Measure, Control, Grow

Bring the plant into the control loop

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Referaat

Dit project, ondersteund door de Club van 100, bevordert geconditioneerde teeltsystemen (CEA) door het ontwikkelen van datagestuurde teeltsystemen waarbij de plant is opgenomen in het feedbacksysteem. Deze biofeedbackcontrole leidt tot geoptimaliseerde opbrengst, kwaliteit en efficiëntie van het gebruik van energie, water, CO_2 en nutriënten in vertical farms en kassen. Vertical farms bieden volledige controle over de omgeving, in tegenstelling tot kassen die worden beïnvloed door externe omstandigheden, wat specifieke kennis en besluitvorming van de teler vereist. Teeltrichtlijnen, samengesteld uit deskundige kennis en inzichten van vijf vertical farms zijn opgesteld ter ondersteuning. Casestudies over sla, jonge tomatenplanten en aardbeien vergelijken teeltpraktijken in kassen en vertical farms en belichten voor- en nadelen van beide CEA-systemen. Een biofeedbacksysteem wordt voorgesteld, gebruikmakend van sensoren voor morfologische (bijv. bladoppervlak) en fysiologische (bijv. transpiratie) kenmerken, naast klimaatsensoren. Technologieën zoals RGB-camera's en weegsystemen maken real-time monitoring mogelijk. Een conceptueel kader identificeert belangrijke kenmerken en sensortechnologieën voor de drie gewassen, met nadruk op de noodzaak van voortdurende sensorontwikkeling en datagestuurde modellen om winstgevendheid en energie-efficiëntie te verbeteren. Deze aanpak ondersteunt duurzame, autonome, hoogproductieve CEA-systemen, draagt bij aan voedselzekerheid en verlaagt operationele kosten, vooral in energie-intensieve vertical farms.

Abstract

This project, supported by the Club of 100, advances controlled environment agriculture (CEA) by supporting data-driven cultivation systems with integrating plant feedback. This biofeedback control will lead to optimized yield, quality, and resource efficiency in vertical farms and greenhouses. Vertical farms offer complete environmental control, unlike greenhouses influenced by external conditions, requiring distinct decision-making. Cultivation guidelines synthesized from expert knowledge and insights from five vertical farming companies are created to support this. Case studies on lettuce, young tomato plants, and strawberries compare cultivation practices and highlights pros and cons of the two CEA systems. A biofeedback system is proposed, utilizing sensors for morphological (e.g., leaf area) and physiological (e.g., transpiration) traits, alongside climate sensors. Technologies like RGB cameras and weighing systems enable real-time monitoring. A conceptual framework identifies key traits and sensing technologies for the three crops, emphasizing the need for ongoing sensor development and data-driven models to enhance profitability and energy efficiency. This approach supports sustainable, autonomous, high-yield CEA systems, addressing food security and reducing operational costs, particularly in energy-intensive vertical farms.

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Disclaimer

Adress

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Summary

This project, made in collaboration with the Club of 100, investigates the next steps for advanced control strategies for optimizing crop production in controlled environment agriculture (CEA), with a focus on vertical farms and greenhouses. It advocates for (autonomous) data-driven cultivation systems that integrate plant feedback to improve yield, quality, and resource efficiency. Vertical farms, offering full control over environmental factors such as light, temperature, and CO_2, are compared to greenhouses, which remain partially dependent on external weather conditions. Moreover, vertical farming systems have more freedom in the design of the growing recipes (within system boundaries) compared to a greenhouse but also necessitate a different decision-making process. Guidelines for cultivation in a vertical farm are thus produced with expert knowledge where all aspects to be considered with relative options are synthesized in to support the definition of the indoor growing conditions and the set-up of the cultivation system. Close to this, experiences from 5 vertical farming companies are reported.

Three case studies on three crops—lettuce, young tomato plants, and strawberries— are discussed comparing cultivation practices and outcomes in vertical farms and greenhouses to highlight the strengths and challenges of each system.

Biofeedback systems to enhance cultivation control by integrating real-time plant and environmental monitoring are proposed. These systems rely on sensors to track morphological traits (e.g., leaf area, plant height) and physiological traits (e.g., transpiration, photosynthesis) as well as on sensors for climate which are already widely used. Technologies like RGB and hyperspectral cameras, chlorophyll fluorescence sensors, and weighing systems are discussed for their ability to provide actionable data. For example, tray weight sensors coupled with algorithms can estimate biomass accumulation in lettuce, while imaging systems can monitor tomato plant development or detect strawberry pests like mildew. These sensors, combined with predictive growth models and/or machine learning, will be able to optimize resource use by dynamically adjusting environmental conditions based on crop needs and resource costs, such as electricity price fluctuations.

By identifying key plant traits and available sensing technologies, the study provides a conceptual framework for a plant feedback monitoring system tailored to lettuce, young tomato plants, and strawberries. It concludes that ongoing research and development of sensor technologies, coupled with data-driven models, are essential to maximize profits and energy efficiency in CEA. This approach not only supports sustainable production but also addresses operational cost challenges, particularly in vertical farms where energy can account for 20–40% of expenses. The findings contribute to the broader goal of establishing autonomous, high-yield, and resource-efficient cultivation systems to ensure food security.

1 Introduction

In the last century, efforts have been made in agriculture to ensure higher yields for the growing world population. To enable this while lowering the environmental impact of agriculture, a shift was made towards protected cultivation systems moving from outdoor agriculture towards controlled environment agriculture (CEA). A first, and largely implemented, system is represented by greenhouses. These partially enclosed systems offer a control over indoor environmental variables while still being dependent and influenced by outdoor conditions (light and temperature). A further step towards full control of the cultivation is represented by fully enclosed cultivation systems known as vertical farms or plant factories. These fully climatized and LED-lit systems offer total control of the growing conditions and independency from outdoor climate enabling local production with predictable high yields and quality (Daniels et al., 2023). Control of the cultivation is mainly based on climate feedback as climate sensors are widely implemented in CEA. Realized climate is used in a simple closed-loop control for feedback control (Figure 1) and regulatio
n of linear systems derived usually by linearization of a nonlinear system (Deng et al., 2018).

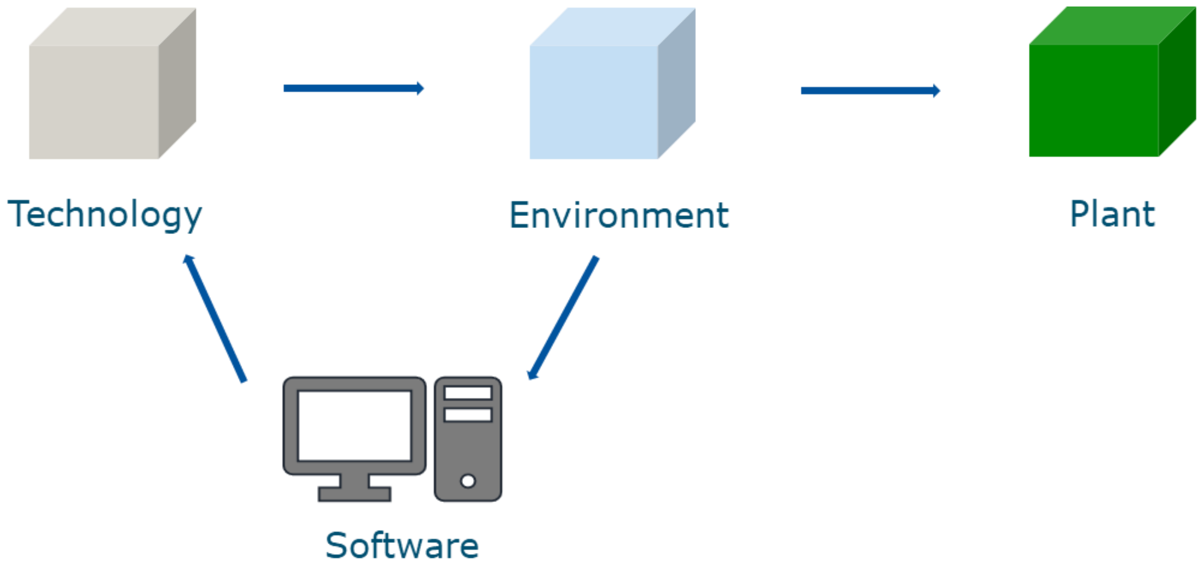

Figure 1 Schematic representation of a simple control-loop only based on environment feedback.

CEA production systems are complex, with many factors affecting production (light, CO_2, temperature, humidity, water, and nutrients) and recourse use (energy, water, CO_2). Growers need to make timely strategic and operational decisions to ensure sustainability, meet market demands, and maximize profit. In view of the shortage of experienced growers worldwide and the growing demand for fresh and nutritious food, autonomous production systems and remote digital data-driven growing offer a promising solution for food security with fresh and nutritious food while reducing resource usage.

Today's high-tech production systems are equipped with different standard sensors for monitoring light, temperature, humidity, and CO_2 and for actively controlling different actuators (e.g., lighting, heating, cooling, CO_2 supply, fogging, dehumidification, irrigation, and fertilizer dosing) in order to control all growth factors that are important for optimal crop production and product quality. Current practice in greenhouses as well as in vertical farms is that growers determine the set points for their greenhouse climate manually, based on the crop status and their experience on how crop growth is affected by the climate. Actuators are operated then based on these setpoints configured in a process computer, while sensors provide information on the realized greenhouse climate to control the greenhouse (Hemming et al., 2020). Figure 2 shows a schematic representation of this supervised control which is strongly dependent on grower's experience.

