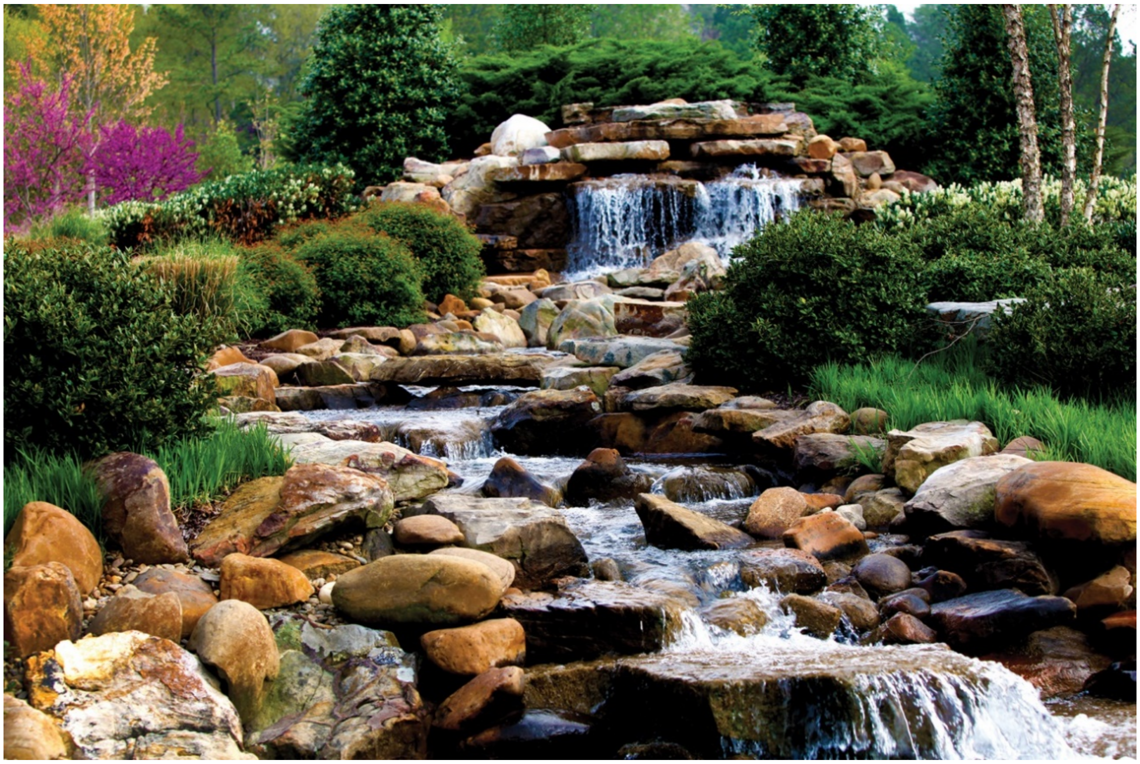
ORNL/SPR-2024/3521

BTRIC Technical Support for Appalachia: FY 2024 Summary Report on Net Negative Carbon Building Demonstration with AgPod



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September 2024

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Buildings and Transportation Science Division

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ABBREVIATIONS

ADUS	automated DAC/utilization system
AgPod	agricultural pod
Ca	atmospheric CO_2 concentration
Ci	internal leaf CO_2 concentration
CEA	controlled-environment agriculture
CO_2	carbon dioxide
DAC	direct air capture
DOE	US Department of Energy
ECEA	enriched controlled-environment agriculture
EGH	enriched greenhouse horticulture
KCDC	Knoxville’s Community Development Corporation
LED	light-emitting diode
ORNL	Oak Ridge National Laboratory
PAR	photosynthetically active radiation

EXECUTIVE SUMMARY

The overall goal of this 3-year project is to demonstrate how a small neighborhood could achieve net negative in carbon dioxide (CO_2) emissions. The project consists of six major tasks: (1) direct air capture (DAC) system development, (2) DAC integration with an agricultural pod (AgPod), (3) deployment of the combined system at Knoxville's Community Development Corporation, (4) research on crop enhancement with CO_2, (5) data collection, and (6) final report. This document reports on the project's progress through the end of fiscal year 2024.

Net negative carbon emissions are defined in this study as offsetting operational carbon emissions for the energy used by a building (power plant emissions) by capturing carbon from the environment and converting it into a useful product. This approach uses the CO_2 onsite, thereby eliminating emissions from transportation of the captured carbon for utilization in an application such as cement. For this study, we are focusing on demonstration in a single building with plans to transition to widespread deployment.

We have incorporated a holistic approach for the net negative carbon demonstration by first designing the building to reduce heat loss with an improved envelope design. Next, high-efficiency electric building equipment, such as heat pumps and heat pump water heaters, is used to reduce energy consumption. The addition of renewable energy sources further reduces energy acquired from the power plant. The last step toward the overall goal involves utilizing a rotating wheel mechanism embedded with a carbon-absorbing material to capture CO_2 from the atmosphere and inject it into an AgPod. As the wheel slowly rotates, outside air enters the rotating wheel mechanism on one side (process air stream) and CO_2 is absorbed from the atmosphere. As the wheel continues to rotate to the other side (regeneration air stream), CO_2 is driven off into the AgPod to enhance crop yield. This holistic approach enables the total carbon emissions to be net negative.

