Rit LbhÍ nr. 165

„Áhrif lýsingar og CO_2 auðgunar á vöxt, uppskeru og gæði gróðurhúsatómata“

FINAL REPORT

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Stjórnarráð Íslands
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Abbreviations

E.C.	electrical conductivity
HPS	high-pressure vapour sodium lamps
kWh	kilo Watt hour
LED	light-emitting diodes
pH	potential of hydrogen
ppm	parts per million
W	Watt
Wh	Watt hours

Other abbreviations are explained in the text.

1 SUMMARY

In Iceland, winter production of greenhouse crops is totally dependent on supplementary lighting and has the potential to extend seasonal limits and replace imports during the winter months. Adequate guidelines for winter cultivation of tomatoes under HPS lamps and different concentrations of CO_2 enrichment are not yet in place for tomato production and need to be developed. The objective of this study was to test how supplemental lighting and different amounts of CO_2 enrichment are affecting growth, yield and quality of tomatoes during the winter and to evaluate the profit margin.

An experiment with ungrafted tomatoes (*Lycopersicon esculentum* Mill. cv. Completo) was conducted from the end of November 2022 to the end of March 2023 at the experimental greenhouse at Reykir, which was under the Agricultural University of Iceland, but is now under the Sudurland College. Tomatoes were grown in rockwool plugs in three replicates with 2,5 tops/m^2 with one top per plant. Four different CO_2 treatments with supplemental HPS top lighting (450-470 µmol/m^2/s) for a maximum of 16 hours light were tested: 1. ambient CO_2 level (0 ppm CO_2), 2. 600 ppm CO_2 enrichment (600 ppm CO_2), 3. 900 ppm CO_2 enrichment (900 ppm CO_2), 4. 1200 ppm CO_2 enrichment (1200 ppm CO_2). The temperature was set on 18°C (day and night). The heating pipes were set to 35°C after transplanting and increased to 40°C in the middle of January and to 45°C in the middle of february. The tomatoes received standard nutrition through drip irrigation. The interaction of supplemental light and the CO_2 concentration were tested, and the profit margin was calculated.

CO_2 enrichment had an influence on the appearance of the plant: The distance between clusters was significantly lower at the enriched CO_2 treatments and tendentially one more cluster developed, while the height of the plant was not affected by the amount of CO_2. In addition, the cluster length was extended with increasing CO_2 enrichment. Water use efficiency increased under enriched compared to ambient CO_2 conditions. Plants had thicker leaves with CO_2 enrichment. Thus, leaf temperature decreased significantly with increasing CO_2 enrichment.

Tomatoes under CO_2 enrichment gave a higher total yield. The early yield and the marketable yield in weight and number of fruits was also higher. In addition, fruits had a significantly higher average weight. Marketable yield was twice as high with CO_2

enrichment. However, the amount of CO_2 enrichment did not affect marketable yield significantly, but first-class yield increased due to heavier fruits and a higher number of marketable fruits, while second-class yield was independent of the CO_2 enrichment in weight and number of fruits. The high yield of „600 ppm CO_2“ compared to the other two CO_2 enrichment treatments might be caused by the higher substrate temperature of plants, while air temperature was comparable between CO_2 treatments.

Marketable yield was 40% under ambient conditions, due to a very high amount of too small fruits. However, with CO_2 enrichment marketable yield could be increased to more than 60%. Thereby, the amount of first-class fruits on total yield increased with increasing CO_2 enrichment, while the percentage of too small fruits and green fruits was independent of CO_2 enrichment.

As daily usage of kWh's was comparable between CO_2 treatments, used kWh's were better transferred into yield when tomatoes were enriched with CO_2 compared to plants grown under ambient CO_2 conditions. Light related costs (electricity costs + investment into lights) decreased slightly with a higher CO_2 enrichment from 44% to 35% of total production costs, while CO_2 costs increased from 18% to 38%.

When the lowest amount of CO_2 was applied compared to the ambient CO_2 treatment, yield was increased by 8,5 kg/m^2 and profit margin by 2.600 ISK/m^2. Increasing the CO_2 enrichment further to "900 ppm CO_2" compared to "600 ppm CO_2" resulted in 0,2 kg/m^2 less yield and 1.600 ISK/m^2 less profit margin. The highest CO_2 enrichment gave compared to "900 ppm CO_2" 0,8 kg/m^2 more yield, but 2.600 ISK/m^2 less profit margin.

Possible recommendations for saving costs other than lowering the electricity costs are discussed. It can be advised to grow tomatoes under supplemental light and CO_2 enrichment. However, from the economic side it is recommended not to exceed more than 900 ppm CO_2 enrichment. More scientific studies are needed with different CO_2 enrichment and PPFD values to find the best combination on these factors.

YFIRLIT

Vetrarræktun í gróðurhúsum á Íslandi er algjörlega háð aukalýsingu. Viðbótarlýsing getur lengt uppskerutímann og komið í stað innflutnings að vetri til. Fullnægjandi leiðbeiningar vegna vetrarræktunar á tómötum undir lýsingu við HPS lampa og mismunandi styrkleika af CO_2 auðgun eru ekki til staðar og þarfnast frekari þróunar. Markmiðið var að prófa samspil ljóss og mismunandi styrkleika CO_2 auðgunar á vöxt tómata, uppskeru og gæði yfir háveturinn og hvort það væri hagkvæmt.

Gerð var tilraun með óágrædda tómata (*Lycopersicon esculentum* Mill. cv. Completo) frá lok nóvember 2022 og fram til lok mars 2023 í tilraunagróðurhúsi sem var áður undir Landbúnaðarháskóla Íslands, en er núna undir Fjölbrautaskóla Suðurlands. Tómatarnir voru ræktaðir í steinullarmottum í þremur endurtekningum með 2,5 toppi/m^2 með einum toppi á plöntu. Prófaðar voru fjórar mismunandi CO_2 meðferðir með HPS topplýsingu (450-470 µmol/m^2/s) að hámarki í 16 klst. ljós: 1. náttúrulegar CO_2 aðstæður (0 ppm CO_2), 2. 600 ppm CO_2 auðgun (600 ppm CO_2), 3. 900 ppm CO_2 auðgun (900 ppm CO_2), 4. 1200 ppm CO_2 auðgun (1200 ppm CO_2). Hiti var 18°C (dag og nótt). Hitarör voru stillt á 35°C eftir útplöntun og hækkað í 40°C um miðjan janúar og í 45°C um miðjan febrúar. Tómatarnir fengu næringu með dropavökvun. Áhrif ljóss og CO_2 auðgunar voru prófaðar og framlegð reiknuð út.

CO_2 auðgun hafði áhrif á plönturnar: Millibil milli klasa var marktækt minni við CO_2 auðgun og plönturnar virðast vera með einn klasa í viðbót, á meðan hæð plantnanna varð ekki fyrir áhrifum af aukningu á CO_2. Að auki jókst klasalengdin með aukinni CO_2 auðgun. Vatnsskilvirkni jókst við CO_2 auðgun samanborið við nátturulegar CO_2 aðstæður. Plönturnar höfðu þykkara lauf með aukinni CO_2 auðgun. Þannig að blaðhiti lækkaði marktækt með aukinni CO_2 auðgun.

Tómatar undir CO_2 auðgun voru með meiri heildaruppskeru. Fyrri uppskera og markaðshæfrar uppskeru í þyngd og fjöldi uppskorinna aldina var einnig meiri. Að auki voru aldin með marktækt hærri meðalþyngd. Markaðshæf uppskera var tvöfalt meiri með CO_2 auðgun. Styrkleikar af CO_2 auðgun hafa hins vegar ekki marktæk áhrif á markaðshæfni uppskeru, en fyrsta flokks uppskera jókst vegna meiri þyngdar aldins og aukins fjölda markaðshæfra aldina. Mikil uppskera í „600 ppm CO_2“ samanborið við hinar tvær CO_2 auðgunarmeðferðirnar gæti orsakast af hærri hita í ræktunarefni plantanna, en lofthiti var sambærilegur milli CO_2 meðferða.

Hlutfall uppskerunnar sem hægt var að selja var 40% við náttúrulegar CO_2 aðstæður og orsakast það vegna mjög mikils magns af of litlum aldinum. Hins vegar, með CO_2 auðgun jókst markaðshæfni uppskeru í meira en 60%. Þar með jókst magn fyrsta flokks aldina af heildaruppskeru með aukinni CO_2 auðgun, en hlutfall of lítilla aldina og grænna aldina var óháð styrkleika af CO_2 auðgun.

Þar sem dagleg notkun á kWh's var sú sama milli CO_2 meðferða, var skilvirkni orkunotkunar meiri með CO_2 auðgun samanborið við plönturnar sem ræktaðar voru við náttúrulegar CO_2 aðstæður. Ljósatengdur kostnaður (orkukostnaður + fjárfesting í ljósum) minnkaði lítillega með meiri CO_2 auðgun úr 44% í 35% af heildarframleiðslukostnaði, á meðan CO_2 kostnaður jókst úr 18% í 38%.

Þegar minnsta magn af CO_2 auðgun var borin saman við meðferð með náttúrulegu CO_2, jókst uppskera um 8,5 kg/m^2 og framlegð um 2.600 ISK/m^2. Að auka CO_2 enn frekar í „900 ppm CO_2" samanborið við „600 ppm CO_2", leiddi til 0,2 kg/m^2 minni uppskeru og 1.600 ISK/m^2 minni framlegð. Hæsta CO_2 auðgunin gaf samanborið við „900 ppm CO_2" 0,8 kg/m^2 meiri uppskeru, en 2.600 ISK/m^2 minni framlegð.

Möguleikar á að lækka kostnað, með öðrum hætti en að lækka rafmagnskostnað, eru taldir upp í umræðukaflanum í þessari skýrslu. Þar er ráðlegt að rækta tómata undir viðbótarljósi og CO_2 auðgun. En mælt er með því að CO_2 auðgun ætti ekki að vera meiri en 900 ppm CO_2 til að ná fram hagvæmni. Fleiri rannsóknir eru nauðsynlegar með mismunandi CO_2 auðgun og PPFD gildi til að finna bestu samsetningu þessara þátta.

2 INTRODUCTION

The extremely low natural light level is the major limiting factor for winter greenhouse production in Iceland and other northern regions. Therefore, supplementary lighting is essential to maintain year-round vegetable production. This could replace imports from lower latitudes during the winter months and make domestic vegetables even more valuable for the consumer market.

The positive influence of artificial lighting on plant growth, yield and quality of tomatoes (*Demers* et al., 1998a), cucumbers (*Hao* & *Papadopoulos*, 1999) and sweet pepper (*Demers* et al., 1998b) has been well studied. It is often assumed that an increment in light intensity results in the same yield increase (*Marcelis* et al., 2006). Indeed, yield of sweet pepper in the experimental greenhouse of the Agricultural University of Iceland at Reykir increased with light intensity (*Stadler* et al., 2010). However, with tomatoes, a higher light intensity resulted either not (*Stadler*, 2012) or in only a slightly higher yield (*Stadler*, 2013).

Supplemental lighting that is normally used in greenhouses has either no, or only a small amount of UV-B radiation. High pressure sodium (HPS) lamps are the most commonly used type of light source in greenhouse production due to their appropriate light spectrum for photosynthesis and their high efficiency. The spectral output of HPS lamps is primarily in the region between 550 nm and 650 nm and is deficient in the UV and blue region (*Krizek* et al., 1998). However, HPS lights suffer from restricted controllability and dimming range limitations (*Pinho* et al., 2013). It has been common in Iceland to use HPS lamps with electromagnetic ballast. However, HPS lamps with electronic ballast will save about 8% energy according to the company Gavita (*Nordby*, oral information). This is especially important as the energy costs represent a high proportion of total production costs of vegetables.

Light-emitting diodes (LED) have been proposed as a possible light source for plant production systems and have attracted considerable interest in recent years with their advantages of reduced size and minimum heating plus a longer theoretical lifespan compared to high intensity discharge light sources such as HPS lamps (*Bula* et al., 1991). These lamps are a radiation source with improved electrical efficiency (*Bula* et al., 1991), in addition to the possibility to control the light spectrum and the light intensity which is a good option to increase the impact on growth and plant development. Several plant species (tomatoes, strawberries, sweet pepper, salad, radish) have been successfully cultured under LEDs (e.g. *Philips*, 2017; *Philips*, 2015; *Tamulaitis* et al., 2005; *Schuerger* et al., 1997; *Brown* et al., 1995; *Hoenecke* et al., 1992). However, with HPS a significantly higher fresh yield of salad was achieved in comparison to LEDs. Two times more kWh was necessary with only HPS lights in comparison with only LEDs. The only use of HPS lights resulted in the highest yield, while the yield with only LEDs was about ¼ less (*Stadler,* 2015). In contrast, the light source did not affect the weight of marketable yield of strawberries. The development of flowers and berries and their harvest was delayed by two weeks under LED lights. This was possibly related to a higher leaf temperature in the HPS treatment due to additional radiation heating. However, nearly 45% lower daily usage of kWh's under LEDs were recorded (*Stadler*, 2018). These results are requesting scientific studies with different temperature settings to compensate the additional heating by the HPS lights and the delayed growth and harvest. When the air temperature was adapted, it was possible to compensate the additional heating by the HPS lights and prevent a delayed growth and harvest (*Stadler*, 2019; *Stadler*, 2020). The yield of tomatoes was the same with Hybrid top lighting (454 µmol/m^2/s, HPS:LED 2:1) and only HPS top lighting (472 µmol/m^2/s). In addition, no energy savings were registered because lighting costs were reduced by using 1000 W bulbs instead of 750 W bulbs (*Stadler*, 2022). A better PAR value could be reached by adjusting the height of lamps in dependence to the plant canopy (*Stadler*, 2022). The Icelandic greenhouse growers are still using a high light intensity with HPS lights and therefore the present experiment was conducted with this light source.

In addition to the yield, the quality of the harvest is also important. Light conditions, together with other environmental variables (e.g., temperature, humidity, CO_2 concentration) affect the yield and quality of crops, so adjusting the environmental growing conditions "light" and amount of CO_2 within the greenhouse is a key to obtaining good yields of high-quality products (*Tewolde* et al., 2016; *Mamatha* et al., 2014; *Gruda*, 2005). Because CO_2 is a key issue for photosynthesis, the use of CO_2 is widely recognized as a key technique to increase photosynthesis and with that increased yield and profit margin (*Chalabi* et al., 2002; *Nilsen* et al., 1983). Numerous studies have shown that CO_2 enrichment can increase growth, affect physiology and increase both yield and quality of tomatoes (*Ikeda* et al., 2020; *Mamatha* et al., 2014;

Nilsen et al., 1983; *Yelle* et al., 1990). *Hicklenton* & *Jolliffe* (1978) reported that flowers opened about three days earlier in the CO_2 enriched plants (800-1000 ppm CO_2) and the number of clusters was always significant greater in the enriched treatment and 30% more yield was optained compared to the treatment with no CO_2 enrichment. According to *Lanoue* et al. (2018) plants grown under CO_2 enrichment (1000 ppm CO_2) flowered eight days earlier and were approximately 15 cm taller than those grown without CO_2 enrichment. If the increase in CO_2 amount is compared, the higher yield of tomatoes was achieved with 700 ppm CO_2 than with 550 ppm CO_2 and this can be attributed to the heavier fruits at 700 ppm CO_2 (*Rangaswamy* et al., 2021).

The combination of CO_2 enrichment and supplemental lighting can have a greater positive effect on plant growth and yield than the increase of either factor alone (*Huber* et al., 2021; *Pan* et al., 2019), although the effect of supplemental lighting on yield was better than CO_2 enrichment when both environmental factors are compared (*Pan* et al., 2019). However, the effect of CO_2 enrichment is usually adjusted according to light conditions (*Kaiser* et al., 2017). Therefore, supplemental lighting and CO_2 enrichment should be combined (*Pan* et al. 2019; *Bergstrand* et al., 2016), because these factors have a positive interactive effect on the growth of the plants by promoting the uptake of nutrients by changing the distribution of dry weight and thus increasing yield (*Pan* et al., 2019). CO_2 enrichment has also been shown to contribute to an earlier harvest (*Nilsen* et al., 1983). A higher amount of CO_2 and a higher light intensity promote, among other things, growth and dry matter accumulation (*Pan* et al., 2020). Their data indicate that a combination of higher CO_2 amount (800 ppm CO_2) and a high PPFD (400 µmol/m^2/s) is optimal for tomato growth (compared were 400 and 800 ppm CO_2 with 200, 300 og 400 µmol/m^2/s).

In Iceland, it can be calculated that the CO_2 costs are distributing to 20% of the total production costs of tomatoes (*Stadler*, 2020). Therefore, the use of CO_2 in greenhouses is quite expensive, and one can ask whether CO_2 enrichment is reflected in an adequate profit margin compared to the yield increase, or whether the use of CO_2 should be restricted. In this context, it must be mentioned that exess use of CO_2 not only increased production costs, but also has a negative effect of plant growth. An appropriate management system of CO_2 needs to be developed. Therefore, research into whether CO_2 enrichment can improve tomato yield in greenhouses sufficiently, considering the costs is well worth investigating.

Experience of the effect of the CO_2 amount in growing tomatoes under HPS top lighting is not available in Iceland. Therefore, the effect of the amount of the CO_2 level on yield over the high winter (with low levels of natural light) needs to be tested under Icelandic conditions. Incorporating lighting and use of CO_2 into a production strategy is an economic decision involving added costs versus potential returns. Therefore, the question arises whether these factors are leading to an appropriate yield of tomatoes.

The objective of this study was to test if (1) the interaction of the CO_2 amount and HPS lighting is affecting growth, yield and quality of tomatoes, if (2) this parameter is converted efficiently into yield, and if (3) the profit margin can be improved by the level of the CO_2 enrichment. This study should strengthen the knowledge on the best method of growing tomatoes and give vegetable growers advice of how to improve their production by modifying the efficiency of tomato production.

3 MATERIALS AND METHODS

3.1 Greenhouse experiment

An experiment with ungrafted tomatoes (*Lycopersicon esculentum* Mill. cv. Completo) and different CO_2 treatments (see chapter “3.2 Treatments”) was conducted at Reykir, formerly under the Agricultural University of Iceland, but now under the Sudurland College (FSu), during winter 2022/2023.

Completo from De Ruiter is a compact vigorous variety suitable for truss and loose harvest with a high yielding potential and uniform fruit weight of 90-95 g (*De Ruiter*, without year).

On 18.10.2022 seeds of tomatoes were sown in rockwool plugs. On 24.11.2022 four plants with one top/plant were planted into rockwool slabs (50 cm x 24 cm x 10 cm). On each bed six slabs were placed in four chambers. Tomatoes were transplanted in rows in three 65 cm high beds (Fig. 1) with 2,5 plants/m^2. Beds were equipped with six slabs respectively 24 tops. Three replicates, one replicate in each bed consisting of two slabs (8 plants) acted as subplots for measurements. Other slabs were not measured. Due to the weekly hanging down, all plants were once at the end of the bed.

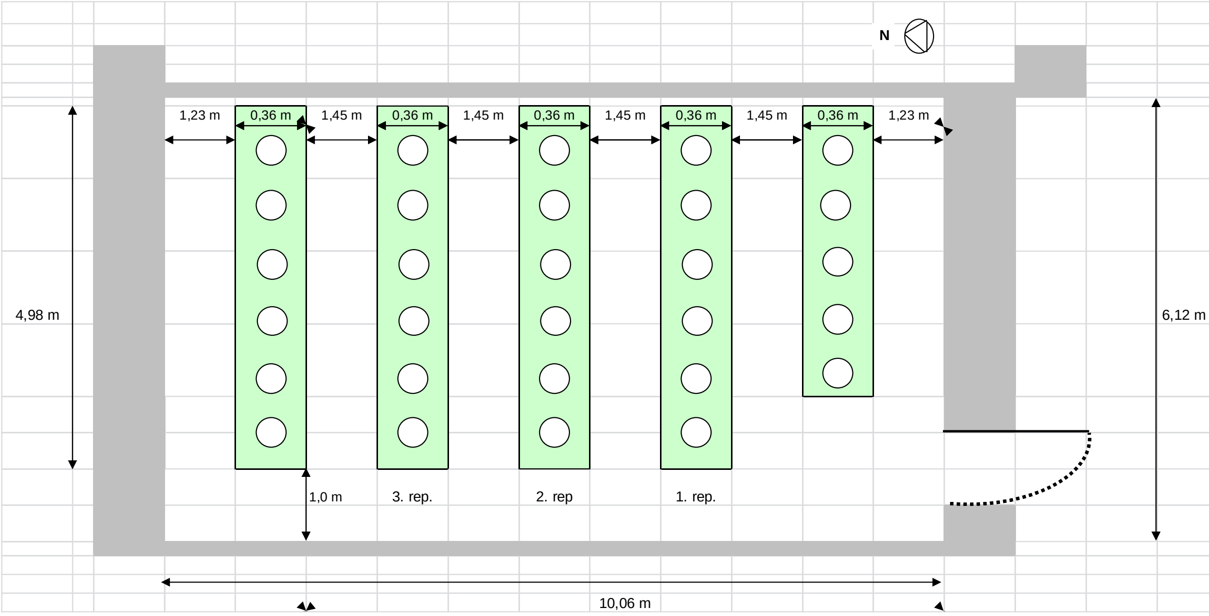


Fig. 1: Experimental design of cabinets.

Shoots were regularly taken of the plants and the plants were deleafed once a week according to 15 leaves per plant or more leaves depending on the condition of the plants. The weekly deleafing was done in the way that most of the time two leaves were taken of the bottom and one top leaf was taken at the upper flowering cluster to create a more open and generative plant habit. That improves light penetration and air circulation and prevents fungal diseases and aphids. The removal of young leaves reduces the total vegetative sink-strength and favours assimilate partitioning into the fruit (*Heuvelink* et al., 2005). Double clusters were removed. Fruits on each cluster were not pruned enabling a high yield potential. Plants were not topped during the experiment to be able to have a "normal" growth until the end of the experiment and to conduct measurements. Wires were placed in 3,5 m height from the floor. Handpollination was used instead of bumblebees to guarantee an even pollination among chambers.

The temperature was set on 18°C / 18°C (day / night) to be able to keep a measured temperature difference between day and night. Ventilation started at 22°C. The underheat was set to 35°C. The heating pipes were increased from 35°C to 40°C on 16.01.2023, and to 45°C on 15.02.2023. Different amounts of CO_2 were applied (see 3.2 Treatments). A misting system was installed. Humidity was set to 70%. Plant protection was planned to manage by beneficial organisms, but as there were no white flies present, no En-Strip (Parasitic wasp, *Encarsia Formosa*) was used.

Tomatoes received standard nutrition consisting of “YaraTera™ Ferticare™ Tomato”, calcium nitrate and potassium nitrate according to the following fertilizer plan (Tab. 1).

Tab. 1: Fertilizer mixture.

Fertilizer (amount in kg)	Stem solution A (100 l)		Stem solution B (100 l)	Irrigation water	Runoff water
	YaraTera™ Ferticare™ Tomato	Potassium nitrate	Calcium nitrate	E.C. (mS/cm)	E.C. (mS/cm)
Planting - flowering on 3. cluster	15		19	5	4-6
Flowering on 3.-6. cluster	15	2	19	5	4-6
Flowering from 6. cluster onwards	15	6	18	5	4-6

Plants were irrigated through drip irrigation (4 tubes per slab). The watering was set up that the plants could root well down, which means a low amount of runoff in the first 2-3 weeks. The slabs were watered with an E.C. of 4-5. The irrigation (100 ml/drip) was arranged to 30% runoff with an E.C. in the drip of 4-6. The first watering was one hour after the lights were turned on and the last watering was one hour before the lights were turned off. The irrigation interval was variable in accordance with the runoff.

3.2 Treatments

Tomatoes were grown from 24.11.2022 until 29.03.2023 under different CO_2 treatments in four cabinets at Reykir:

1. HPS top lighting, ambient CO_2 level, no CO_2 applied, **0 ppm CO_2**
2. HPS top lighting, 600 ppm CO_2 enrichment, **600 ppm CO_2**
3. HPS top lighting, 900 ppm CO_2 enrichment, **900 ppm CO_2**
4. HPS top lighting, 1200 ppm CO_2 enrichment, **1200 ppm CO_2**

While in one chamber no additional CO_2 to the ambient CO_2 amount was applied, in the other chambers was either 600, 900, or 1200 ppm CO_2 provided. Also, with ventilation the desired CO_2 amount was applied. The ambient CO_2 amount in the air during winter is in Iceland 430 ppm CO_2 according to the Global Monitoring Laboratory (n.d.).

To test if the CO_2 enrichment had an influence on the yield of tomatoes, plants that got only the ambient CO_2 amount were compared to plants that got a low amount of CO_2 (compare 1 and 2). In addition, it was tested which CO_2 enrichment can be used to increase yield and profit margin (compare 2 and 3, compare 3 and 4).

HPS lights were used with an electronic ballast and 1000 W bulbs (Philips) to reduce lighting costs. The lamps were distributed in the way that tomatoes got the most equal light distribution according to the light plan of Agrolux (Tab. 2). HPS lamps were mounted horizontally in 1,0 m distance over the canopy, which corresponds to a height of 4,5 m from the floor.

White plastic on the surrounding walls helped to get a higher light level at the edges of the growing area. The µmol level of the lights amounted 446-469 µmol/m^2/s and was therefore comparable between the CO_2 treatments (Tab. 3). The setup of the HPS lights corresponded to 300 W/m^2 (HPS). Light was provided from 05:00-21:00 until 03.02.2023 and after that from 03:00-19:00.

Tab. 2: Number of lights and their distribution in the chambers.

CO_2 treatment	Lights	Lights/chamber (no)	Distance between lights
0 ppm CO_2, 600 ppm CO_2, 900 ppm CO_2, 1200 ppm CO_2	HPS top lighting	16	3 C profiles with 4 / 6 HPS, 1,75 m for HPS distance centre centre and 2 m for HPS centre centre

Tab. 3: Light distribution in the chambers.