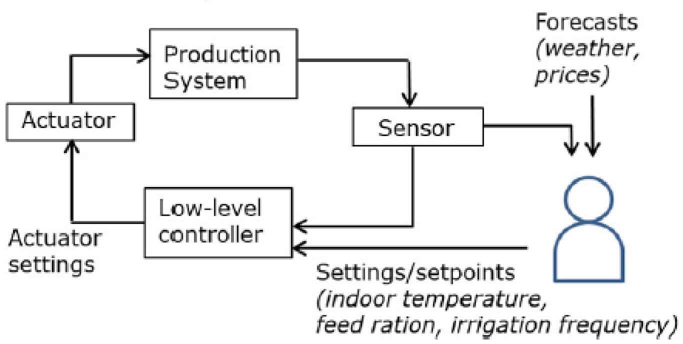

Figure 2 *Supervised control: Low-level control is performed automatically, with growers making high-level control decisions on settings and setpoints. Growers may be informed by sensor information on current system states (e.g. indoor temperature) and by forecasts in order to anticipate future events (e.g. outdoor weather)(from: van Mourik et al., 2021).*

Ventilated climate boxes, and measuring temperature, humidity and CO_2 concentration are standard in high-tech greenhouses in The Netherlands, where PAR sensors are also commonly applied. However, sensors measuring crop status are still scarce in greenhouse horticulture. Although multiple types of sensors are available on the market that can provide information on photosynthesis traits, sap flow, leaf temperature and water uptake, these sensors are still rarely used. Reasons for this are the fact that they may not be proven technology, are considered to be expensive and most importantly that the output does not have a place yet in the grower's decisions on climate control and crop management. The crop has a central role in every greenhouse production system. Crop management decisions and actions are mostly taken by the greenhouse staff. Manual labor is still required for planting, crop training, leaf and fruit pruning, and fruit harvesting in greenhouses with high-wire vegetable production. While manual labor requirement is high, crop management decisions can be supported. Since experienced and well-trained crop managers are scarce, crop simulation models can play a role in decision making. Crop models can be used to simulate different growing conditions and crop management strategies and predict crop development and yield, and fruit quality. Crop models can help to understand the crop behavior under different growing conditions and can support the grower in making decisions and be integrated in a decision-support system for the greenhouse (Hemming et al., 2020). Figure 3 shows a schematic overview of supervised control which integrates a decision support system.

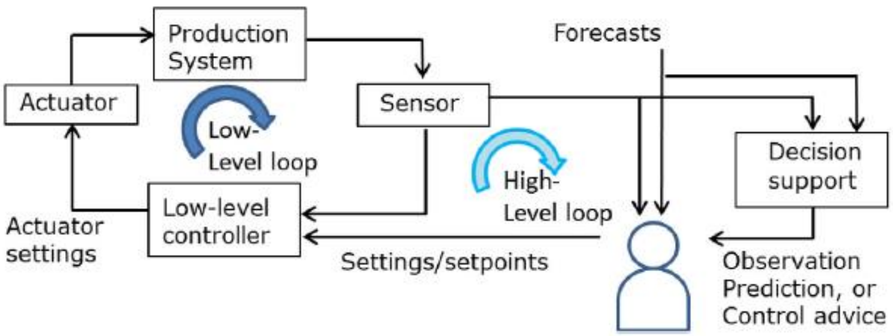

Figure 3 *Supervised control with decision support: close to a low-level control with input consisting of the set-points provided by growers, a high-level management loop is present in which growers make decisions on settings and setpoints based on sensor information, forecasts and input from a decision support system. The decision-support system may use both sensor information and forecasts and be a simple observation tool, such as a dashboard, showing current state of the system; a predictive tool, such as a mechanistic model, that will predict outcomes based on current or new input; or a control algorithm that will schedule input in order to achieve specific objectives such as high yields and/or low resource use (from: van Mourik et al., 2021).*

Automated greenhouse climate control algorithms have already been developed in the past and are widely introduced in modern high-tech greenhouses. However, automated control on crop status is still in its infancy. At the Business Unit Greenhouse Horticulture of Wageningen University & Research, mechanistic crop and climate models are available (Marcelis et al., 2009; De Zwart, 1996). In order to control crop production by an automated algorithm (Figure 4), these mechanistic greenhouse climate and crop models can be used and coupled with a real greenhouse, to send automatically determined setpoints via a process computer to control the different actuators (Hemming et al., 2020). Such optimum control experiments have already been conducted with tomato (Elings et al., 2004), sweet pepper (Buwalda et al., 2006, Van Henten et al., 2006) and pot plants (SØrensen et al., 2019). Recently, AI based algorithms were used to control production of cucumber, tomato, lettuce and dwarf tomato crops, in the Greenhouse Challenge contests (Hemming et al., 2020, 2021; Petropoulou et al., 2023).

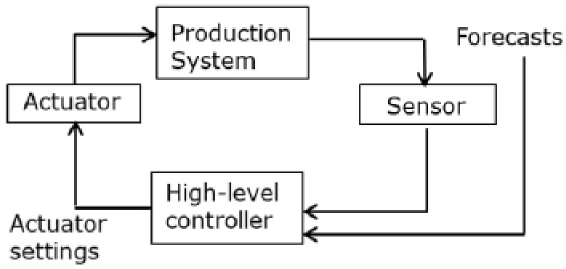

Figure 4 *Automated control: A closed control loop is formed by connecting actuation and sensing technologies through a high-level controller. This configuration does not necessarily require any grower involvement (from: van Mourik et al., 2021).*

Nowadays, most of the existing environmental control systems combine sensors and actuators, and actively set thresholds based on human experience to create the environmental conditions required for plant growth. For this control method, plant growth demand is taken account via the eye and experience ('green fingers') of the grower and no objective (sensor-based) plant data is directly used in the control system. Missing an objective plant feedback for cultivation control can result in insufficient or excessive environmental regulation, which negatively affects plant growth and causes excess use of natural resources.
A feedback control system, which integrates plant responses, can realize environmental optimization according to the required growth conditions of plants, reasonably schedule actuators, so as to improve the utilization of environmental resources and reduce system energy consumption (Wang et al., 2023). It is thus necessary to bring plant-feedback into the control loop (Figure 5).

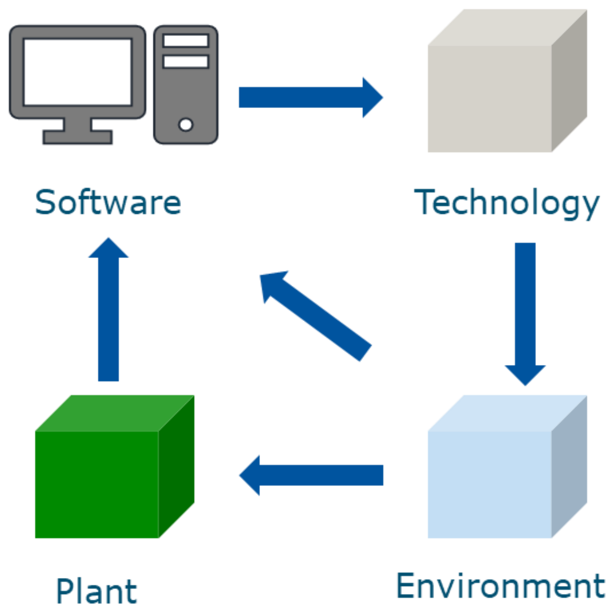

Figure 5 *Schematic representation of a control-loop which integrates plant feedback.*

The idea of integrating plant feedback in cultivation control has been already proposed in the past. In the Speaking Plant Approach (SPA), the environmental factors are defined as the input and the plant responses as the output (Nishina, 2015). The term speaking plant refers to plant responses measured by sensors. Thus, the measurement of both plant responses and environmental factors and the optimization of plant responses are the core of the SPA. This concept was already introduced almost 50 years ago (Udink ten Cate et al.,1978) but its implementation in CEA has become more feasible in the last decade thanks to the advances in easy-to-use, affordable technology and information and communication technologies. In fact, while sensors for environmental measurements (ex. air temperature and humidity sensors) were already in use, only recently plant monitoring technologies such as load cells, sap flow sensors and chlorophyll fluorescence imaging are being developed and implemented in practice. Moreover, advances in IoT made sensor networks and remote sensing a possibility.

Given the full control over the environment in a vertical farm, this cultivation system offers great opportunities for optimal control of yield and quality assuming that knowledge of which climate factors provide high yield and quality is available. However, the high initial capital costs and the high operational costs make it still a non-viable option for many crops (Daniels et al., 2023).
Great effort is thus being invested in increasing the efficiency of resource use in such farms. The typical way of controlling plant growth in a vertical farm (VF) is to keep environmental conditions as constant as possible. However, this approach ignores the costs associated with maintaining the environment. Some essential resources such as electricity have times of the day, week, or year where their costs can be significantly higher. Other resources such as carbon dioxide (CO_2) can be used more efficiently at certain times in the development of a crop. Using this knowledge, along with models that predict plant growth under different environmental conditions, it might be possible to dynamically alter the environment around a crop to enhance resource use efficiency and lower operating costs. Such dynamic models are not yet available. This approach is the basis for, and fundamental benefit of, dynamic control of the growing environment; however, an accurate plant growth model and feedback metrics are critical to success. For example, increasing CO_2 instead of light can save costs, as CO_2 is cheaper. HVAC (Heating, Ventilation and Air Conditioning) systems can also be optimized to use outside air efficiently without wasting CO_2. Dynamic control systems can analyse these exchanges in real-time, adjusting lighting and HVAC usage based on cost and efficiency.

Shaasteen and Kacira (2023) propose three main components for a dynamic control system:

- A predictive growth model, which allows the control system to know where a crop should be in its development for a given sequence of environmental conditions.
- A plant-based feedback mechanism that allows the system to correct any deviation from the model predictions, allowing the system to know where the crop actually is.
- A machine learning algorithm, which, together with the predictive growth model and cost functions for resources, gives the system a means of evaluating future scenarios and finding an optimal sequence for minimizing costs while maintaining a target yield and harvest time (Shasteen and Kacira, 2023).

Together with the Club of 100, this project was initiated in order to bring crop responses in a central position of a control-loop so that vertical farms can be optimally operated to achieve high yields of high quality while minimizing resource use (mainly energy) and related costs.
The dot on the horizon is to be able to control the system based on real-time plant feedback and environment monitoring (Figure 5) which will allow to balance crop needs with resources consumption exploiting the flexibility of plants under dynamic environment created by dynamic resource costs and/or availability. The integration of sensing technology for plant traits and environmental monitoring will be the base of a biofeedback system which, together with plant growth model and machine learning model, will be used to optimally operate vertical farms.

To achieve this, first steps were developed in this project starting from a plant and cultivation perspective (Figure 6).
The aim of the project is to deliver a conceptual framework consisting of relevant plant traits for three selected crops (lettuce, strawberry and young tomato plants) and available sensing technology to measure them which will be the base of the plant feedback monitoring system.