This report investigates the effects of various concentrations of CO_2 on the photosynthesis and biomass accumulation of crops growing in an AgPod, using kale as the test crop. In the first year of the study, increasing the CO_2 concentration in the AgPod was found to promote higher photosynthetic rates in kale plants up to 1,300 ppm (the highest CO_2 concentration measured). An interesting finding was that net photosynthetic rates of kale leaves remain unsaturated until reaching unusually high levels of photosynthetically active radiation (PAR, > 1,200 μmol m^{-1} s^{-1}) and CO_2 concentration (> 1,100 ppm). Such high levels of saturating PAR and CO_2 concentration values rarely occur under natural conditions, suggesting a promising potential for carbon capture via enriched controlled environment agriculture (ECEA).

During the second year of the study, a second crop was planted to confirm the actual effects on growth with increased CO_2 concentrations. Our results suggest that growing kale plants in the AgPod system at higher CO_2 levels resulted in a successful and highly productive crop, up to three times the amount grown at 415 CO_2. Further, the kale plants grown under higher CO_2 conditions (1000 ppm) are not CO_2 saturated and can potentially further improve yield at even higher CO_2 environments.

The promising results show that this system has the potential to provide a sustainable agricultural solution that can both increase food availability, especially in urban environments, and contribute to carbon capture for a net zero carbon future.

ACKNOWLEDGEMENTS

Funding for this research was provided by the US Department of Energy, Office of Energy Efficiency and Renewable Energy. The authors would like to thank Hayes Jones, Program Manager, Commercial Buildings Integration for support of this work.

1. BACKGROUND

1.1 EMISSIONS

Global carbon dioxide (CO_2) emissions have been increasing over the last century. In the United States, emission levels have dropped since around 2007, mainly as the result of a decrease in the number of coal plants and an increase in renewables (Figure 1). Emission reductions can also be achieved with carbon capture technologies, although the carbon must be captured and sequestered in some manner. Natural forms of sequestration, such as forests, grasslands, soil, oceans, and other water bodies that can store carbon, are known as carbon sinks. Geological carbon sequestration happens when carbon is stored in places such as underground geological formations or rocks. This process is largely artificial or "direct," representing an effective way of neutralizing emissions from manufacturing or construction. The CO_2 emissions, especially flue gases, can be captured in various forms before they are emitted to the atmosphere (Wang and Song 2020).

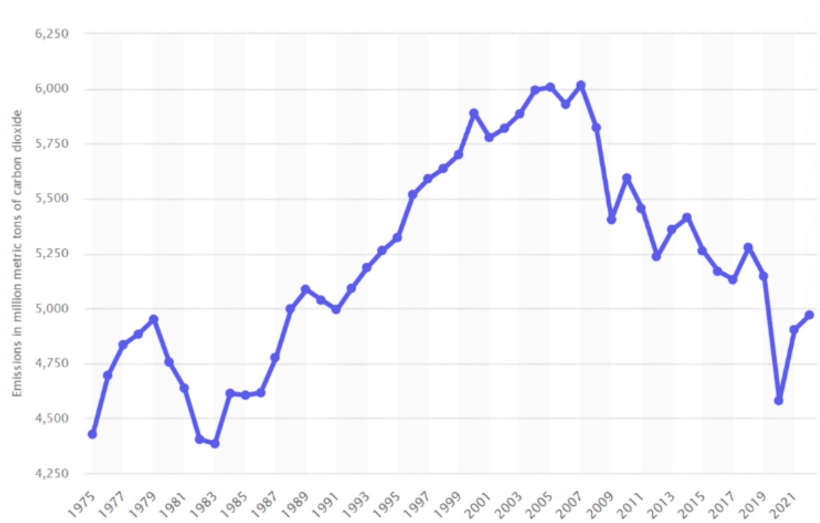

Figure 1. Carbon dioxide emissions in the United States, 1975–2022.

1.2 DIRECT AIR CAPTURE

Direct air capture (DAC) is a method of carbon capture used to selectively extract CO_2 from atmospheric air so that it can be moved and/or used in a concentrated form (Brilman 2020). However, the cost of DAC is significantly higher than the cost of extracting CO_2 from a point source, such as a fossil-fueled power plant (National Academies of Sciences, Engineering, and Medicine 2018). Therefore, ideas for lowering the cost of DAC, such as piggybacking the DAC function on existing infrastructure, could be appropriate. HVAC and other air moving equipment can be leveraged for their dual use—as a space conditioning machine and as a mechanism to capture carbon from air passing through or by the machine. These ideas could also help reach the US Department of Energy's (DOE's) Energy Earthshots Initiative goal of reducing the cost of DAC to below \$100/t of CO_2 (DOE 2021).

1.3 NET NEGATIVE CARBON DEMONSTRATION

The demonstration in this study, shown in Figure 2, in a low-income neighborhood uses captured CO_2 from a building to saturate the CO_2 of a greenhouse to maximally accelerate plant growth. Decarbonization of low-income neighborhoods can be accomplished through the engineered removal of ambient CO_2 through community-scale DAC and plant-based carbon absorption/storage in facilities such as community gardens or greenhouses. In combination, these have the potential to offer significant benefits to both community members and broader decarbonization goals. The approach in this study is to integrate DAC with an agricultural pod (AgPod) to provide supplemental CO_2 to optimize growing conditions in the AgPod.

Figure 2. Net negative carbon demonstration including electric vehicles, agricultural pod, photovoltaic cells, and building envelope with improved insulation.

1.4 DIRECT AIR CAPTURE SYSTEM DEVELOPMENT/INTEGRATION WITH AGPOD

A DAC system can provide economic value by utilizing the captured CO_2 in a greenhouse carbon enrichment exercise. The captured CO_2 can be directly released from capture devices and used for processing without purification or post-processing to reach a high purity of CO_2. This simplifies the overall integration process. As an added benefit, the present practice of burning hydrocarbon to produce supplemental CO_2 for greenhouse crop production can be eliminated.