	CO_2 (ppm)			
	0	600	900	1200
Measurement points	(µmol/m^2/s)			
1,5 m (floor to top lights)	362	372	372	375
2,0 m (floor to top lights)	398	410	418	428
2,5 m (floor to top lights)	475	482	506	518
3,0 m (floor to top lights)	546	545	578	553
Top lighting (average)	**446**	**452**	**469**	**468**

3.3 Measurements, sampling and analyses

Substrate temperature was measured in 1-2 cm depth by a portable thermometer (TP1110-HD2307.0 Temperature meter, Nieuwkoop, Aalsmeer, The Netherlands) and leaf temperature by a portable infrared contact thermometer (BEAM infrared thermometer, TFA Dostmann GmbH & Co. KG, Wertheim-Reicholzheim, Germany) by hand. The amount of fertilization water (input, runoff) was measured every day.

To be able to determine plant development, in all treatments the weekly growth, the number of leaves, leaf length, the number of clusters, the number of open flowers, the diameter of head on the highest flowering cluster, the distance between clusters, the length of clusters, the diameter of the cluster and total fruits per cluster was measured each week on six plants.

During the harvest period fruits were regularly collected (two times per week) in the subplots. Total fresh yield, number of fruits, fruit category (A-class (> 55 mm), B-class (45-55 mm) and not marketable fruits (too little fruits (< 45 mm), fruits with blossom end rot) was determined. At the end of the experiment on each plant from the subplots the number of immature fruits (green) were counted by harvesting five clusters with only green fruits above the last harvested cluster with mature fruits.

The interior quality of the fruits was determined. A brix meter (Pocket Refractometer PAL-1, ATAGO, Tokyo, Japan) was used to measure sugar content in the fruits at the beginning, in the middle and at the end of the growth period.

Energy use efficiency (total cumulative yield in weight per kWh) and costs for lighting per kg yield were calculated for economic evaluation and the profit margin was determined.

3.4 Statistical analyses

SAS Version 9.4 was used for statistical evaluations. The results were subjected to one-way analyses of variance with the significance of the means tested with a Tukey/Kramer HSD-test at $p \leq 0,05$.

4 RESULTS

4.1 Environmental conditions for growing

4.1.1 Solar irradiation

Solar irradiation was allowed to come in the greenhouse. Therefore, incoming solar irradiation was affecting plant development and was regularly measured. The natural light level was low during the whole growth period. The value after transplanting was less than 1 kWh/m^2 at the beginning of November and was staying at this value until the end of January. With longer days increased solar irradiation naturally continuously, however with up to 6 kWh/m^2 was this value still low (Fig. 2).

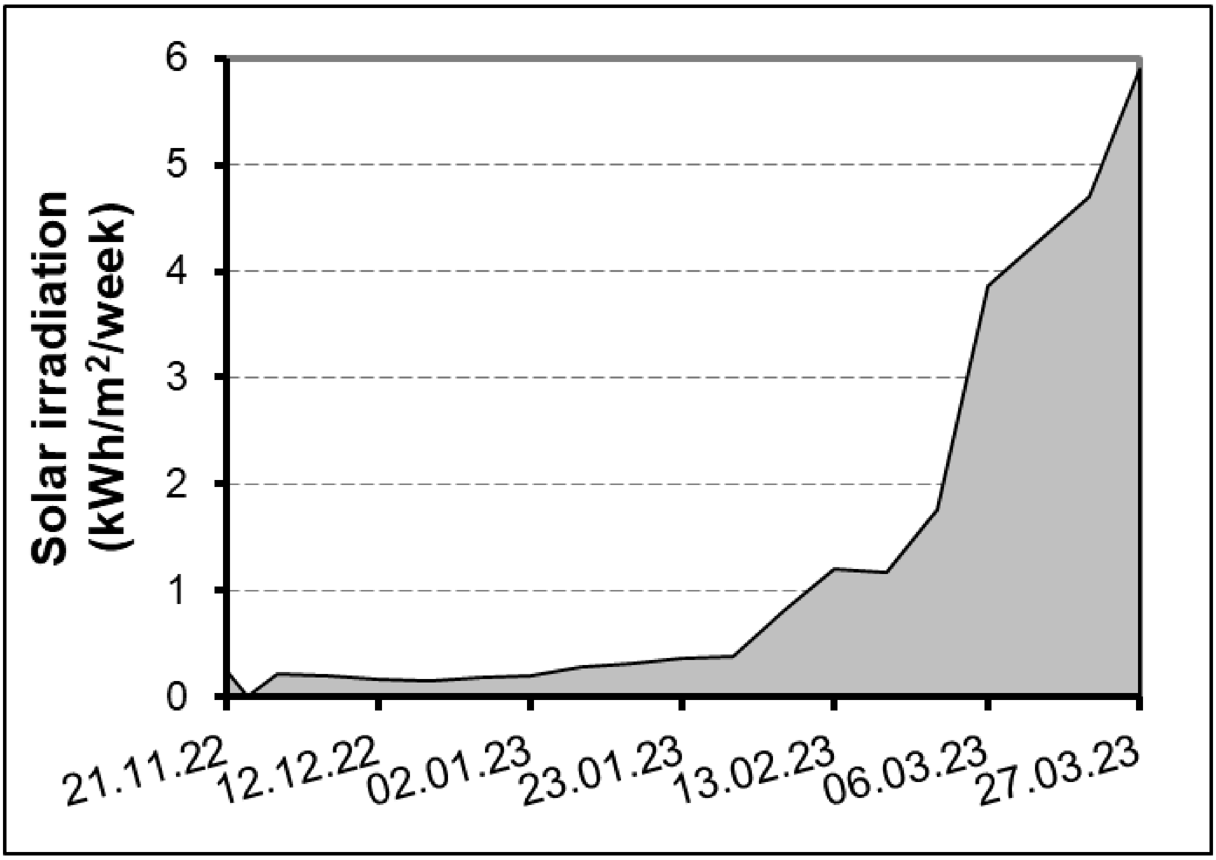


Fig. 2: Time course of solar irradiation.
Solar irradiation was measured every day and values for one week were cumulated.

4.1.2 Chamber settings

The settings in the chambers were regularly recorded. Table 4 shows the average of the air temperature, floor temperature, CO_2 amount, windows opening and humidity.

The average air temperature amounted less than 22°C and was very similar between the CO_2 treatments. The average air temperature during the day was about 22,5°C in all treatments and the average night temperature was less than 20°C.

The floor temperature during the day was comparable between the CO_2 treatments. The floor temperature during the night increased with a higher amount of CO_2.

The mean CO_2 amount increased naturally with increasing CO_2 enrichment. However, five days after planting was the CO_2 tank empty and it took the CO_2 selling company two weeks to supply CO_2. This is the reason for the lower average CO_2 levels compared to the desired CO_2 enrichment. However, normally the desired CO_2 enrichment could be kept during the day. Windows were in all treatments most of the time closed. Humidity amounted to 57-64%.

Tab. 4: Chamber settings according to greenhouse computer.

Greenhouse computer data (Average over the experimental period)	**CO_2 (ppm)**			
	0	**600**	**900**	**1200**
Air temperature (°C)	21,6	21,8	21,6	21,5
day (°C)	22,4	22,7	22,4	22,5
night (°C)	19,9	19,9	19,8	19,9
Floor temperature day (°C)	40,5	40,4	40,8	40,1
Floor temperature night (°C)	40,1	38,6	41,5	42,6
CO_2 (ppm)	372	564	819	1068
Windows opening 1 (%)	1,6	1,5	0,9	1,0
Windows opening 2 (%)	3,9	4,6	4,0	3,7
Humidity (%)	64	62	57	59

4.1.3 Substrate temperature

Substrate temperature was measured weekly at low solar radiation at around noon and it fluctuated between 19-23°C. Substrate temperature was on average significantly higher for “600 ppm CO_2” compared to the other CO_2 treatments. On average amounted this difference 0,5°C (Fig. 3).

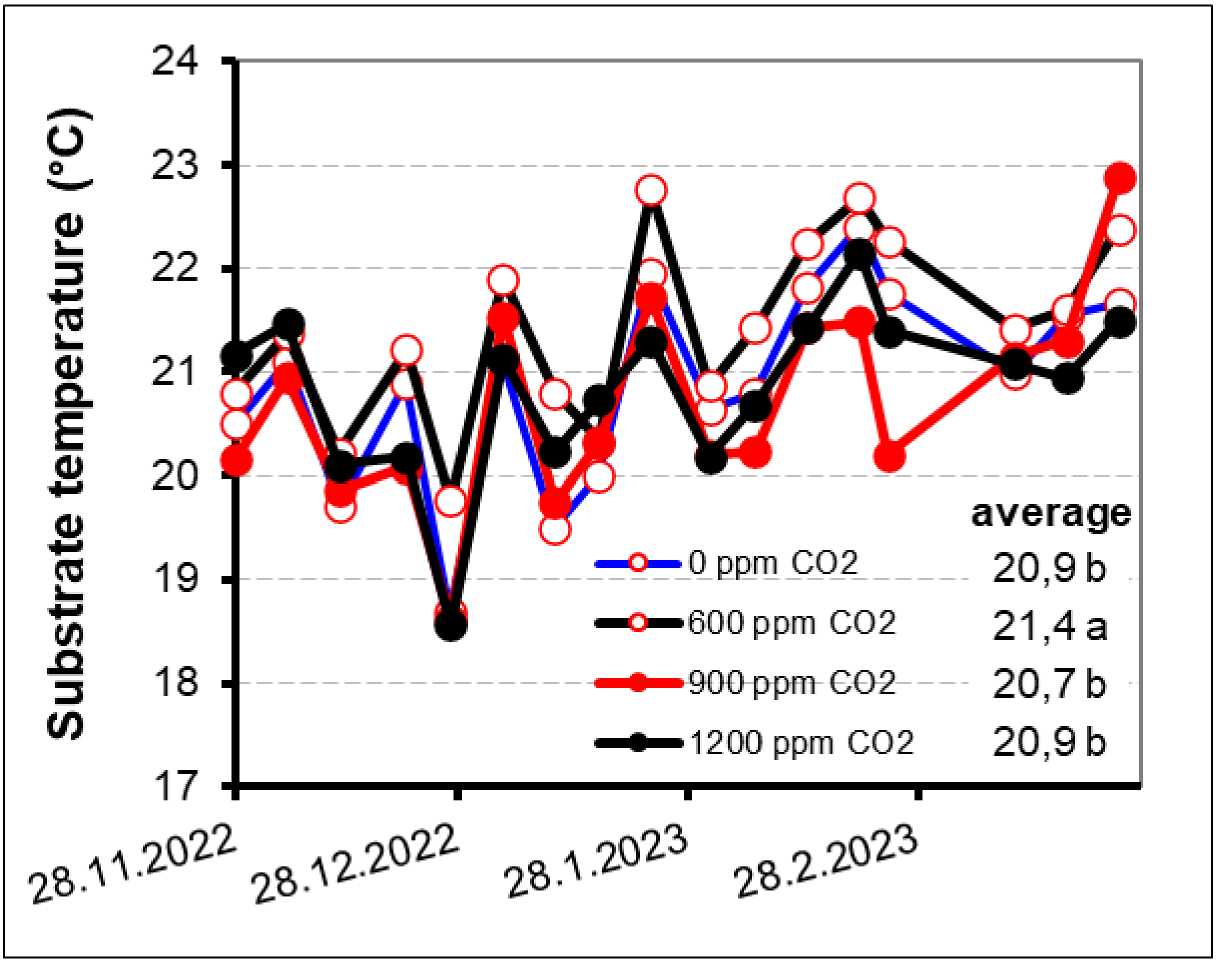


Fig. 3: Substrate temperature.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.1.4 Leaf temperature

Leaf temperature was measured weekly at low solar radiation at around noon and it fluctuated between 15-23°C. On average the leaf temperature was significantly lower with increasing CO_2 enrichment (Fig. 4).

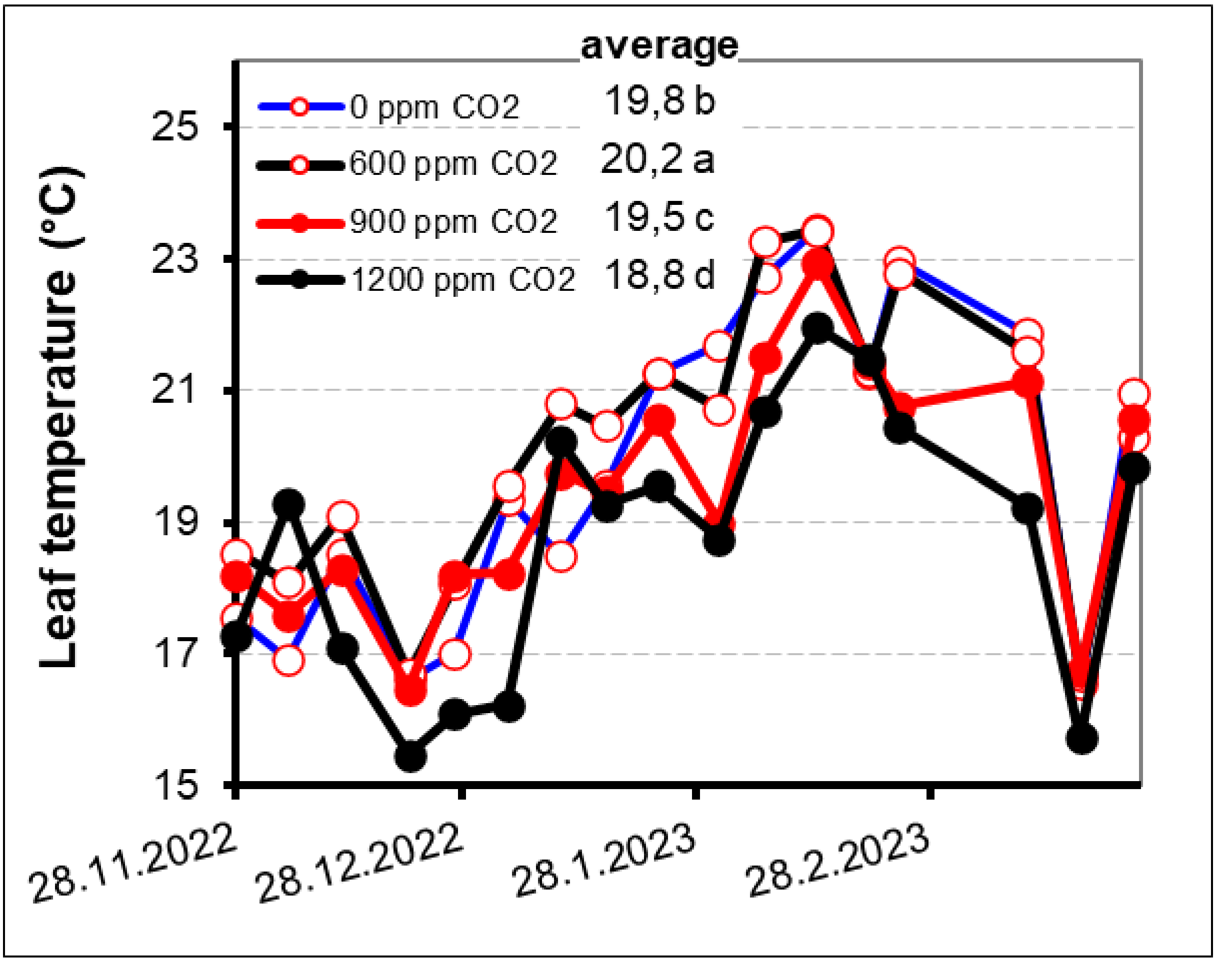


Fig. 4: Leaf temperature.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.1.5 Irrigation of tomatoes

The amount of applied water varied most of the time between 2 and 10 l/m^2 (Fig. 5). By calculating the daily applied water rate per month (Fig. 6) it is getting obvious that irrigation decreased with a higher amount of applied CO_2.

E.C. and pH of irrigation water was fluctuating much (Fig. 7). The E.C. of applied water ranged most of the time between 3,5-5,0 and the pH between 5,5-6,5. The E.C. of runoff stayed most of the time between 4,5-8,0 and the pH between 5,0-8,0. The E.C. of the runoff seem to decrease with higher CO_2 enrichment.

The amount of runoff from applied irrigation fluctuated very much and varied most of the time between 20-60% runoff. It seems that the runoff increased with higher CO_2 enrichment (Fig. 8).

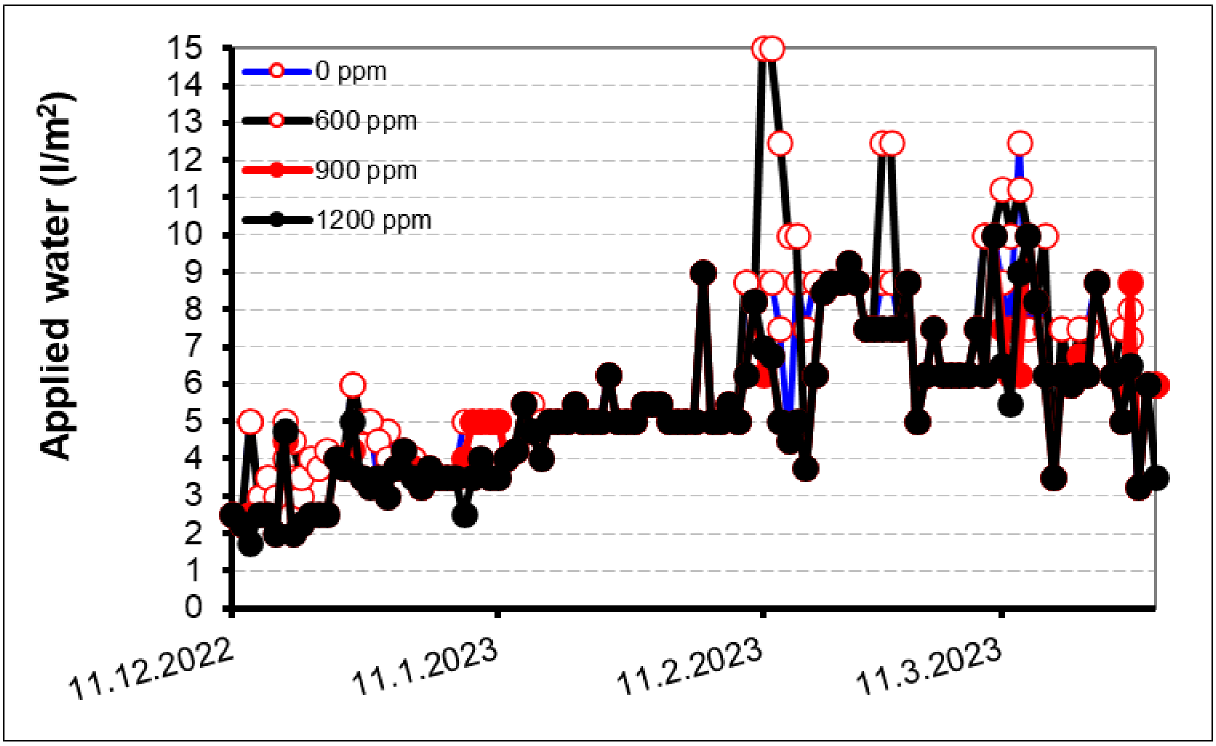


Fig. 5: **Daily applied water.**

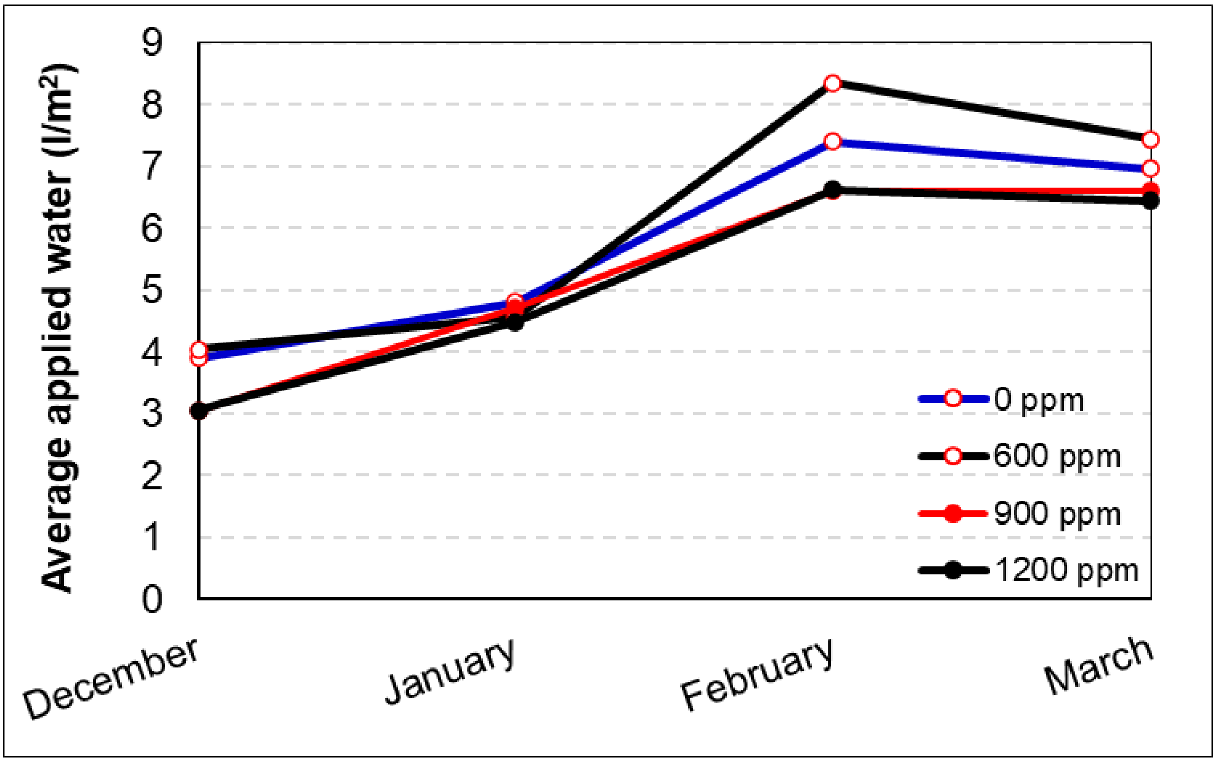


Fig. 6: **Average daily applied water in each month.**

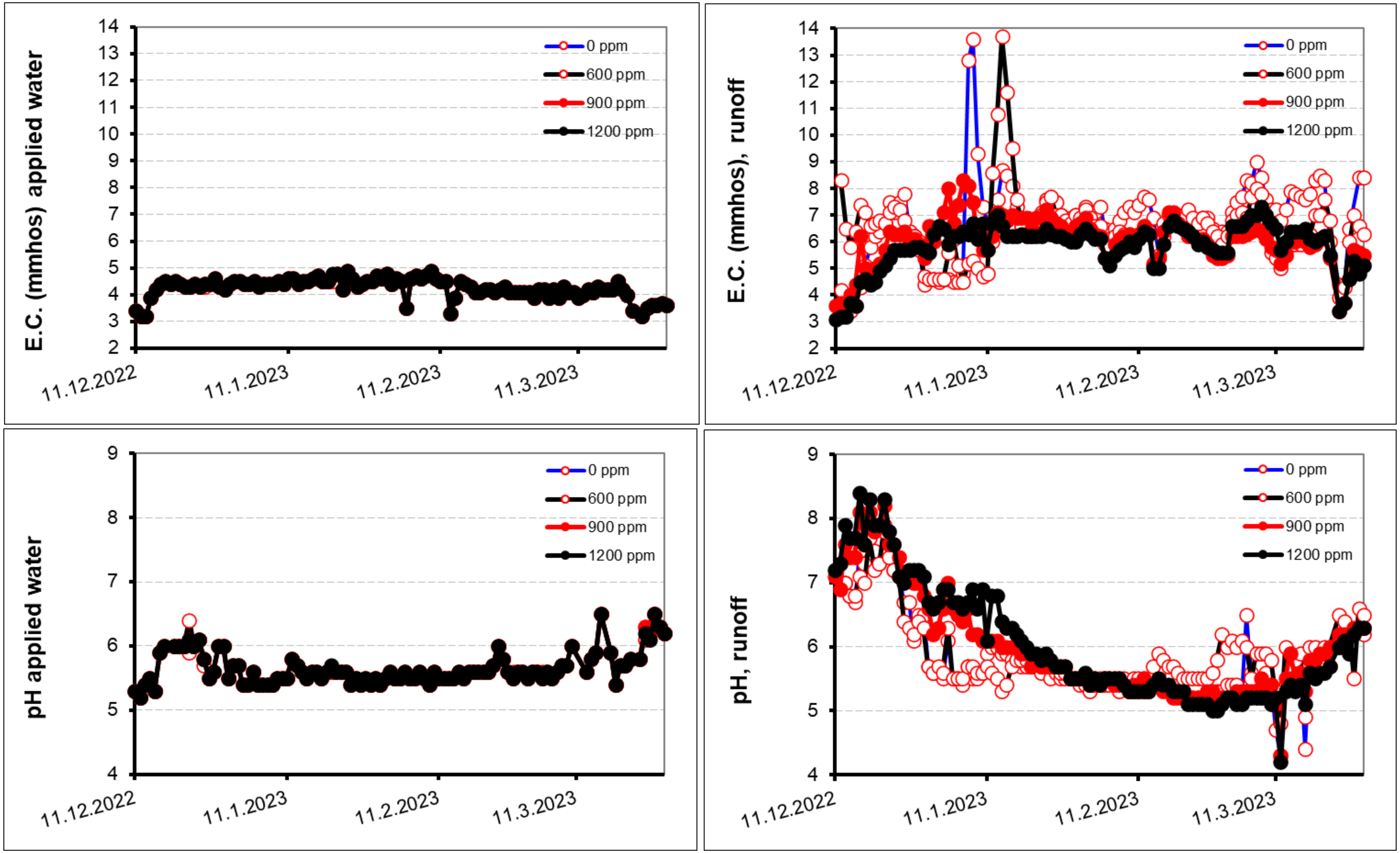


Fig. 7: **E.C. and pH of irrigation water and runoff.**

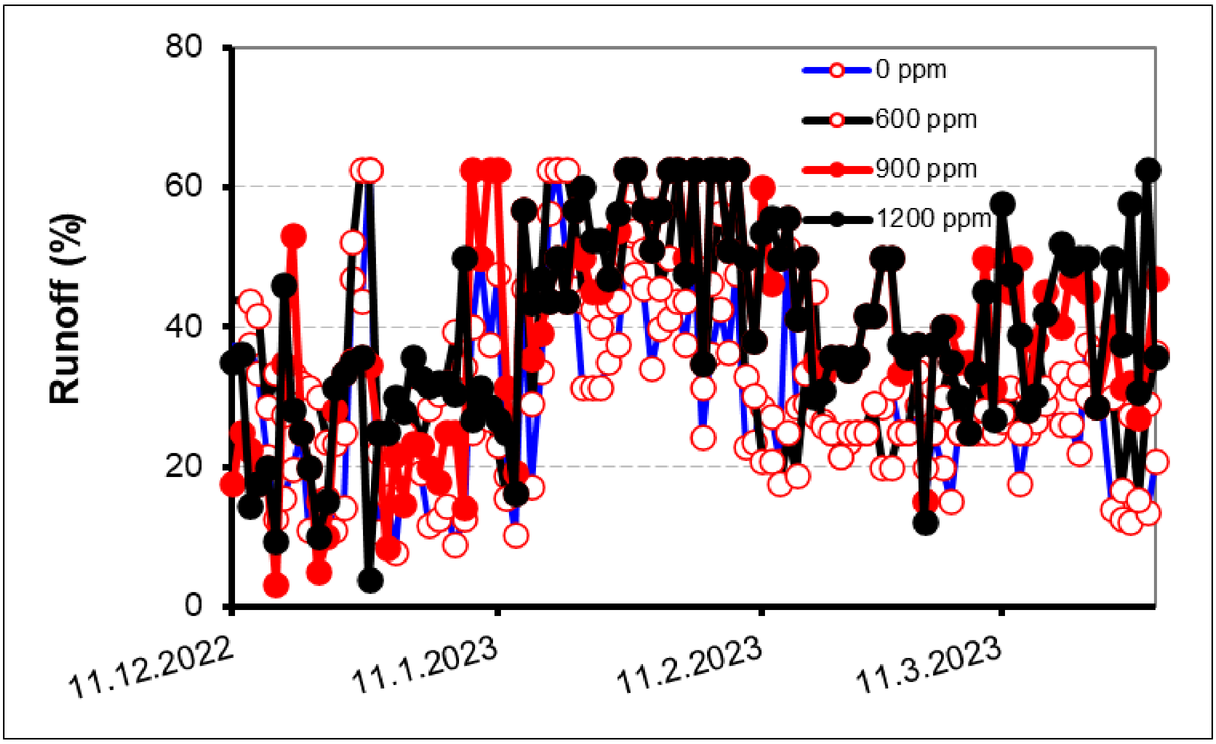


Fig. 8: Proportion of amount of runoff from applied irrigation water.

