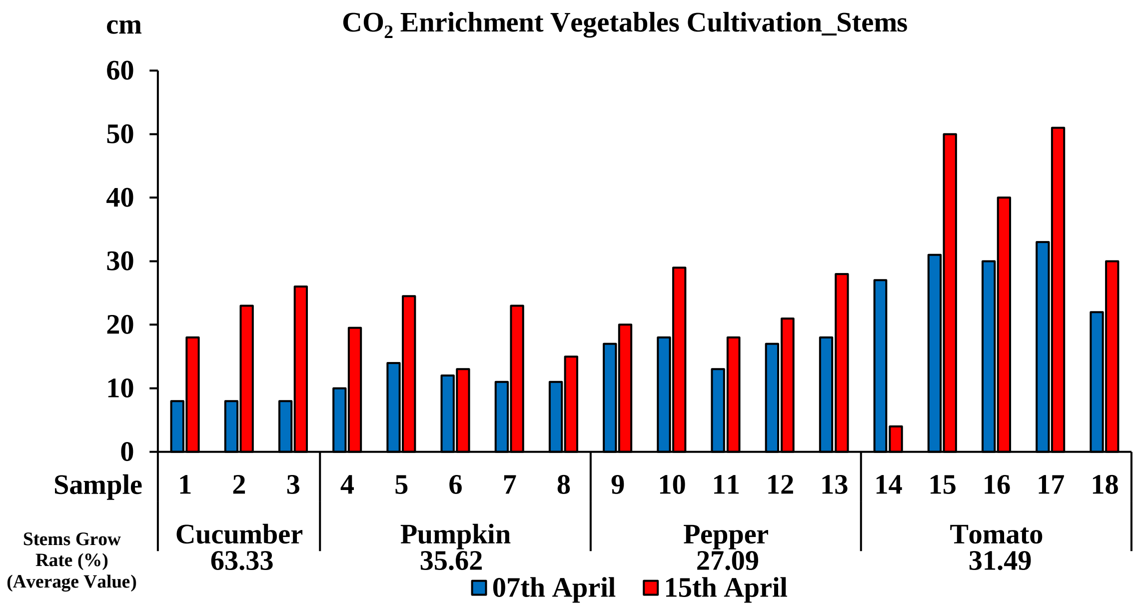


Figure 6.13 Growth rate of total length (cm) (greenhouse- CO_2)

6.5. Biometrics Measurement of Plants in Different Greenhouse

After cultivating and harvesting crops, **Table 6.3** shows the CO_2 concentration in the atmospheric culture room was set to approximately 300-400 ppm, and the CO_2 concentration in the CO_2 cultivation room was set to about 800-1200 ppm, and the number and biological weight of fruits were measured. For each greenhouse, cucumber, red pepper, and pumpkin were cultivated, and tomatoes were cut from the dome and the biological weight, including fruit, was assessed as shown in **Figure 6.14**. Growing cucumbers for 70 days in each greenhouse resulted in a total weight of 1143g in the case of 300 to 400 ppm, which is the general air concentration, and a 10.7% increase in the case of 800 to 1200 ppm. Chili peppers climbed by 52.3 % from 300 to 400 ppm to 891.5 grams and 800 to 1200 ppm to 1867.5 grams, while zucchini increased by 6.8% from 300 to 400 ppm to 1367.5 grams and 800 to 1200 parts per million to 1466.5 grams. When grown at a carbon dioxide concentration of 800 to 1200 ppm, all three plants, cucumber, pepper, and zucchini, tended to produce more biomass as shown in **Table 6.4**.

Table 6.3 Harvested quantity and plant parts at various CO_2 concentrations

Total biomass of atmospheric and CO_2 enrichment cultivation crops		Atmospheric Cultivation (300 ~ 400 ppm)	CO_2 Enrichment Cultivation (800 ~ 1200 ppm)
Leaves	Cucumber	315.5	340.5
	Pepper	318	648
	Green Pumpkin	627	695.5
Stems	Cucumber	306.5	312
	Pepper	275.5	746
	Green Pumpkin	704	725
Roots	Cucumber	521	627
	Pepper	298	473.5
	Green Pumpkin	36.5	46

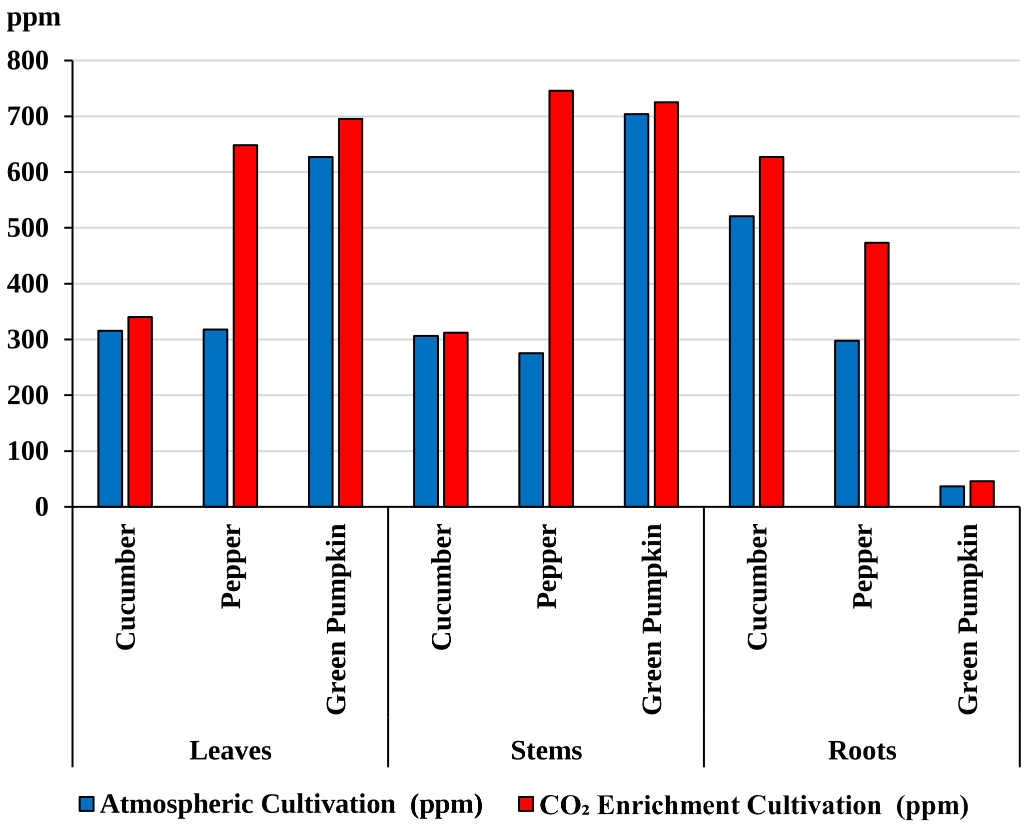


Figure 6.14 Comparison of total biomass

Table 6.4 Amount of biomass harvested at various CO_2 concentrations

Concentration Classification	Cucumber	Pepper	Green Pumpkin
300 ~ 400 ppm	1143	891.5	1367.5
800 ~ 1200 ppm	1279.5	1867.5	1867.5

6.6. Moisture Content of each Greenhouse Crop Measurement

The biological weight and dry weight of cucumbers, peppers, and zucchini were measured to measure the moisture content of cultivated crops by concentration in each glass greenhouse in order to measure the moisture content of each concentration of CO_2. The moisture content of CO_2 fertilizer cultivation (800-1200 ppm) was determined to be somewhat greater than that of atmospheric culture as a result of the moisture content measurement (300-400 ppm) as shown in **Figure 6.15, Figure 6.16, Figure 6.17**.