The research team at DOE's Oak Ridge National Laboratory (ORNL) has successfully demonstrated that a building air handling system can be used for direct CO_2 removal from ambient air (Figure 3).[1] The study included the regeneration process of the adsorbents for reutilization in experimentation. However, this

[1] US Patent App. 17/974,227, "Multi-functional equipment for direct decarbonization with improved indoor air quality."

regeneration process was performed off-site in a lab environment. As such, further investigation is required to develop a system for automatically transporting enriched CO_2 streams to the AgPod. One such concept is shown in Figure 4. The idea is to capture CO_2 on a process side, regenerate on the other side, and then send CO_2 to the AgPod through ducting.[2]

Figure 3. A direct CO_2 removal demonstration.

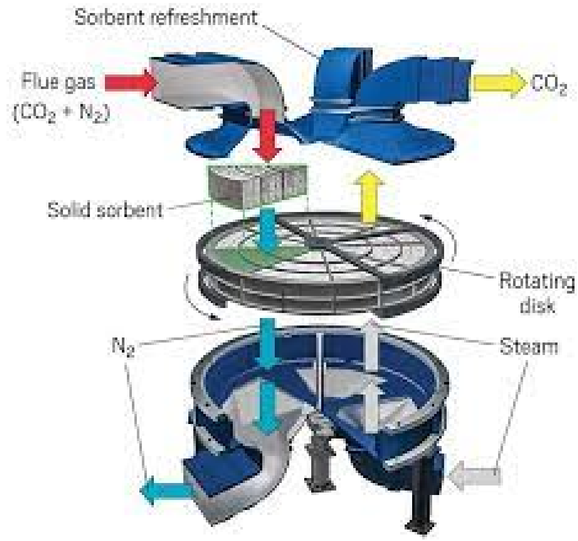

Figure 4. An automated direct air capture/ utilization system (ADUS).

Deployments leveraging existing infrastructure can revolutionize DAC technology with minimal operational and capital costs associated with retrofit approaches. In one promising case, existing modular and scalable building equipment represents an excellent platform for an application in which the DAC modules can be included with marginal increments in required fan power to operate the system. Using the waste heat for regeneration of DAC modules to offset a dedicated energy source for process (directly or after upgrades) provides an additional value. The captured CO_2 would provide CO_2 enrichment for the greenhouse, resulting in an environment that can be controlled to optimize photosynthesis, rather than opportunistically capturing CO_2 from building exhaust. This would eliminate the potential for introducing less-desired components of indoor air to the growing space.

Dong et al. (2018) reviewed the influence of elevated CO_2 concentration on the yields of vegetables and found that elevated CO_2 (827 ppm) increased the yield of vegetables by 34%. The benefits of CO_2 enrichment (higher CO_2 concentration) are well documented for commercial greenhouse crops, including fruits, flowers, and vegetables (such as tomato, cucumber, pepper, lettuce, and rose crops). On average, greenhouse crops benefit from concentrations between 700 and 1,000 ppm, which produce yield increases from 21% to 61% in dry mass. Currently, CO_2 enrichment is conducted with pure CO_2 or from the combustion of hydrocarbon fuel, such as natural gas or propane.

1.5 DATA COLLECTION

The building to be used in the scaled-up study is a 32-unit apartment complex (Figure 5). A groundbreaking ceremony was conducted in August 2023, and the building is expected to be completed by September 2024 (KCDC 2023). Electricity consumption of the whole building is equal to the combined electricity usage of various sources including HVAC systems, domestic water heaters, indoor

[2] ID no. 202305285 DAC integrated to AgPod or GreenHouse for CO_2 enrichment.

lighting, and appliances such as TVs, clothes dryers, refrigerators, dishwashers, and ceiling fans. The collected data will serve the purpose of assessing the building's total energy usage and operational carbon emissions. Additionally, the data can be further analyzed to differentiate between HVAC and other electric loads. Furthermore, the data will also be used to evaluate the estimated energy and carbon savings compared with typical multifamily buildings in the same climate zones.

Figure 5. Rendering of the 32-unit apartment complex being used in this study.

To determine the electricity consumption of the whole building, watt transducers will be utilized to measure electricity usage. Depending on the specific measurement point, the number of required sensors may vary. If a measurement can be obtained through a single data point, then only one watt transducer is necessary for measuring electrical consumption. However, if that is not possible, multiple sensors may be required for each residential unit and commercial area. In addition, unit-level electricity consumption will be monitored in selected sample residential units.

For the main energy-use equipment (space conditioning and water heating), ORNL worked with Knoxville's Community Development Corporation (KCDC) to specify higher efficiency heat pumps (SEER = 16.5) and heat pump water heaters (UEF = 3.8), rather than the originally planned equipment (standard efficiency heat pump [SEER = 14.5] and electric resistance water heater). The building will have a solar photovoltaic (PV) system with a capacity of 76.3 kW estimated to generate approximately 95,912 kWh of electricity per year. A monitoring system will track the solar PV system's energy generation data. Analyzing the electricity output makes it possible to determine the amount of energy and carbon emissions that potentially could be reduced. Energy generated by the solar array will be subtracted from the total building energy consumption to determine the net energy consumed by the building. The CO_2 emissions will be determined by multiplying energy consumption by a carbon emission factor for the region available from the US Environmental Protection Agency's eGrid.