Plants took up to 1,5-7,0 l/m^2. It seems that plants took up less water with increasing CO_2 enrichment (Fig. 9), thus increasing water use efficiency.

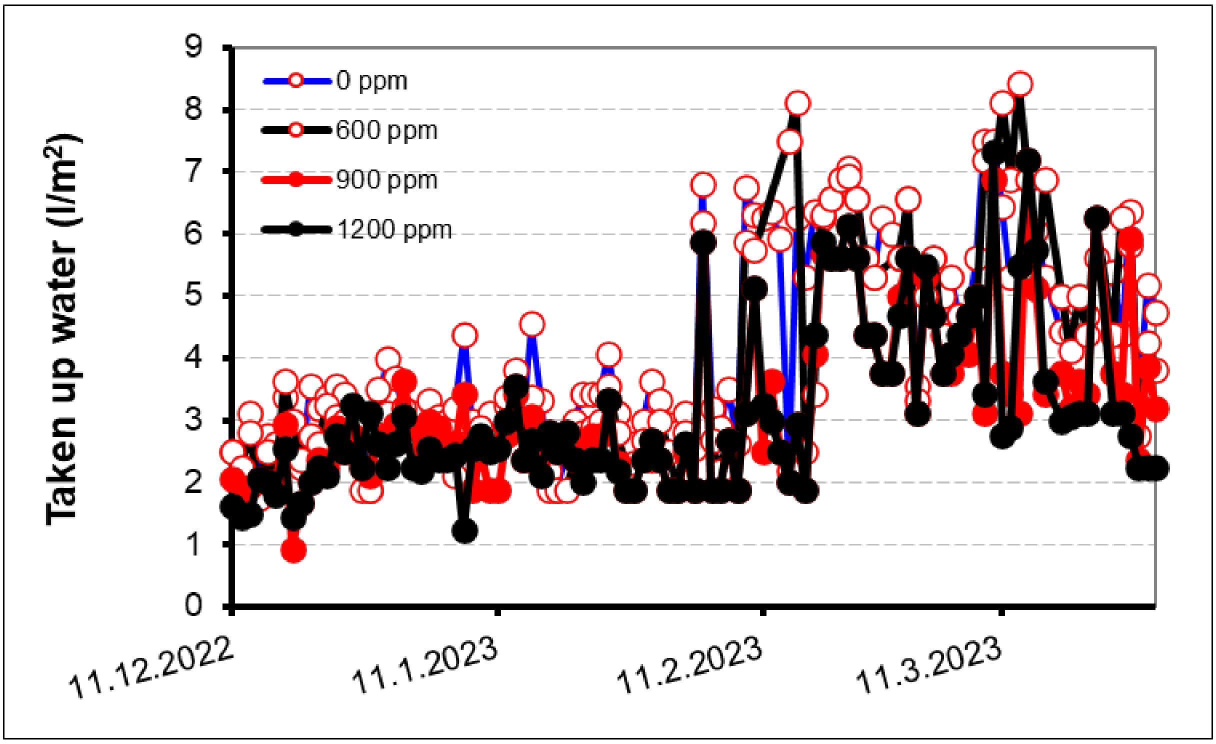


Fig. 9: Water uptake.

4.2 Development of tomatoes

4.2.1 Plant diseases and pests

Neither plant diseases nor pests were observed.

4.2.2 Height

Tomato plants were growing about 2-4 cm per day and reached at the end of the experiment around 5 m (Fig. 10). There was no difference observed in the height of the plants regarding the applied CO_2 amount.

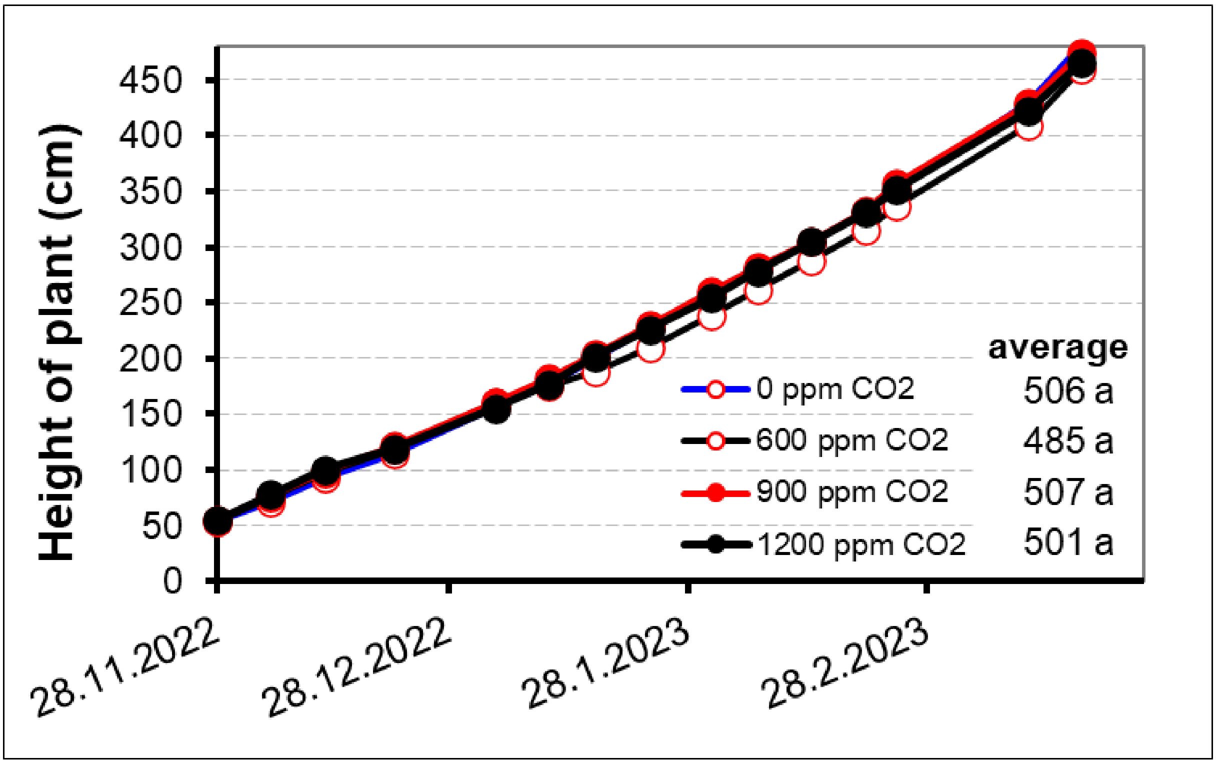


Fig. 10: Height of tomatoes.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.2.3 Weekly growth

The weekly growth amounted 15-30 cm. Plants were growing independently of the CO_2 treatment (Fig. 11).

4.2.4 Number of leaves

Plants had on average 17 leaves, independent of the CO_2 treatment (Fig. 12).

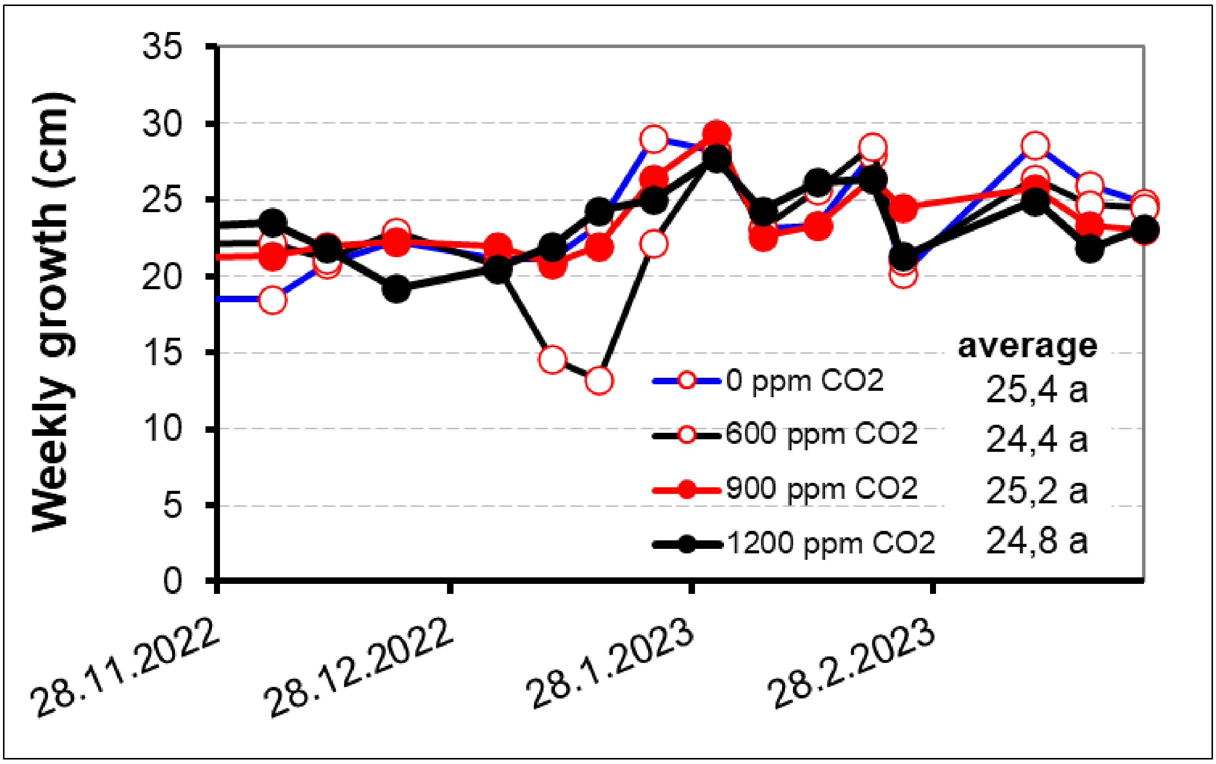


Fig. 11: Weekly growth.

Letters indicate significant differences (HSD, p ≤ 0,05).

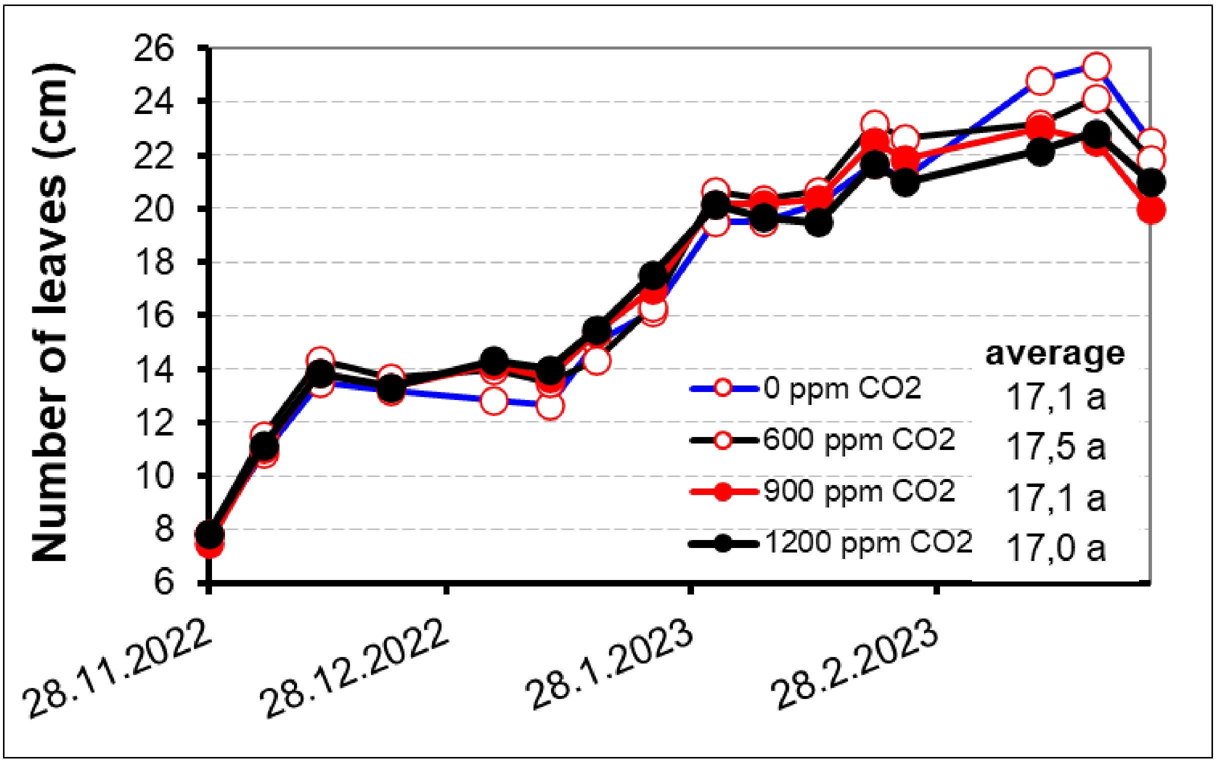


Fig. 12: Number of leaves on the tomato plant.

Letters indicate significant differences (HSD, p ≤ 0,05).

4.2.5 Length of leaves

Length of leaves during the experiment remained at 32-52 cm (Fig. 13). In average leaves were at 600 ppm CO_2 enrichment significantly shorter than leaves under ambient CO_2 conditions, whereas the other treatments did not differ in the length of the leaves.

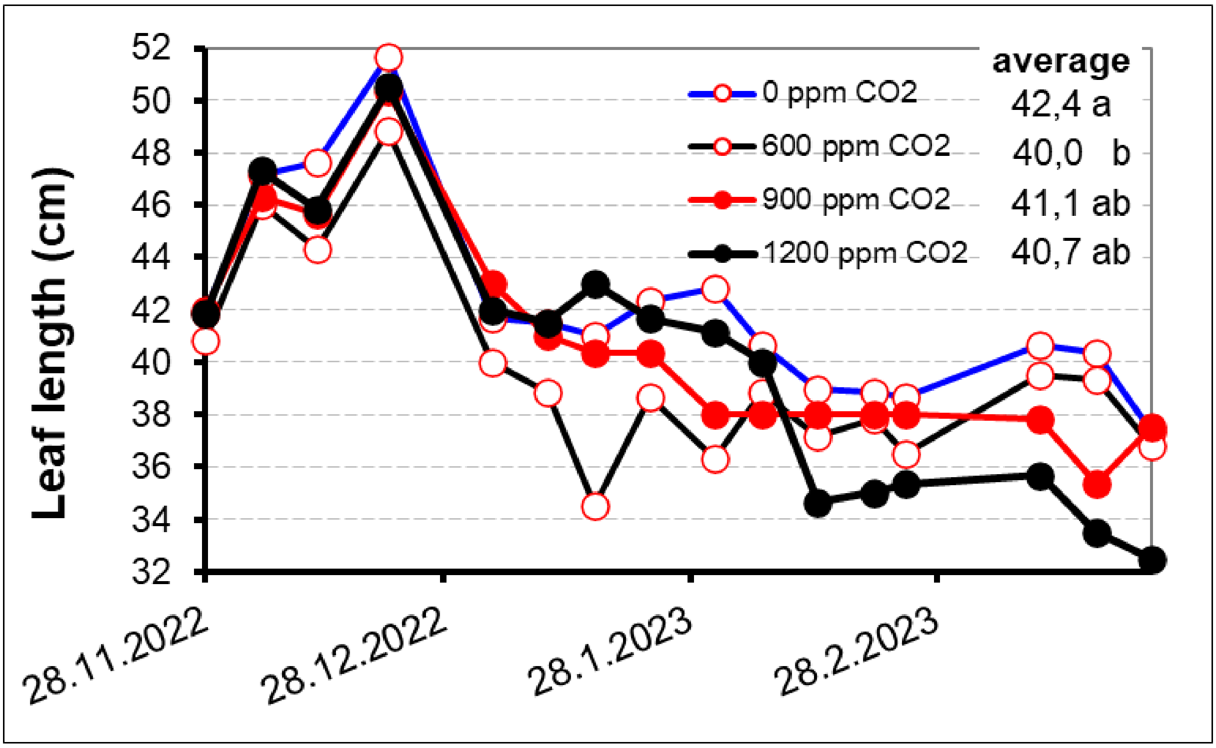


Fig. 13: Length of leaves.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.2.6 Number of clusters

The number of clusters increased with approximately one additional cluster per week. At the end of the growth period were 19-20 clusters reached. No statistically differences in the number of clusters between the CO_2 treatments were observed, however under ambient CO_2 conditions was tendentially one less cluster counted (Fig. 14).

4.2.7 Length of clusters to top

The length from the uppermost flowering cluster to the top of the plant amounted on average 24-25 cm with no significant differences between CO_2 treatments (Fig. 15).

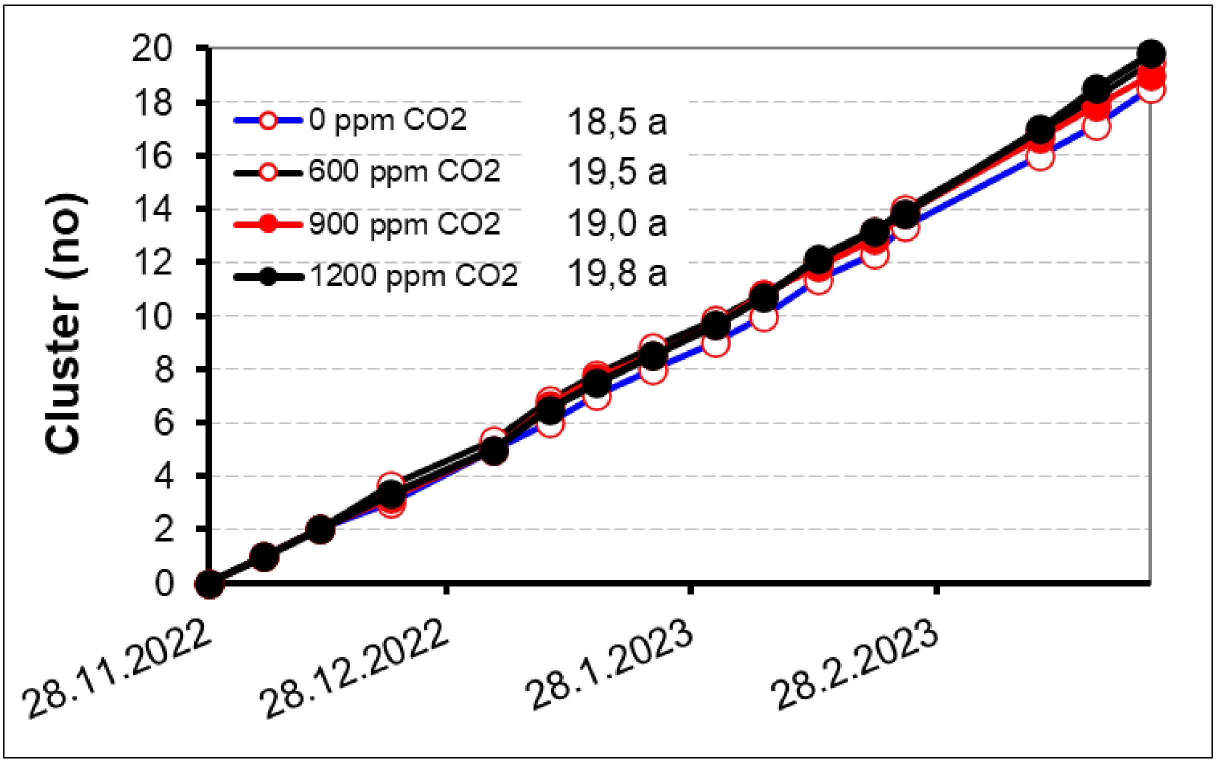


Fig. 14: Number of clusters.

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

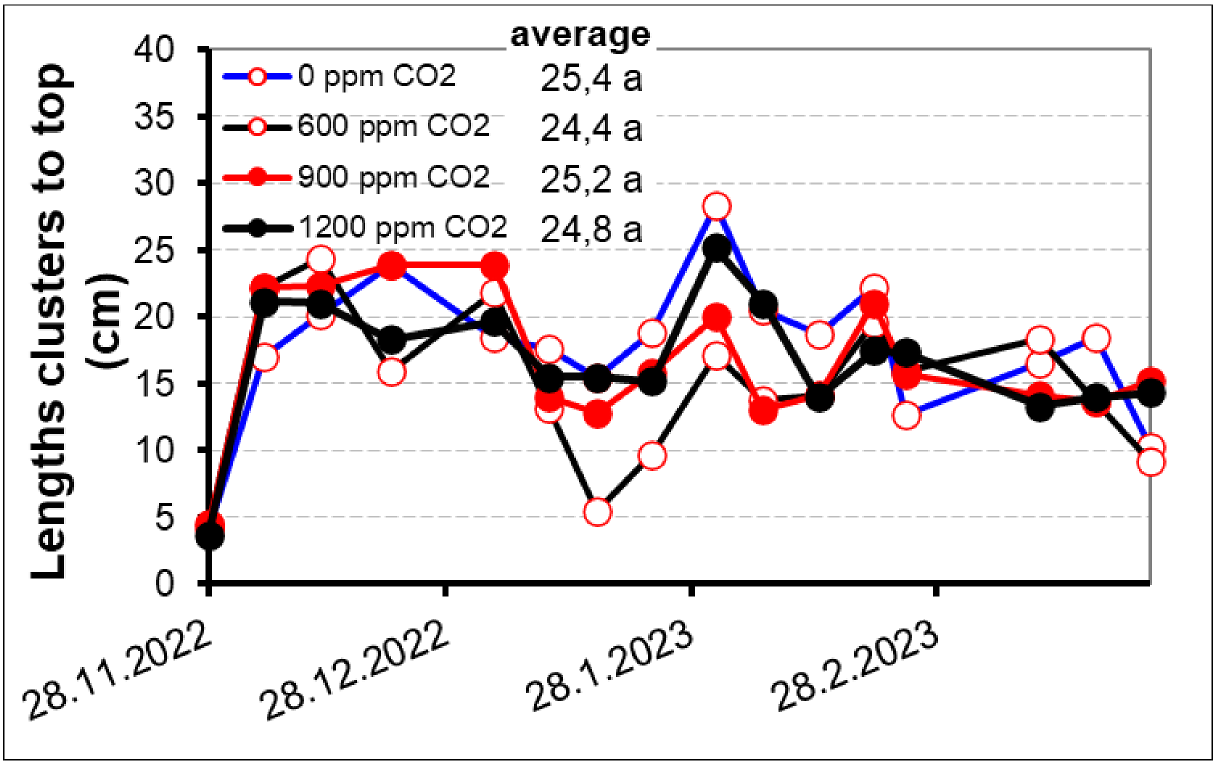


Fig. 15: Length of uppermost flowering cluster to plant top.

Letters indicate significant differences (HSD, p ≤ 0,05).

4.2.8 Distance between clusters

The distance between clusters was fluctuating between 18-28 cm during the growth period. On average amounted the distance 22-25 cm and was significantly higher under ambient CO_2 conditions compared to enriched CO_2 treatments (Fig. 16).