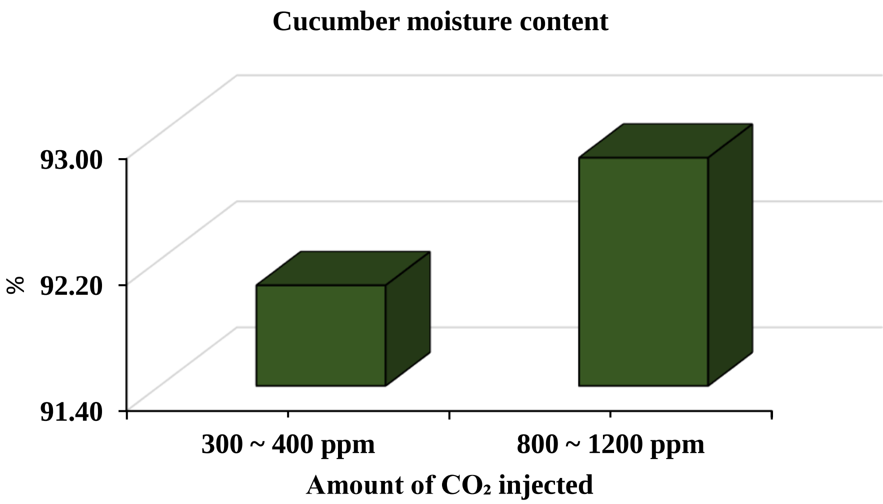


Figure 6.15 Cucumber moisture content measurement (stem + leaf + root)

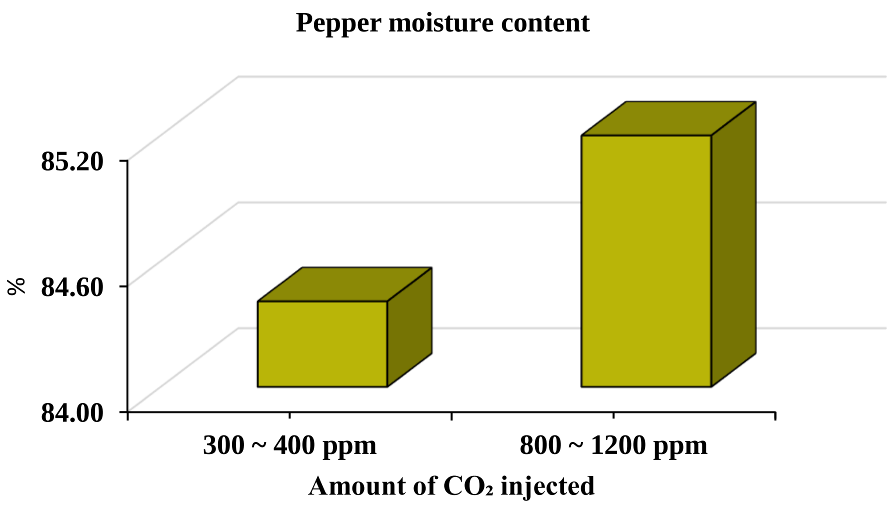


Figure 6.16 Pepper moisture content measurement (stem + leaf + root)

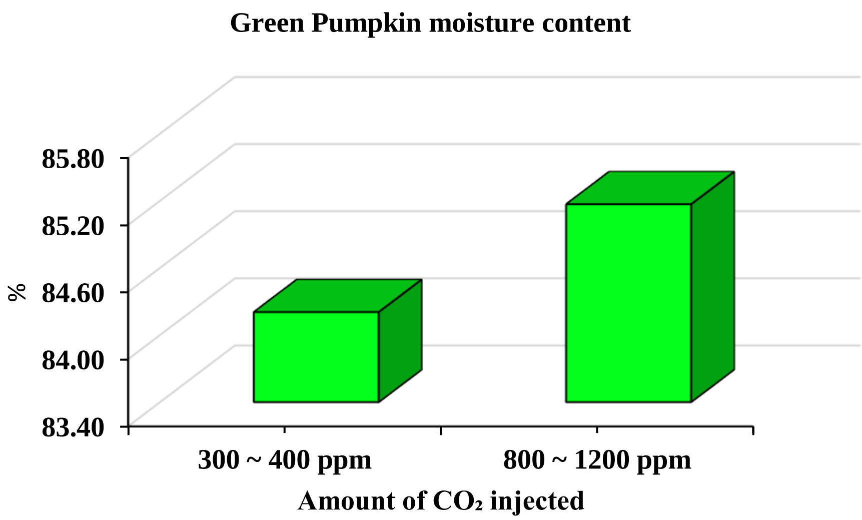


Figure 6.17 Green Pumpkin moisture content measurement (stem + leaf + root)

6.7. Chlorophyll Fluorescence Measurement

In plants, photosynthesis is a very basic metabolic activity. The chlorophyll fluorescence index Fv/Fm can be used to calculate photosynthesis efficiency (FV: variable fluorescence value, FM: maximum fluorescence value). Because illnesses of other important activities appear to be disorders of photosynthesis, the measurement of fluorescence induction processes is used to diagnose the health state of plants, much like a stethoscope would be used to examine irregularities in the body. By picking five plants at random based on the entrance of cucumbers and tomatoes by CO_2 concentration, the amount of photosynthesis was determined. A cancer reaction state was created using a photosynthetic equipment, and a fluorescence value was measured when chlorophyll molecules absorb light from the lowest energy level, i.e., the ground state, and transfer it to a molecule. Because the fluorescence reaction value was slightly lower than that of 800 to 1,200 ppm in a crop grown under atmospheric cultivation conditions with a CO_2 concentration of 300 to 400 ppm, it is assumed that the environmental stress was affected in comparison to other CO_2 concentration injected crops. The transition of chlorophyll according to light absorption rate between 800 to 1,200 ppm is considered to be good, and environmental stress appears to be less than at other concentrations.

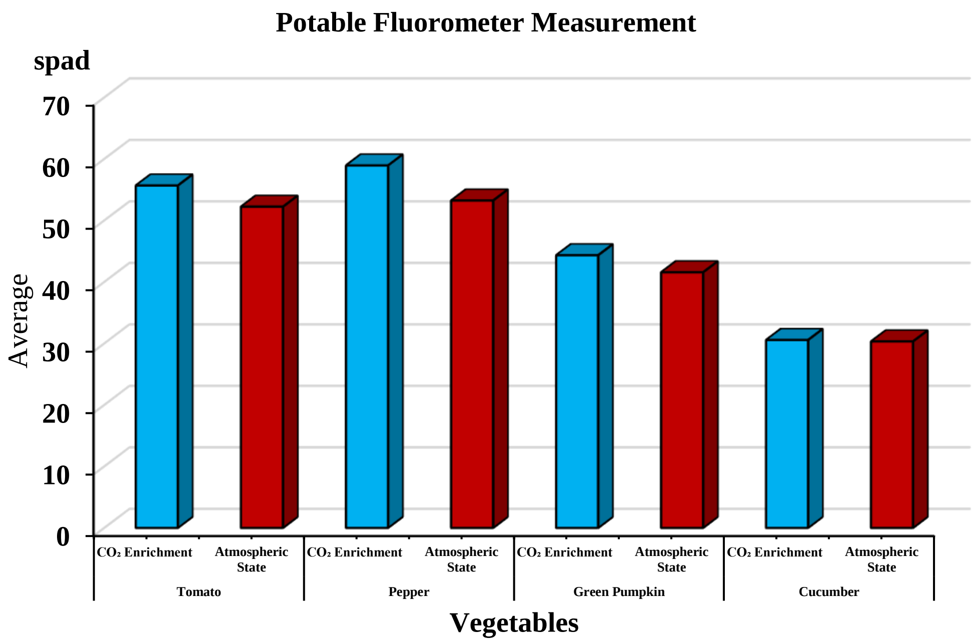


Figure 6.18 Potable fluorometer measurement result

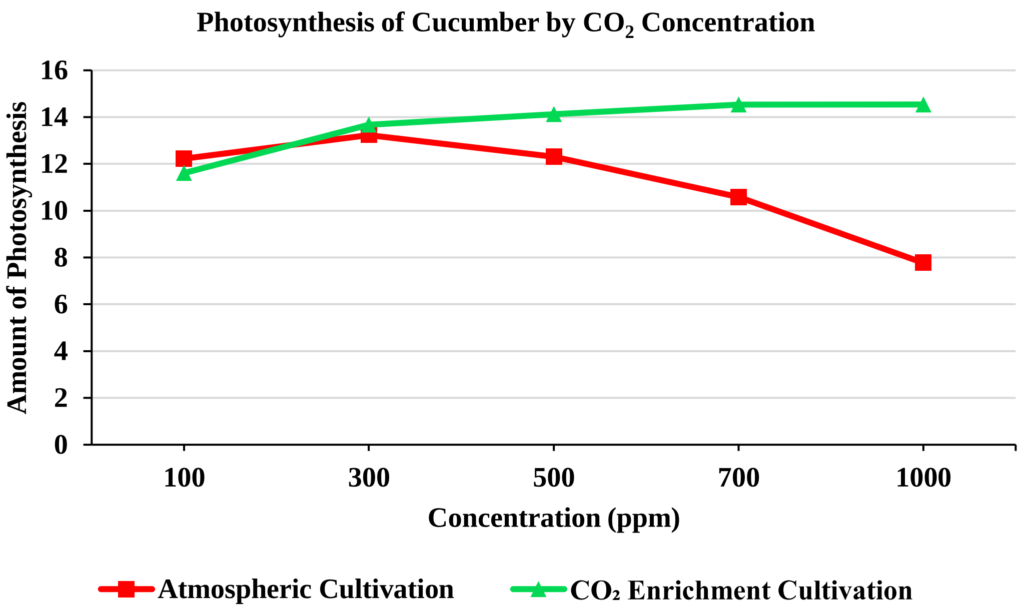


Figure 6.19 Porometer measurement results for different CO_2 concentration (cucumber)