A Measurement and Verification Plan was developed during the second year of the study. All instrumentation was ordered, and installation began in September 2024.

1.6 IMPACT

Global demand for food and biofuel is projected to increase substantially in the coming decades because of population growth and economic development. This increased demand is not expected to be met via traditional means of agricultural production such as expanding arable land area and improving crop productivity, both of which have plateaued worldwide. However, this project could aid in meeting that demand. Meanwhile, climate change has led to more frequent occurrences of extreme events such as drought, heat waves, and floods, which increasingly disrupt agricultural production worldwide. Although genetic modification of crops can increase photosynthetic efficiency and crop yields, such efforts are still at the conceptual stage (Gu 2023). A new green revolution could be realized by a marriage between energy industries and controlled-environment agriculture (CEA). A major strategy will be to feed flue gas and waste heat to greenhouse horticulture (i.e., enriched greenhouse horticulture, or EGH), to enable year-round growth of vegetables, fruits, and staple crops. Flue gas contains a high CO_2 concentration but a low O_2 concentration. High CO_2 concentration increases the carboxylation efficiency of Rubisco (the main photosynthetic enzyme), and low O_2 concentration suppresses photorespiration; both processes increase the rate of photosynthesis. Therefore, fumigating greenhouse horticulture with flue gas can significantly increase horticultural productivity. Currently, agricultural production is largely a summertime activity in subtropical and temperate regions where most populations reside, primarily because of temperature limitation in winter. Using waste heat to warm greenhouses makes winter horticulture possible. Enriched controlled-environment agriculture (ECEA), under which EGH is a major approach, can be a significant negative carbon emission activity because it reduces greenhouse gas emissions from power plants and refineries and from traditional agricultural production that ECEA displaces. ECEA can also reduce greenhouse gas emissions associated with food transportation because it can be developed close to population centers.

2. CROP EVALUATION PROCEDURE

Research on the effects of increased levels of CO_2 on crop growth are being conducted in the AgPod, Figure 6, located onsite at Oak Ridge National Laboratory (ORNL). The AgPod is equipped with a nursery and growth panels for germinating and growing the plants (Figure 7). Light-emitting diodes LEDs (Figure 8) are controlled at different wavelengths to produce light optimized for each type of crop grown in the AgPod. Nutrients are supplied with a proprietary nutrient supply system to achieve optimal growing based on the crop.

Figure 6. The agricultural pod facility at Oak Ridge National Laboratory.

Environmental conditions (temperature and relative humidity) are controlled to maintain optimal growing conditions regardless of outdoor ambient temperatures down to 20^{o}F.

Figure 7. AgPod nursery and growth panels.

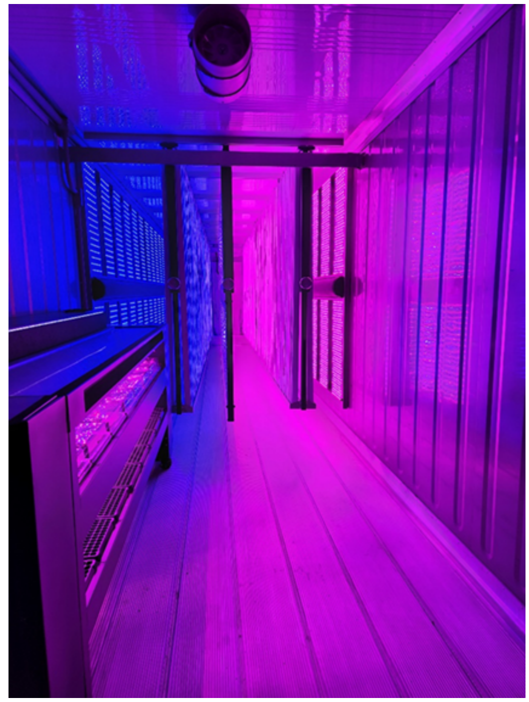

Figure 8. AgPod LED grow lights.

During the growing period, the growth rate (head dimensions/height, outer leaf length/width) is monitored weekly (e.g., Table 1). Two leaves on each plant are monitored for length and width, and the total number of leaves on each plant is recorded. The first leaf selected on each plant for monitoring is the longest leaf one week after the seedlings are placed in the growth panels. The second leaf on each plant is selected for monitoring after each plant has 10 leaves on its stem. Any leaf can be selected midway from the center of the plant and the end of the stem. The same leaves are monitored throughout each plant's lifetime.

Table 1. Example data from the 1st crop (1000 ppm CO_2) plant growth measurements

ID of the plant monitored	1-3D			ID of the plant monitored	1-3D	
Date 9/15/23				Date 9/22/23		
First Leaf	Length (inches)	3.75		First Leaf	Length (inches)	4.00
	Width (inches)	1.50			Width (inches)	1.75
Second Leaf	Length (inches)			Second Leaf	Length (inches)	
	Width (inches)				Width (inches)	
Total number of leaves		7.00		Total number of leaves		9.00
Observer	Jobe			Observer	Jobe	

At weekly intervals during the growth period, eight random samples are harvested for analysis and data collection. Biomass of the harvested plants is assessed to track total vegetative growth rate over time.

Harvested plants are dried to constant weight at 70°C in ovens at ORNL's Environmental Sciences Division facilities, then total biomass is recorded. Dried plant material is ground, then percent carbon and percent nitrogen content are measured. With knowledge of the number of plants per unit area in the AgPod, results can be scaled to quantify the total carbon that could be sequestered into the plant biomass on an annual basis, depending on the number of crop cycles and maximum CO_2 concentration levels.