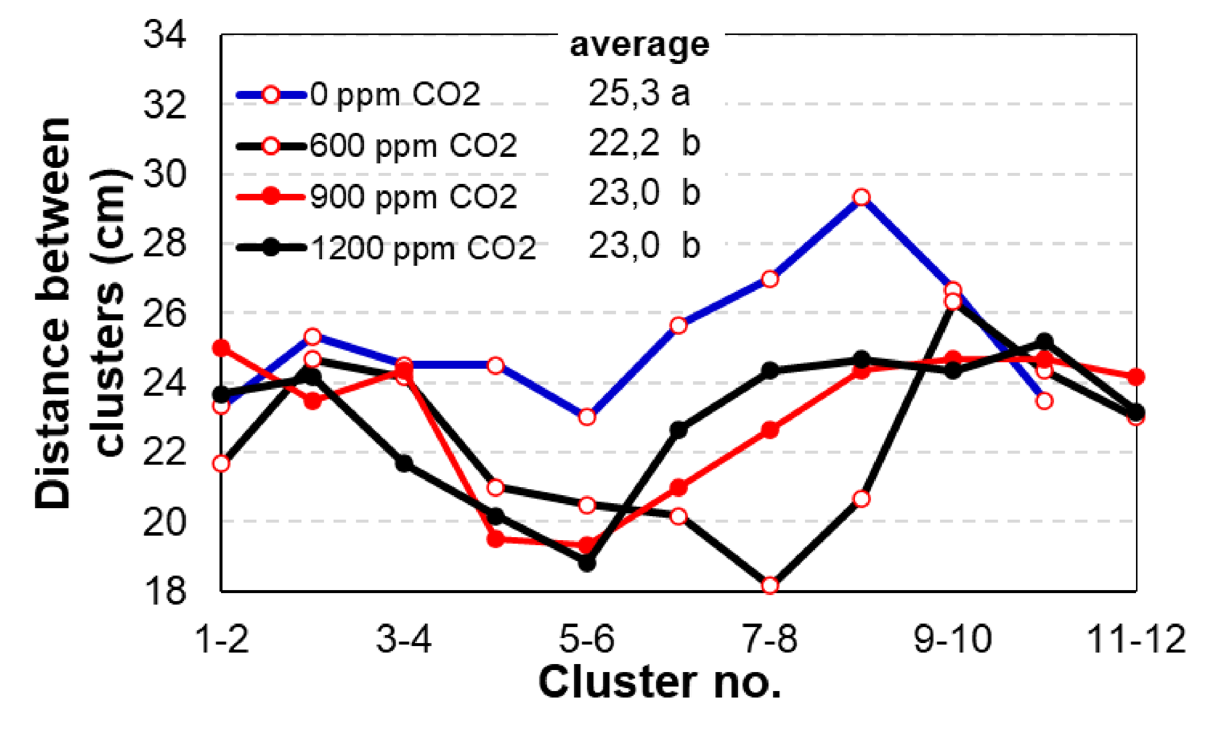


Fig. 16: Distance between clusters.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.2.9 Length of clusters

The length of clusters decreased from about 30 cm to about 20 cm at the end of the experiment (Fig. 17). On average the length of the cluster increased with more CO_2 enrichment. Statistically differences were found between “1200 ppm CO_2” to “0 ppm CO_2” and “600 ppm CO_2”.

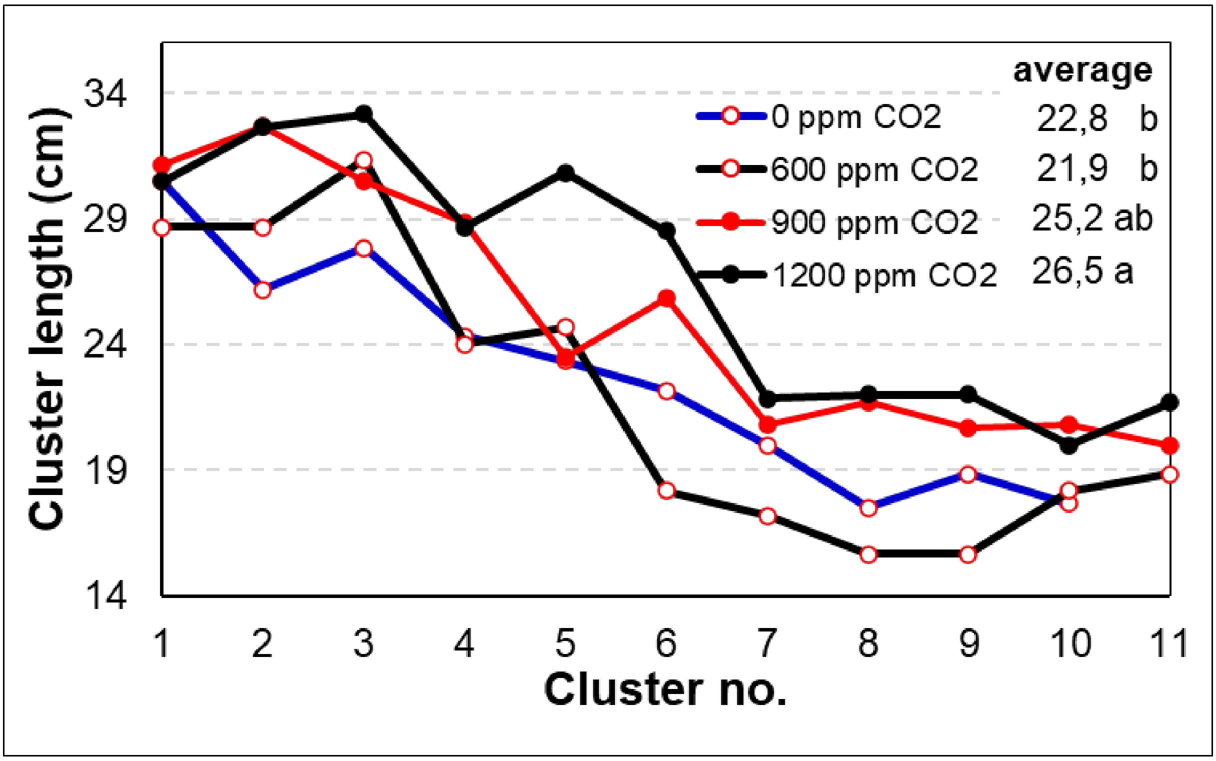


Fig. 17: Length of clusters.

Letters indicate significant differences (HSD, p ≤ 0,05).

4.2.10 Fruits per cluster

Clusters were not pruned. Consequently, the number of fruits per cluster fluctuated (Fig. 18). The number of fruits per cluster decreased during the harvest period from around 12 at the beginning of the harvest period to about 9 at the end of the harvest period. The average number of fruits per cluster amounted around 10. The average number was significantly lower under ambient CO_2 conditions compared to “600 ppm CO_2” and “1200 ppm CO_2”, while no significant differences were found to “900 ppm CO_2”.

The number of not pollinated fruits per cluster was fluctuating between 0 and 2, however, with a peak on the third to fifth cluster. The average number of not pollinated fruits amounted around one but was lower for the “600 ppm CO_2” treatment. A significant higher number of unpollinated fruits per cluster was observed for “1200 ppm CO_2” compared to “600 ppm CO_2” (Fig. 19).

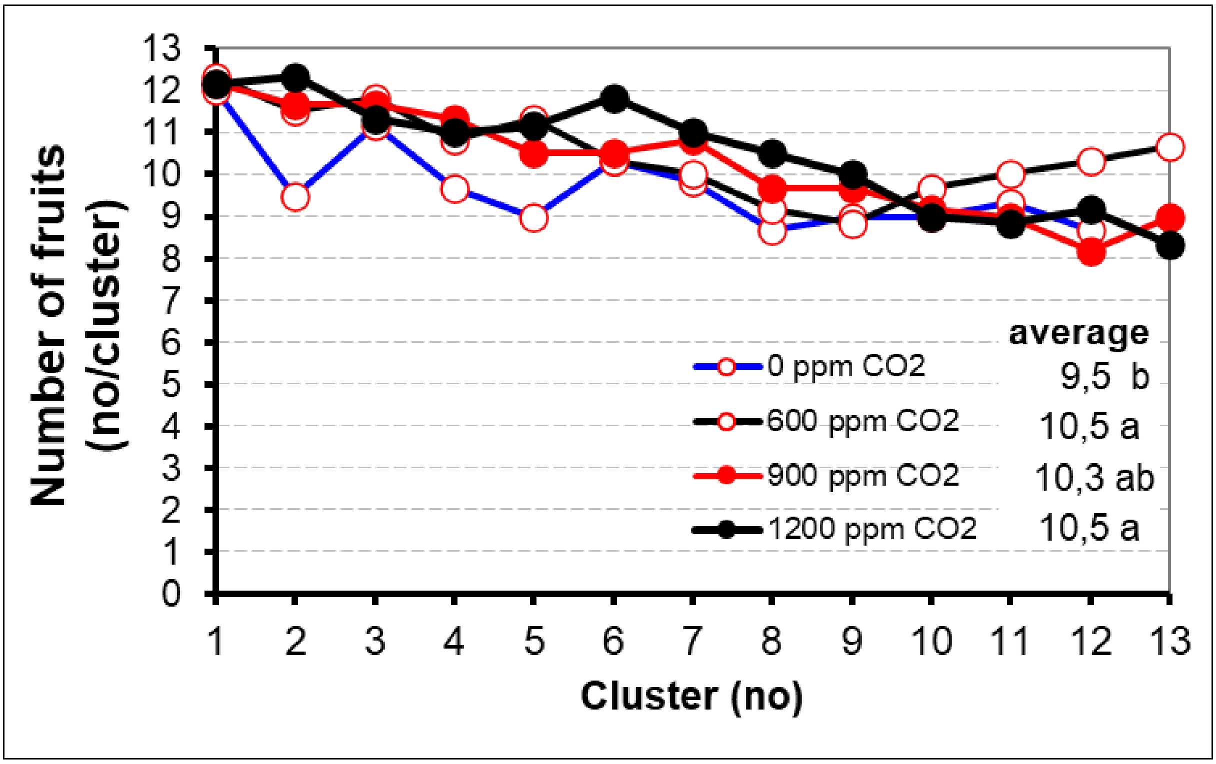


Fig. 18: Number of fruits per cluster.

Letters indicate significant differences (HSD, $p \leq 0{,}05$).

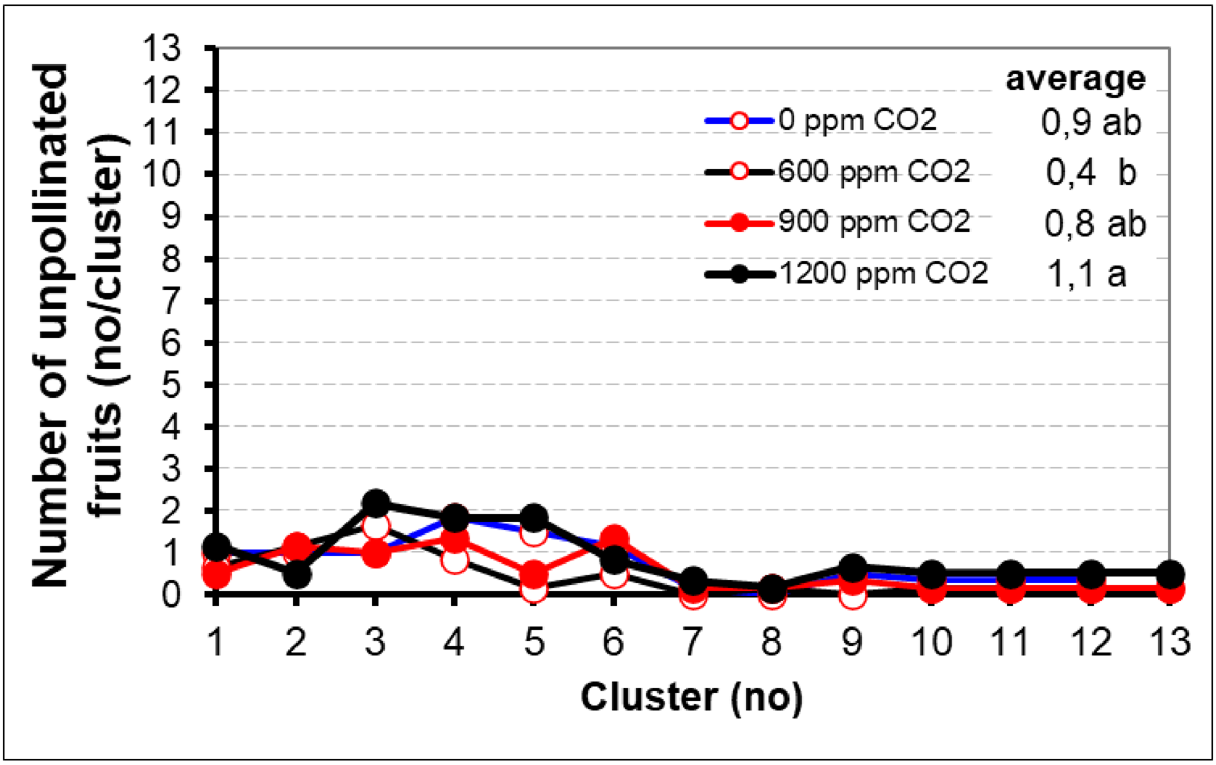


Fig. 19: Number of unpollinated fruits per cluster.

Letters indicate significant differences (HSD, $p \leq 0{,}05$).

4.2.11 Number of open flowers

On the uppermost cluster was the number of open flowers counted. The number of open clusters fluctuated during the growth period between 2 to 6 per cluster. On average were more than three open flowers counted and this number was independent of the CO_2 treatment (Fig. 20).

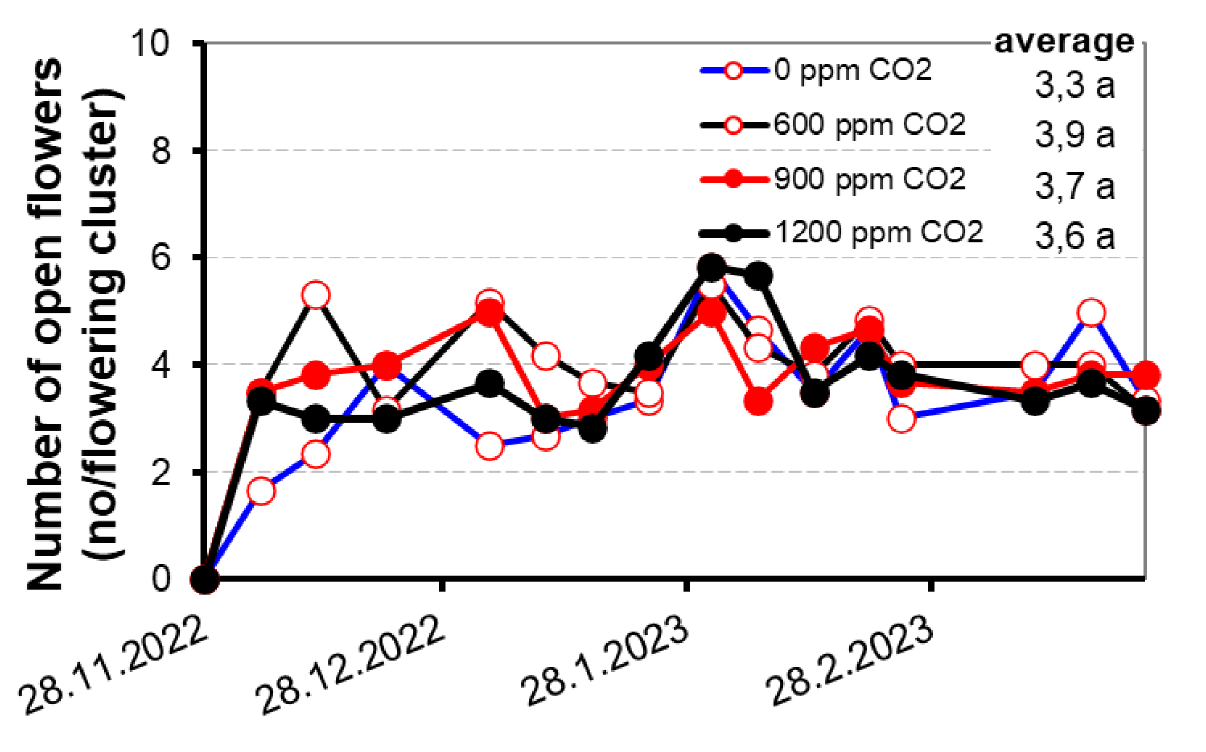


Fig. 20: Number of flowers.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.2.12 Stem diameter

Stem diameter was varying from 0,6 to 1,5 cm (Fig. 21). On average amounted the diameter of the stem 0,88-1,03 cm and was independent of the treatment. Plants were most of the growing period weak vegetative, respectively very vegetative.

4.2.13 Diameter of the uppermost flowering cluster

The diameter of the uppermost flowering cluster decreased from about 1,0 mm to about 0,7 mm during the growth period. No significant differences between the CO_2 treatments were measured, however there seems to be a tendency of a lower diameter of the uppermost flowering cluster under ambient CO_2 conditions.

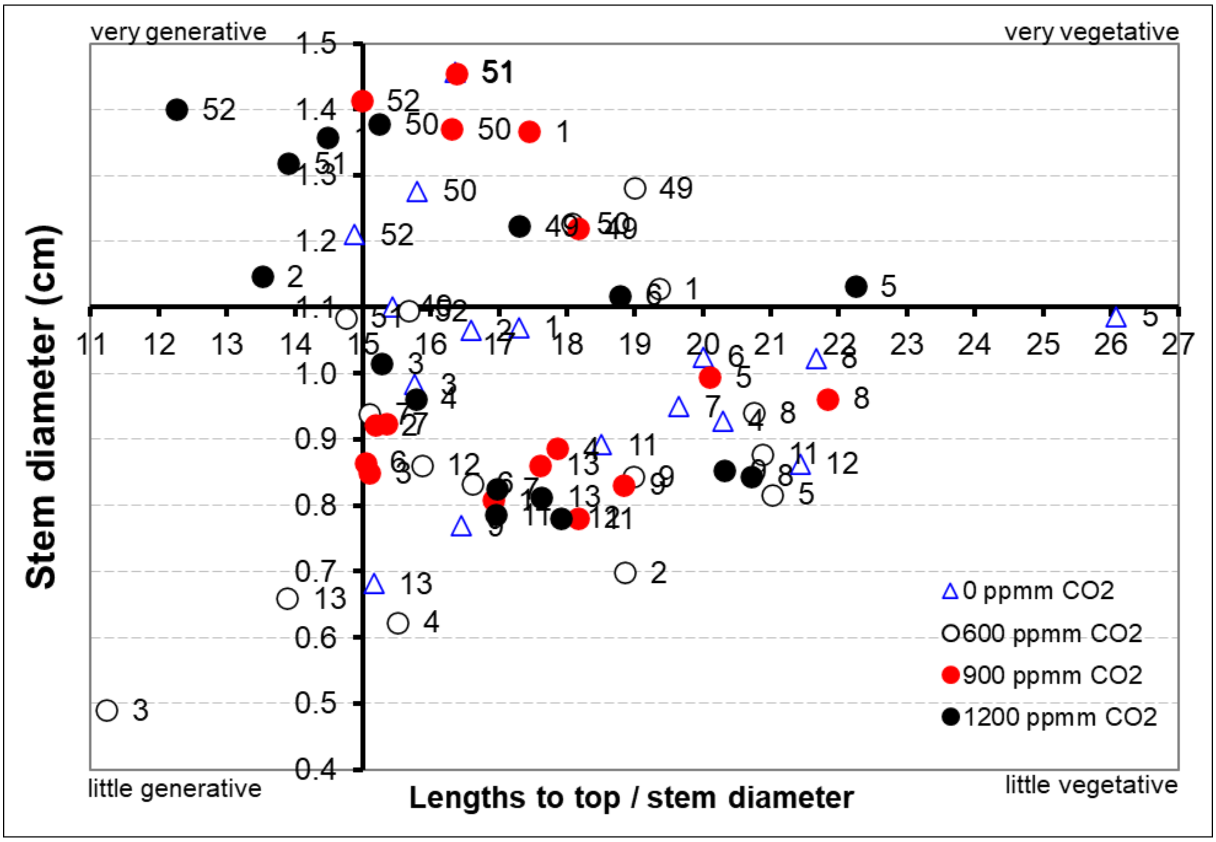


Fig. 21: Stem diameter and quotient lengths to top and stem diameter.
Numbers are representing the week number.

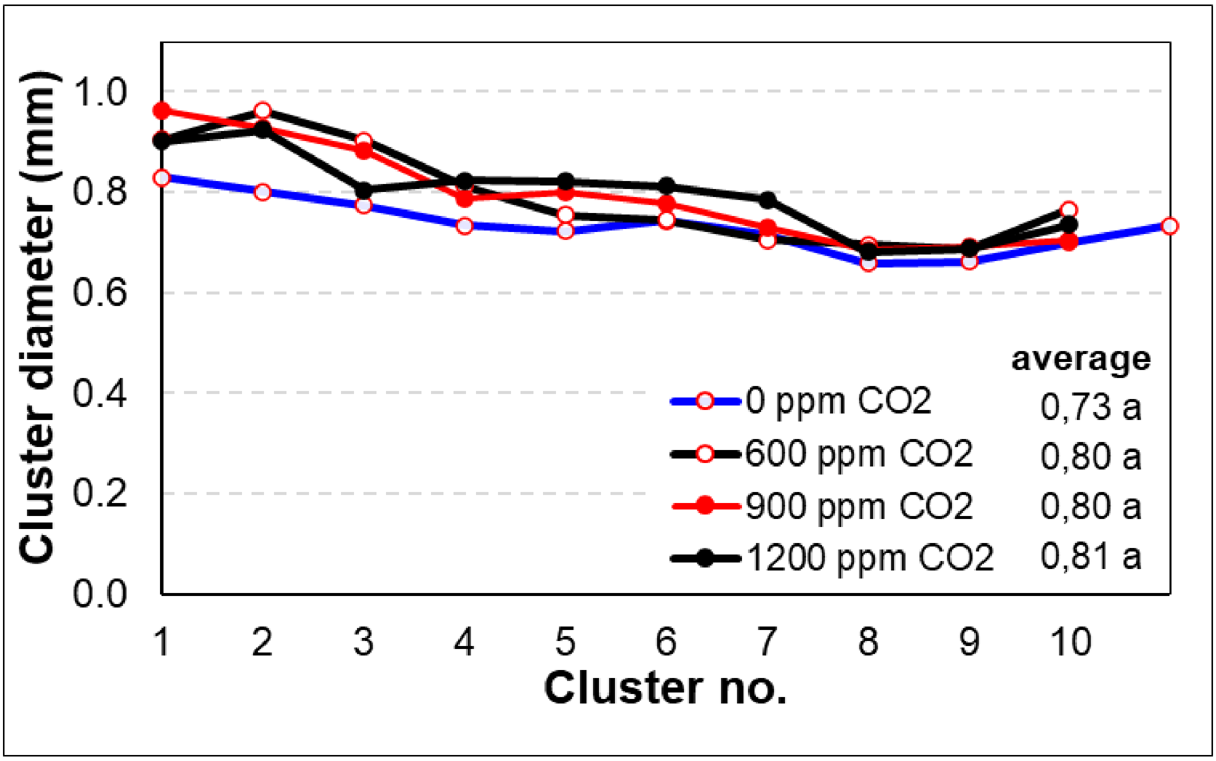


Fig. 22: Diameter of the uppermost flowering cluster.

Letters indicate significant differences (HSD, $p \le 0,05$).

4.3 Yield

4.3.1 Total yield of fruits

The yield of tomatoes included all harvested red fruits during the growth period. The fruits were classified in 1. class (> 55 mm), 2. class (45-55 mm) and not marketable fruits (too little fruits (< 45 mm), fruits with blossom end rot, not well shaped fruits, and green fruits at the end of the harvest period).

Cumulative total yield of tomatoes ranged between 13-20 kg/m^2 (Fig. 23). The cumulative total yield of tomatoes was independent of the CO_2 enrichment ("600 ppm CO_2" versus "900 ppm CO_2" versus "1200 ppm CO_2"), but significantly lower under ambient CO_2 conditions ("0 ppm CO_2"). However, the 1. class yield was affected by the CO_2 treatment. Under "0 ppm CO_2" a significantly lower 1. class yield was measured compared to the other CO_2 treatments. The treatment "1200 ppm CO_2" had a significantly higher 1. class yield than "600 ppm CO_2". Instead, the 2. class yield was

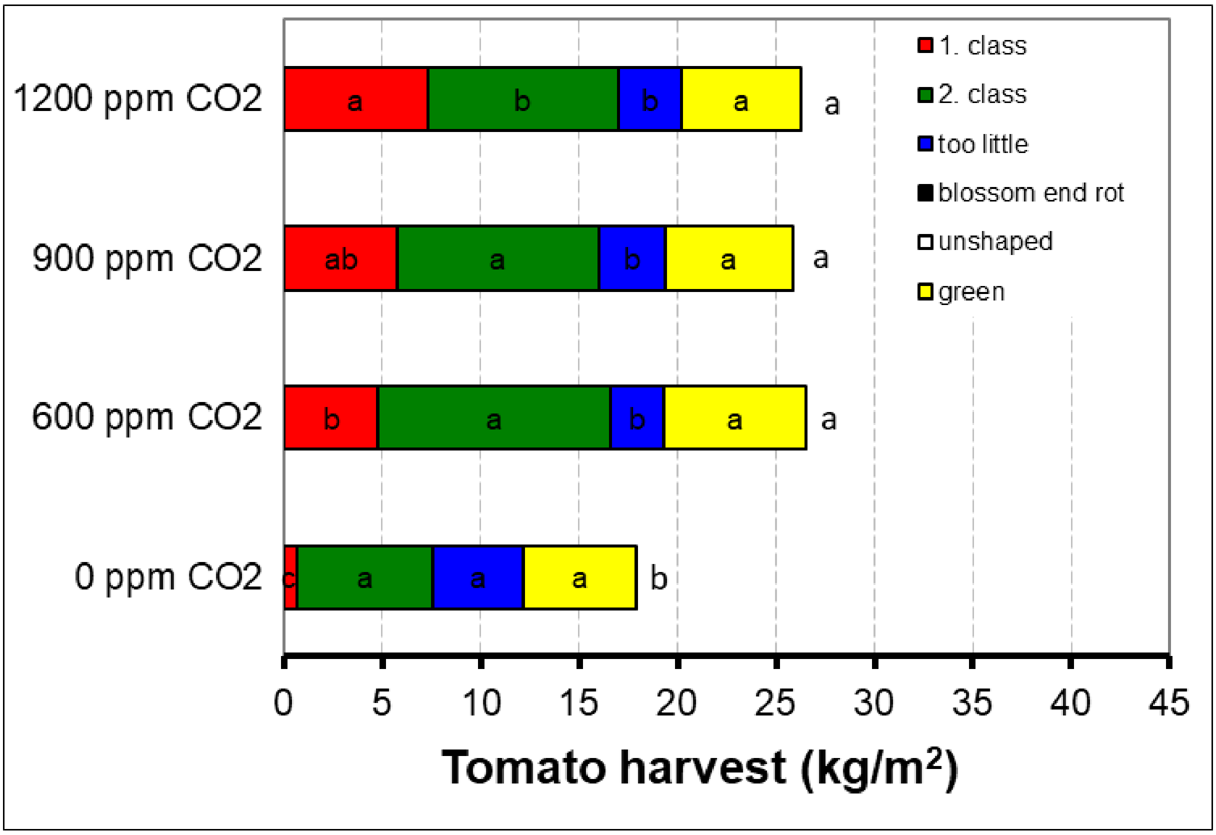


Fig. 23: Cumulative total yield of tomatoes in kg.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

significantly lowest under “1200 ppm CO_2” compared to the other CO_2 treatments. The treatment “0 ppm CO_2” had significantly more too little fruits compared to the other CO_2 treatments. In contrast, the green fruits were not affected by the CO_2 treatment.