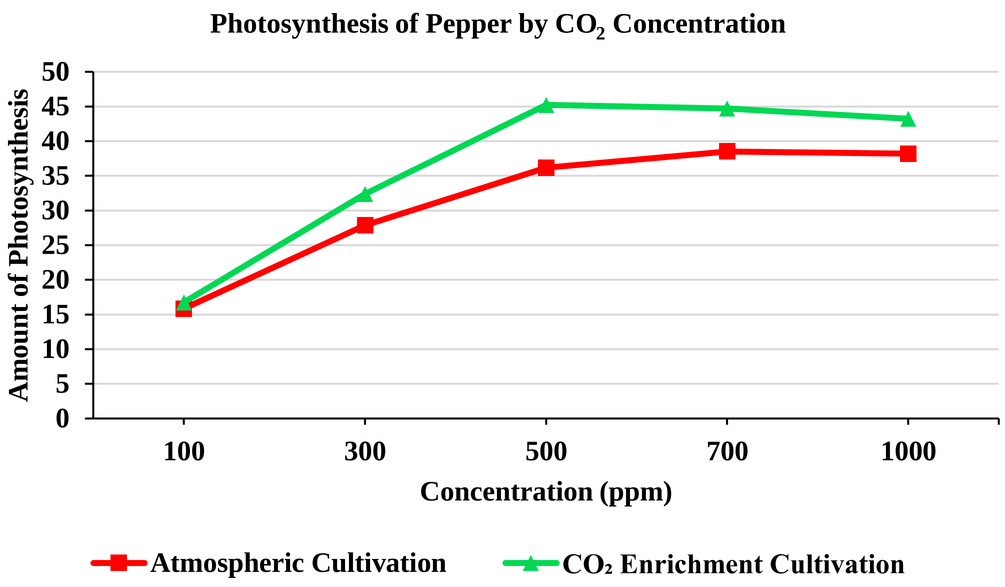


Figure 6.20 Porometer measurement results for different CO_2 concentration (pepper)

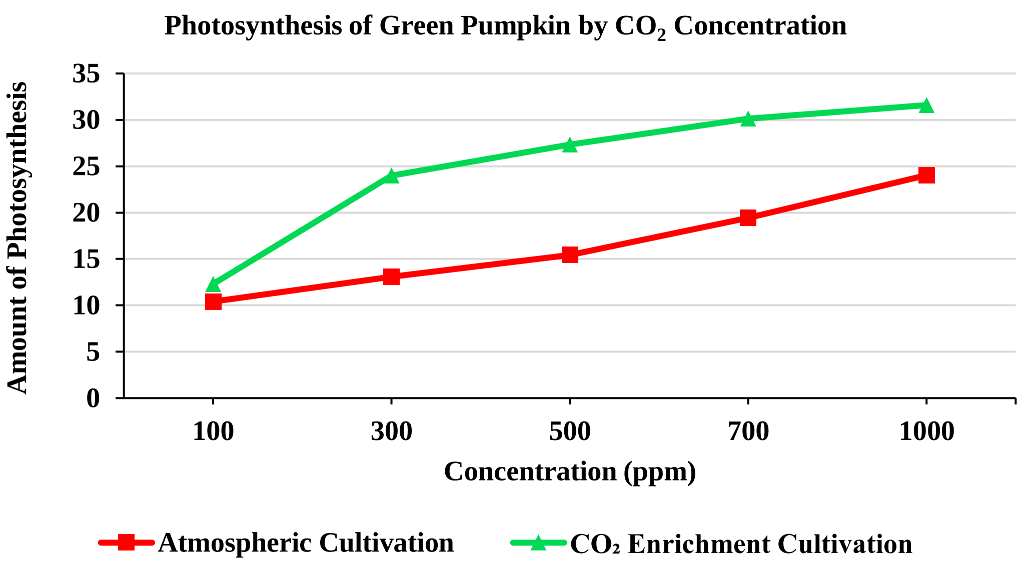


Figure 6.21 Porometer measurement results for different CO_2 concentration (green pumpkin)

7. CONCLUSION

7.1. Conclusion

Given the global uncertainty around resource scarcity, climate change, and food competition from a growing population, policymakers in any country must consider all possibilities for assuring a continuous supply of food, including vegetables. The research reported in this paper allowed for a comprehensive techno-economic and environmental assessment of a "plant to plant" Coal Power Plant Carbon Capture Utilization and Storage (CPPCCU) pathway for CO_2 enrichment in plant greenhouse systems. By predicting diverse material flows and resource consumption at the level of the CO_2 source, CO_2 transportation network, and CO_2 sink of the CPPCCU system, the integrated system can assess the interlinkages between Power Plant resources. As a result, for this study, we capture CO_2 from the coal power plant's source chimney, purify it, and use it in agriculture with cucumber, tomato, green pumpkin, and pepper. Consequently, we analyzed the experiment between two different CO_2 concentrations: CO_2 from the atmosphere and CO_2 enrichment concentrations and found that if we injected the various CO_2 enrichment concentrations, the vegetables grew well. Furthermore, even though the leaf, stem, and root grew extremely quickly in the CO_2 enrichment injected into the glass greenhouse, photosynthesis absorbed the sunlight well. As a result, we may conclude that CO_2 is effective for vegetables growing when the CO_2 content is controlled. In general, CCUS was successful in converting CO_2 from a gas to a liquid state during the purification process. Furthermore, the CCUS method performs well in CO_2 extraction, with a rate of around 96 percent (inlet=17.31 percent, outlet=16.60 percent). Importantly, the CO_2 enrichment cultivation idea used by the CCUS method effectively enhances the growth rate of vegetable leaves by roughly 15.85 percent and stems by 37.02 percent on average when compared to atmospheric cultivation.

7.2. Summary and Future Perspective

CCU can be seen as part of a portfolio of CO_2 reduction alternatives available to policymakers and business, alongside CCS and renewable energy technologies, to achieve a sustainable circular economy solution **[28-30]**. However, for CCU (and CCS) to be deployed on a large scale, a variety of technological, economic, and environmental problems, as well as regulatory and public perception issues, must be overcome. Nonetheless, this technique offers considerable potential to not only reduce CO_2 levels, but also to encourage innovation and commercial development, as well as new supply chain topologies centered on the use of waste CO_2 for diverse industrial uses. The value chain proposed in the research study can aid in the industrial growth of CCU technologies by meeting the interests of diverse stakeholders at the source, capture, transport, and usage phases of the chain. Hence, the recommendations for the future studies must be including the following:

1. Further study should be carried out to optimize the operation economically, considering labor cost, maintenance cost, machineries, duration etc **[31]**.
2. Further investigation should be done to identify the payback period of the CCUS system for future planning.
3. The input and output of energy involved in this operation should be exanimated in term of its energy consumption rate **[32]**.
4. Regulatory and public perception toward CCUS and how it can benefit the society should be publicized more to widen its usage not only in agriculture but also in other industries such as food, recycling, production etc **[33]**.