To assess the impact of carbon dioxide treatments on plant photosynthetic performance, photosynthetic parameters are assessed under different treatment condition such as ambient (415ppm) and at higher CO_2 concentration levels. Plant photosynthetic performance is measured with specialized leaf gas exchange and fluorometry equipment (Figure 9). Response curves for photosynthetic light and CO_2 ire measured on three randomly selected plants using portable gas exchange systems (model LI-6800, Licor BioSciences). Photosynthetic response is normalized by leaf area and nitrogen content. Light response curves are completed by measuring the photosynthetic rate at progressively increasing light levels, from 0 to 1,800 µmol m^{-1} s^{-1} of photosynthetically active radiation. The CO_2 response curves are created by measuring the photosynthetic rate at progressively increasing atmospheric CO_2 levels, from 0 to 2,000 µmol m^{-1} s^{-1} of CO_2.

Figure 9. Photosynthesis measurements.

The major goals of the crop evaluation are to understand the amount of increase in crop yield at elevated CO_2 concentrations and determine how much CO_2 can potentially be captured and sequestered with the AgPod.

3. YEAR 1 RESULTS

Results from the first year indicated that photosynthesis increases with rising CO_2 concentrations, initially with a steep slope that then approaches a point of saturation above 1,100 ppm of atmospheric CO_2. The saturation light level varied by plant; maximum CO_2-saturated photosynthesis under ambient conditions was in the range of 40–50 µmol m^{-1} s^{-1} of net carbon dioxide removal. Higher CO_2 concentrations could lead to larger leaves and larger plants. Therefore, in 2024, the goal is to grow a crop in the AgPod at a higher CO_2 concentration level (1000 ppm) to determine if the plants grow larger.

Plant monitoring showed that about 30 days after leaf emergence, leaf width reaches its maximum, whereas leaf length keeps extending and new leaves continue emerging. Total plant biomass monitoring was started, but data were not processed at the time of reporting. These data will be used to determine the optimal harvest time for kale.

Photosynthesis measurements reveal several interesting properties of the AgPod-grown kale. First, the plants exhibited very high rates of photosynthesis, suggesting that the AgPod operation has the capability to outperform field conditions in atmospheric CO_2 uptake per unit area.

Among the key research findings, short-term elevated CO_2 applied to plants grown under ambient CO_2 conditions greatly enhances maximum net photosynthesis rates, doubling the amount of CO_2 removal from the atmosphere under high CO_2 conditions. Photosynthetic rates above 40 µmol CO_2 m^{-1} s^{-1} are very high compared with rates of non-AgPod grown plants.

Results with other systems grown under elevated CO_2 indicate that there can be feedback and down-regulation of photosynthetic capacity, depending on other limitations. This would, in effect, reduce the slope of the photosynthetic CO_2 response curves such that increasing CO_2 would have a reduced response on photosynthesis for plants grown under elevated CO_2 in comparison with plants grown under ambient CO_2. This will be evaluated in the next phase when plants are grown under elevated CO_2 conditions.

Data from ambient and elevated photosynthetic CO_2 response curves will also be used to assess if the underlying mechanistic limitations to photosynthesis are impacted by CO_2 treatments. Specifically, these are derived from the curves and estimate the maximum carbonylation rate, V_{cmax} (the rate of actual capture and conversion of atmospheric CO_2 to plant metabolites), J_{max} (the rate of conversion of solar energy to chemical potential energy based on electron transport within the leaf chloroplast membranes), and TPU (triosephosphate utilization, indicating if sugars produced by photosynthesis are being used). Optimal nutrition and fast vegetative growth rates of the kale suggest this last mechanistic limitation may not be realized.

4. YEAR 2 RESULTS

For the baseline crop grown in year 1, CO_2 concentration was equal to the ambient conditions, approximately 415 ppm. In year 2, the second crop was grown at a CO_2 concentration of 1000 ppm. Seedlings, shown in Figure 10, were grown in the nursery in the AgPod for approximately four weeks and then transplanted into growing panels. Figure 11 shows the crop growing in the AgPod approximately 9 weeks after transplanting.

Figure 10. Nursery seedlings.

Figure 11. Plants at nine weeks in panels.

Figure 12 shows the light response curves for Lacinato kale grown under ambient (415 ppm) CO_2 in 2023 or elevated (1000 ppm) CO_2 in 2024 in the AgPod at Oak Ridge National Laboratory. Two replicates are shown for the ambient CO_2 plants. For the elevated CO_2 plants, three replicates were used to measure light response curves at actual CO_2 growing conditions (triangles) and at ambient CO_2 levels (circles). Measurements were conducted on mature leaves on 35–36-day-old (ambient CO_2) or 50–53-day-old (elevated CO_2) plants.

The light response curves indicate that photosynthesis increases with increasing light levels and approaches a point of saturation above 1,200 µmol m^{-2} s^{-1} of light. The saturation light level varied by plant; instantaneous maximum light-saturated photosynthesis under ambient CO_2 conditions (at 415 ppm) ranged from about 20 to 30 µmol m^{-2} s^{-1} of net carbon dioxide removal and was not affected by the CO_2 concentrations that the plants developed under. However, under growing conditions, the elevated CO_2 plants had greater photosynthesis even at lower light levels. The enhancement of photosynthesis continued increasing with increasing light levels until saturating at about 40 µmol m^{-2} s^{-1}, 1.5X greater than plants grown under ambient conditions.