The total amount of fruits harvested was independent of the CO_2 enrichment (“600 ppm CO_2” versus “900 ppm CO_2” versus “1200 ppm CO_2”), but significantly lower under ambient CO_2 conditions (“0 ppm CO_2”). However, the 1. class yield was affected by the CO_2 treatment. Under “0 ppm CO_2” a significantly lower number of 1. class fruits were counted than under the CO_2 enrichment. The treatment “1200 ppm CO_2” had a significantly higher number of 1. class fruits than “600 ppm CO_2”. Instead, the number of 2. class fruits were significantly lowest under “1200 ppm CO_2” compared to the other CO_2 treatments. The treatment “0 ppm CO_2” had significantly more too little fruits compared to CO_2 enrichment treatments. In contrast, the number of green fruits was not affected by the CO_2 treatment (Fig. 24).

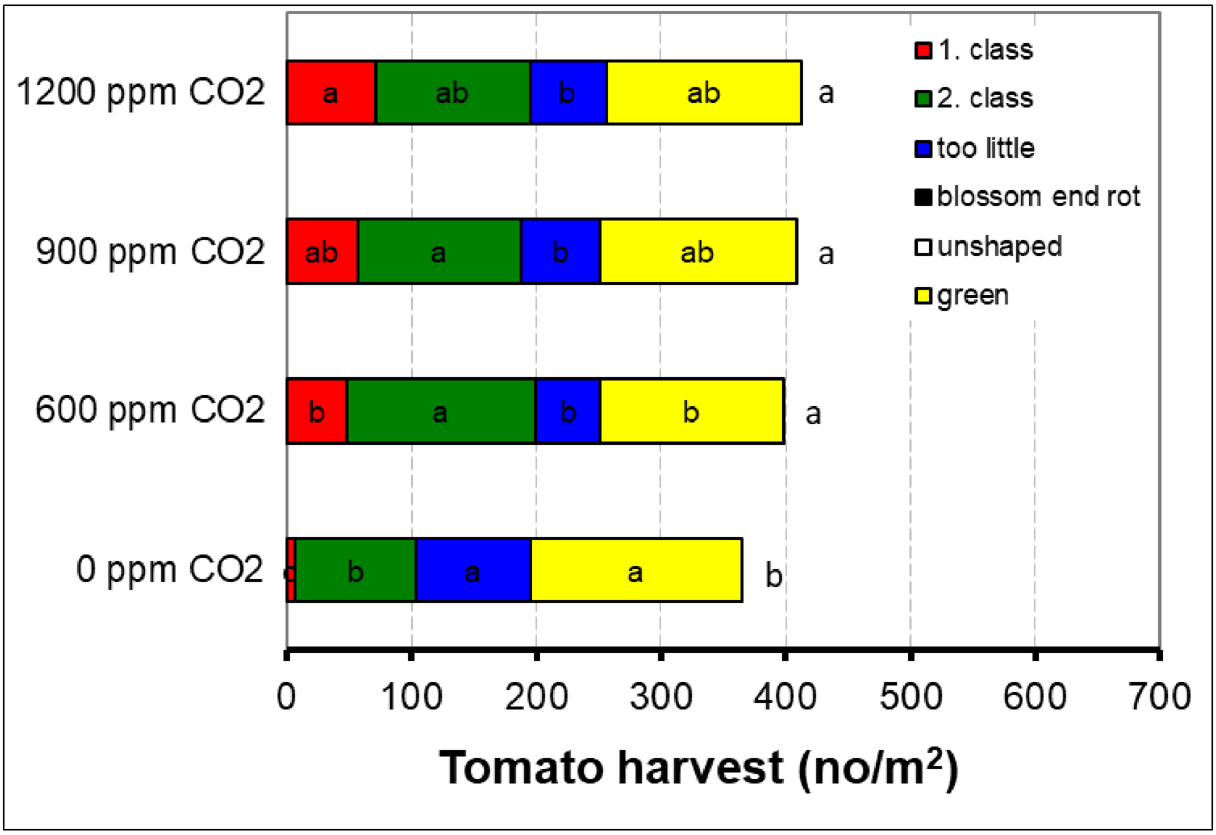


Fig. 24: Cumulative total yield of tomatoes in number.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.3.2 Marketable yield of tomatoes

Plants that received 600 ppm CO_2 started to give red fruits about a week earlier than plants in the other CO_2 treatments. At the end of the harvest period amounted marketable yield of tomatoes 7-16 kg/m^2 (Fig. 25). There were no significant differences in the marketable yield between CO_2 enrichment treatments, but under ambient CO_2 conditions the marketable yield was significantly lower. This difference amounted more than 50% less marketable yield (46% for „0 ppm CO_2“ compared to „600 ppm CO_2“, 47% for „0 ppm CO_2“ compared to „900 ppm CO_2“ and 45% for „0 ppm CO_2“ compared to „1200 ppm CO_2“).

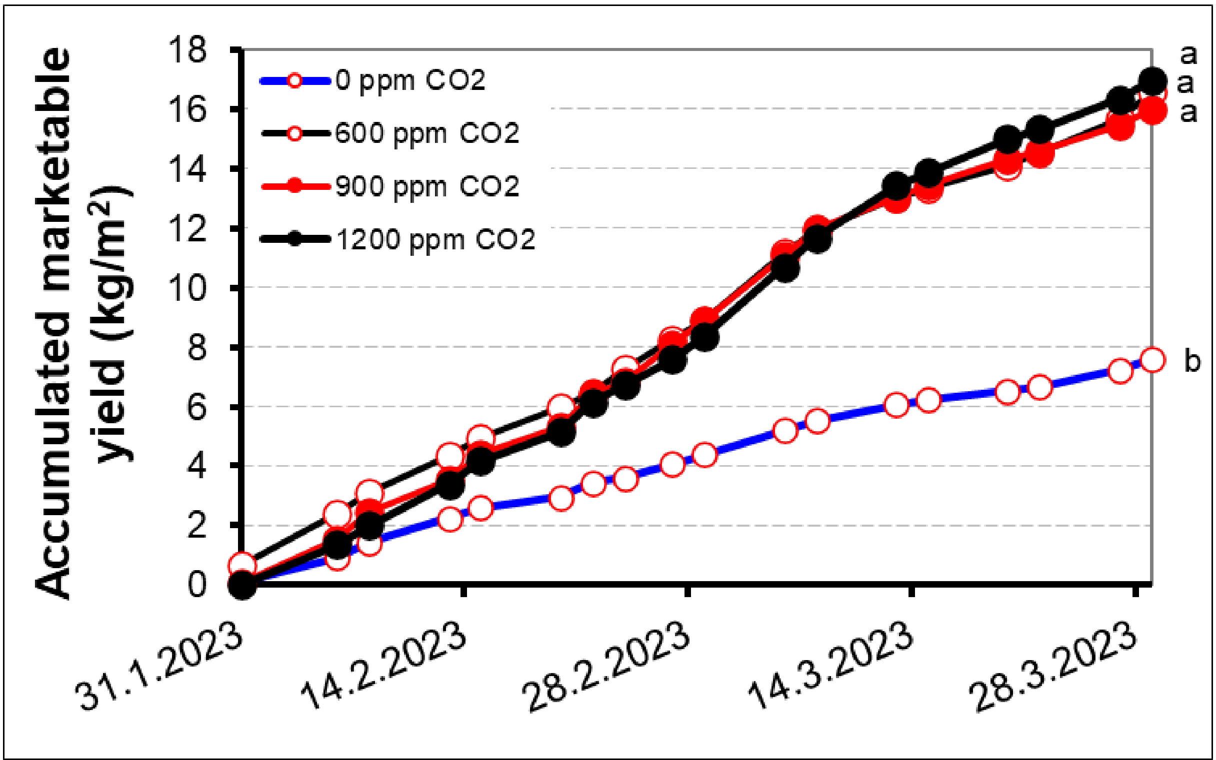


Fig. 25: Time course of marketable yield (1. and 2. class tomatoes).
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

The 1. class yield amounted 1-7 kg/m^2 (Fig. 26) and the 2. class yield 7-11 kg/m^2 at the end of the harvest period (Fig. 27). The 1. class yield was affected by the CO_2 treatment and was significantly lowest under ambient CO_2 conditions. With increasing CO_2 enrichment increased the 1. class yield. Significant differences between “600 ppm CO_2” and “1200 ppm CO_2” were observed. In contrast, the 2. class yield was independent of the CO_2 enrichment. However, the 2. class yield was significantly lower under ambient CO_2 conditions (Fig. 27).

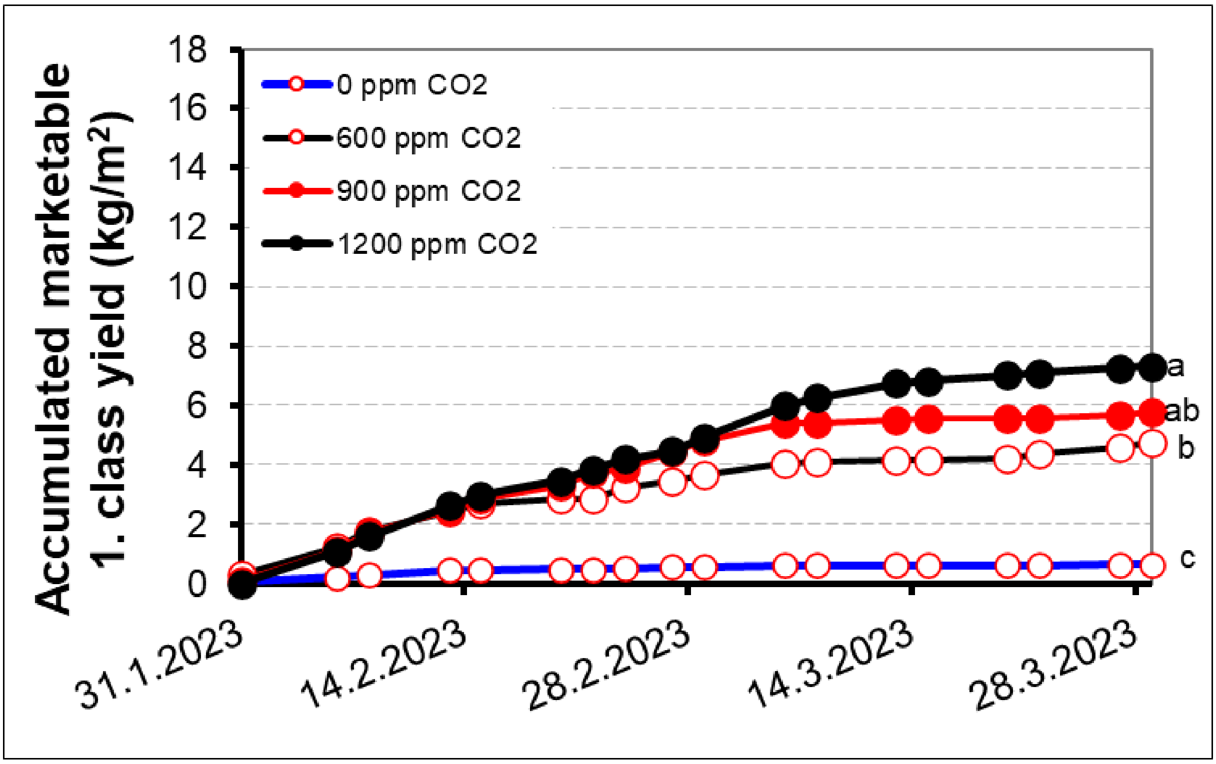


Fig. 26: Time course of marketable 1. class yield.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

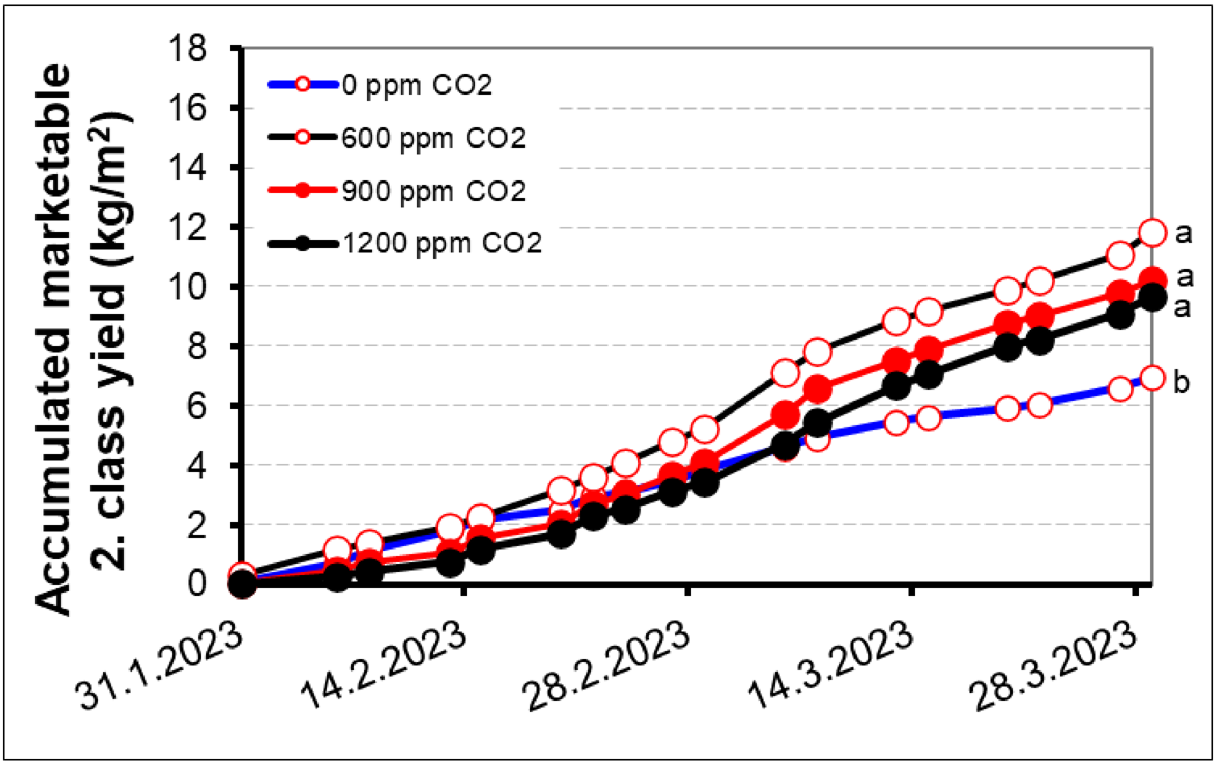


Fig. 27: Time course of marketable 2. class yield.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

The weekly harvest of 1. class and 2. class fruits amounted 1-3 kg/m^2. The early yield was higher under CO_2 enrichment compared to ambient CO_2 conditions. In the early and middle part of the harvest the weekly harvest was 2-3 kg/m^2, but in the latter part 1-2 kg/m^2 for the treatments with CO_2 enrichment. Under ambient CO_2 conditions the weekly harvest was much lower and amounted around 1 kg/m^2 (Fig. 28).

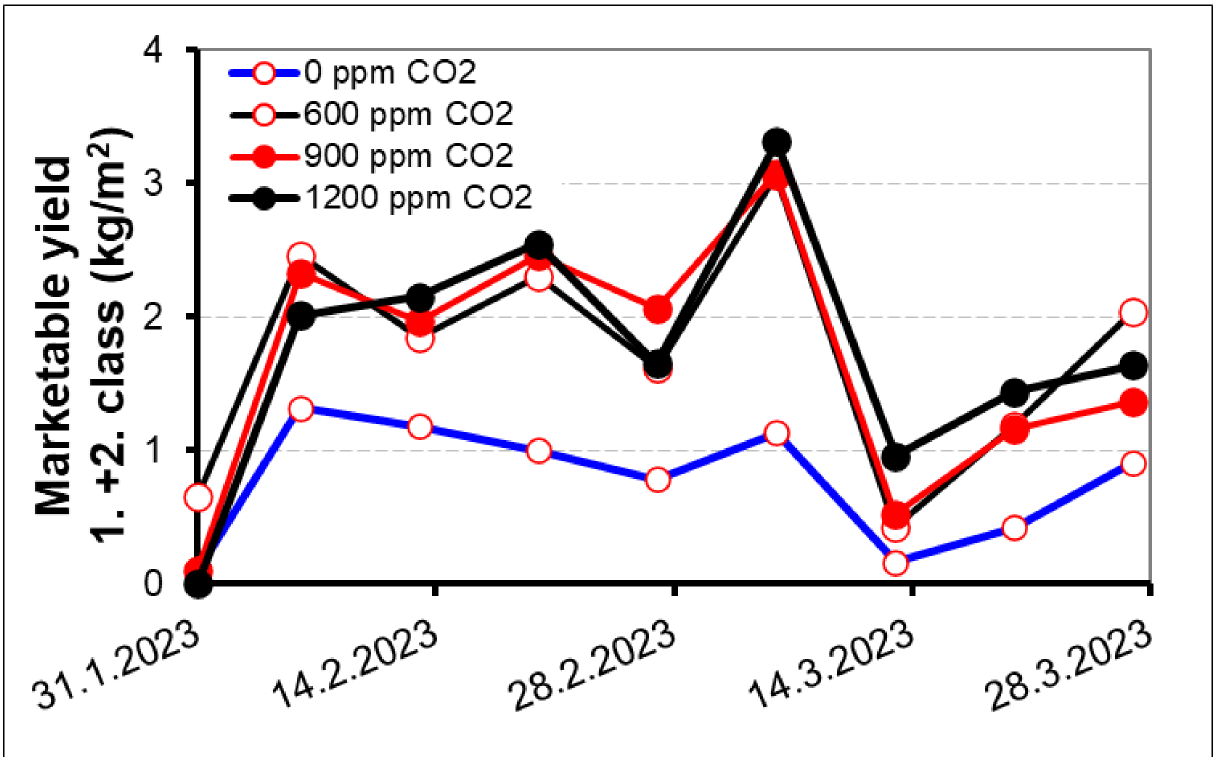


Fig. 28: Time course of marketable yield.

The number of 1. class fruits was dependent of the CO_2 treatment (Tab. 5). The number of 1. class fruits was significantly lowest under ambient CO_2 conditions. The highest CO_2 enrichment (1200 ppm CO_2) had the highest number of marketable 1. class fruits.

The number of 2. class fruits was significantly lower for “0 ppm CO_2” compared to “600 ppm CO_2” and “900 ppm CO_2”. The total number of marketable fruits was not significantly different between the CO_2 enrichment treatments, whereas a significantly lower number of marketable fruits was counted under ambient CO_2 conditions.

Average fruit size of 1. class tomatoes varied between 90-110 g / fruit and decreased slightly from 95-110 g / fruit to 90-100 g / fruit during the harvest period (Fig. 29). On average the weight of 1. class tomatoes was dependent of the CO_2 treatment and increased with higher CO_2 enrichment. The significantly highest average weight of 1. class fruits was under “1200 ppm CO_2” and “900 ppm CO_2”. The significantly lowest average weight had 1. class tomatoes grown under “0 ppm CO_2”.

Tab. 5: Cumulative total number of marketable fruits.

Treatment	Number of marketable fruits		
	1. class (no/m^2)	2. class (no/m^2)	total (1. class + 2. class) (no/m^2)
0 ppm CO_2	7 c	96 b	103 b
600 ppm CO_2	48 b	152 a	199 a
900 ppm CO_2	56 ab	131 a	198 a
1200 ppm CO_2	71 a	124 ab	195 a

Letters indicate significant differences (HSD, p ≤ 0,05).

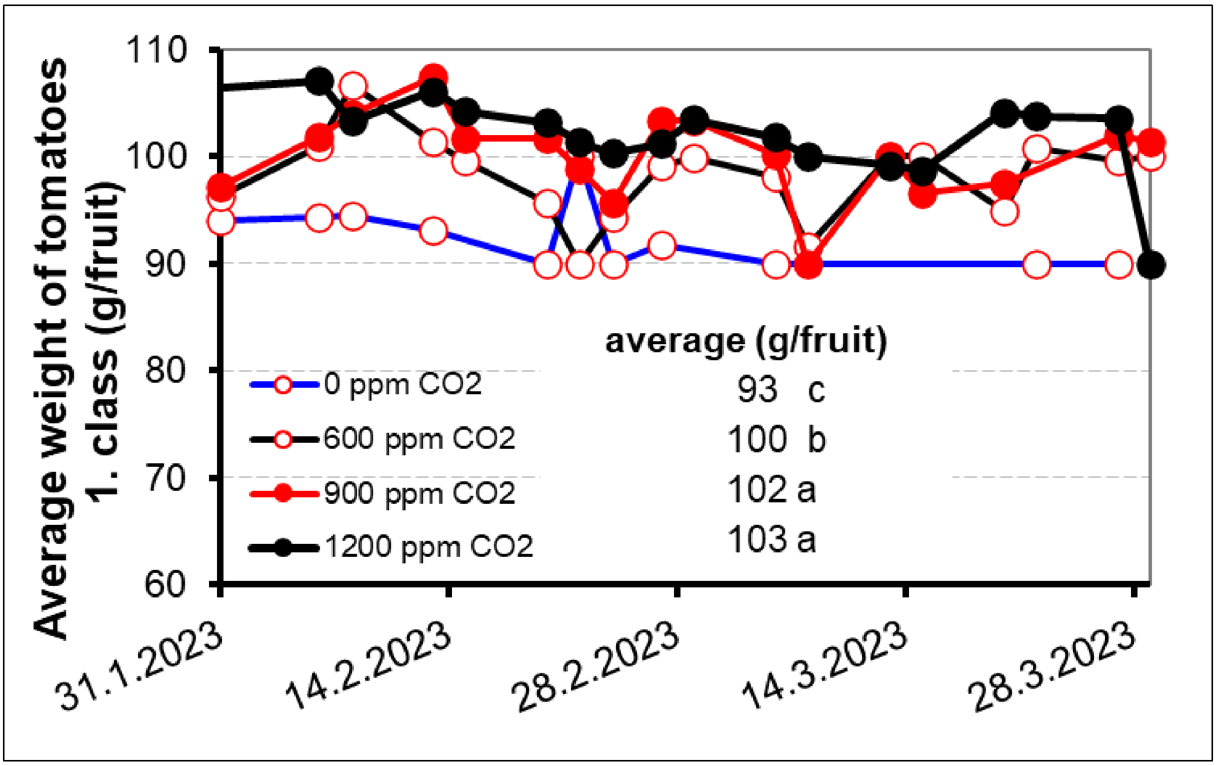


Fig. 29: Average weight of tomatoes (1. class fruits).

Letters indicate significant differences (HSD, p ≤ 0,05).

Average fruit size of 1. and 2. class tomatoes was varying between 60-100 g / fruit (Fig. 30). The fruit size decreased at proceeded harvest period from 85-100 g / fruit to

60-85 g / fruit. The CO_2 treatment did affect average fruit size. The fruit size increased at CO_2 enrichment by at least 10 g compared to ambient CO_2 conditions. The marketable fruit size was in average significantly lower under “0 ppm CO_2” compared to CO_2 enrichment. Also, a significant lower average size was reached with “600 ppm CO_2” compared to “1200 ppm CO_2”. With higher CO_2 enrichment the average weight could be increased by 4 g.

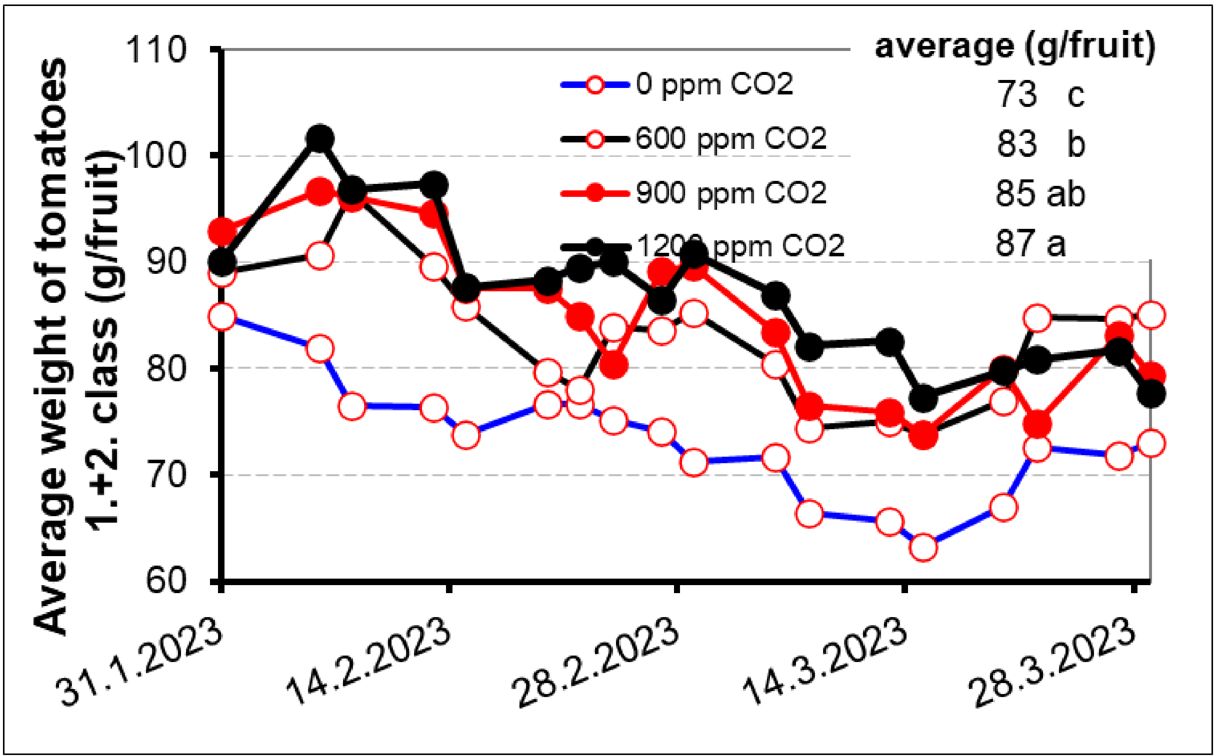


Fig. 30: Average weight of tomatoes (1. and 2. class fruits).