Steps developed in this project are:

1. Design a cultivation and make a cultivation plan based on cultivation and crop physiology knowledge.
   Vertical Farming is still a relative new cultivation concept which attracted so far tech-driven companies, investors and younger generations. Due to this lack of experienced “growers” and the differences with other cultivation systems such as greenhouses as well as the limited knowledge about good practices and success stories from profitable farms, guidelines for cultivation in a fully closed system are produced and shared openly. This forms the starting point for any new cultivation design (Chapter 2).

2. Select the relevant crop traits which contains essential information that can be used to steer cultivation.
   For 3 different crop groups (lettuce, strawberry and young tomato plants) a case-study consisting of a cultivation in a vertical farm is described following the guidelines. Given the interest of the horticulture sector in understand and positioning both forms CEA systems being greenhouse and vertical farm, the same cultivation is compared to one performed in a greenhouse. All cultivations were performed at Wageningen University & Research for research purposes. Attention is paid on which crop traits have been measured, how, and which crop status/cultivation information was deduced from it in Chapter 3.

3. Idealization of a plant (and environment) monitoring system based on smart technologies and/or soft-sensors.
   A monitoring system for environmental parameters is already present in all CEA system as climate and irrigation are essential information used for control. For crop responses, a number of smart technologies being both physical and soft sensors have been developed in the recent years but not all of them are easily applicable for any crop or any environment or accurate enough. A general overview is described in Chapter 4.

4. Crop trait selection and monitoring system.
   Most essential crop information is crop-independent, for example, growth and development rate. For each crop group described in chapter 2, essential crop traits are indicated, based on literature and described trials, as a guide towards which traits are reasonable to start monitoring and control upon. In addition, the ability to measure the selected traits with available monitoring technology is discussed.

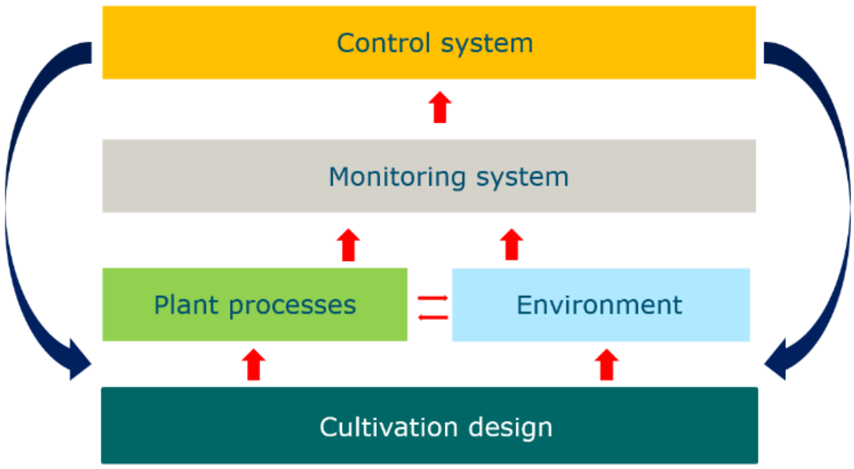

Figure 6 *Schematic representation of building blocks of this project and their connection.*

2 Guidelines for cultivation in a vertical farm

A vertical farm offers several advantages over a traditional greenhouse, including complete control over growing conditions. This control requires growers to make detailed decisions about every aspect of cultivation to be balanced with both environmental and financial sustainability.

Guidelines for cultivation in a vertical farm (Carpineti et al., 2024) can be found with this DOI: https://doi.org/10.18174/656035

Abstract
Designing a cultivation in a vertical farm is not a simple copy-paste of greenhouse settings. Growing conditions in an indoor farm are provided in a different way to the crop compared to a greenhouse. For example, light is solely artificial and provided by LEDs which creates both a different spectral composition as well as a different energy load (no radiative heat) compared to sunlight; air is constantly conditioned (cooled and dehumidified) and circulated at pre-set wind speeds which can affect the ability of the crop to release latent heat and consequently the uptake water and nutrients. Moreover, the independency of a vertical farm from outdoor conditions gives more degrees of freedom on the design of the growing recipes (within system boundaries) compared to a greenhouse but also necessitating different decision-making processes. From these and with the support of the Club of 100, all aspects to be considered with relative options are synthesized in these guidelines to support the definition of the indoor growing conditions and the set-up of the cultivation system. Experience from 5 Vertical Farming companies is also reported, in anonymous form, to gather their experiences with growing in a fully controlled environment. These interviews revealed that successful companies have a strong connection with their customers, ensuring they know exactly what product is needed, when, in what quantity, and with which quality attributes. This customer insight allows growers to set up their vertical farms accordingly.
The interviews and the publicly available guidelines show that steps from the industry start to be taken toward openness and cooperation.

3 Crop cultivation and monitoring in CEA: case studies

Carpineti et al., 2024 discussed, in the guidelines, the aspects that need to be considered before starting a cultivation like the planting material, cultivation system, irrigation etc. Copying a greenhouse cultivation recipe (such as environmental setpoints) to a cultivation in a vertical farm is not the way to go given the different way the environmental conditions are generated and maintained in a fully closed system. Moreover, even among vertical farms it is challenging to copy cultivation recipes and expect the same yield and quality. Due to lack of standardization in system design and equipment and different ways of monitoring and steering climate conditions, differences up to 32% in fresh yield were found when lettuce crops were grown under the same set conditions in different vertical farming facilities (Carpineti et al. 2024b). While facilities were able to realize the set conditions, these were monitored at different locations within the system (ex. in the return air pipes or in the cultivation area) and were realized in different ways (ex. when wind speed is higher of the inlet air, its temperature is also higher). This resulted in different realized climates around the crops at different facilities. The climate around the plant (air flow, temperature and VPD) directly determines crop development and physiological processes such as transpiration which in the end affect the yield and quality of the final product. Measuring in close proximity to the crop as well as using crop feedbacks such as transpiration rate and ETR (electron transport rate) was suggested as a way to standardize crop recipes or, in other words, to be better in control of your cultivation (Carpineti et al. 2024b).

In this chapter, 3 different "crop groups" are described following the guidelines structure and comparing a vertical farming cultivation with a greenhouse cultivation carried out at Wageningen University & Research. On request of the steering committee of this project, greenhouse cultivation was included as well in order to make a comparison of these two Controlled Environment Agriculture systems and understand pros and cons of performing a cultivation in any of the two.
Besides the aspects of cultivation, the way the crop was monitored and gathering of data are described to get a first impression of relevant plant parameters and its interpretation: what and how did we measure crop performance?
The experiments that are described were carried out with a certain aim and specific treatments were compared regarding crop performance. In this report a different approach is used to describe and analyse the experiments. The focus is on figuring out what data would have been needed to monitor the crop to be able to explain crop performance and also to be able to control the cultivation.

Examples of 3 different 'crop groups' are given: (1) leafy greens (2) propagation material and (3) fruit bearing crops. The first growing phase of any plant is a vegetative phase where, starting from seeds, cuttings or tissue culture, a seedling or small plant is produced. This can be the total indoor cultivation until harvest (like for microgreens) or only a phase of plant cultivation that lasts up to selling the propagation material to a grower. This separation between "propagator" and "grower" is quite common practice in Dutch horticulture.

3.1 Leafy green: lettuce

Leafy greens and herbs are most common crops in vertical farms. These crops are relatively 'easy to cultivate' because they fit in a stacked vertical system and no crop handling is needed from the moment of planting to the end harvest. Production cycles are short and fully controlled which in theory make them predictable, especially regarding growth and development. But in case of unexpected conditions, like technical issues, plants will respond and the cultivation will not have the expected progress. Monitoring the crop is needed to be informed about crop performance. It can function as a warning system and provide information to be able to control the cultivation. Although the knowledge about influencing and predicting quality aspects, like glassiness, tip burn and poor shelf-life is not always clear.

3.1.1 Lettuce cultivation in a VF and in a greenhouse

Having full control over the climate requires knowledge about interaction of climate factors: what is the optimal light intensity, temperature, root zone temperature without having limitations of water, nutrients and CO_2?. In this research carried out at Wageningen University and Research, 48 different of combinations of light intensity, air temperature and root-zone temperature were applied on lettuce and fresh and dry weight were monitored after 29 days of cultivation (Carotti et al. 2021). Experiments were conducted in climate chambers with a stacked system. Four air and root zone temperatures (20, 24, 28, or 32∘C) and three light intensities (200, 400, or 750 µmol m^{-2} s^{-1}, corresponding to Daily Light Integrals of 11.5, 23.0, and 43.2 mol m^{-2} d^{-1}, respectively) were used during the experiment which resulted 48 combinations of climates. Two times per week destructive harvests were carried out (without changing plant density) to assess the growth curve.

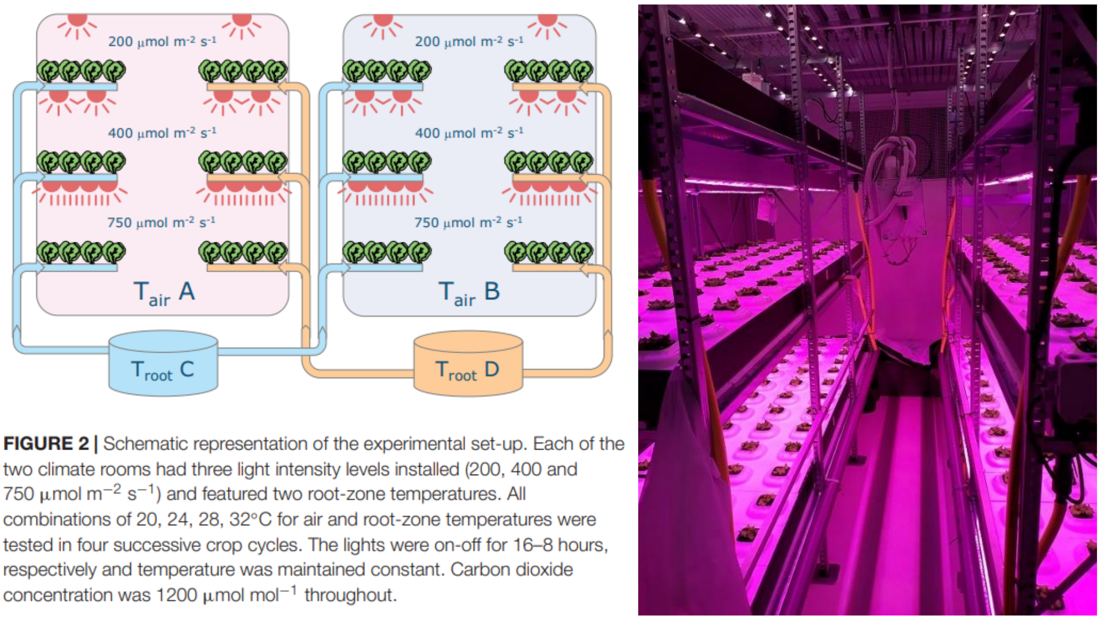

Figure 4 *Schematic representation (left) of the experimental set-up and on the right 1 chamber with 6 production layers (Carotti et al. 2021).*

The VF cultivation is described following the guidelines introduced in chapter 2 (Carpineti et al. 2024).