APPENDIX A: Investigation of Plant Grow

Figure A.1 Measuring branch length of the tomato, cucumber, pepper, green pumpkin

APPENDIX B: Fluorescence induction process analysis

Table B.1 Potable fluorometer measurement result for tomato

Number of Analyses	CO_2 Enrichment (spad)	Atmospheric State (spad)
1	50.8	51.5
2	55.7	48.2
3	65.9	59.8
4	56.2	55.3
5	53.8	50.8
6	55.8	59.1
7	52.3	50.8
8	55.1	57.8
9	53.6	45.2
10	57.6	43.8
Average	**55.68**	**52.23**

Table B.2 Potable fluorometer measurement result for pepper

Number of Analyses	CO_2 Enrichment (spad)	Atmospheric State (spad)
1	56.8	55.4
2	63.2	57.2
3	66.4	51.5
4	54.3	56
5	64.3	50.1
6	54.7	51.1
7	57	55.9
8	61.3	54.1
9	86.6	52.7
10	53.7	49.6
11	50.8	52.3
12	51.9	55.9
13	45.2	50.3
Average	**58.94**	**53.24**

Table B.3 Potable fluorometer measurement result for green pumpkin

Number of Analyses	CO_2 Enrichment (spad)	Atmospheric State (spad)
1	49.7	40
2	43.3	43
3	39.6	40
4	45.1	39.2
5	43.1	47.9
6	38.7	40.2
7	48.9	47.2
8	41.6	42.8
9	45.2	36
10	48.2	39.4
Average	**44.34**	**41.57**

Table B.4 Potable fluorometer measurement result for cucumber

Number of Analyses	CO_2 Enrichment (spad)	Atmospheric State (spad)
1	29.7	30.5
2	31.5	27.8
3	29.1	25.9
4	30.6	29.1
5	30.3	29.5
6	27.5	32.6
7	27.6	31.8
8	23.8	30.9
9	39.1	35
10	36.4	30.1
Average	**30.56**	**30.32**

APPENDIX C: Vegetable’s growth characteristics analysis

Table C.1 Result of inorganic material analysis

Classification			Total N	Cl	S	P	K	Na	Ca	Mg	Fe	Mn	Zn	B	Cu	Mo
			mmol/kg D.W				mmol/kg D.W				mmol/kg D.W				μmol/kg D.W	
Fruit	CO_2	Pepper	2800	143	65	180	568	2	34	68	1.3	0.5	0.6	1.2	186	6
		Cucumber	3800	217	78	241	723	2	79	71	0.6	0.6	1.7	2.6	141	8
		Tomato	2800	206	49	210	680	23	10	55	0.7	0.3	0.7	1.3	138	11
		Green Pumpkin	3400	136	58	195	457	2	13	62	0.7	0.3	0.9	1.3	155	8
	Normal	Pepper	2600	190	67	166	630	3	35	67	0.9	0.5	0.7	1.2	177	3
		Cucumber	4400	236	80	255	794	3	69	75	0.9	0.7	2	2.5	191	7
		Tomato	2450	197	48	201	697	17	11	55	0.7	0.3	0.7	1.1	126	8
		Green Pumpkin	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Leaf	CO_2	Pepper	4850	370	152	312	591	7	269	131	3.9	2.6	1.6	7.1	301	14
		Cucumber	4650	532	94	215	471	3	364	102	6	2.8	3.1	5.4	218	16
		Tomato	4200	276	142	353	419	71	185	93	5	1.8	1.4	6.7	521	19
		Green Pumpkin	400	388	84	212	478	1	304	105	10	2.4	2.7	3.8	204	12
	Normal	Pepper	5350	421	145	249	652	2	247	137	2.1	0.5	1.6	5.5	326	11
		Cucumber	5200	598	101	200	667	5	361	127	11.4	3.3	3.1	7	222	15
		Tomato	5350	350	175	336	642	68	229	115	9.1	2.1	1.4	8.7	464	21
		Green Pumpkin	5400	453	114	221	656	2	262	111	4.3	2.5	2.9	4.9	273	16

Table C.2 Chlorine content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	190
	800 ~ 1200 ppm	143
Cucumber	300 ~ 400 ppm	236
	800 ~ 1200 ppm	217
Tomato	300 ~ 400 ppm	197
	800 ~ 1200 ppm	206
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	136

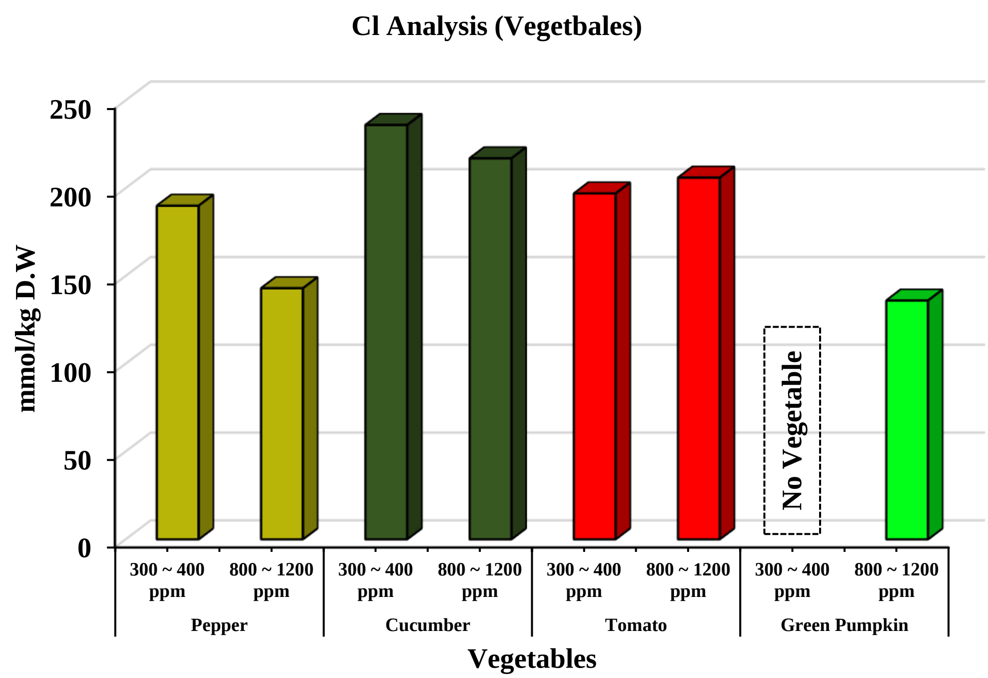


Figure C.1 Analysis of chlorine content with harvested plant

Table C.3 Sulfur content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	67
	800 ~ 1200 ppm	65
Cucumber	300 ~ 400 ppm	80
	800 ~ 1200 ppm	78
Tomato	300 ~ 400 ppm	48
	800 ~ 1200 ppm	49
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	58

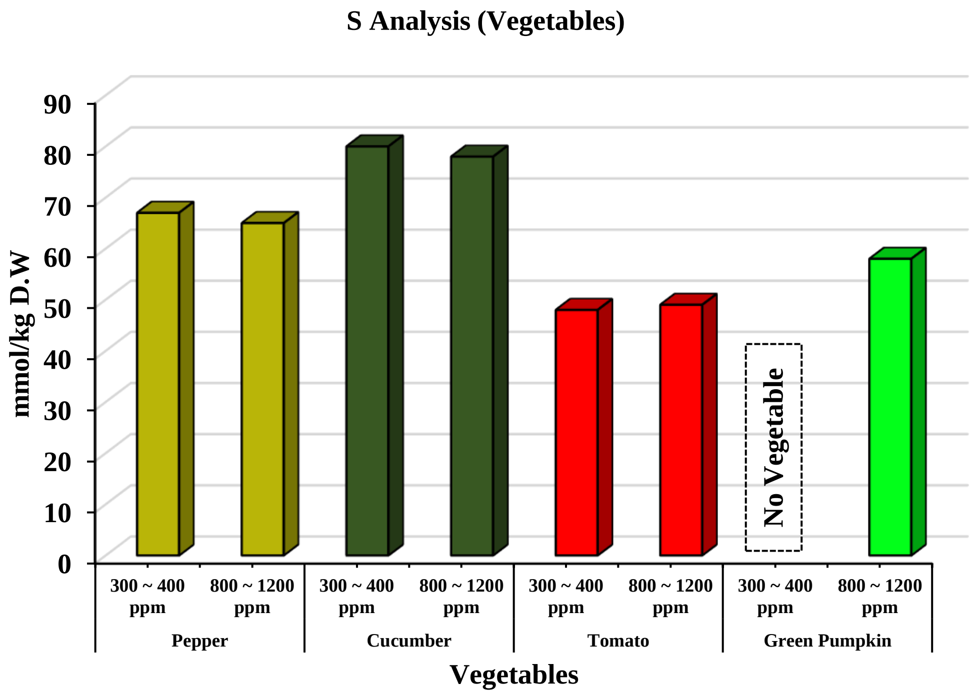


Figure C.2 Analysis of sulfur content with harvested plant

Table C.4 Phosphorus content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	166
	800 ~ 1200 ppm	180
Cucumber	300 ~ 400 ppm	255
	800 ~ 1200 ppm	241
Tomato	300 ~ 400 ppm	201
	800 ~ 1200 ppm	210
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	195