Letters indicate significant differences (HSD, $p \leq 0{,}05$).

4.3.3 Outer quality of yield

Marketable yield was more than 60% for the treatments with CO_2 enrichment. However, a lower marketable yield of just over 40% was reached under ambient CO_2 conditions (Tab. 6). The percentage of 1. class fruits, 2. class fruits and too little fruits was dependent of the CO_2 treatment. The treatment “0 ppm CO_2” had the significantly lowest proportion of 1. class fruits. The proportion of 1. class fruits on total yield increased with a higher CO_2 enrichment. The proportion of 2. class fruits was significantly higher under “600 ppm CO_2” compared to the other CO_2 treatments. The treatment “0 ppm CO_2” had significantly the highest proportion of too little fruits compared to the CO_2 enrichment treatments. Blossom end rot fruits as well as unshaped fruits had a proportion of zero on total yield. The proportion of green fruits on total yield was in all CO_2 treatments very high because tomato plants were not topped and allowed to grow "naturally" until the end of the experiment. Therefore, the proportion of green fruits was high as new clusters developed until the end of the experiment, which were then harvested as green fruits. The proportion of green fruits was significantly highest under "0 ppm CO_2" compared to CO_2 enrichment.

Tab. 6: Proportion of marketable and unmarketable yield.

Treatment	**Marketable yield (%)**		**Unmarketable yield (%)**			
	1. class > 55 mm	2. class > 45-55 mm	too little weight	blossom end rot	not well shaped	green
0 ppm CO_2	4 c	39 b	26 a	0 a	0 a	31 a
600 ppm CO_2	17 b	44 a	13 b	0 a	0 a	26 b
900 ppm CO_2	22 ab	40 b	13 b	0 a	0 a	25 bc
1200 ppm CO_2	28 a	37 b	12 b	0 a	0 a	23 c

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.3.4 Interior quality of yield – sugar content

Sugar content of tomatoes was measured three times during the harvest period. Completo had a sugar content of 3,6-4,2°BRIX. It seems that the sugar content increased slightly with proceeding harvest period. The sugar content was independent of the CO_2 treatment. However, the sugar content seems to be tendentially lower under the higher CO_2 enrichment (Fig. 31).

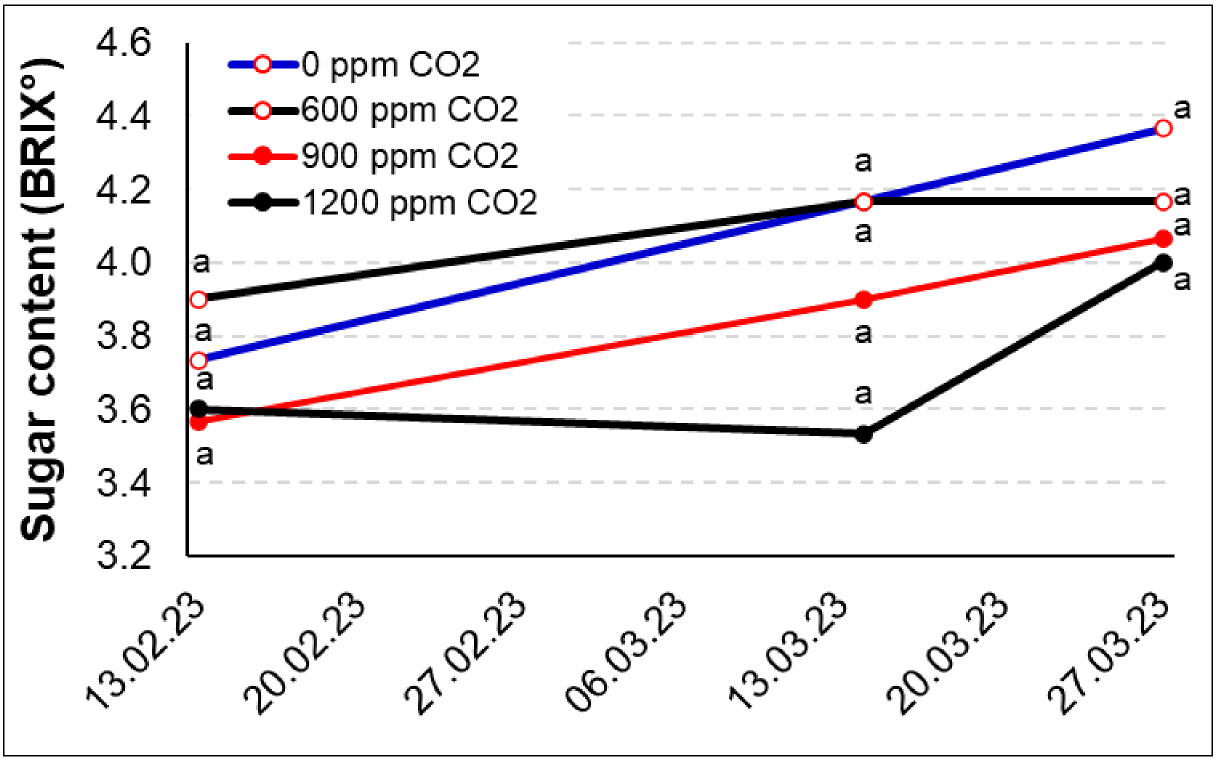


Fig. 31: Sugar content of tomatoes.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.4 Economics

4.4.1 Used energy

The number of lighting hours is contributing to high annual costs and needs therefore special consideration to consider decreasing lighting costs per kg "yield". The total hours of lighting and the used kWh's during the growth period after transplanting were measured with dataloggers in the previous tomato experiment. However, as the setup of the lights in winter 2022/2023 was equal to one chamber in the year before (winter 2021/2022), data from previous year were used as no logging was conducted during this experiment.

Production of tomatoes resulted in each CO_2 treatment in a daily usage of 235,9 kWh. This means that the energy costs for growing tomatoes were in all CO_2 treatments the same (Tab. 7).

Tab. 7: Used energy under different CO_2 treatments.

Treatment	CO_2 (ppm)			
	0	**600**	**900**	**1200**
Energy (kWh/day)	235,9	235,9	235,9	235,9
Energy (kWh/growth period)	29.723	29.723	29.723	29.723
Energy/m² (kWh/m²)	**566**	**566**	**566**	**566**

4.4.2 Energy use efficiency

Under ambient CO_2 conditions, kWh's were transferred less good into yield compared to the treatments with CO_2 enrichment (Fig. 32). This difference amounted to around 55%. However, the amount of CO_2 enrichment had no influence on energy use efficiency.

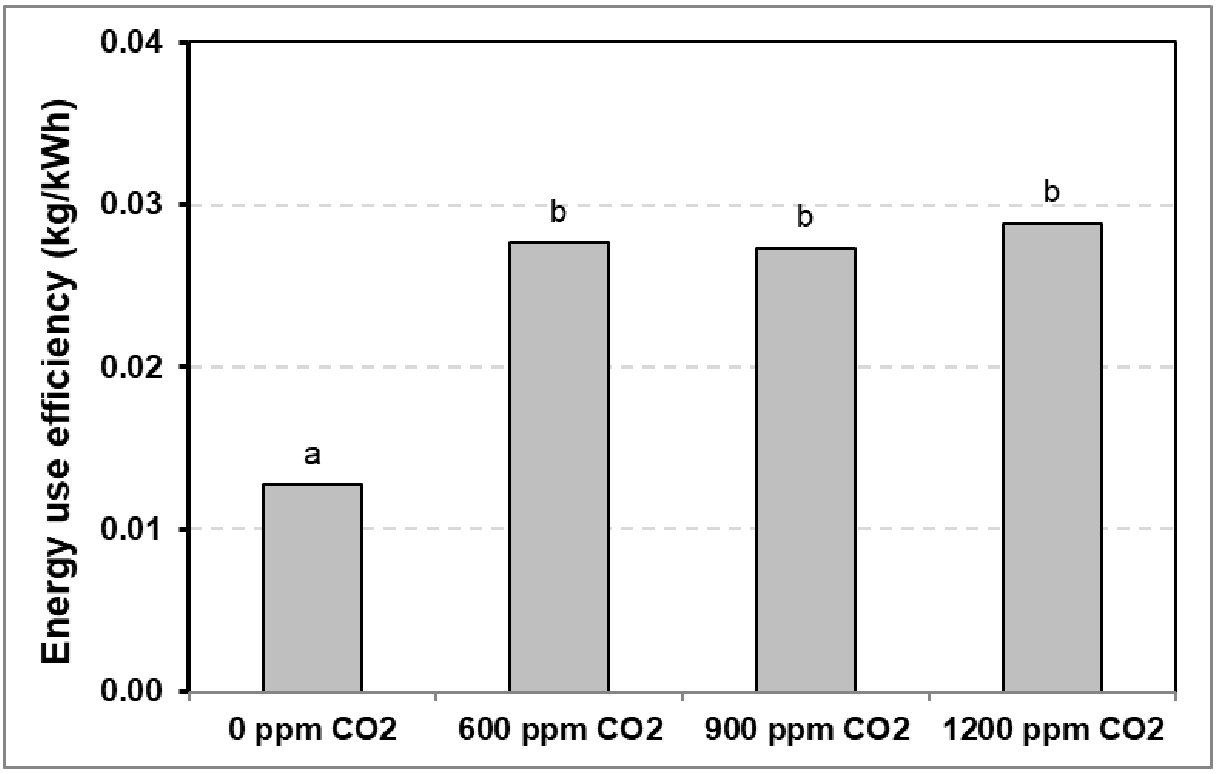


Fig. 32: Energy use efficiency (= marketable yield per used energy) for tomatoes under different CO_2 treatments.

4.4.3 Light related costs

Since the application of the electricity law 65/2003 in 2005, the cost for electricity has been split between the monopolist access to utilities, transmission and distribution and the competitive part, the electricity itself. Most growers (95%) are, due to their location, mandatory customers of RARIK, the distribution system operator (DSO) for most of Iceland except in the Southwest and Westfjords.

The government subsidises the distribution cost of growers that comply to certain criterias. In recent years, the subsidies fluctuated quite much. After substitution / direct payment from the state of variable cost of distribution (95%) resulted in costs of about 1 ISK/kWh for distribution, while for the sale values amounted 5,89-8,35 ISK/kWh. However, it must be taken into account that big vegetable growers can get at least 50% discount on the tariff values. Based on this information, energy costs for tomato production were calculated (Tab. 8). The electricity costs did not differ between the CO_2 treatments as the setup of the lights was the same between treatments. Also, the investments into lights were the same between the CO_2 treatments (Fig. 33).

Tab. 8: Energy costs and investment into lights for one growing circle of tomatoes under different CO_2 treatments.

Costs (ISK/m²)	CO_2 (ppm)			
	0	600	900	1200
Electricity distribution [1]	566	566	566	566
Electricity sale [2]	3.334-4.726	3.334-4.726	3.334-4.726	3.334-4.726
∑ **Electricity costs**	3.900-5.292	3.900-5.292	3.900-5.292	3.900-5.292
Lamps [3]	1.172	1.172	1.172	1.172
Bulbs [4]	604	604	604	604
∑ **Investment lights**	1.776	1.776	1.776	1.776
Total light related costs	**5.676-7.068**	**5.676-7.068**	**5.676-7.068**	**5.676-7.068**

1 Assumption: On average around 1 ISK/kWh after substitution / direct payment from the state
2 Assumption: Around 5,89-8,35 ISK/kWh (according to data from Rarik in the year 2023)
3 HPS lights: 33.000 ISK / 1000 W lamp, lifetime: 8 years
4 HPS bulbs: 5.275 ISK / 1000 W bulb, lifetime: 2 years

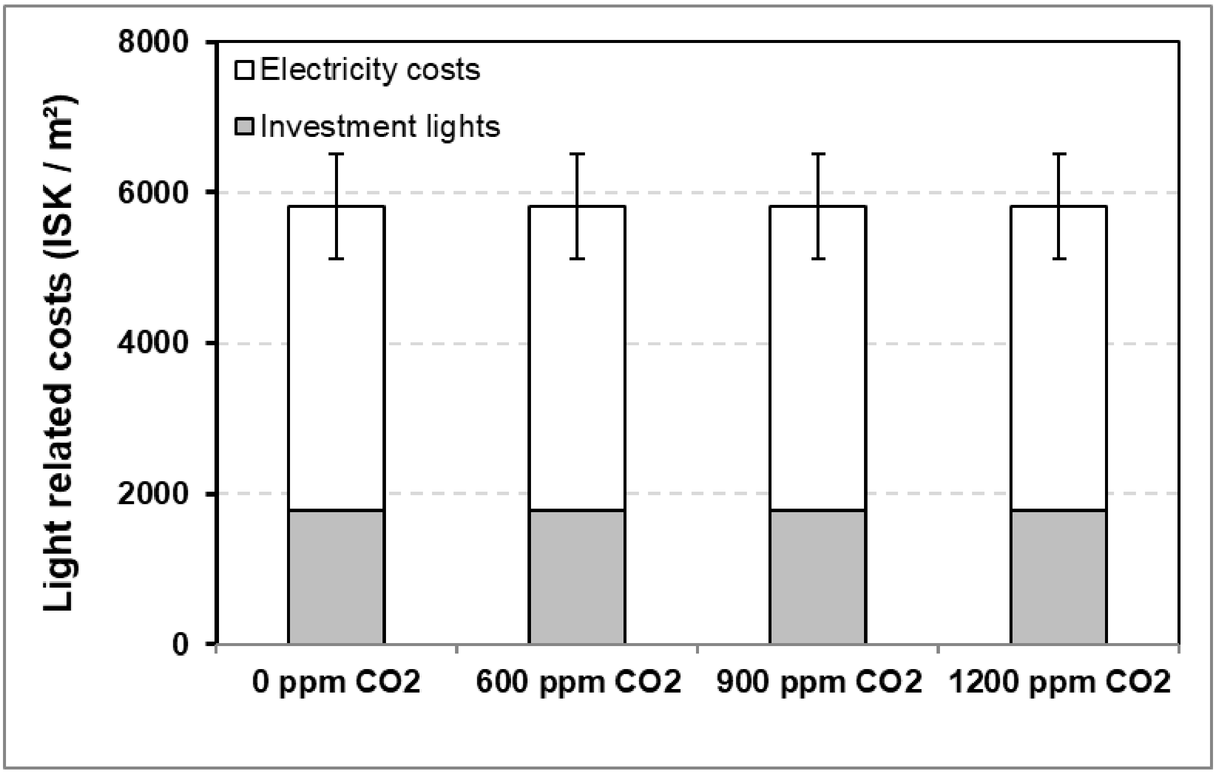


Fig. 33: Light related costs in tomato production under different CO_2 treatments.

4.4.4 Costs of electricity in relation to yield

Costs of electricity in relation to yield for wintergrown tomatoes were calculated (Tab. 9). The costs of electricity per kg yield increased by more than double under ambient CO_2 conditions. Between the treatments with CO_2 enrichment, varied the electricity costs marginally.

Tab. 9: Variable costs of electricity in relation to yield.

Treatment	CO_2 (ppm)			
	0	**600**	**900**	**1200**
Yield (kg/m^2)	7,2	15,7	15,5	16,3
Electricity costs (ISK/kg yield)	463-656	212-301	215-305	205-290

4.4.5 Profit margin

The profit margin is a parameter for the economy of growing a crop. It is calculated by subtracting the variable costs from the revenues. The revenues itself, is the product of the price of the sale of the fruits and kg yield. For each kg of tomatoes, growers are getting about 580 ISK from Sölufélag garðyrkjumanna (SFG, The Horticulturists' Sales Company) and in addition about 122 ISK from the government. Therefore, the revenues increased with more yield (Fig. 34). The amount of CO_2 enrichment had no influence on the revenue, whereas a lower revenue was reached under ambient CO_2 conditions.

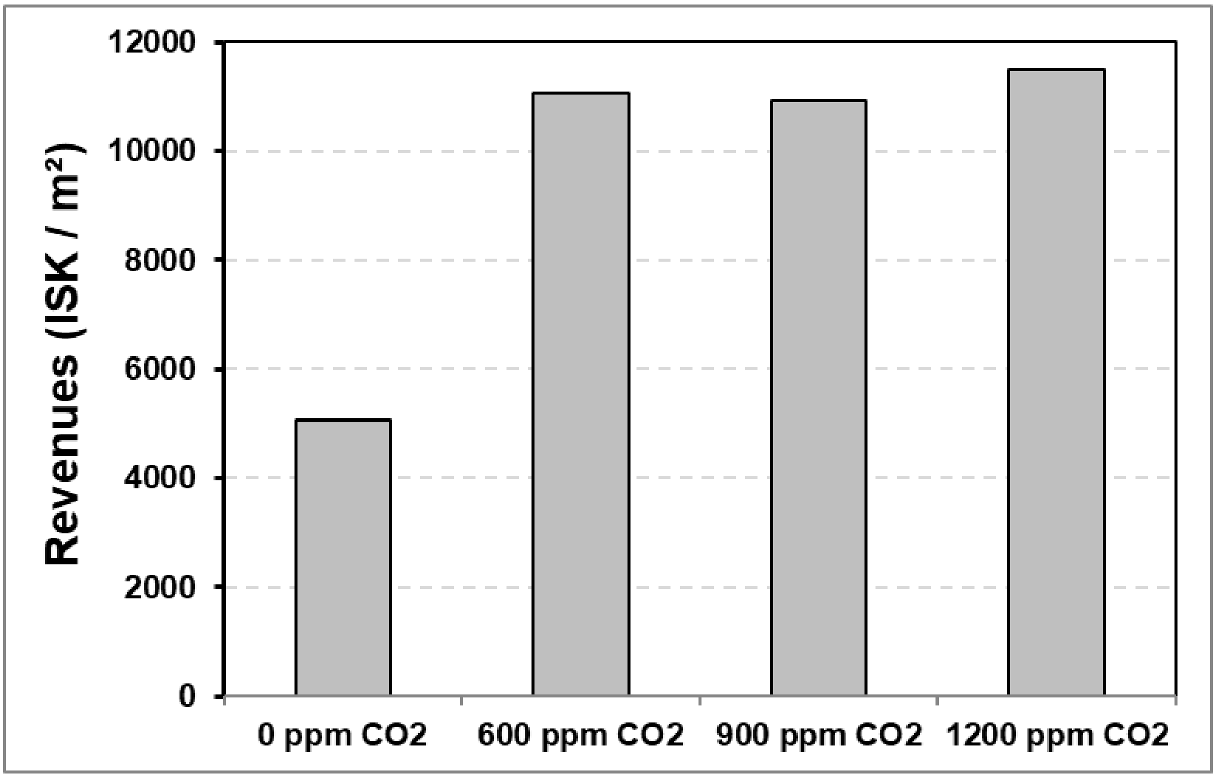


Fig. 34: Revenues at different CO_2 treatments.

When considering the results of previous chapter, one must keep in mind that there are other cost drivers in growing tomatoes than electricity alone. Among others, those are e.g. the costs for seeds and seedling production (≈ 400 ISK/m^2) and transplanting (≈ 560 ISK/m^2), costs for gutters (≈ 100 ISK/m^2), and watering system (≈ 350 ISK/m^2), costs for plant nutrition (≈ 700 ISK/m^2), truss support (≈ 70 ISK/m^2), CO_2 transport (≈ 140 ISK/m^2), liquid CO_2 (≈ 1.400 ISK/m^2), the rent of the tank (≈ 620 ISK/m^2), the rent of the green box (≈ 110 ISK/m^2), material for packing (≈ 170 ISK/m^2), packing costs with the machine from SFG (≈ 340 ISK/m^2) and transport costs from SFG (≈ 180 ISK/m^2) (Fig. 35).

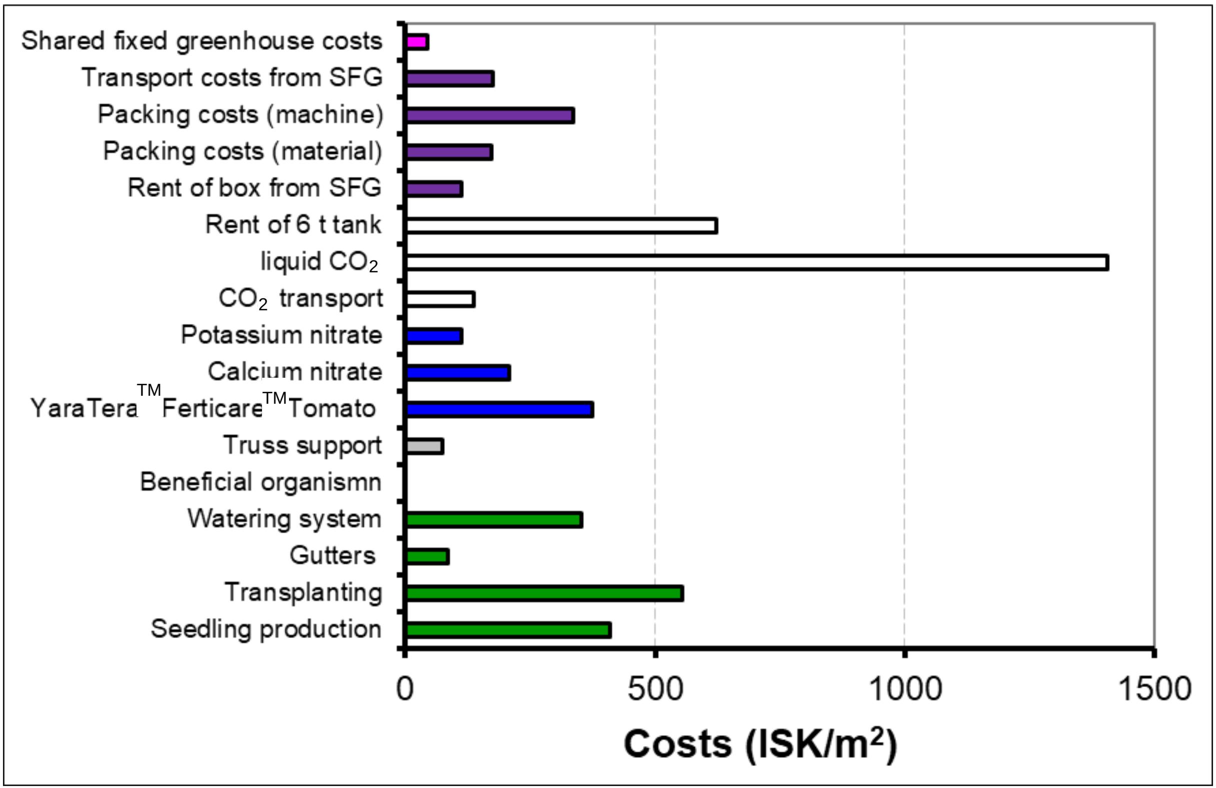


Fig. 35: Variable and fixed costs (without lighting and labour costs).

However, in Fig. 35 three of the biggest cost drivers are not included and these are investment in lamps and bulbs, electricity, and labour costs. These costs are also included in Fig. 36 and it is obvious, that especially the electricity and the investment in lamps and bulbs as well as the CO_2 and labour costs are contributing much to the variable and fixed costs beside the costs for seedling production, transplanting and cultivation and the costs for packing and marketing. The proportion of the variable and fixed costs is mainly comparable for all CO_2 treatments, except that with more CO_2 enrichment increased naturally the CO_2 cost, whereas the light related costs (electricity + investment into lamps and bulbs) on total production costs decreased. Attention must be paid on the big proportion of 35-59% of light related costs on the one hand and of 0-38% of CO_2 costs on the other hand. However, light related costs were still higher than CO_2 costs for the treatments "600 ppm CO_2" and "900 ppm CO_2".

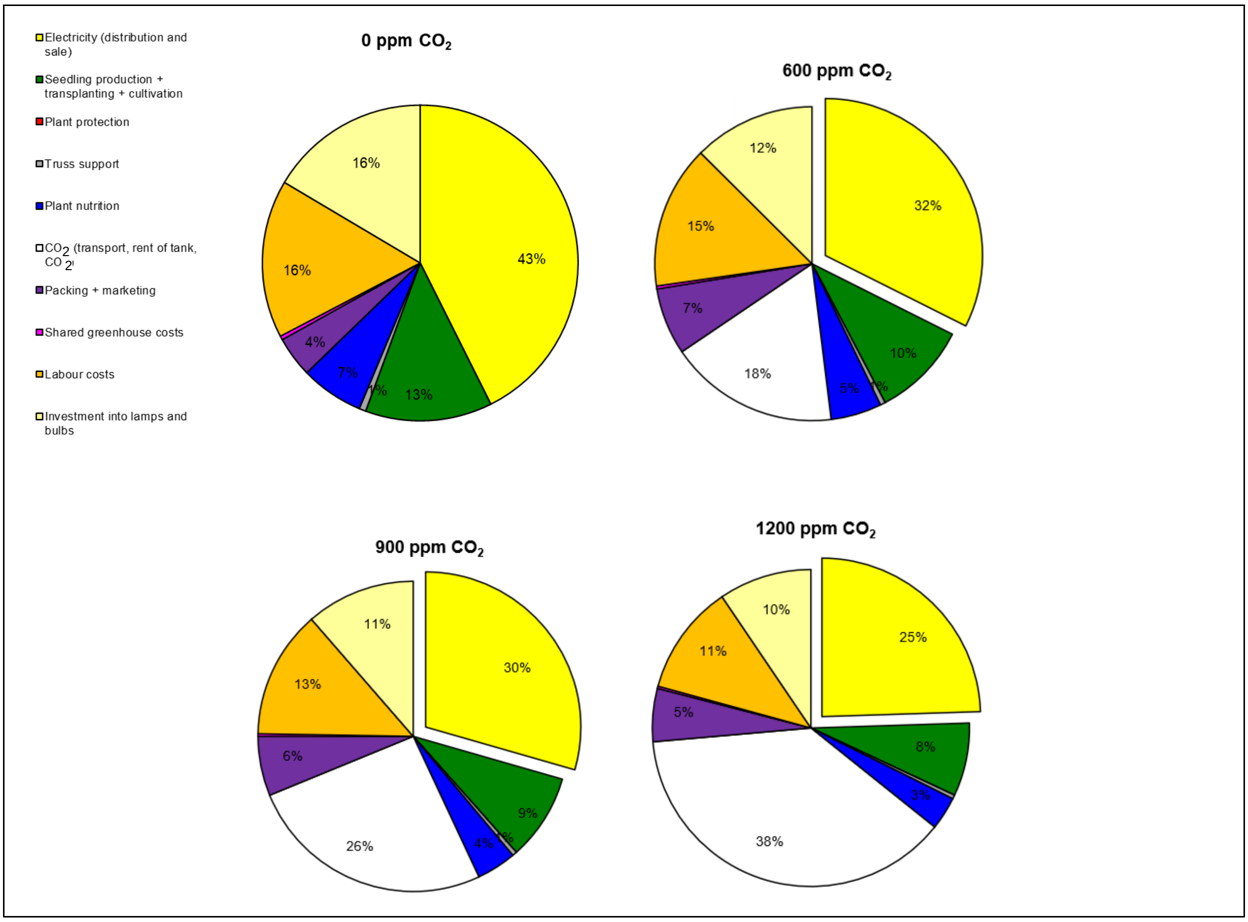


Fig. 36: Division of variable and fixed costs.