Factor	***Specification***	***VF***
Facility		2 thermally insulated climate chambers of 15 m^2 in Wageningen 6 production layers per cell of 2.4 m^2
Crop		Lettuce: Lactuca sativa cv. Batavia Othilie
Plant density	During cultivation	25 pl/m^2
Starting material		Young seedlings of 19 days in 4x4 cm stone wool cubes (625 pl/m^2)
Cultivation period		29 days
Light	Type	Philips GP LED production module (2.2 DR/W 150 cm LB HO) for the 200 µmol/m2/s treatments Philips GP LED Top light (1.2 DR/W LB 400V) for the 400 and 750 µmol treatments
	Daylength (h)	16
	Light intensity	200, 400, and 750 µmol m^{-2} s^{-1} (no fading)
	DLI (mol/m2)	11.52, 23, 43 respectively
	Spectrum	PAR: 8/6/86 blue/green/red; no UV or FR

Factor	*Specification*	*VF*
Climate control		1 central climate box in the middle of the cell
Temperature	Day and night	air temperature (24 h): 20, 24, 28, and 32◦C root-zone temperature (24 h): 20, 24, 28, and 32◦C
CO_2		1200 ppm
RH		RH varied depended of temp.
Vpd light		5.8 kPa
Vpd dark		3.4 kPa
Ventilation		Air was continuously circulated, resulting in an air exchange rate of approximately 40 times per hour Air entered the facility through the perforated side walls and was exhausted at the back side.
Substrate		Stonewool cubes in 20 x 80 cm floaters Stonewool cubes (4x4) during germination. Hydroponics (deep flow) in 20x80 cm floaters; plants were still in the 4x4 cm (dry) stonewool and the roots in the nutrient solution.
Irrigation		Deep water culture system
EC		2 Ions (mmol L^{-1}) : 12 NO_3^-, 1 NH_4^+, 6 K^+, 3 Ca_2^+, 0.84 Mg_2^+, 1.1 $H_2PO_4^-$, 0.79 SO_4^{2-}, and Ions in µmol L^{-1} : 50 Fe, 8 Mn, 5 Zn, 40 B, 0.5 Cu, and 0.5 Mo
Cultivation strategy	Description	Lettuce seeds were sown in stone wool cubes (4 × 4 cm; 625 pl/m^2) and covered with plastic (dark and at 18◦C). After 2 to 3 days, the seeds germinated and the plastic was removed. Temperature was maintained at 20◦C, vapor pressure deficit 5.8 and 3.5 kPa during light and dark period, respectively, and a photosynthetic photon flux density (PPFD) of 200 µmol m^{-2} s^{-1} (photoperiod 16 h) was provided by fluorescent tubes. The temperature of the germination room was increased gradually over the course of 3 days to acclimate the plants to the air temperatures of 28 and 32◦C. Transplanting 19 days later into the floaters of the deep water culture system (each floater 20 × 80 cm, 4 plants) and roots touch the water. The stone wool did not touch the water and was kept dry. After transplanting, the air temperature and root zone temperatures were gradually increased over the course of 48 h to reach the final temperatures for the treatment 32◦C. The treatment with the highest light intensity (750 µmol m^{-2} s^{-1}) was shaded for 48 h to allow the plants to acclimate to the light levels.
Beneficial insects	Pollination	none
	Biological control	none
Monitoring system		Each climate room was provided with: 6 ventilated sensors, one for each layer (Sensirion SHT75, WiSensys, Wireless Value, Netherlands) measuring air temperature (±0.3◦C) and relative humidity (±1.8%) 4 sensors (two for each side, top and bottom layer, SHT71, WiSensys, Wireless Value, Netherlands) for the root-zone temperature (±0.3◦C). CO_2 was measured and controlled using the central climate control box. Measurements were recorded at 5 min intervals. 2x per week: growth (fresh- and dry weight, leaf area) Visual observation of the crop
Automation/robotic		none
Sustainability		Electricity: grid CO_2: Ocap Water: rain (basin) Consumables (waste)

The cultivation cycles lasted 29 days and after that period the plants were harvested. The destructive measurements during cultivation showed clearly the differences in growth rate between the 3 light intensities and the different air temperatures. All treatments resulted in different final fresh and dry weights after 29 days of cultivation. A marketable plant weight of 250 g had a shorter cultivation period at higher light intensities (e.g. 25-20-18 days at 200-400-750 µmol/m^2/s calculated from transplanting).
A main factor determining the feasibility of vertical farming is the ratio 'fresh produce' per unit of incident light: light use efficiency (LUE). Carotti et al. (2021) calculated the LUE based on the FW increase during the last 2 weeks of cultivation when the canopy was closed and shows the potential maximum LUE (slope of FW of the last 4 harvests divided by the cumulative PARsum). The LUE decreased with increasing light intensity

and was 29, 27 and 21 gram fresh weight/mol light at 200, 450 and 700 µmol/m^2/s when all air and root zone temperatures were averaged. Maximum LUE was 44 g fresh weight /mol and 1.23 gram dry weight/mol light which was reached at 200 µmol/m2/s and 24° air temperature and 28 °C root zone temperature. The quality of the crop was affected by the treatments: tip burn occurrence increased with air temperature, and leaves were thicker at high light intensities.
The experiments show that yield and quality can be controlled by steering climate factors. However, the optimal light intensity has to be determined in view of the value of the crop and the capital and running cost of light (Carotti et al. 2021).
These data of lettuce grown in a VF cultivated under fully controlled and extreme conditions are compared with a greenhouse cultivation of the same lettuce (*Lactuca sativa* cv. Batavia Othilie) in a research compartment of 144 m^2 at Wageningen University & Research in Bleiswijk (Janse et al. 2018). Seven cultivations were carried out in 2 periods: from December until May 2017 and from September until January 2018. Lettuce was cultivated using the same deep flow system as used in the VF described before. Plants were grown on floaters (Dry Hydroponics) in a plant density of 20.8 plants/m^2 and 100 plants/m^2 in the propagation phase. Assimilation light 135 µmol/m^2/s was provided by LED (95/5% red/blue of Signify) during 17 hours (8.3 mol/day) and switched off when more than 13 mol/day was expected. Realized PAR was 13.2 and 11.5 mol/day for 2 cultivations. Realized CO_2 during light period was 1100 ppm. Cooling was done using a heat exchanger and cold air was supplied via plastic tubes at the top of the greenhouse compartment. Average temperature was aimed for 23°C for the first (Dec-May 2017) and 21°C for the second cultivation (Sep-Jan 2018) which was also realized. Average yield was 250 and 280 g per plant which was reached 23 and 22 days after planting. LUE calculated from transplanting was 16 and 24 g fresh weight/mol for Batavia Othilie.

3.1.2 Comparison yield and LUE in VF and greenhouse

The results of Janse et al. (2018) show that greenhouse cultivations during different periods of the year resulted in different yields and LUE because of the different climate conditions realized inside the greenhouse. Average climate, plant- and production data of greenhouse and VF cultivation are listed in Table 1. In 1 column VF data are presented choosing the treatment that relates to the realized greenhouse conditions. In the last column VF data are presented that indicates the range that was found in the studied research of Carotti et al. (2021).

Table 1 *Comparison of cultivation characteristics and yield of Batavia Othilie cultivated in a greenhouse (Janse et al. 2018) and in a VF (Carotti et al. 2021).*

Characteristic	Dimension	Greenhouse Dec-May	Greenhouse Sept-Jan	VF*	VF range of 40 conditions
Plant density	Pl/m^2	20.8	20.8	25	25
DLI	Mol/day	13.2	11.5	11.52	11.5-43
Light intensity LED	µmol/m^2/s	135	135	200	200-700
Air temp (average)	°C	23	21	24	20-32
Root temp	°C			24	20-32
CO_2	ppm	1100	1100	1200	1200
Planting-harvest	days	23	22	29	29
FW shoot	g/plant	250	280	330	200-810
Planting-harvest 250 g	days			24	
FW after 23 days*	g/plant			213	100-550
Yield after 23 days*	kg/m^2	5.2	5.8	5.3	2.5-13.8
LUE (planting-harvest)	g FW/mol	16	24	23.4**	4-26
LUE (sowing-harvest)	g FW/mol	13	18	22.9	***

*data in Carotti et al. 2021 using the air and root temperature of 24°C
** calculations based on final harvest and total Parsum
*** not calculated