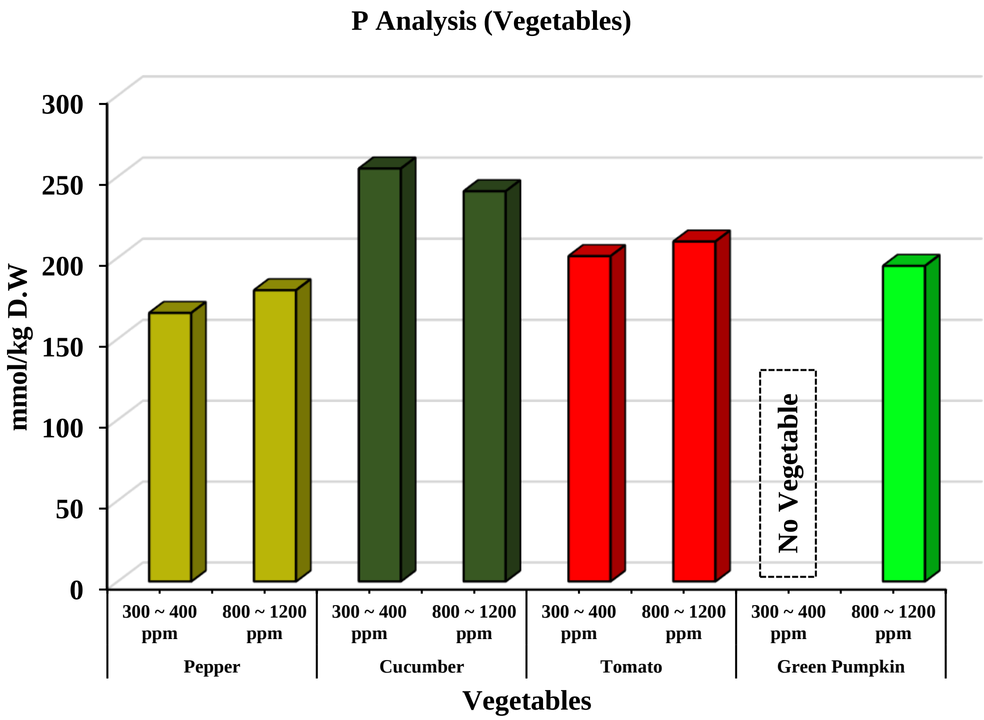


Figure C.3 Analysis of phosphorus content with harvested plant

Table C.5 Potassium content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	630
	800 ~ 1200 ppm	568
Cucumber	300 ~ 400 ppm	794
	800 ~ 1200 ppm	723
Tomato	300 ~ 400 ppm	697
	800 ~ 1200 ppm	680
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	457

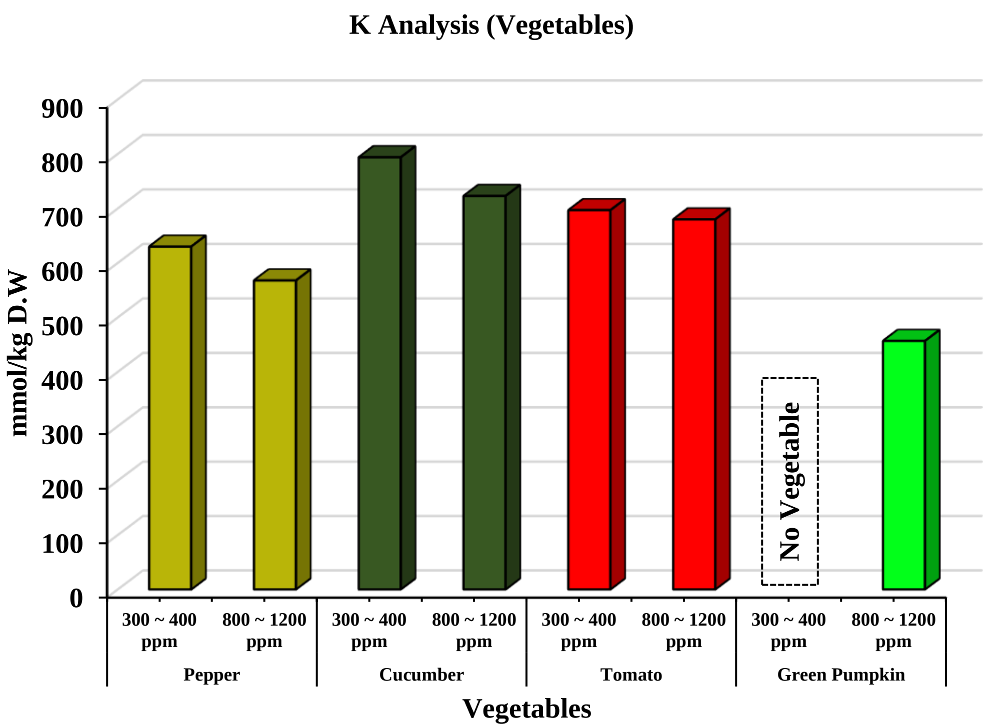


Figure C.4 Analysis of potassium content with harvested plant

Table C.6 Sodium content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	3
	800 ~ 1200 ppm	2
Cucumber	300 ~ 400 ppm	3
	800 ~ 1200 ppm	2
Tomato	300 ~ 400 ppm	17
	800 ~ 1200 ppm	23
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	2

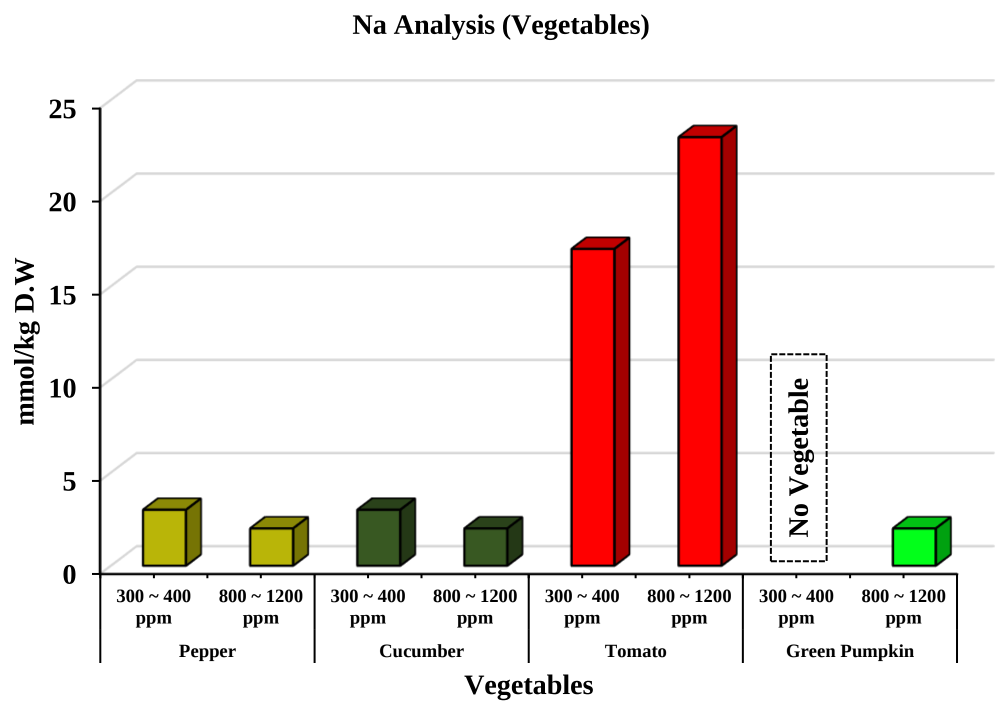


Figure C.5 Analysis of sodium content with harvested plant

Table C.7 Calcium content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	35
	800 ~ 1200 ppm	34
Cucumber	300 ~ 400 ppm	69
	800 ~ 1200 ppm	79
Tomato	300 ~ 400 ppm	11
	800 ~ 1200 ppm	10
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	13