A detailed composition of the variable costs at each treatment is shown in Tab. 10.

Tab. 10: Profit margin of tomatoes at different CO_2 treatments.

Treatment	CO_2 (ppm)			
	0	**600**	**900**	**1200**
Marketable yield (kg/m²)	7,2	15,7	15,5	16,3
Sales				
SFG (ISK/kg) [1]	583	583	583	583
Government (ISK/kg) [2]	121,66	121,66	121,66	121,66
Revenues (ISK/m²)	**5.074**	**11.063**	**10.922**	**11.486**
Variable and fixed costs (ISK/m²)				
Electricity distribution [3]	566	566	566	566
Electricity sale [4]	3.334-4.726	3.334-4.726	3.334-4.726	3.334-4.726
Seeds [5]	180	180	180	180
Grodan small [6]	15	15	15	15
Grodan big [7]	214	214	214	214
Slab [8]	471	471	471	471
Strings [9]	84	84	84	84
Gutters [10]	85	85	85	85
Watering system	353	353	353	353
Truss support [11]	74	74	74	74
YaraTera™Ferticare™ Tomato[12]	377	401	349	343
Potassium nitrate [13]	208	221	192	189
Calcium nitrate [14]	111	120	105	103
CO_2 transport [15]	0	137	273	547
Liquid CO_2 [16]	0	1.406	2.811	5.622
Rent of CO_2 tank [17]	0	935	935	935
Rent of box from SFG [18]	63	137	136	143
Packing material [19]	97	212	209	220
Packing (labour + machine) [20]	189	413	407	428
Transport from SFG [21]	99	216	213	224
Shared fixed costs [22]	43	43	43	43
Lamps [23]	1.172	1.172	1.172	1.172
Bulbs [24]	604	604	604	604
∑ variable costs	8.340-9.732	11.393-12.785	12.827-14.219	15.950-17.342
Revenues -∑ variable costs	-3.267--4.659	-330--1.722	-1.905--3.297	-4.464--5.856
Working hours (h/m²)	0,72	0,86	0,86	0,87
Salary (ISK/h)	2.427	2.427	2.427	2.427
Labour costs (ISK/m²)	1.747	2.091	2.083	2.116
Profit margin (ISK/m²)	**-5.014--6.406**	**-2.421--3.813**	**-3.988--5.380**	**-6.580--7.972**

[1] Price winter 2022/2023: 583 ISK / kg (with VAT)
[2] Price for 2021: 121,66 ISK / kg
[3] Assumption: On average around 1 ISK / kWh after substitution / direct payment from the state
[4] Assumption: Around 5,89-8,35 ISK / kWh (according to data from Rarik in the year 2023)
[5] 71.920 ISK / 1.000 Completo seeds
[6] 36x36x40mm, 1.171 ISK / 240 Grodan small
[7] 27/35, 69 ISK / 1 Grodan big
[8] 50x24x10cm, 608 ISK / slab
[9] 27 ISK / string
[10] 4.388 ISK / m gutter; assumption: 10 years lifetime, 1,33 circles / year
[11] 2 ISK / truss support
[12] 9.900 ISK / 25 kg YaraTera™ Ferticare™ Tomato
[13] 8.575 ISK / 25 kg Potassium nitrate
[14] 4.500 ISK / 25 kg Calcium nitrate
[15] CO_2 transport from Rvk to Hveragerði / Flúðir: 9,97 ISK/kg CO_2
[16] Liquid CO_2: 82,65 ISK/kg CO_2
[17] Rent for 11 t tank: 170.000 ISK/month, assumption: rent in relation to 1.000 m^2 lightened area
[18] 113 ISK / box
[19] Packing costs (material):
Costs for packing of tomatoes (1,00 kg): Platter: 7,5 ISK / kg,
plastic film: 2,75 ISK / kg,
label: 0,65 ISK / kg
[20] Packing costs (labour + machine): 21,2 ISK / kg
[21] Transport costs from SFG: 11,1 ISK / kg
[22] 94 ISK/m^2/year for common electricity, real property and maintenance
[23] HPS lights 1000 W: 33.000 ISK/lamp, lifetime: 8 years
[24] HPS bulbs: 5.275 ISK / 1000 W bulb, lifetime: 2 years

The profit margin was dependent on the light treatment and was varying between -3.100 to -7.300 ISK/m^2 (Fig. 37). The profit margin was lowest under the treatment with the highest CO_2 enrichment (-6.600 to -8.000 ISK/m^2) and next lowest under ambient CO_2 conditions (-5.000 to -6.400 ISK/m^2). The highest profit margin was reached with the lowest CO_2 enrichment (-2.400 to -3800 ISK/m^2). That means by using the lowest CO_2 enrichment compared to ambient CO_2 conditions increased profit margin by 2.600 ISK/m^2. "900 ppm CO_2" had a profit margin of -4.000 to -5.400 ISK/m^2. That means by using the lowest CO_2 enrichment was an advantage in profit margin of 1.600 ISK/m^2 gained. However, it must be considered that the profit margin depends much on the price of CO_2.

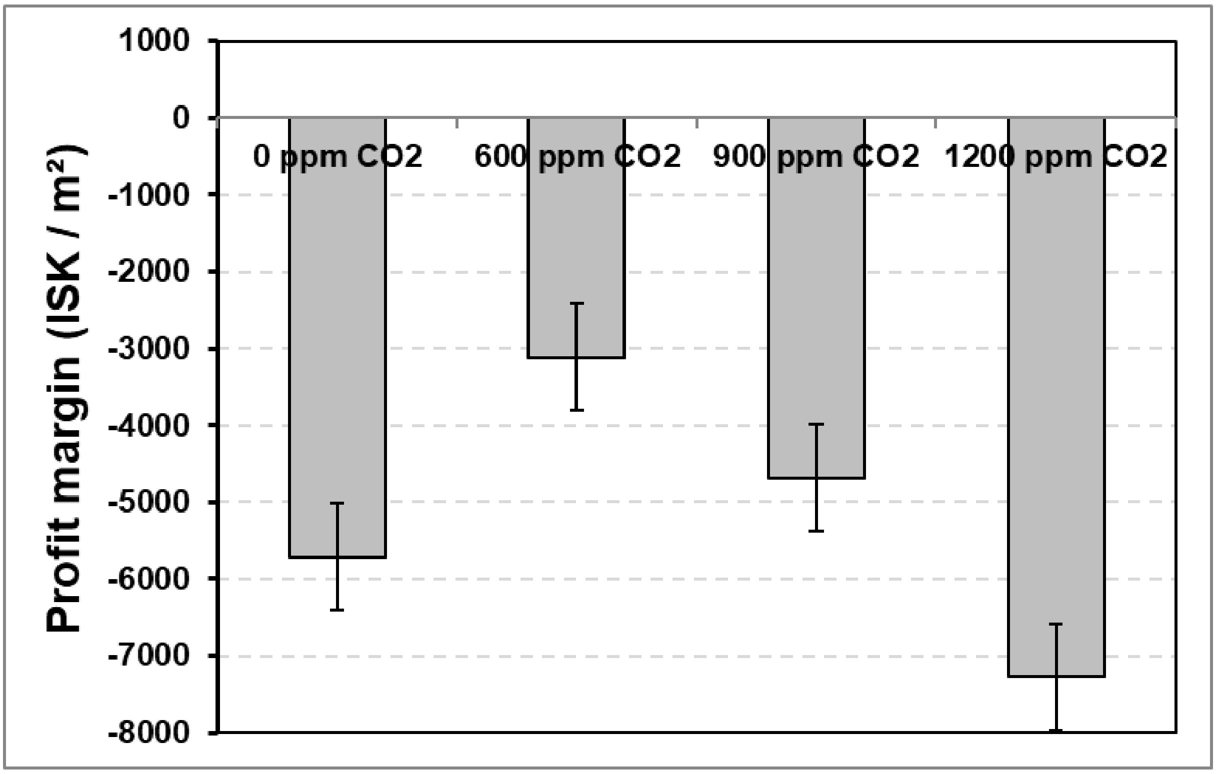


Fig. 37: Profit margin in relation to the CO_2 treatment.

5 DISCUSSION

In winter production, the success of vegetable growing strongly depends on supplemental lighting. In this experiment, the interaction of the effect of the CO_2 amount and supplemental lighting was tested on tomatoes.

5.1 Yield in dependence of the CO_2 application

Under ambient conditions (naturally occurring, 430 ppm CO_2) the level of CO_2 dropped to about 200 ppm CO_2 as it is consumed by plants. Therefore, the use of supplemental CO_2 is needed to keep the levels in the ambient range or above. Increasing the CO_2 concentrations above ambient levels resulted in improved plant growth, increased number of flowers/fruits, more marketable fruits and in higher yields. Then, the distance between clusters was significantly reduced, resulting in tendentially one cluster more, while the height of the plants was not affected by CO_2 enrichment. Also, *Hicklenton & Jolliffe* (1987) reported a significantly higher number of clusters with CO_2 enrichment compared to tomatoes grown under ambient conditions. But, contrary to the present results, several authors reported that under CO_2 enrichment increased the height of transplants by 22-54% compared to ambient CO_2 conditions (*Lanoue* et al., 2018; *Mamatha* et al., 2014; *Fan* et al., 2013). In general, CO_2 enrichment to levels higher than the ambient conditions increased yield of tomato plants (*Pan* et al., 2019; *Mamatha* et al., 2014; *Nilsen* et al., 1983; *Calvert* & *Slack*, 1975). *Yelle* et al. (1990) found that yield increased by 21,5% when CO_2 level was increased from ambient (330 ppm) to enriched (900 ppm) CO_2 concentration. However, higher effects were reported at CO_2 enrichment to 1000 ppm, which increased yields and plant dry weight of tomato plants by 30% (*Hicklenton* & *Jolliffe*, 1987; *Slack*, 1986) and 36% (*Yelle* et al., 1987). Compared to these authors, in the present experiment yield could be doubled under “600 ppm CO_2” compared to ambient CO_2 conditions. Thereby, the yield increase was both in early yield and total yield and attributed to a higher number of marketable fruits and a higher average weight. This was in accordance with *Fierro* et al. (1994) who reported higher early and cumulative yields when tomato and sweet pepper seedlings were enriched with CO_2. Also, *Rangaswamy* et al. (2021) attributed the higher tomato yield under enriched compared to ambient CO_2 conditions to heavier fruits. *Pan* et al. (2019) observed an increase of 16-27% in dry mass when increasing the CO_2 concentration from an ambient level to 700-800 ppm. Similarly, as in the present results, CO_2 enrichment reduced water consumption due to lower transpiration, thus increasing water use efficiency (*Pan* et al., 2020).

The application of CO_2 (600 ppm CO_2) resulted in a 2.600 ISK/m^2 higher profit margin than the use of only the ambient CO_2 level (Fig. 38). The yield was increased by 8,5 kg/m^2. When the yield of “0 ppm CO_2” would have been nearly 4,5 kg/m^2 higher, the profit margin would have been comparable to “600 ppm CO_2”. However, the profit margin was negative for both treatments. To be able to get a positive profit margin a yield increase would be necessary: Yield must reach nearly 17 kg/m^2 under ambient CO_2 conditions and nearly 21 kg/m^2 under “600 ppm CO_2”. Although ambient CO_2 levels are acceptable for plant growth, CO_2 enrichment is recommended as yield as well as profit margin increased.

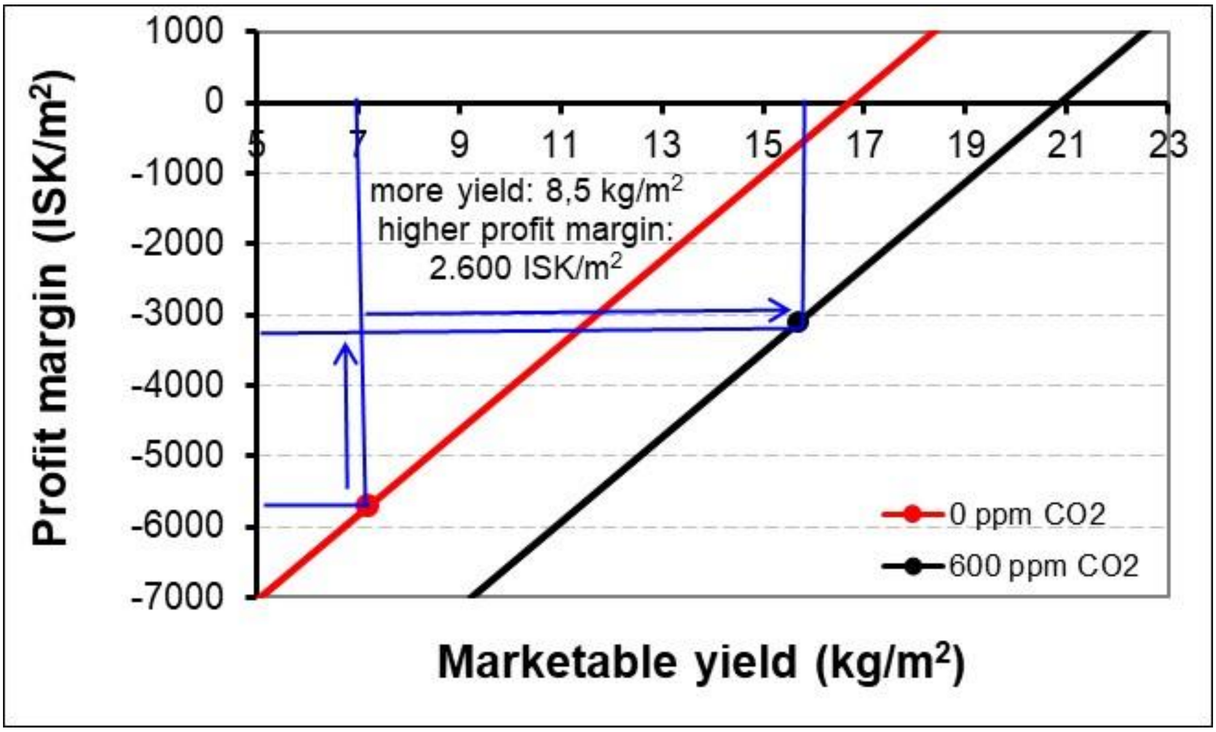


Fig. 38: Profit margin in relation to yield with and without CO_2 application in tomato production – calculation scenarios.

5.2 Yield in dependence of the CO_2 enrichment

CO_2 enrichment is a common practice in protected cultivation of tomatoes. In general, the yield responses to increases in CO_2 enrichment followed a logarithmic curve, increases in yield are observed until a saturation point is reached. After this CO_2 saturation point, yield no longer increases with increases in CO_2 enrichment (Fig. 39). A higher CO_2 level than 600 ppm had only a small effect on tomato yield. According to the logarithmic trendline did yield increase by less than 2 kg/m^2 when CO_2 level was increased from 600 to 900 ppm CO_2, while an increase from 900 to 1200 ppm CO_2 did increase yield by 1 kg/m^2. However, attention must be paid that Fig. 39 refers to the applied amount of CO_2. Using the average CO_2 values over the growth period resulted in a different picture (Fig. 40). Then, according to the logarithmic trendline yield did increase by 3 kg/m^2 when the average CO_2 level was increased from 600 to 900 ppm CO_2, while a further increase to nearly 1200 ppm CO_2 did increase yield by 2 kg/m^2. Therefore, it is obvious that the average CO_2 amount (Fig. 40) resulted in a higher effect on yield according to the trendline compared to the applied amount of CO_2 (Fig. 39). However, it has to be taken into account, that the significantly higher

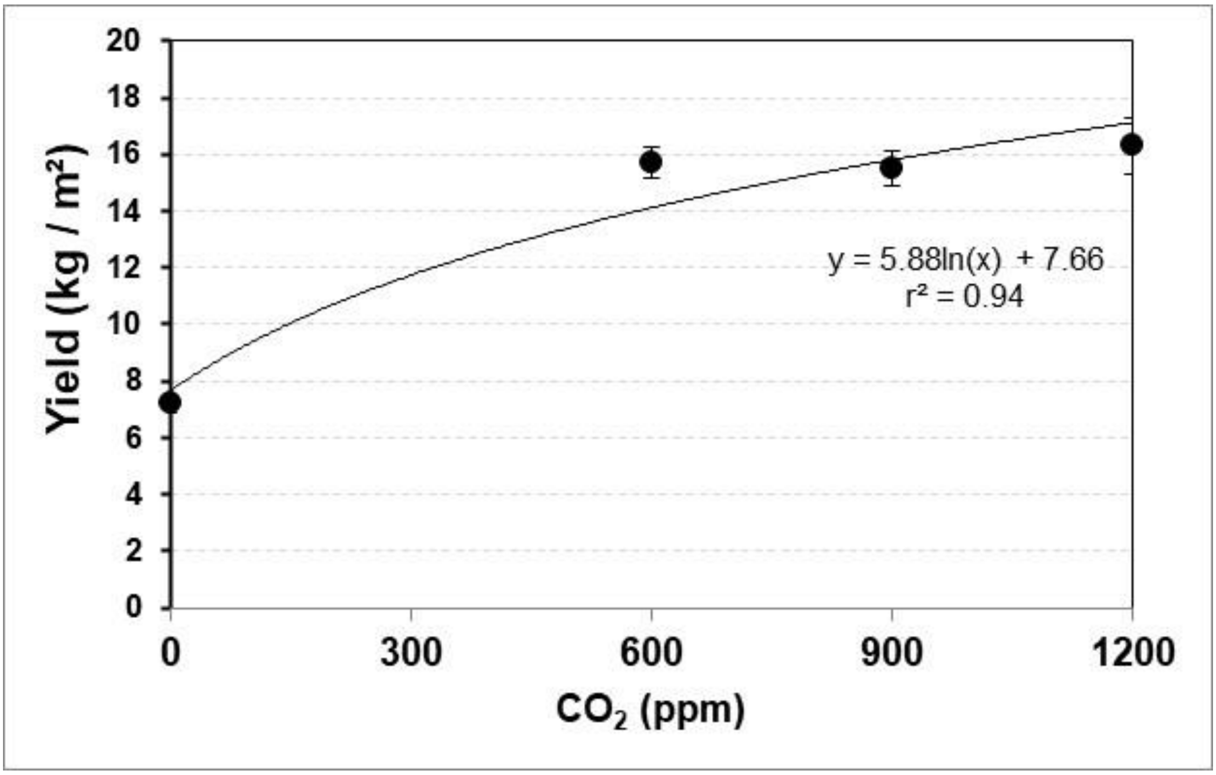


Fig. 39: **Relationship between applied CO_2 amount and yield.**

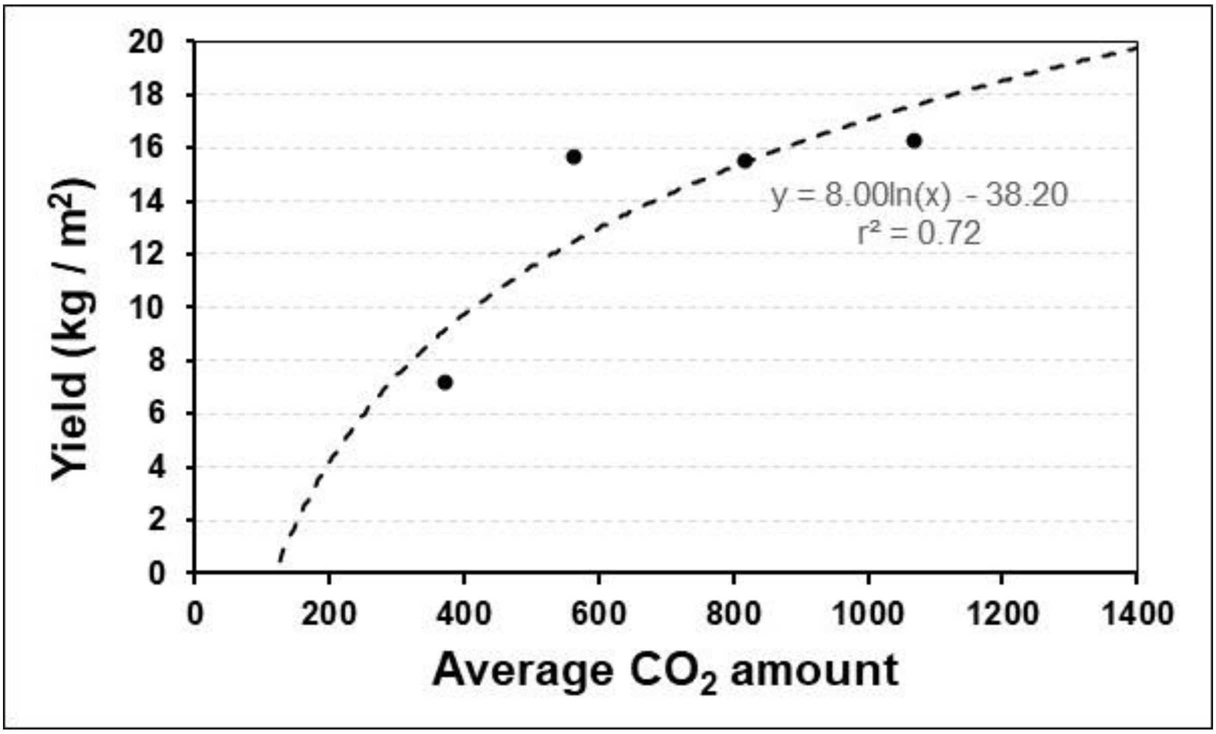


Fig. 40: **Relationship between average CO_2 amount and yield.**

substrate temperature under the lowest CO_2 enrichment, despite of a comparable air temperature between treatments, could have had a positive influence on yield compared to the other enriched CO_2 treatments. When the substrate temperature would have been as low as under the other CO_2 treatments, a lower yield might have been expected and then the logarithmic trendline would record a steeper gradient.

The low effect of a higher CO_2 enrichment on yield could be related to increases of leaf thickness, as opposed to leaf expansion under high CO_2, suggests that the extra assimilates were stored in the leaves rather than translocated into the developing fruits (*Calvert* & *Slack*, 1975). Indeed, the significantly lower leaf temperature with increasing CO_2 enrichment could point to thicker leaves at higher CO_2 enrichment, indicating less effect on yield. The total number of marketable fruits was increased with CO_2 enrichment but could not be increased further with an increased amount of CO_2 enrichment. However, the average weight of tomatoes is indicating, that with an increased CO_2 enrichment, a higher average weight could be reached.

When the marketable yield per cluster was set into relation to the number of harvested clusters (Tab. 11), the marketable yield per cluster was not influenced by the amount of CO_2 enrichment, but much lower at ambient CO_2 conditions.

Tab. 11: Marketable yield per cluster with CO_2 treatments.