Lettuce production in the VF under comparable conditions as in a greenhouse results in a comparable yield (5.3 kg/m^2) with the greenhouse cultivations (resp. 5.2 and 5.8 kg/m^2 during 2 periods of the year) when the same cultivation period of 23 days is used. On forehand it was not clear based on the realized conditions in VF and greenhouse if the productions would be comparable. More factors play a role than climate data that are presented in Table 1. For example, the air temperature was higher in the VF compared to the greenhouse cultivations. Higher air temperatures generally imply higher plant temperatures and higher plant temperatures will lead to a higher development rate. However, plant temperatures were not measured, so it is not clear if plant temperatures were different in VF and greenhouse cultivations. In the greenhouse cultivation sunlight is present including infrared light which can lead to an increase of plant temperature. That means that we don't know if plant temperatures – and development rates – were different in the compared cultivations between greenhouse and VF.
Another aspect that can play a role are the different light spectra that the plants received in VF and in the greenhouse. In the greenhouse plants received sunlight and LED light (95/5 R/B) which is different compared to the spectrum in the VF. Spectral quality can influence development of leaf area which can influence light interception, crop photosynthesis and biomass production. Increasing the fraction red light in the spectrum increased the leaf area and biomass in red and green lettuce types (Somma et al. 2025). But apparently the effect of different spectral quality in both systems did not have a big effect on biomass production.
Differences in production could also have occurred when factors that were not measured (like plant temperature, ventilation, transpiration) were different in greenhouse and VF.
Light Use Efficiencies (LUE) were calculated where the fresh weight of the lettuce head was divided by the light sum cumulated from the moment of transplanting. The LUE is comparable in the VF (23.4 g FW/mol) to the second period of greenhouse cultivation (24 g FW/mol). Calculating the LUE from sowing, (instead of from transplanting) the LUE in the VF decreased slightly to 22.9 g/mol, because in the first phase of cultivation the canopy is not closed and light is used less efficiently. The LUE of lettuce cultivated in the greenhouse decreased more (13 and 18 g/mol) and the difference with the LUE of the VF (22.9 mol/g) is substantial. The difference can be explained by the different plant density during the first phase of cultivation; in the VF plants were cultivated in cubes of 4x4 cm (625 pl/m^2) and in the greenhouse at 100 pl/m^2. This shows the importance of optimizing plant density for high light interception from the start of cultivation for optimal use of the (expensive) provided light.
Carotti et al. (2021) found the highest LUE under 200 µmol/m^2/s, 24°C air temperature and 28°C root temperature and the lowest under de conditions of 750 µmol/m^2/s, 32°C air temperature and 32°C root temperature.
A literature study (Jin et al. 2022) compared LUE of lettuce cultivated in VF, greenhouse and open field and concluded that LUE in the VF was on average highest (0.55 g DW/mol) followed by greenhouse cultivation (0.39 g DW/mol) and lowest for field cultivation (0.23 g DW/mol). This is explained by the fact that all climate factors can be controlled in a VF and less in a greenhouse and not in the open field. For example, CO_2 can be kept at a non-limiting high concentration in the whereas in a greenhouse supplied CO_2 will be lost when ventilation is needed to control the temperature. In the greenhouse cultivation here described, windows where not open to ventilate for temperature control because of the cooling capacity of the greenhouse. Besides that, we used data of greenhouse cultivations that were done from September until May, which means that the summer period was excluded. LUE in the summer period is in general lower compared to cultivations in winter (Jin et al. 2022).
In an 'Autonomous Greenhouse Challenge' executed at Wageningen University & Research in 6 greenhouse compartments in Bleiswijk lettuce ('Lugano', Rijk Zwaan, the Netherlands) was cultivated in winter and spring (Feb-March and May-June 2022). The competition's goal was the realization of the highest net profit in fully autonomous lettuce production. Two cultivation cycles were conducted in six high-tech greenhouse compartments with operational greenhouse decision-making realized at a distance and individually by algorithms of international participating teams (Petropoulou et al. 2023). The cultivations differed in realized climate, cultivation duration and plant densities during cultivation and resulted in different LUE (calculated from transplanting until harvest for the cultivation Feb-March 2022) in a range between 9 and 24 g FW/mol PAR (data not published). This variation shows the great impact of decisions regarding cultivation (climate settings, spacing) on the light use efficiency.

In the VF experiments, the climate (air temperature, RH and CO_2) and root-zone temperature were monitored. The crop was visually observed and monitored by destructive harvests which provides information about development (leaf area increase) and growth (biomass). During the greenhouse cultivations climate

conditions were monitored (temperature, RH, CO_2, light). Plant monitoring was done by visual observation of the condition of the crop regarding development and tipburn for example.
The fact that comparable yields were achieved with a comparable LUE calculated from transplanting could not be foreseen based on data of plant performance because no monitoring was done. It would have been informative if plant characteristics were measured and compared between the different cultivations and related to the yield data.

3.2 Propagation material: tomato

A VF is an ideal facility to create optimal conditions for young plants because RH can be set and LED lighting does not provide as much heat radiation as high pressure sodium lamps or the sun. In the first phase after sowing, high relative humidities are applied to prevent too much transpiration. This is also important for young cuttings that have no roots yet. Besides that, cultivation in a VF provides the opportunity to 'play' with the moments of using the lamps and turn them off during expensive hours.

3.2.1 Young tomato cultivation in a VF and greenhouse

To test the flexibility of plants regarding light periods, experiments were conducted in climate chambers with a stacked system at Wageningen University & Research in Wageningen. This research was carried out for the 'Club of 100' (Dieleman et al. 2021).
Young tomato plants (Merlice and Sassari) were grafted on Maxifort at the propagator and delivered in Wageningen. After 1 day the top of the plants were removed and 2 stems start to develop. For the reference treatment plants were cultivated with 125 μmol $m^{-2}s^{-1}$ during 16 hours resulting in 7.2 mol $m^{-2}d^{-1}$. In the other treatments, plants also received 16 hours light but lamps were switched of during expensive hours. Two strategies were applied with the dark period cut in 2 periods: 2 x 4 hours or 2 and 6 hours. After 15 and 34 days plants were destructively harvested and plant characteristics and biomass were measured.
The effects of night interruption on development and biomass production of young tomato plants were cultivar specific. For Sassari no effects on biomass were observed, but biomass was reduced for Merlice for the treatment with 2 and 6 hours darkness. For Sassari effect of this treatment were observed in morphology: stem length and leaf area were reduced. The treatment with 2 times 4 hours darkness resulted in 1 extra leaf below the first truss for both cultivars compared to the reference treatment.

In a second experiment the temperature was increased from 20°C (during day and night) to 21 °C (during day and night) because germination was slow at 20°C (data of seedlings are not included in this comparison). Treatments were carried where low light intensities were applied to save energy at different moments during cultivation and were compared to a reference treatment with 16 hours constant 125 μmol $m^{-2}s^{-1}$. When light sum was built up during the first 10 days, 6% energy was saved without negative effect on the biomass of tomato plants. Reducing light intensity during 2 blocks of 4 hours during the day saved 24% energy and reduced the biomass of the plants. No effects were observed on the number of leaves below the first truss and on stem length. In the last treatment light was reduced by alternating 2 days with low light with 2 days of reference light, which saved 25% of energy. Biomass was reduced, but no effects were observed on the number of leaves below the first truss and on stem length. The calculated light use efficiency expressed in dry weight per mol light was comparable for all treatments of experiment 2. This implies that the provided light for all treatments was used with the same efficiency for biomass production.

Figure 5 Picture of 4 layers in 1 climate chamber(left) and young tomato plants at 1 layer (right) (Dieleman et al. 2021).

The VF cultivation is described following the guidelines described in chapter 2 (Carpineti et al. 2024):

Factor	Specification	VF
Facility		2 thermally insulated climate chambers of 15 m^2 in Wageningen 4 production layers per cell of 2.4 m^2 Free height 44 cm
Crop		Tomato Lycopersicum esculentum Merlice/Maxifort, Sassari/Maxifort
Plant density		300, 100 and 25 pl/m2
Starting material		Grafted plants in plugs in trays
Cultivation period		34 days
Light	Type	Philips LED Production 2.2 DR/W 150 LB HO and Philips GreenPower LED Module DR/W 150 LO.
	Daylength (h)	16 h (experiment 1), 8 and 16 h (experiment 2)
	Light strategy exp 1	Same light sum; different lighting strategies (light of in expensive periods): LD (long day; practice): 16 h light, 8 h dark 4/4: dark period in 2 x 4 hours 2/6: dark period split in 2 and 6 h
	Light strategy exp 2	LD (long day; practice): 16 h light, 8 h dark (7.7 mol $m^{-2}d^{-1}$) Photoperiod increased the first 10 days to 16 h (DLI from 3.8 to 7.7 mol $m^{-2}d^{-1}$) 2 days low light alternated with 2 days high light (all 16 h). DLI resp.4.2 and 7.7 mol $m^{-2}d^{-1}$ Low light during expensive hours (2 x 4 h) and other 8 hours reference light intensity (DLI 5.7 mol $m^{-2}d^{-1}$)
	Light intensity reference	125 µmol m^{-2} s^{-1} (no fading)
	DLI (mol/m^2)	Exp 1: 7.2; realized 6.7 – 7.3 Exp 2: different for treatments: see light strategies
	Spectrum (%)	PAR: 10/20/70 blue/green/red; no UV or FR
Climate control		1 central climate box in the middle of the cell
Temperature		Experiment 1: air temperature: 20/20◦C Experiment 2: air temperature: 21/21◦C
CO_2		500 ppm
RH		70%
Ventilation		Air was continuously circulated, resulting in an air exchange rate of approximately 40 times per hour Air entered the facility through the side walls and was exhausted at the back side.
Substrate		Rockwool plug in tray; transplanted in rock wool blocks
Irrigation		Start manual watering; ebb and flow system when plants were on rock wool blocks
Nutrient solution		Confidential (provided by propagator)

Factor	Specification	VF
Cultivation strategy		Delivery 21 days after sowing and just grafted below the cotyledons. Delivered in trays (54 and 45 plants/tray). After 1 day the top was removed. One week later plants were transferred to rock wool blocks in a density of 72 pl/m2 and 14 days later to a density of 14 pl/m2.
Beneficial insects	Pollination	none
	Biological control	none
Monitoring system		Climate (box and sensors): Temp, RH, light, CO2 Temp/RH sensors: 4 per treatment (Agrisense wireless) Temp of substrate: 1 per treatment Plant measurements: morphology (observations, leaf orientation) End harvest: length, LA, dry weight, position truss, roots (visual)
Automation/robotic		none
Sustainability		Electricity: grid CO2: Ocap Water: rain (basin) Consumables (waste)