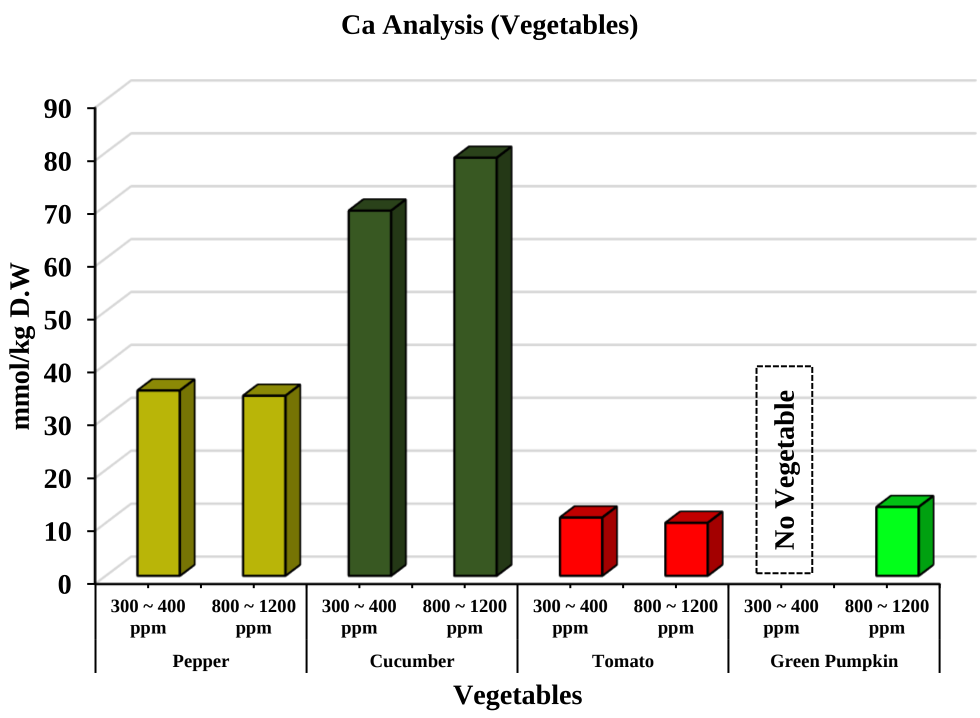


Figure C.6 Analysis of calcium content with harvested plant

Table C.8 Magnesium content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	67
	800 ~ 1200 ppm	68
Cucumber	300 ~ 400 ppm	75
	800 ~ 1200 ppm	71
Tomato	300 ~ 400 ppm	55
	800 ~ 1200 ppm	55
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	62

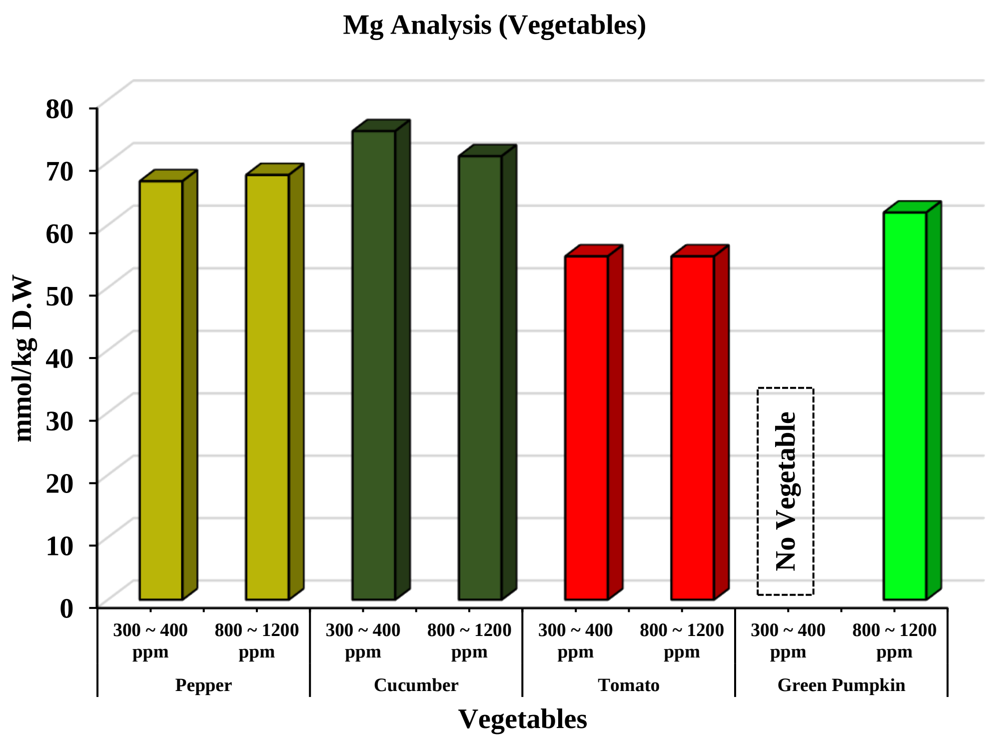


Figure C.7 Analysis of magnesium content with harvested plant

Table C.9 Iron content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	0.9
	800 ~ 1200 ppm	1.3
Cucumber	300 ~ 400 ppm	0.9
	800 ~ 1200 ppm	0.6
Tomato	300 ~ 400 ppm	0.7
	800 ~ 1200 ppm	0.7
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	0.7

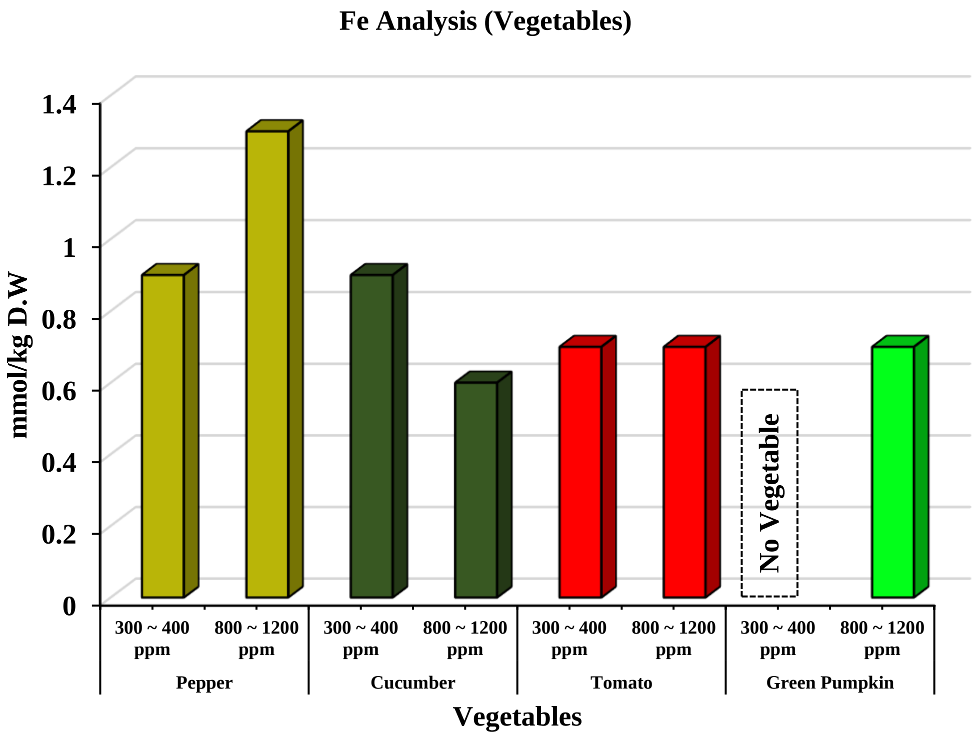


Figure C.8 Analysis of iron content with harvested plant

Table C.10 Manganese content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	0.5
	800 ~ 1200 ppm	0.5
Cucumber	300 ~ 400 ppm	0.7
	800 ~ 1200 ppm	0.6
Tomato	300 ~ 400 ppm	0.3
	800 ~ 1200 ppm	0.3
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	0.3

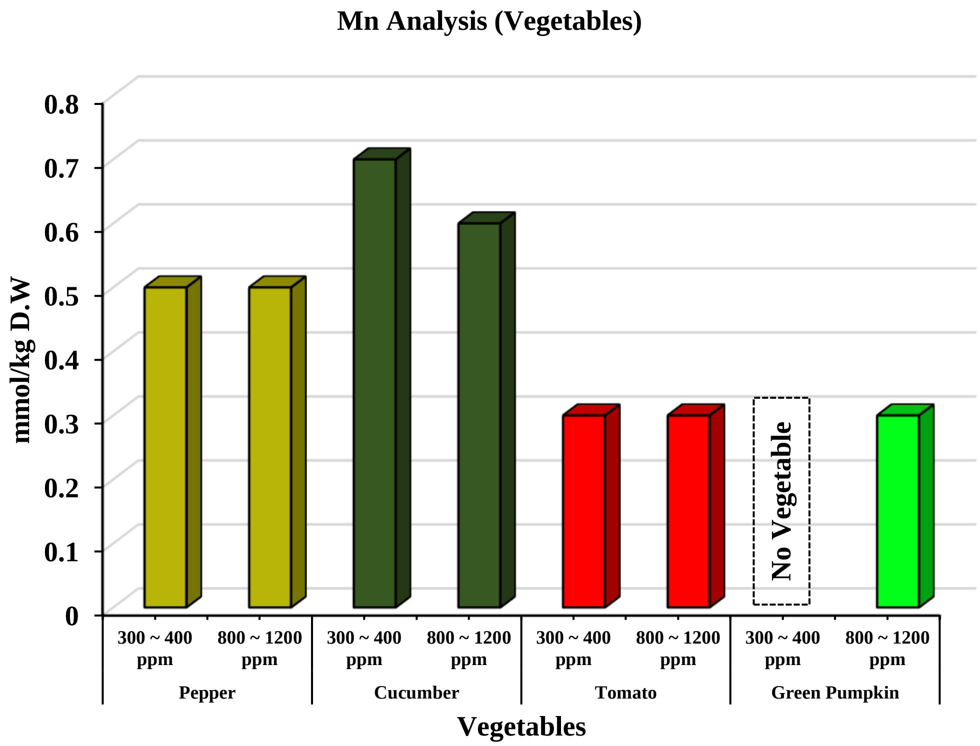


Figure C.9 Analysis of manganese content with harvested plant

Table C.11 Zinc content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	0.7
	800 ~ 1200 ppm	0.6
Cucumber	300 ~ 400 ppm	2
	800 ~ 1200 ppm	1.7
Tomato	300 ~ 400 ppm	0.7
	800 ~ 1200 ppm	0.7
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	0.9