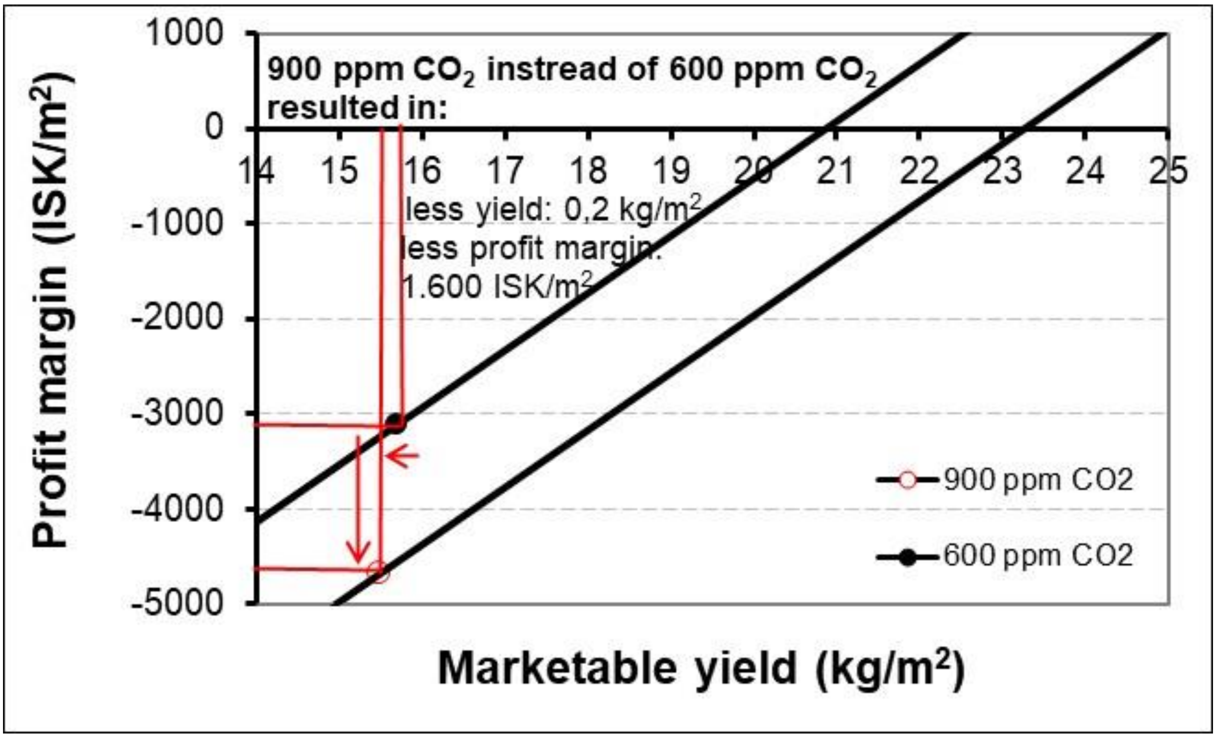
	CO_2 (ppm)			
Treatment	**0**	**600**	**900**	**1200**
Yield (kg/m^2)	7,2	15,7	15,5	16,3
Harvested clusters (no/m^2)	25	28	28	28
Yield (kg/cluster)	0,29	0,56	0,55	0,58

In total, few studies have highlighted the beneficial interaction of supplemental lighting and CO_2 enrichment (*Pan* et al., 2019; *Ting* et al., 2017). It has been demonstrated that CO_2 enrichment increased the tomato yield in a range of 19-124% when CO_2 is increased to a range of 700-1400 ppm separately from that of supplemental lighting (*Pan* et al., 2019; *Mamatha* et al., 2014; *Calvert* & *Slack*, 1975). Increasing the PPFD and the CO_2 concentration under transplants increased the photosynthetic rate (*Pan* et al., 2019; *Lanoue* et al., 2018; *Fan* et al., 2013). For example, tomato transplants exhibit an increase in their photosynthetic rate of 90% when PPFD was increased from

150 to 300 µmol/m^2/s (*Fan* et al., 2013). *Pan* et al. (2019) reported a 21-39% increase in the photosynthetic rate with an increase in the PPFD of 200 µmol/m^2/s with HPS lighting under tomato seedlings. In response to CO_2 enrichment from 400 to 1000 ppm *Lanoue* et al. (2018) found a 52% increase in the photosynthetic rate of tomato seedlings. Similarly, *Pan* et al. (2019) showed that the photosynthetic rate of tomato seedlings increased by 9-27% with the enrichment from 400 to 800 ppm CO_2. Increasing the PPFD and CO_2 enrichment increased the net photosynthetic rate and consequently resulted in increased fresh and dry mass of tomato seedlings (*Huber* et al., 2021). The saturation point regarding the benefits of CO_2 enrichment on the net photosynthetic rate for tomato seedlings were reported to be 1500 ppm with a PPFD of 600 µmol/m^2/s, and under a PPFD of 900 µmol/m^2/s a CO_2 level of 1200 ppm reached the photosynthetic rate threshold (*Ting* et al., 2017). In the study of *Huber* et al. (2021) the net photosynthetic rate was not saturated at 200 µmol/m^2/s and 1600 ppm CO_2, which suggested that the light intensity and CO_2 concentration can be further increased to increase the photosynthetic rate. Also, no additional increase in dry mass was observed at CO_2 level above 1000 ppm. However, attention must be paid not only to the saturation point, but also to the economic side.

By increasing the CO_2 amount from 600 to 900 ppm CO_2, yield was reduced by 0,2 kg/m^2 and profit margin by 1.600 ISK/m^2 (Fig. 41). And by increasing the CO_2 amount from 900 to 1200 ppm CO_2, yield was increased by 0,8 kg/m^2, but profit margin reduced by 2.600 ISK/m^2 (Fig. 41). Profit margin was for all CO_2 application amounts negative. To be able to get a positive profit margin would a yield increase be necessary: Yield must reach nearly 21 kg/m^2 for “600 ppm CO_2”, more than 23 kg/m^2 for “900 ppm CO_2” and more than 28 kg/m^2 for “1200 ppm CO_2”. Therefore, it can not be advised to apply 1200 ppm CO_2 to tomatoes. These results show very clearly that purchasing liquid CO_2 is expensive.

According to *Nederhoff* (1994) 400 ppm CO_2 enrichment requires 50 kg CO_2/ha and 1000 ppm CO_2 enrichment requires 200 kg CO_2/ha. With that, a higher CO_2 enrichment is making it necessary to increase yield more than proportional to have a positive influence in yield. Therefore, too high CO_2 concentrations may not be economically feasible. However, as *Pan* et al. (2019) concluded has supplemental light a greater



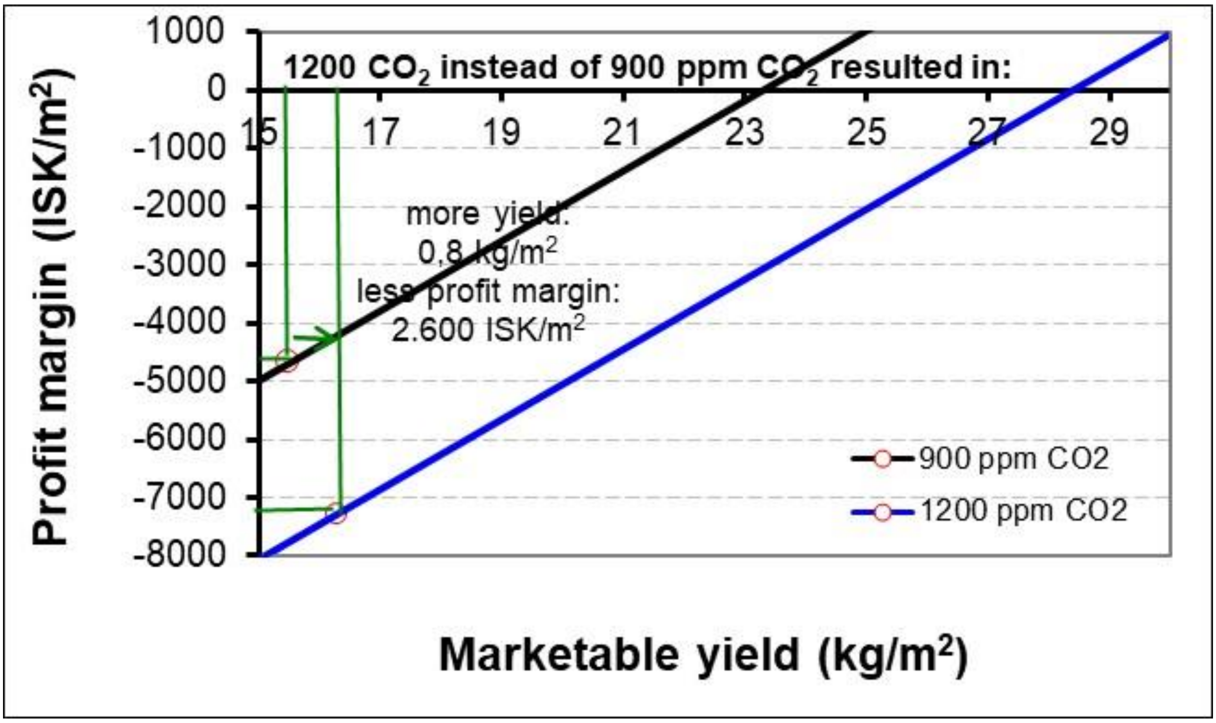


Fig. 41: Profit margin in relation to yield with different CO_2 amounts in tomato production – calculation scenarios.

effect than CO_2 enrichment on growth, yield and quality. The authors concluded because of different CO_2 concentrations and/or different light intensities may exert varying effects on tomato growth and yield, much work should be conducted in the future to explore the optimal combination of CO_2 concentration and light intensity to obtain the greatest yield and quality of tomatoes. *Pan* et al. (2019) summarized that the combination of increased CO_2 (800 ppm CO_2) and high light intensity (400 µmol/m^2/s) resulted in optimal growth and carbon assimilation. Also, other research reports have shown an increase in CO_2 enrichment to more than 700-900 ppm CO_2 provides little improvement in growth (*Fierro* et al., 1994; *Mamatha* et al., 2014). This was in accordance with the present experiment. Therefore, from the point of view of yield and from the economic side, lower CO_2 enrichment than 1200 ppm are clearly recommended.

5.3 Future speculations concerning energy prices

In terms of the economy of lighting it is also worth to make some future speculations about possible developments also regarding the fluctuation of the subsidy. So far, the lighting costs (electricity + bulbs) are contributing to a big part of the production costs of tomatoes. In the past and present, there have been and there are still a lot of discussions (for example in Bændablaðið (farmer's magazine), 11. tölublað 2022, blað nr. 612) concerning the energy prices. Therefore, it is necessary to highlight possible changes in the energy prices (Fig. 42). So far, the lighting costs are contributing to about 1/3 of the production costs.

The white columns are representing the profit margin according to Fig. 37. Where to be assumed, that growers would get no subsidy from the state for the distribution of the energy, that would result in a profit margin of -10.700 to -16.500 ISK/m^2 (black columns, Fig. 42). Without the subsidy of the state, probably less Icelandic growers would produce tomatoes over the winter months. When it is assumed that the energy costs, both in distribution and sale, would increase by 25%, but growers would still get the subsidy, then the profit margin would range between -4.300 to -8.400 ISK/m^2 (dotted columns). When it is assumed that growers must pay 25% less for the energy, the profit margin would increase to -2.000 to -6.100 ISK/m^2 (gray columns). From these scenarios, it can be concluded that from the grower's side it would be preferable to get subsidy to be able to get a higher profit margin and grow tomatoes over the winter. It is obvious that actions must be taken, that growers are also producing during the winter at low solar irradiation. The profit margin at a high CO_2 amount was very much dependent on the level of the subsidy.

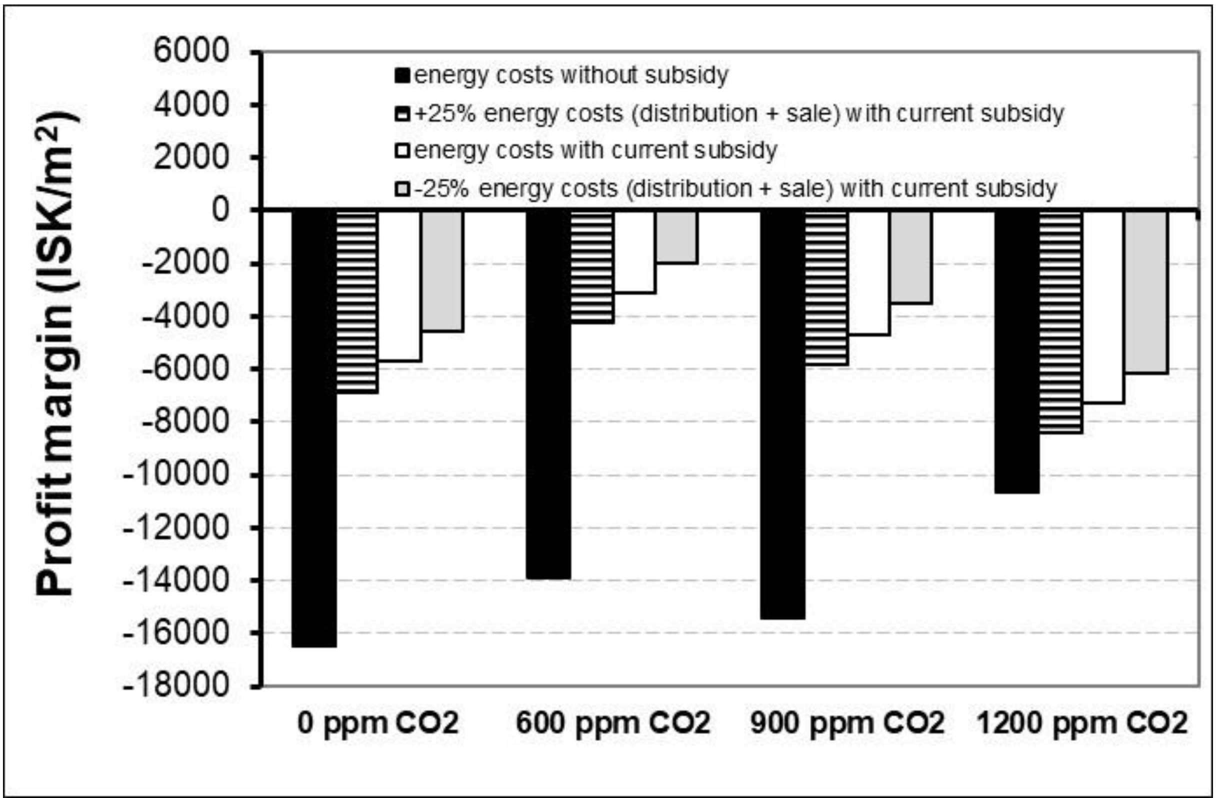


Fig. 42: Profit margin in relation to the CO_2 treatment – calculation scenarios.

5.4 Recommendations for increasing profit margin

The current economic situation for growing tomatoes necessitates for reducing production costs to be able to heighten profit margin for tomato production. On the other hand, growers need to decide, if tomatoes should be grown during low solar irradiation and much use of electricity in addition to a high amount of CO_2.

It can be suggested that growers can improve their profit margin of tomatoes by:

1. Getting higher price for the fruits
   It may be expected to get a higher price when consumers would be willing to pay even more for Icelandic fruits than imported ones. Growers could also get a higher price for the fruits with direct marketing to consumers (which is of course difficult for large growers). They could also try to find other channels of distribution (e.g. selling directly to the shops and not through SFG).

2. Decrease plant nutrition costs

   Growers can decrease their plant nutrition costs by mixing their own fertilizer. When growers would buy different nutrients separately for a lower price and mix out of this their own composition, they would save fertilizer costs. However, this takes more time, and it is more difficult to perform this task by employees. At low solar irradiation, watering with a scale can save up to 20% of water – and with that plant nutrition costs – with same yield when compared to automatic irrigation (*Stadler*, 2013). It is profitable to adjust the watering to the amount of last water application (*Yeager* et al., 1997).

3. Lower CO_2 costs

   The costs of CO_2 are rather high, but CO_2 enrichment is giving a higher profit margin if not too high CO_2 values are chosen. The CO_2 selling company has currently a monopoly position in the market and a competition might be good.

4. Decrease packing costs

   The costs for packing (machine and material) from SFG and the costs for the rent of the boxes are high. Costs could be decreased by using cheaper packing materials. Also, packing costs could be decreased when growers would do the packing on site.

5. Efficient employees

   The efficiency of each employee needs to be checked regularly and growers will have an advantage to employ faster workers. Growers should also check the user-friendliness of the working place to perform only minimal manual operations. It is often possible to optimize by not letting each employee doing each task, but to distribute tasks among employees by creating a flow line where employees become more specialized and thus achieve better productivity. In total, employees will work more efficiently due to the specialisation.

6. Decrease energy costs

   - Lower prices for distribution and sale of energy (which is not realistic)
   - Growers should decrease artificial light intensity at increased solar irradiation because this would possibly result in no lower yield (*Stadler* et al., 2010).

- Growers need to make sure that they are using the right RARIK tariff and the cheapest energy sales company tariff. Unfortunately, it is not so easy, to say, which is the right tariff, because it is grower dependent.
- Growers should check if they are using the power tariff in the best possible way to be able to get a lowered peak during winter nights and summer (max. power -30%). It is important to use not so much energy at the most expensive time but have a high use during cheap times.
- Growers can save up to 8% of total energy costs by dividing the winter lighting over all day. That means growers should not let all lamps be turned on at the same time. This would be practicable, when they are growing in different independent greenhouses. Of course, this is not so easy to implement, when greenhouses are connected but can also be solved there by having different switches for the lamps to be able to turn one part of the lamps off at a given time. Then, plants in one compartment of the greenhouse would be lightened only during the night. When yield would be not more than 2% lower with lighting at nights compared to the usual lighting time, dividing the winter lighting over all day would pay off. However, a tomato experiment showed that the yield decreased by about 15% when tomatoes got from the beginning of November to the end of February light during nights and weekends (*Stadler*, 2012). This resulted in a profit margin that was about 18% lower compared to the traditional lighting system and therefore, normal lighting times are recommended.
- Also, growers could decrease the energy costs by about 6% when they would lighten according to 100 J/cm^2/cluster and 100 J/cm^2 for plant maintenance (*Stadler*, 2012). This would mean that especially at the early stage after transplanting, plants would get less hour’s light. Also at high natural light, lamps would be turned off. In doing so, compared to the traditional lighting system, profit margin could be increased by about 10% (assuming similar yield).

- For large growers, that are using a minimum of 2 GWh it could be recommended to change to “stórnotendataxti” in RARIK and save up to 35% of distribution costs.
- It is expected that growers are cleaning their lamps to make it possible, that all the lights are used effectively and that they are replacing their bulbs before the expensive season is starting.
- *Aikman* (1989) suggests using partially reflecting material to redistribute the incident light by intercepting material to redistribute the incident light by intercepting direct light before it reaches those leaves facing the sun, and to reflect some light back to shaded foliage to give more uniform leaf irradiance.
- By moving lights closer to the plants the µmol level is increasing. This is positively influencing yield and with that profit margin.
- By replacing 750 W bulbs by 1000 W bulbs less lights are necessary. With that the investment costs of lights can be reduced and a positive effect on profit margin was reached.
- The use of a high light level is required for getting a high yield and with that a positive profit margin.

6 CONCLUSIONS

Supplementary light and CO_2 enrichment during the low natural light level in Iceland enhanced yield of tomatoes compared to supplementary light and ambient CO_2 conditions. However, the yield was not affected by the amount of CO_2 enrichment, whereas profit margin was reduced with increased CO_2 enrichment. CO_2 values between 600-900 ppm CO_2 seem to be recommended. However, further experiments with varying CO_2 enrichment values and different PPFD values must be conducted to find the best combination of these factors. Growers should pay attention to possible reduction in their production costs for tomatoes other than energy costs.

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8 APPENDIX

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
24.nóv	transplanting, light from 5-21, 18°C/18°C (day/night), ventilation 22°C, underheat 35°C, 0 ppm CO_2 (0 ppm CO_2 with ventilation), humidity 70%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)		transplanting, light from 5-21, 18°C/18°C (day/night), ventilation 22°C, underheat 35°C, 600 ppm CO_2 (600 ppm CO_2 with ventilation), humidity 70%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)		transplanting, light from 5-21, 18°C/18°C (day/night), ventilation 22°C, underheat 35°C, 900 ppm CO_2 (900 ppm CO_2 with ventilation), humidity 70%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)		transplanting, light from 5-21, 18°C/18°C (day/night), ventilation 22°C, underheat 35°C, 1200 ppm CO_2 (1200 ppm CO_2 with ventilation), humidity 70%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)	
25.nóv								
26.nóv								
27.nóv								
28.nóv	weekly measurements	2. cluster visable, flowers on 1. cluster not yet open	weekly measurements	2. cluster visable, flowers on 1. cluster not yet open	weekly measurements	2. cluster visable, flowers on 1. cluster not yet open	weekly measurements	2. cluster visable, flowers on 1. cluster not yet open
29.nóv								
30.nóv								
1.des			CO_2 finished		CO_2 finished		CO_2 finished	
2.des								
3.des	temperature increased to 20°C/20°C (day/night)	first flowers open	temperature increased to 20°C/20°C (day/night)	first flowers open	temperature increased to 20°C/20°C (day/night)	first flowers open	temperature increased to 20°C/20°C (day/night)	first flowers open
4.des								

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
5.des	weekly measurements, temperature decreased to 18°C/18°C (day/night), handpollination		weekly measurements, temperature decreased to 18°C/18°C (day/night), handpollination		weekly measurements, temperature decreased to 18°C/18°C (day/night), handpollination		weekly measurements, temperature decreased to 18°C/18°C (day/night), handpollination	
6.des								
7.des								
8.des	handpollination		handpollination		handpollination		handpollination	
9.des	handpollination		handpollination		handpollination		handpollination	
10.des								
11.des								
12.des	1 h between waterings, weekly measurements, handpollination		1 h between waterings, weekly measurements, handpollination		3 h between waterings, weekly measurements, handpollination		4 h between waterings, weekly measurements, handpollination	
13.des	deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster	
14.des	handpollination		handpollination		handpollination		handpollination	
15.des			again CO_2 supply		again CO_2 supply		again CO_2 supply	
16.des	handpollination		handpollination		handpollination		handpollination	
17.des								
18.des								
19.des	handpollination		handpollination		handpollination		handpollination	
20.des	deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster	
21.des	weekly measurements		weekly measurements		weekly measurements		weekly measurements	
22.des	handpollination		handpollination		handpollination		handpollination	
23.des								

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
24.des								
25.des								
26.des								
27.des	weekly measurements, handpollination		weekly measurements, handpollination		weekly measurements, handpollination		weekly measurements, handpollination	
28.des	deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster	
29.des								
30.des	handpollination		handpollination		handpollination		handpollination	
31.des								
1.jan								
2.jan	handpollination		handpollination		handpollination		handpollination	
3.jan	weekly measurements		weekly measurements		weekly measurements		weekly measurements	many leaves at cluster end, many double clusters
4.jan	deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster	
5.jan	handpollination		handpollination		handpollination		handpollination	
6.jan								
7.jan								
8.jan								
9.jan	handpollination		handpollination		handpollination		handpollination	
10.jan	weekly measurements		weekly measurements		weekly measurements		weekly measurements	
11.jan	no deleafing		removed leaf behind the cluster		removed leaf behind the cluster		removed leaf behind the cluster	
12.jan	handpollination		handpollination		handpollination		handpollination	
13.jan								

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
14.jan								
15.jan								
16.jan	weekly measurements, handpollination, underheat increased to 40°C		weekly measurements, handpollination, underheat increased to 40°C		weekly measurements, handpollination, underheat increased to 40°C		weekly measurements, handpollination, underheat increased to 40°C	
17.jan								
18.jan	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
19.jan								
20.jan								
21.jan								
22.jan								
23.jan	weekly measurements, handpollination		weekly measurements, handpollination		weekly measurements, handpollination		weekly measurements, handpollination	
24.jan	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom + from the middle		deleafed 1 leaf from the bottom + from the middle	
25.jan								
26.jan	handpollination		handpollination		handpollination		handpollination	
27.jan								
28.jan								
29.jan								
30.jan	handpollination		handpollination		handpollination		handpollination	
31.jan	first harvest, weekly measure-ments, deleafed 2 leaves from the bottom		first harvest, weekly measure-ments, deleafed 2 leaves from the bottom		first harvest, weekly measure-ments, deleafed 2 leaves from the bottom		first harvest, weekly measure-ments, deleafed 2 leaves from the bottom	
1.feb	removed leaf behind the cluster		removed leaf behind the cluster		removed leaf behind the cluster		removed leaf behind the cluster	
2.feb	harvest		harvest		harvest		harvest	

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
3.feb	handpollination		handpollination		handpollination		handpollination	
4.feb	changed the lighting time to 03-21 because of missing heat		changed the lighting time to 03-21 because of missing heat		changed the lighting time to 03-21 because of missing heat		changed the lighting time to 03-21 because of missing heat	
5.feb								
6.feb	harvest, weekly measurements handpollination		harvest, weekly measurements handpollination		harvest, weekly measurements handpollination		harvest, weekly measurements handpollination	
7.feb	increased the lighting time do to missing heat (lights turned off between 17-20)		increased the lighting time do to missing heat (lights turned off between 17-20)		increased the lighting time do to missing heat (lights turned off between 17-20)		increased the lighting time do to missing heat (lights turned off between 17-20)	
8.feb	deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster		deleafed 2 leaves from the bottom, removed leaf behind the cluster	
9.feb	harvest, light from 03-21		harvest, light from 03-21		harvest, light from 03-21		harvest, light from 03-21	
10.feb	handpollination		handpollination		handpollination		handpollination	
11.feb								
12.feb								
13.feb	harvest, weekly measurements, BRIX, handpollination		harvest, weekly measurements, BRIX, handpollination		harvest, weekly measurements, BRIX, handpollination		harvest, weekly measurements, BRIX, handpollination	
14.feb								
15.feb	harvest, underheat increased to 45°C		harvest, underheat increased to 45°C		harvest, underheat increased to 45°C		harvest, underheat increased to 45°C	
16.feb	handpollination		handpollination		handpollination		handpollination	
17.feb								
18.feb								

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
19.feb								
20.feb	harvest, weekly measurements		harvest, weekly measurements		harvest, weekly measurements		harvest, weekly measurements	
21.feb	deleafed, handpollination		deleafed, handpollination		deleafed, handpollination		deleafed, handpollination	
22.feb	harvest		harvest		harvest		harvest	
23.feb								
24.feb	harvest, no deleafing		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 3 leaves from the bottom	
25.feb								
26.feb								
27.feb	harvest		harvest		harvest		harvest	
28.feb	deleafed 1 leaf from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
1.mar	harvest		harvest		harvest		harvest	
2.mar								
3.mar	handpollination		handpollination		handpollination		handpollination	
4.mar								
5.mar								
6.mar	harvest		harvest		harvest		harvest	
7.mar	deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom	
8.mar	harvest		harvest		harvest		harvest	
9.mar								
10.mar	handpollination		handpollination		handpollination		handpollination	
11.mar								
12.mar								
13.mar	harvest, weekly measurements		harvest, weekly measurements		harvest, weekly measurements		harvest, weekly measurements	
14.mar	deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 2 leaves from the bottom	
15.mar	harvest		harvest		harvest		harvest	
16.mar								

	0 ppm CO_2		600 ppm CO_2		900 ppm CO_2		1200 ppm CO_2	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
17.mar	handpollination, deleafed 1 leaf from the bottom		handpollination, deleafed 1 leaf from the bottom		handpollination, deleafed 1 leaf from the bottom		handpollination, deleafed 1 leaf from the bottom	
18.mar								
19.mar								
20.mar	harvest, weekly measurements, night temperature decreased to 18°C		harvest, weekly measurements, night temperature decreased to 18°C		harvest, weekly measurements, night temperature decreased to 18°C		harvest, weekly measurements, night temperature decreased to 18°C	
21.mar	deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom	
22.mar	harvest		harvest		harvest		harvest	
23.mar	usage of VICI Rhyso WG, Potassium Phosphite 50% liquid, Intra Hydropure		usage of VICI Rhyso WG, Potassium Phosphite 50% liquid, Intra Hydropure		usage of VICI Rhyso WG, Potassium Phosphite 50% liquid, Intra Hydropure		usage of VICI Rhyso WG, Potassium Phosphite 50% liquid, Intra Hydropure	
24.mar	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
25.mar								
26.mar								
27.mar	harvest, weekly measurements		harvest, weekly measurements		harvest, weekly measurements		harvest, weekly measurements	
28.mar								
29.mar	final harvest		final harvest		final harvest		final harvest	