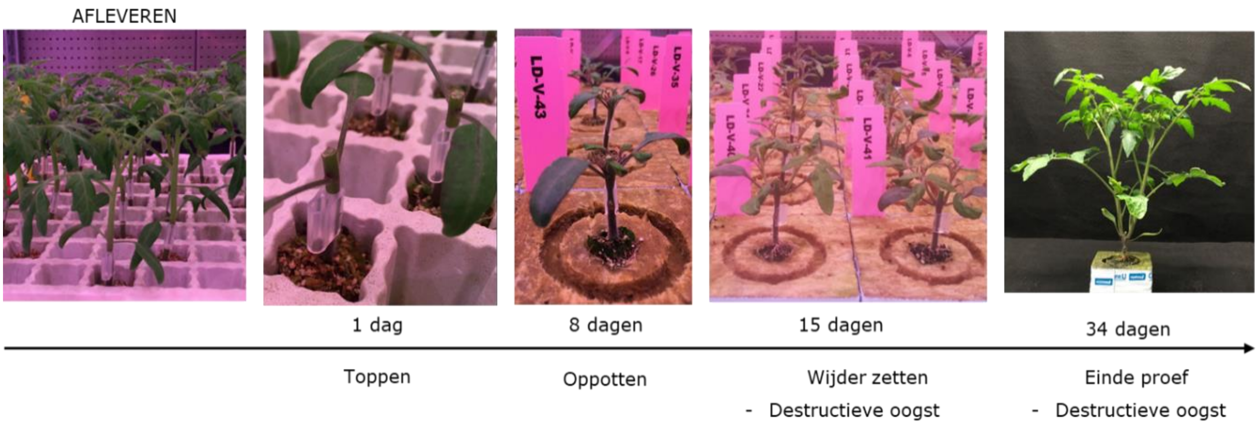

Figure 6 *Overview plant material from delivery until end harvest (Dieleman et al. 2021).*

The cultivation and data of the VF experiment are compared with a cultivation of young tomato plants cultivated in a conditioned greenhouse where the effect on spectral quality was investigated on shoot uniformity (Dieleman et al, 2025). Tomato plants (Xaverius grafted on Maxifort) were cultivated with LED (5/6/89 blue/green/red) with a light intensity of 50 µmol/m^2/s during 10 to 14 hours per day. Sunlight was limited to 8 hours per day and 1 to 1.5 mol/m^2/day (20 to 40% of total light) by using screens. In the reference treatment sunset was natural, without LED lighting. The plants were cultivated on tables with an ebb and flow system for watering. The plant density at the start was 67 plants/m^2. After 1 week the top was removed and 2 shoots per plant developed. Plant density was lowered to 48 plants/m^2 (high density) and 24 plants/m^2 (low density). Ten days later the plants were spaced to 12 plants/m^2 (for both density treatments) until the end harvest 10 days later.

Figure 7 *Picture of the greenhouse trial with young tomato plants Xaverius (IDC-LED WUR in Bleiswijk) at the start (left) and 27 days later at end harvest (right) (Dieleman et al., 2025).*

3.2.2 Comparison yield and LUE in VF and greenhouse

In Table 2 characteristics of the cultivation are summarized. In the VF long days were applied of 16 hours which resulted in light sums of around 7 to 8 mol/m^2/day. In the greenhouse the photoperiod was limited to 10 to 14 hours using assimilation light. The light sum was on average 3 mol/m^2/day (LED and sunlight) and lower compared to the VF experiment. At the end harvest in the VF experiments the dry weights were around 1.7 gram/plant. Despite the lower light sum and shorter cultivation period in the greenhouse, the dry weight of the plants in the greenhouse was more or less comparable (1.47 g/plant).
Calculating the light use efficiency shows the efficiency of plants of using light to turn into biomass. LUE of tomato cultivated in the VF varies between 0.54 and 0.85 g DW/mol and is higher compared to the LUE in the greenhouse experiment (0.34 g DW/mol). An explanation is that more light is intercepted by the plants in the VF because of the higher plant density during the whole cultivation compared to the greenhouse. Especially in the initial phase of a cultivation a lot of light is not intercepted by the crop and is not contributing to biomass production. In the VF the initial plant density was 300 pl/m^2 for 1 week followed by 1 week of 100 pl/m^2 and ended with 25 pl/m^2. In the initial phase the plant density in the greenhouse was 67 plants/m^2 which is substantial lower and implies lower light interception and less efficient use of the light. In general, higher plant densities result in higher productions per area, but this higher production can be at the expense of quality when the plant density is too high. Dynamic spacing of dwarf tomatoes during cultivation resulted in the same fruit quality compared to low plant densities and doubled the harvestable yield per area and thereby increasing LUE (Karpe, Marcelis and Heuvelink 2024). In this research, production was expressed in harvested fruits per area. The same principle holds for propagation material; a high plant density implies less light per plant and will results at a certain point to loss of quality of the plant material. This can manifest itself in for example less plant weight, stem diameter, morphology, quality of the truss etc. This emphasizes the importance of monitoring the essential plants traits during cultivation.

Table 2 *Comparison of cultivation characteristics and yield of young tomato plants grown in a VF and a reference treatment with 8 h photoperiod and in a conditioned greenhouse.*

Characteristic	**Dimension**	Experiment 1 **VF Merlice**	Experiment 1 **VF Sassari**	Experiment 2 **VF Merlice**	Experiment 2 **VF Sassari**	**Greenhouse Xaverius**
Plant density	pl/m^2	300->100->25	300->100->25	300->100->25	300->100->25	67->12
DLI	mol/day	7.2	7.2	7.7	7.7	3.0
Light intensity LED	μmol/m^2/s	125	125	134	134	50
Air temp (average)	°C	20	20	21	21	21.2/21
CO_2	ppm	500	500	500	500	434
Planting-harvest	days	34	34	34	34	27
FW after 34 days	g/plant	20.1	19.2	26.6	27.0	
DW after 34 days	g/plant	1.7	1.3	1.97	1.80	
FW after 27 days	g/plant					26.1
DW after 27 days	g/plant					1.47
LUE (planting-harvest)	g DW/mol	0.72	0.54	0.85	0.74	0.34
LA	(cm^2/plant)	441	353	480	462	*
Leaves below truss		7.2	7.1	7.7	6.8	

3.3 Fruit bearing crop: strawberry

Cultivation in a fully closed environment like a VF provides the opportunity to influence the added value of strawberry. Added value can be intended as yield efficiency, like total production and the pattern of production (peak production or a flat pattern) and fruit size. Organoleptic quality, like Brix, firmness and acidity and nutritional quality, like vitamin C and anthocyanin concentration are also important characteristics and ‘add value’ to the product. Strawberry is considered as a functional fruit thanks to its health benefits (vitamin C and antioxidant content). In Europe it is a high value market and there is need for out-of-season product.

3.3.1 Strawberry cultivation in a VF and greenhouse

To illustrate the potential of climate steering on production of strawberry, strawberries were cultivated in 2 VF compartments with completely different climate settings resulting in the same average temperature and light sum. In parallel, a greenhouse experiment was conducted with the same cultivar aiming for comparable average climate conditions as the VF cultivations.
The climate settings of the ‘reference climate’ was based on the realized climate of a strawberry cultivation of 2022 carried out at Wageningen University & Research in Bleiswijk.

The VF cultivation is described following the guidelines described in chapter 2 (Carpineti et al. 2024):

Factor	**Specification**	**VF**
Facility		2 research multilayer cell facility Bleiswijk: Airtight 2 production layers of 10.3 m^2 Free height 1.6 m
Crop		Strawberry everbearing variety Favori
Starting material		6 weeks old propagated tips from greenhouse
Light	Type	Philips/Signify Greenpower LED production module dynamic (Philips 9290 014 84306 PM 210 DRBWFR L150)
	Daylength (h)	16
	DLI (mol/m^2)	11.52
	Spectrum (%)	PAR: 15% blue 25% green 60% red Plus 20% far red
Climate control		1 central climate box in the middle of the cell between the 2 gutters

Factor	Specification	VF
Temperature		20/14°C
CO2		700 ppm
RH		80/85%
Vpd light		4.68
Vpd dark		2.4
Ventilation		Conditioned air entered the facility via 4 strips of perforated wall. On the two long sides of each layer, one strip was placed. Air was exhausted via the perforated ceiling placed behind the LEDs of each layer.
Substrate		Boxes and coco
Irrigation		Drip irrigation steered on 30% drain and with EC drain + EC gift = 3
Beneficial insects	Pollination	Hoverfly Eristalis tenax (Polyfly) with nectar and pollen (Biogluc, Biobest)
	Biological control	Against aphids,thrips,whitefly,sawflies
		Chemical control was needed against mildew (Abir and preventively Sonata/Tegro) and against aphids (Flipper)
Monitoring system		Irrigation and drain Temp, RH, CO_2. Measuring box between the 2 gutters Scouting for pests and diseases (weekly-manual) Light interception (sensor; monthly) Crop morphology (width, height, number of leaves, truss, leaf length (manually every fortnight) Visual observation crop
Automation/robotic		none
Sustainability		Electricity: grid CO2: pipeline from Rotterdam's harbour Water: rain (basin) Consumables (waste)

Strawberry 'Favori' was cultivated in 2 cells of the VF where 2 strategies were followed which had the same average light sum and temperature. In 1 cell the climate (light intensity, temperature, RH) was stable during day and during night (200 μmol/m^2/s, DLI 11.5 mol/m^2/d, 20/14°C d/n, 85/80% d/n). In the other cell the climate was dynamic: 4 different climates were alternating for 1 week, and having the same average temperature, DLI and vapour pressure deficit. The 4 four typical climates in the 'fluctuating treatment' were:

- Bright: 23/14 °C and 17.3 mol/m^2/s
- Dull: 18.4/14 and 5.8 mol/m2/d (bright - stable)
- Variations during the day
- Big fluctuations during the day