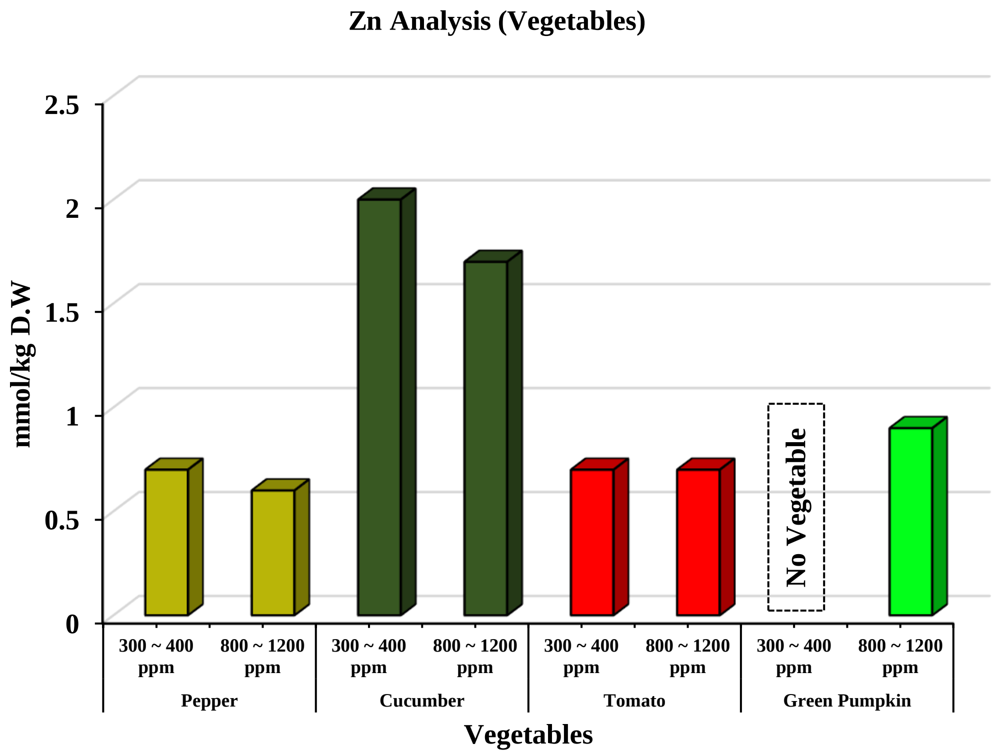


Figure C.10 Analysis of zinc content with harvested plant

Table C.12 Boron content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	1.2
	800 ~ 1200 ppm	1.2
Cucumber	300 ~ 400 ppm	2.5
	800 ~ 1200 ppm	2.6
Tomato	300 ~ 400 ppm	1.1
	800 ~ 1200 ppm	1.3
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	1.2

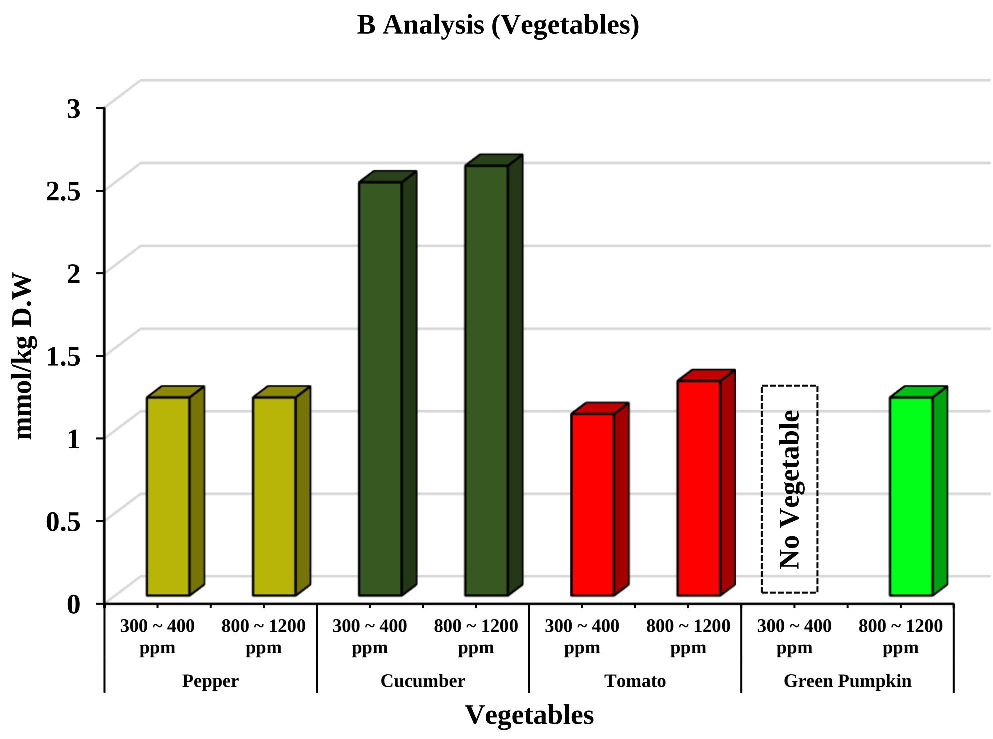


Figure C.11 Analysis of boron content with harvested plant

Table C.13 Copper content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	177
	800 ~ 1200 ppm	186
Cucumber	300 ~ 400 ppm	191
	800 ~ 1200 ppm	141
Tomato	300 ~ 400 ppm	126
	800 ~ 1200 ppm	138
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	155

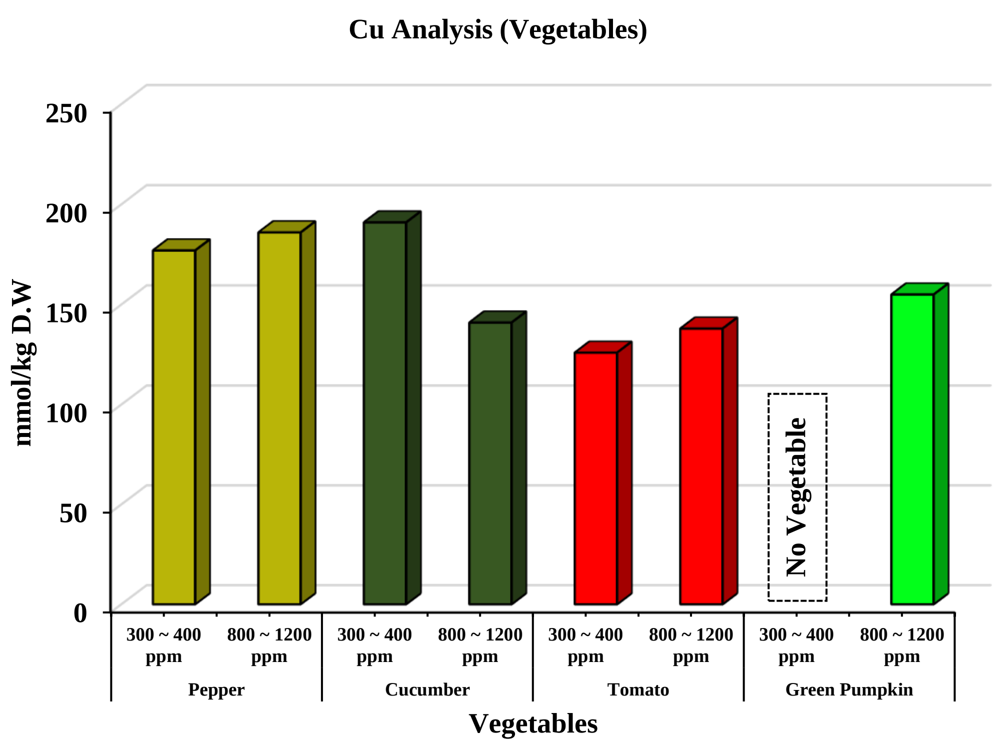


Figure C.12 Analysis of copper content with harvested plant

Table C.14 Molybdenum content with different CO_2 conditions

Vegetables	Amount of CO_2 Injected	mmol/kg D.W
Pepper	300 ~ 400 ppm	3
	800 ~ 1200 ppm	6
Cucumber	300 ~ 400 ppm	7
	800 ~ 1200 ppm	8
Tomato	300 ~ 400 ppm	8
	800 ~ 1200 ppm	11
Green Pumpkin	300 ~ 400 ppm	-
	800 ~ 1200 ppm	3