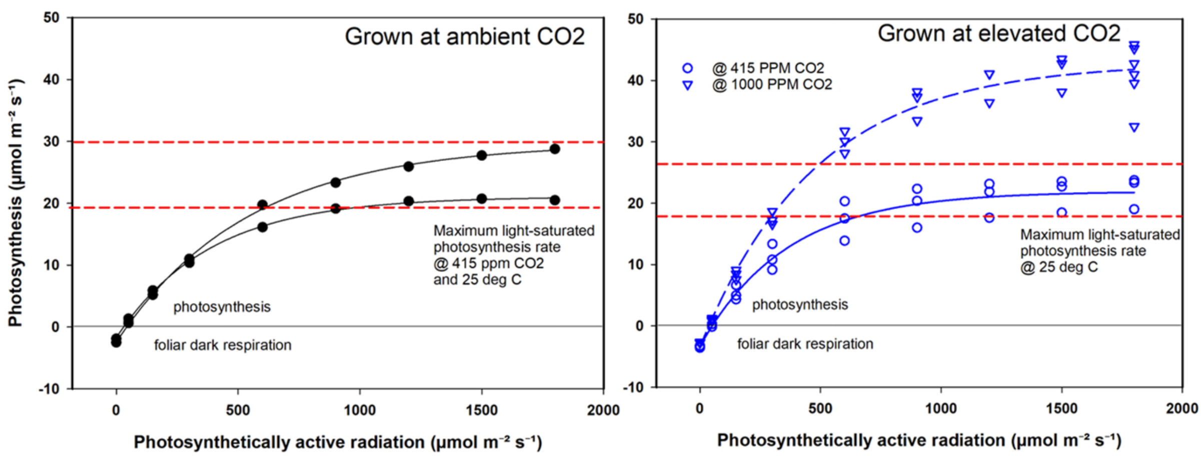

Figure 12. Light response curves for Lacinato kale at two CO_2 levels.

Figure 13 shows light-saturated CO_2 response curves for Lacinato kale grown under ambient (415 ppm) CO_2 or elevated (1000 ppm) CO_2 in the AgPod. Photosynthesis was measured at different atmospheric CO_2 conditions ranging from 0-2000 ppm CO_2 resulting in internal leaf concentrations up to 1400 ppm CO_2.

The CO_2 response curves illustrate how photosynthesis increases with rising CO_2 concentrations, initially with a steep slope that then approaches a point of saturation above 1,200 ppm of atmospheric CO_2 (when leaf internal CO_2 concentration (Ci) was ~1000 ppm). This result indicates that there may be even greater net carbon uptake for plants growing at CO_2 levels up to 1200 ppm vs the 1000 ppm used in the 2024 AgPod trials. Maximum CO_2 and light saturated photosynthesis varied by plant and plateaued in the range of 40–50 µmol m^{-1} s^{-1} of net carbon dioxide removal. This maximum rate was unaffected by the CO_2 concentrations that the plants developed under.

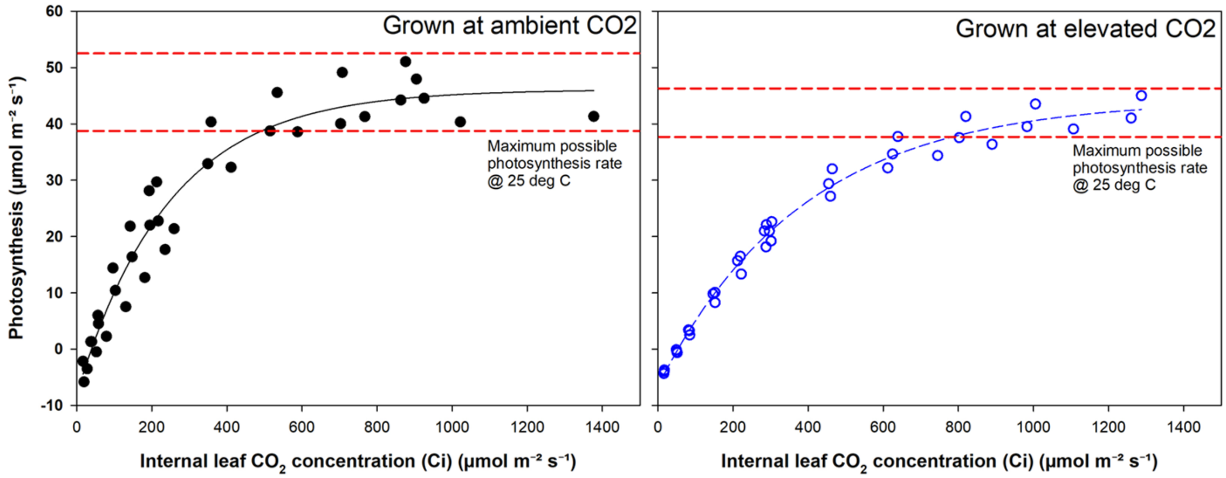

Figure 13. Light-saturated CO_2 response curves for Lacinato kale at two CO_2 levels

Leaf nitrogen concentration from Lacinato kale leaves measured for photosynthesis are shown in Figure 14. Mean ± standard error; n = 4 – 6 replicates. There was no difference in % C between CO_2 treatments; values were 39.1 ± 1.5 % or 42.0 ± 1.4% for ambient or elevated CO_2, respectively. There was no difference in the C:N ratio between CO_2 treatments; values were 5.5 ± 0.2 or 8.4 ± 1.1. Nitrogen content was lower for the elevated CO_2 plants, but these values are likely higher than needed by the plant, which may more typically be in the 3-4% range. The lower nitrogen content in elevated CO_2 plants did not seem to affect photosynthesis, e.g., Figure 12-13.