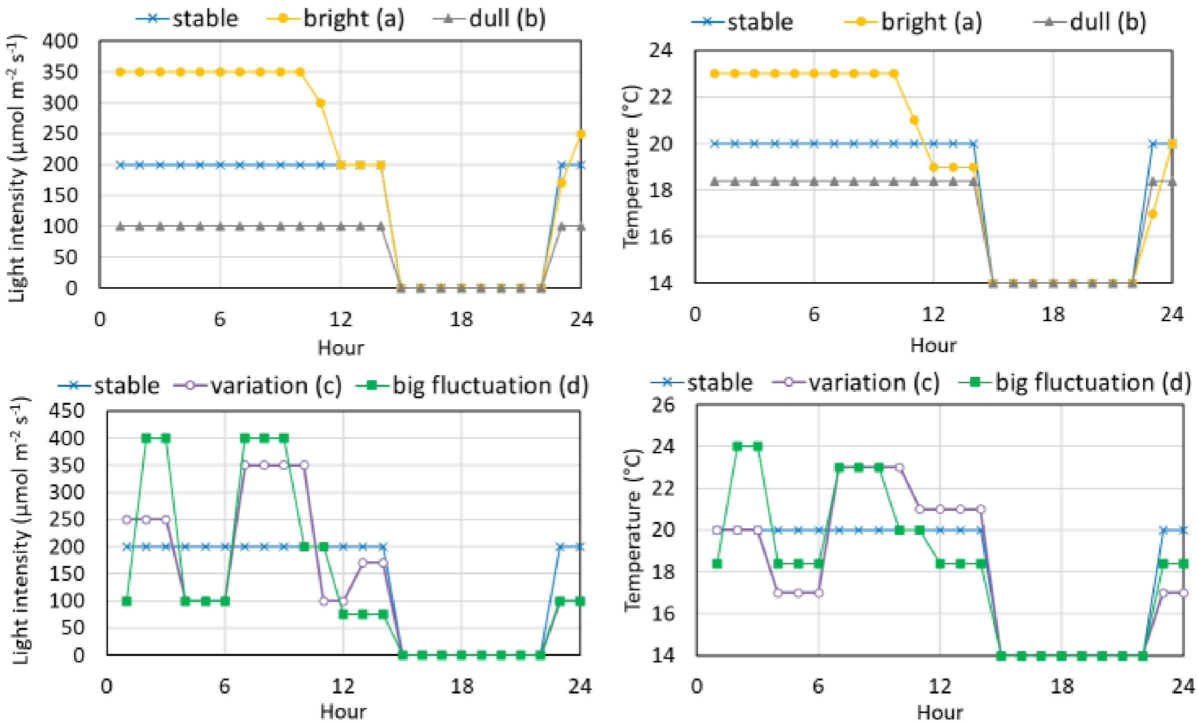

Figure 8 *Illustration of the 2 light and temperature strategies in the 2 cells of the VF with a stable climate and a fluctuating climate.*

The fluctuations in 1 of the vertical farms mimic realized fluctuations in a greenhouse regarding absolute values but not in frequency. In a greenhouse cultivation for example light conditions can vary every second or minute, which exceeds the programming steps of the VF. Comparing the 2 VF cultivation provides insight in the effect of fluctuations of the climate on the production pattern of strawberry. The hypothesis is that a stable climate will result in a stable yield (more flat production pattern) and organoleptic quality compared to the treatment with a fluctuating climate.

3.3.2 Comparison yield and quality in VF and greenhouse

After a cultivation period of 21 weeks in the VF the cumulative total yield was 11.6 kg/m^2 and 11.1 kg/m^2 for respectively the stable climate and the fluctuating climate. For the first 11 weeks the production pattern was comparable between the 2 treatments. In week 12 the production in the stable climate increased and a production flush was observed during 3 weeks. In the fluctuating climate this flush started 2 weeks later. After the flush a slightly higher production was observed in the fluctuating climate for 3 weeks (Figure 9). After 20 and 21 weeks of cultivation, the production in both treatments declined to low productions of 0.2 kg/week/m^2.
Since the light sums were comparable between the 2 treatments and the production was higher in the stable climate, the light use efficiency was also slightly higher in the stable climate.

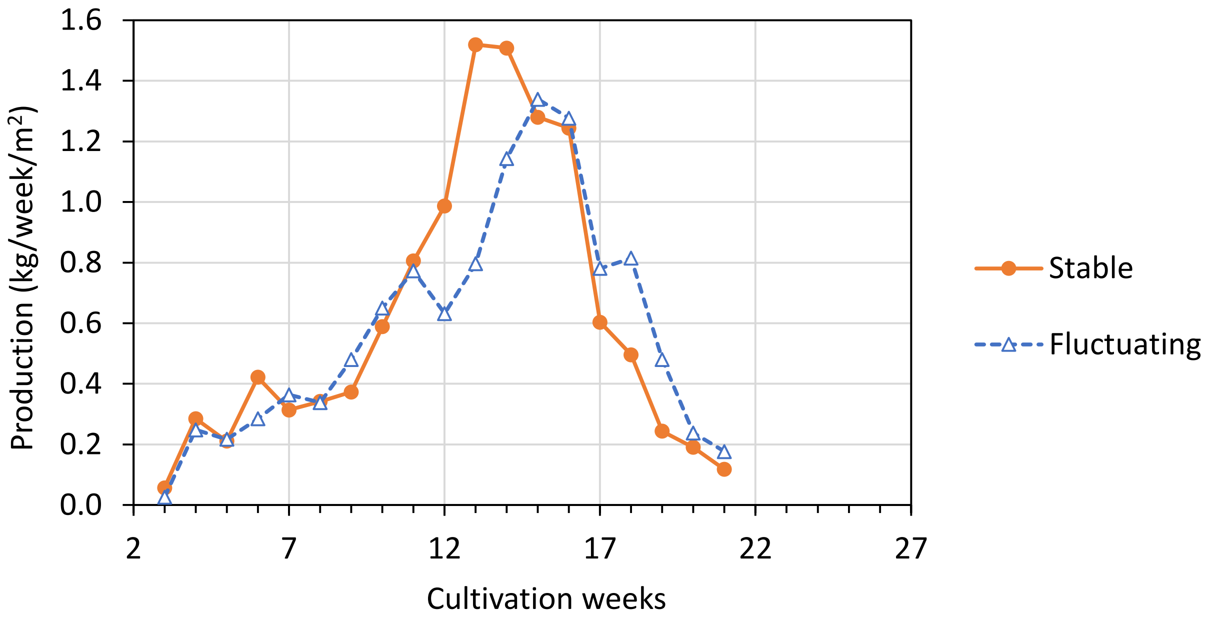

Figure 9 *Total weekly production of strawberry fruits in a VF with a stable climate and a fluctuating climate (all harvested fruits class 1, 2 and mildew).*

The production pattern shows that a stable climate in strawberry did not result in a stable production during cultivation, but a flush of production was measured. The fluctuating climate resulted in a less steep peak compared to the stable climate. Carpineti et al. (2024) calculated the radiation temperature ratio (RTR) during cultivation. RTR is stable for the stable climate (0.6) and for the fluctuating climate RTR fluctuated depending on the week climate. Apparently the stable RTR resulted in assimilate partitioning to the fruits with a peak production of the first flush in week 13. The first flush of the treatment with a fluctuating climate was lagging 2 weeks behind compared with the stable climate. Six weeks before, when trusses were initiated, a lower RTR was applied in this fluctuating treatment resulting in less initiation of fruits. Due to their simultaneous vegetative and generative growth behaviour, everbearing strawberries need to allocate their sugars into both developing leaves and fruits. Because a lower maximum weekly production is achieved in this period in the treatment with fluctuating climate, the plant has more assimilates to invest in new trusses and fruits. This can explain the small peak of production in week 18.
Organoleptic and nutritional quality attributes have been measured during the experiment. Brix was higher in the stable climate: 8.6 and 8.1 for respectively the stable and fluctuating climate. Bite of the fruits and vitamin C were slightly higher in the fluctuating climate compared to the stable climate. Dry matter content, acidity and consumer taste liking were comparable.
The same propagated plant material that was transplanted in the VF was also used for a greenhouse trial at Wageningen University & Research in Bleiswijk. Plants grew in the same potting trays with the same substrate composition and irrigation system (drip irrigation) as in the vertical farm experiment in a compartment of 144 m^2. Sunlight was supplemented with HPS assimilation lamps. Comparison of the cultivations in the greenhouse cultivation and VF is difficult because of a different set-up (plant density), lamps and realized climates were different. In Table xx the characteristics and differences are listed.

Table 3 *Comparison of the cultivation in the VF and greenhouse of strawberry Favori.*

Characteristic	Dimension	VF Stable	VF Fluctuating	Greenhouse	Greenhouse/VF
Plant density	Pl/m^2	10	10	8	
Plants per meter	Pl/m	8	8	8	
Cultivation period	weeks	21	21	26	
DLI	mol/m^2/day	11.5	11.5	13.2	+ 15%
DLI lamp	mol/m^2/day	11.5	11.5	6.5	
DLI sun	mol/m^2/day	0	0	6.7	
Air temp (average)	°C	18	18	18.8	

Characteristic	Dimension	VF Stable	VF Fluctuating	Greenhouse	Greenhouse/VF
Air temp (light)	°C	20.0	19.9	20.4	
Air temp (dark)	°C	14.1	14.1	15.4	+1.3°C
CO_2 (light)	ppm	743	748	503	-32%
RH (24 h)	(%)	77	77	84	+7%
RH light	(%)	76	76	81	
RH dark	(%)	79.4	79.6	89	

In all cultivations, fruit harvest started after 3 weeks of cultivation. Fruits produced in this first small flush were already present in the plants at the moment they were planted. From around 6 weeks after planting the developed fruits were initiated in the conditions of the VF or greenhouse for this everbearer crop.
Until 19 weeks of cultivation, the weekly production in the greenhouse was lower compared to the production in the VF (Figure 10). In both VF treatments peak productions were observed and in the greenhouse a more constant (flat) production pattern was achieved.

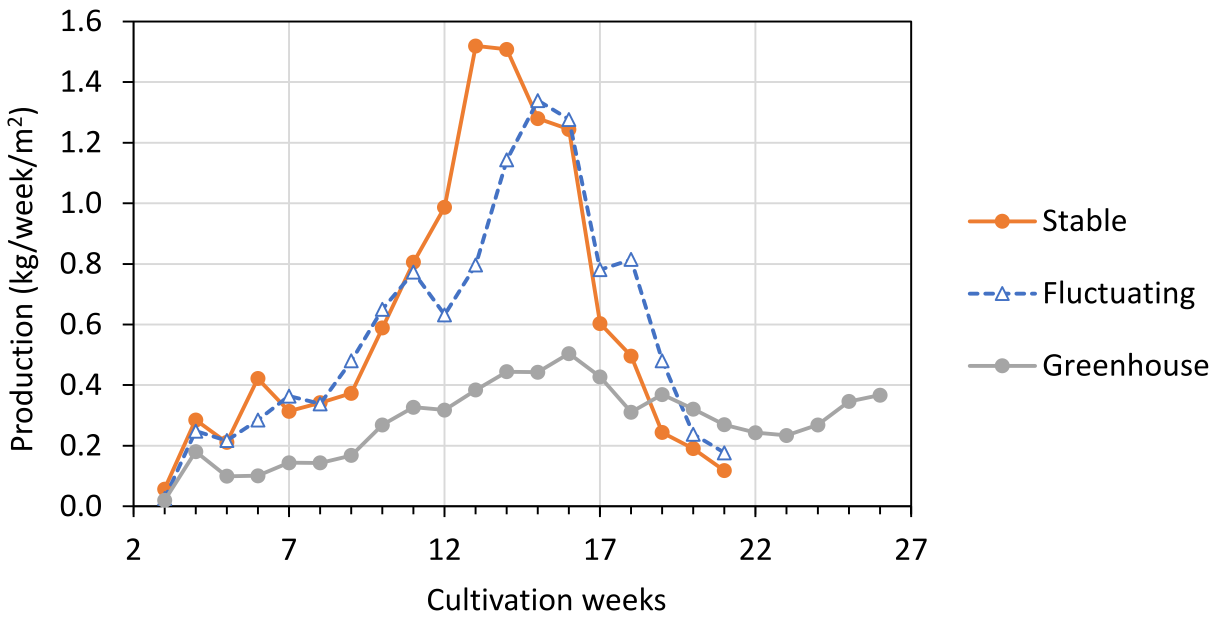

Figure 10 *Total production of strawberry fruits in a VF with a stable climate and a fluctuating climate and in the separate greenhouse experiment. Graphs show production of all harvested fruits (class 1, 2 and mildew).*