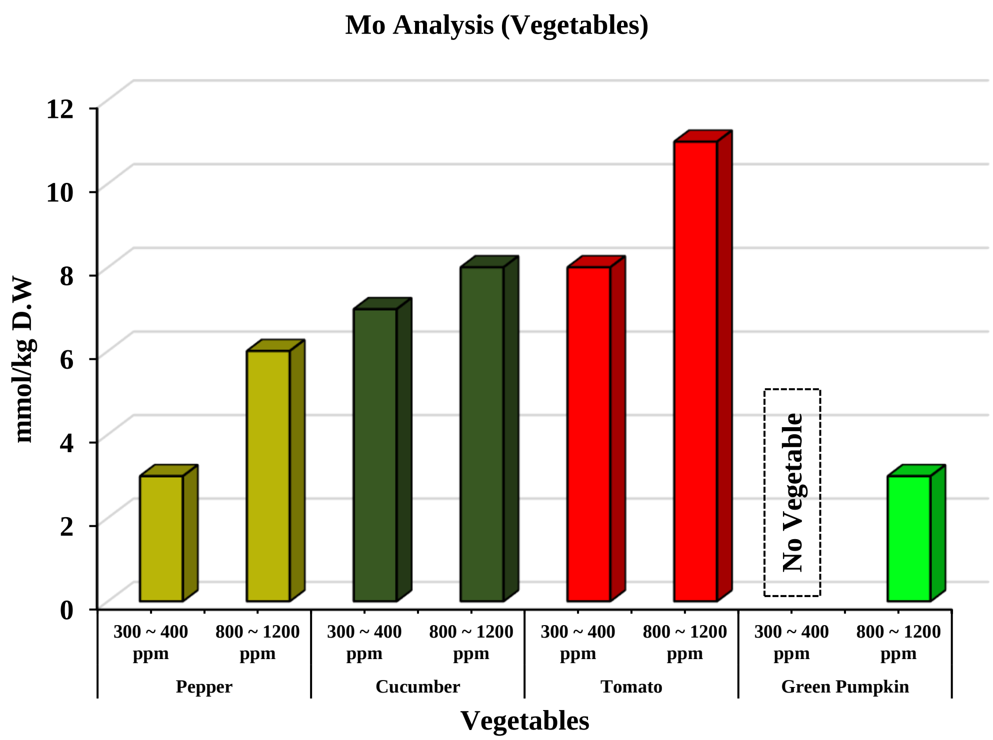


Figure C.13 Analysis of molybdenum content with harvested plant

APPENDIX D: Flow rate of exhaust gas through membrane

Table D.1 Gas property analysis after passing through the membrane (flow rate/Product: 120L/min, Purge: 300L/min)

Time (s)	CO_2	CO	NO	SO_2
0	16.01	2	0	0
60	25.53	1	0	0
120	29.44	1	0	0
180	28.94	1	0	0
240	29.34	1	0	0
300	29.69	1	0	0
360	32.11	1	0	0
420	31.87	1	0	0
480	32.25	2	0	0
540	31.59	1	0	0
600	31.47	2	0	0
660	31.50	1	0	0
720	34.03	1	0	0
780	33.25	1	0	0

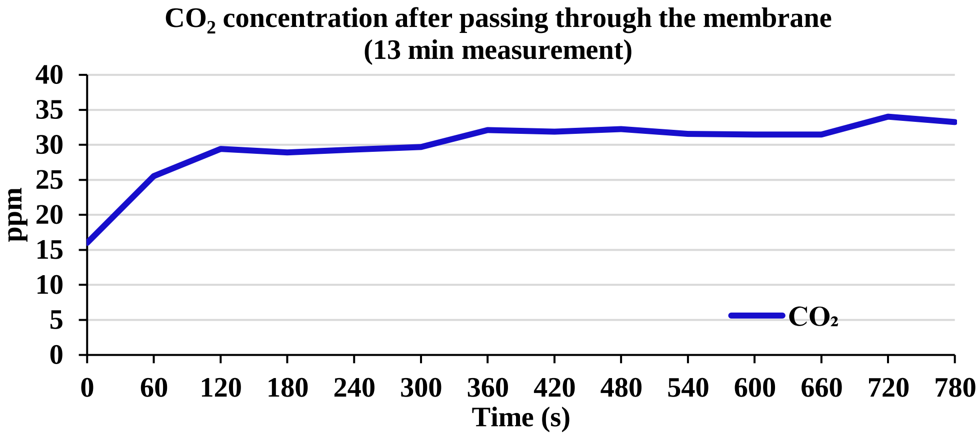


Figure D.1 Gas property analysis after passing through the membrane (flow rate/Product: 120L/min, Purge: 300L/min)

Table D.2 Gas property analysis after passing through the membrane (flow rate/Product: 110L/min, Purge: 380L/min)

Time (s)	CO_2	CO	NO	SO_2
0	44.82	0	0	0
10	44.88	0	0	0
20	44.87	0	0	0
30	44.65	0	0	0
40	44.70	0	0	0
50	45.06	0	0	0
60	45.39	0	0	0
70	45.58	0	0	0
80	45.50	0	0	0
90	45.91	0	0	0
100	47.66	1	0	0
110	49.44	0	0	0

120	50.00	0	0	0
130	50.00	0	0	0
140	50.00	1	0	0
150	49.91	1	0	0
160	50.10	0	0	0
170	50.23	1	0	0
180	50.22	1	0	0
190	50.20	1	0	0
200	50.13	1	0	0
210	50.05	0	0	0
220	50.12	1	0	0
230	50.12	0	0	0
240	50.15	0	0	0

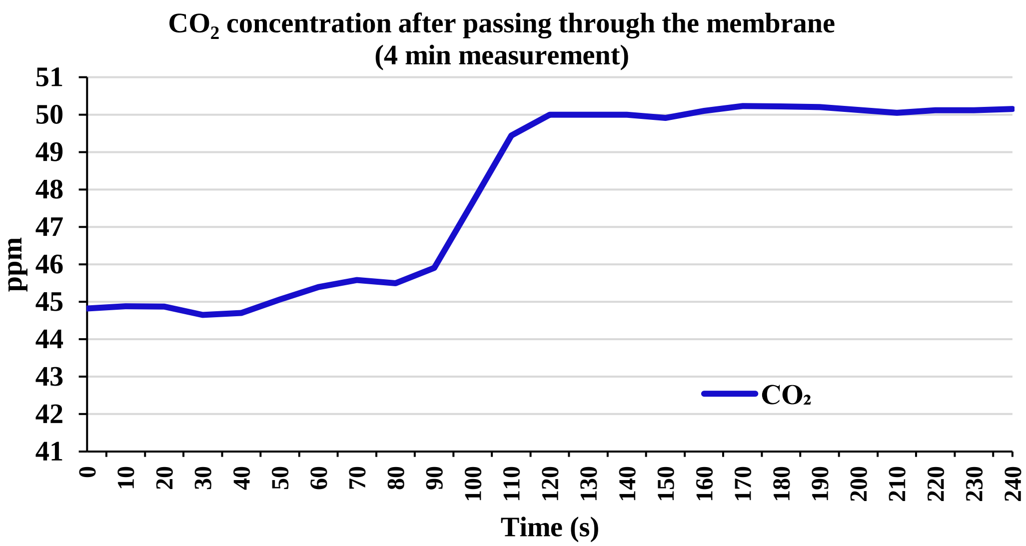


Figure D.2 Gas property analysis after passing through the membrane (flow rate/Product: 110L/min, Purge: 380L/min)

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