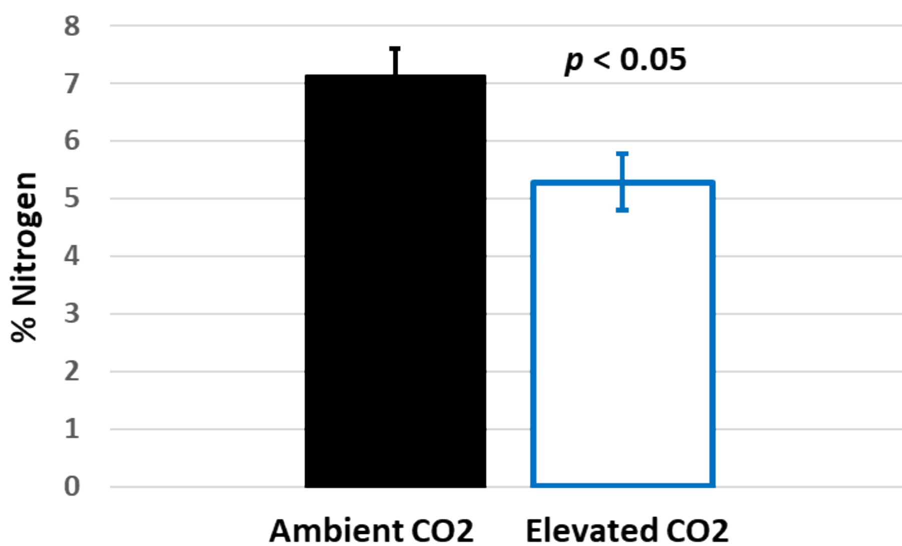

Figure 14. Leaf nitrogen concentration from Lacinato kale at two CO_2 levels.

Plant growth monitoring (Figure 15) at a both CO_2 treatments showed that approximately 5 weeks after leaf emergence, leaf length and width reaches its maximum, whereas new leaves continued emerging. There was no apparent difference in leaf size between CO_2 treatments. However, there was a large increase in the number of leaves for plants grown under elevated CO_2.

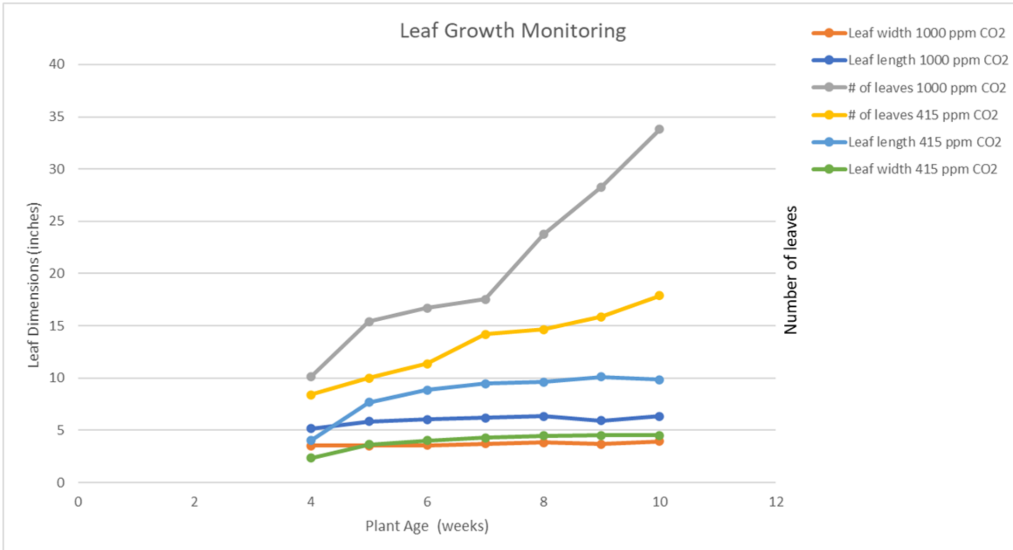

Figure 15. Leaf growth monitoring over time.

Figure 16 shows the biomass growth rate for Lacinato kale grown under ambient (415 ppm) or elevated (1000 ppm) CO_2 conditions. Data represent the combined root and shoot biomass components of harvested plants, ± standard error, n= 6 – 8 replicates. Plant biomass increased over time, and total plant biomass after 70 days was greater for the elevated CO_2 plants, indicating the enhanced photosynthesis at 1000 ppm did indeed lead to strong increases in net carbon uptake, with approximately 3X more carbon sequestered by 1000 ppm plants compared to the 415 ppm plants. In 2023, there were some differences in planting density (higher density than for the elevated CO_2 plants in 2024), and crop timing was staggered, leading to different aged plants growing in different parts of the AgPod growth panel system. This may have contributed some to the smaller harvest biomass in 2023. To evaluate this, a second ambient crop is currently being planted at the same density as the 2024 elevated CO_2 crop and will be grown under identical conditions except at 415 ppm. CO_2 plants.

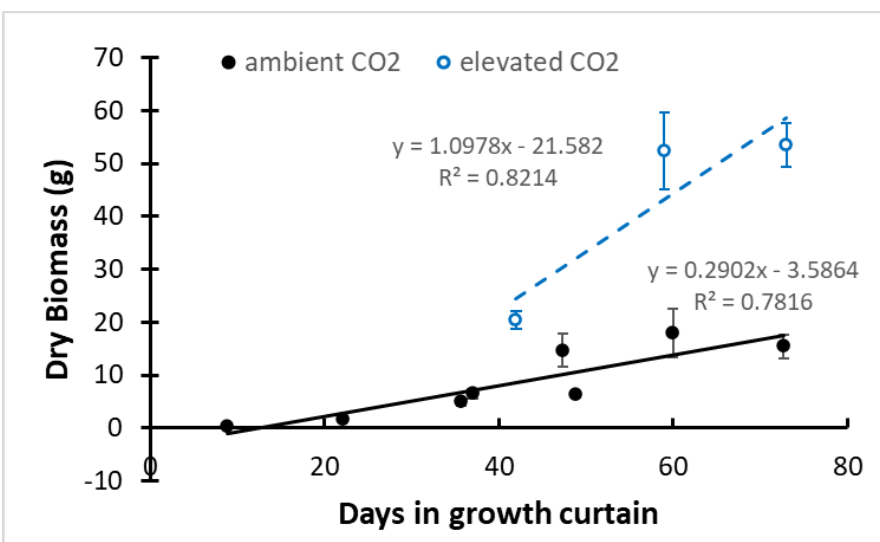

Figure 16. Biomass growth rate for Lacinato kale at two CO_2 levels.

5. CONCLUSIONS

Photosynthesis measurements reveal several interesting properties of the AgPod-grown kale. First, these are very high rates of photosynthesis, suggesting that the AgPod operation has the capability to outperform field conditions in atmospheric CO_2 uptake per unit area. Claims of the equivalent of 3 acres annual production by the manufacturer are plausible.

Among the key research findings, elevated CO_2 growth conditions significantly increased the rate of photosynthesis, which, along with more leaves per plant resulted in greater biomass accrual as compared with plants grown under ambient CO_2 conditions.

Results with other systems grown under elevated CO_2 indicate that there can be feedback and down-regulation of photosynthetic capacity, depending on other limitations. This would, in effect, reduce the slope of the photosynthetic CO_2 response curves such that increasing CO_2 would have a reduced response on photosynthesis for plants grown under elevated CO_2 in comparison with plants grown under ambient CO_2. We found no reduction in this slope (Figure 10-11), which is reflected by the enhanced net carbon uptake and fixation by plants grown under elevated CO_2 conditions.

Data from ambient and elevated photosynthetic CO_2 response curves can also be used to assess if the underlying mechanistic limitations to photosynthesis are impacted by CO_2 treatments. Specifically, these are derived from the curves and estimate the maximum carboxylation rate, V_{cmax} (the rate of actual capture and conversion of atmospheric CO_2 to plant metabolites), J_{max} (the rate of conversion of solar energy to chemical potential energy based on electron transport within the leaf chloroplast membranes), and TPU (triosephosphate utilization, indicating if sugars produced by photosynthesis are being used). Optimal nutrition and fast vegetative growth rates of the kale suggest this last mechanistic limitation may not be realized.

Many large-scale field studies on elevated CO_2 plant growth enhancement show that CO_2 enhancement primarily occurs under limited conditions, such as in tandem with water limitation (Ainsworth and Long 2004). Another important consideration is plant nutrient content under elevated CO_2 conditions. Plants can acclimate to higher CO_2 by decreasing plant nitrogen (Ainsworth and Long 2004), and this can result in lower leaf nitrate and total plant protein concentration (Taub et al. 2008; Dong et al. 2018). However, even though nitrogen content was lower for the elevated CO_2 plants, these values are likely higher than needed by the plant and did not seem to affect photosynthesis.

Our results suggest that growing kale plants in the AgPod system at higher CO_2 levels resulted in a successful and highly productive crop, up to three times the amount grown at 415 CO_2. Further, the kale plants grown under higher CO_2 conditions (1000 ppm) are not CO_2 saturated and can potentially further improve yield at even higher CO_2 environments.

The promising results show that this system has the potential to provide a sustainable agricultural solution that can both increase food availability, especially in urban environments, and contribute to carbon capture and utilization for a net zero carbon future.

6. FY 2025 PLANS

The following major tasks are planned for FY 2025:

Task 1. Complete the automated DAC/utilization system (ADUS) – Complete the testing of the ADUS with the carbon capture material integrated with the wheel and develop a control system to accurately deliver the correct amount of CO_2 to the AgPod during the crop growing cycle.

Task 2. Integrate the ADUS in the AgPod – The ADUS infrastructure developed in Task 1 will be integrated into the AgPod with ducting to achieve a standalone unit that will enable the seamless transfer of captured CO_2 to the AgPod during the regeneration process.

Task 3. Install the data acquisition system in Veterans Home – Install all instrumentation and perform shakedown testing to ensure all channels are reading accurately. Verify remote access to site.

Task 4. Initiate data acquisition and analysis – Monitor energy consumption of space conditioning (six residential units and common areas), water heating equipment for six residential units, and solar array output. Perform analysis on a monthly basis and identify any channel errors.

Task 5. Complete crop testing in the AgPod – Plant third crop at same density as first crop and evaluate growth and conduct photosynthesis and biomass measurements. Evaluate results and compare against previous crops.

Task 6. Report on third crop grown in AgPod and analysis of energy use, solar array output, and overall carbon emission and savings at Veteran's Home.

Task 7. Deploy the AgPod with ADUS (dependent on funding) – Deploy an AgPod or greenhouse at Veteran's Home site. Install ADUS on AgPod. Train residents in seeding, harvesting, and maintenance.

7. REFERENCES

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