The total production in the greenhouse was 5.2 kg/m^2 and lower compared to the VF (11.6 and 11.1 kg/m^2 for stable and fluctuating climate). When the fruit production is expressed per linear meter the differences are less: respectively 6.3, 9.3 and 8.8 kg/m in the greenhouse, VF stable and VF with fluctuating climate respectively. In the greenhouse the DLI was on average 15% higher which is positive for photosynthesis. A higher assimilate production combined with similar average day temperature in the greenhouse compared to vertical farm should potentially led to higher productions in the greenhouse. Other factors must have limited the availability of assimilates which reduced flowering. CO_2 in the light period was on average 32% lower in the greenhouse (503 ppm) because of opening of windows for ventilation. At 200 micromoles, and leaf temperature of 20 degrees, CO_2 levels below 600 ppm have been found limiting for photosynthesis rate (Elings et al. 2023). This can explain the lower fruit production achieved in the greenhouse compared to the vertical farm where CO_2 was not limiting. The more stable production could be attributed to the lower CO_2 availability which limits assimilate production thus keeps the plant in a better balance between vegetative and generative (Carpineti et al. 2024).

When production is defined as class 1 fruits in kg/linear meter, the production in the greenhouse was comparable (5.9 kg/m) with VF (6.1 and 5.7 kg/m). In the greenhouse less mildew was observed because regular disinfection of the plants was carried out with a UV machine, which was not available in the VF.

Table 4 *Comparison of the cultivation in the VF and greenhouse of strawberry Favori.*

Characteristic	Dimension	VF Stable	VF Fluctuating	Greenhouse	Greenhouse/VF stable
Yield total	Kg/m^2	11.6	11.1	5.2	-55%
	# fruits/m^2	885	857		
	Kg/linear m	9.3	8.8	6.3	-32%
Yield class 1	Kg/m^2	7.7	7.1	4.9	-36%
	Kg/linear m	6.1	5.7	5.9	-3%
LUE	g DW/mol	0.62	0.59		
	g FW/mol	6.9	6.6	2.7	
WUE	L/kg FW	15.8	17.5		
Electricity use	KWh/kg FW	26.1	30.4		

To try to explain the ‘flat’ production obtained in the greenhouse and compare it with the vertical farm, weekly production was compared to the radiation temperature ratio (RTR) calculated with average 24h temperature and DLI per week up to cultivation week 25. In the greenhouse, the average RTR after 21 weeks of cultivation was 0.7 (with fluctuations between 0.6 and 0.9) while in the vertical farm it was 0.6. In the greenhouse both average DLI and temperature were higher compared to the vertical farm and a higher RTR means that more light was provided compared to the temperature. More light and a higher temperature both contribute to a higher production which was not achieved in the greenhouse. This leads back to the hypothesis that another factor, probably the CO_2 concentration, was the limiting factor in the greenhouse cultivation for assimilate production (Carpineti et al. 2024).
The light use efficiency was lower in the greenhouse compared to the VF cultivation: more light was applied and the total production (and class 1 fruits per linear meter) was less.
In the VF water and electricity use were monitored and were expressed per kg of harvested fruits.
Water Use (WU) was calculated as litter of water taken up by the plant per unit fresh yield. Electricity Use from lamps was calculated as electricity used by lamps per unit fresh yield. Water use efficiency and electricity use efficiency were both lower in the stable climate compared with the fluctuating climate (Table 4).
Since mildew hardly occurred in the greenhouse, a higher percentage of the harvested fruits in the greenhouse were sellable compared to the VF, which means that the quality was higher in the greenhouse cultivation.
Organoleptic measurements (Brix and acidity) and nutritional measurements (vitamin C content) were performed in both cultivation experiments (Table 5). Brix value was on average higher in the greenhouse compared to the vertical farm. Values were more stable in the greenhouse over the whole cultivation while they went below a Brix value of 8 between week 11 and 17 which corresponded to the high production peak in the vertical farm (Carpineti et al. 2024).
Vitamin C was measured once in the greenhouse trial during cultivation week 9 and it is compared to same measurement date taken in the vertical farm. The slightly higher value in the greenhouse could be attributed to the higher exposure of the fruits to light (in the vertical farms, fruits were hanging at the border of the light installation) or to the exposure of the UV treatment against mildew (Carpineti et al. 2024).

Characteristic	Refraction (°Brix)	Acid (mmol H3O+/100g)	Vit C (mg/100g)	DMC (%)
VF stable	8.6	12.8	52	8.5
VF fluctuating	8.1	12.7	52	8.5
Greenhouse	8.8	14.0	57	7.1

To summarize, in the described strawberry cultivation experiments in VF and greenhouse different productions and qualities were achieved. The production pattern in the greenhouse was more flat compared to the peak production in the VF. In the VF more mildew was present due to impossibility to apply UV treatment resulting in more non-sellable fruits.
Monitoring of crop performance in these examples was done by visual observations, manual measurements (VF) and weekly harvests. In fruit bearing crops monitoring the harvest is a result of physiological processes that took place weeks before like flower initiation, truss formation and assimilate balance between vegetative and generative parts. Monitoring these processes would be helpful in controlling the production patterns.

4 Smart sensing technology for cultivation control

4.1 Climate monitoring for control

So far, climate and irrigation monitor are the most widely implemented and its data is used in cultivation control.
The main climate parameters used for control in CEA systems are radiation, temperature, humidity and CO_2 given their known influence on crop growth and development. The optimal range of those climate conditions varies for different crops but in general an optimal range can be defined for every plant; outside this range plants' growth and production are negatively affected.
Using tomato, the most commonly grown crop in greenhouses worldwide, as an example, the effect of the climate can be summarized as following:

- **Radiation**: A rule of thumb says: 1% less light results in 1% less production. This is not always exactly correct but for tomato (and most fruit producing vegetables) it comes pretty close. *Marcelis et al.* 2006 concluded based on a literature review, that for tomato and cucumber 1% more light results in 0.7-1% more yield. For these crops light levels are rarely too high. For instance, a light requirement equal or higher than 30 mol m^{-2} d^{-1} is reported in literature for a tomato cultivation (Heuvelink, 2005). Low light levels result in in flower abortion.
  However, it could be that high light levels result in supra-optimal greenhouse temperature but then the temperature or humidity control is the problem, not the light level.
  Sunlight has a spectral composition including UV, PAR (for photosynthesis), FR, NIR and FIR. Spectral composition affects a lot of characteristics and processes in plants like morphology (photomorphogenesis), stomatal behaviour, dry matter partitioning, secondary metabolites, resilience, appearance like colour (Mishra et al., 2023). In a VF, LED lamps are used providing PAR for photosynthesis, and sometimes far-red is added as well. In sunlight the ratio between B/G/R is around 30/35/35%. The ratio between red and far-red is around 1; this ratio influences morphology. In VF the spectral quality can be chosen and this will influence morphology which will have effects on light interception, crop photosynthesis and biomass production. For example, when no far-red is added to the light spectrum, some species become compact or the photosynthetic efficiency declines. Adding far-red to the spectrum can also improve dry matter partitioning towards the fruits in tomato (Dieleman et al., 201).
  In summary, using assimilation lamps to provide PAR light for photosynthesis in a VF will affect more processes than just biomass production.
- **Temperature**: Temperature, when not extreme, primarily influences the developmental rate of plants. This affects the number of leaves and fruits produced, as well as the individual fruit weight. Importantly, plants respond to plant tissue temperature rather than ambient air temperature. Plant temperature impacts several physiological processes, including developmental rate, transpiration, and, to a lesser extent, photosynthesis.
  When PAR (Photosynthetically Active Radiation) is supplied via LED lighting, the crop receives less infrared radiation compared to sunlight or HPS (High-Pressure Sodium) lamps. This results in lower plant tissue temperatures. In traditional greenhouses using sunlight or HPS lamps, the upper parts of the plant, especially the apex, are exposed to more infrared radiation, leading to higher temperatures in those regions. This localized heating accelerates development, as plant growth is temperature-driven.
  In VF systems, plant temperature is more closely aligned with air temperature due to the LED lights, and is also influenced by the distance between the LED lamps and the crop. Using identical temperature setpoints in both greenhouses and VF setups can lead to lower overall plant temperatures and different temperature gradients along the plant structure in VF environments.
  Sub-optimal and supra-optimal temperatures primarily limit production due to poor fruit set, while photosynthesis is comparatively less sensitive to temperature fluctuations (Heuvelink, 2005). A literature review on tomato cultivation (Vanthoor et al., 2011) highlights several additional points: both instantaneous and average temperatures significantly affect crop yield; sub- and supra-optimal temperatures disrupt multiple growth processes, leading to reduced yield; stress sensitivity varies by

cultivar; both negative DIF (difference between day and night temperature) and large positive DIF can negatively impact crop yield.

- **Humidity**: Even though humidity strongly affects stomatal conductance. Humidity does not affect crop physiology and development within a wide range of humidity levels (0.2-1.0 kPa Vapor Pressure Deficit (VPD) (Grange et al., 1987)), however, it may affect risk of diseases. A too high humidity means a VPD less than 0.2 kPa (less than 1.5 g/m^3) which means a RH larger than 94% at 25°C. Too high humidity results in limited transpiration and uptake of nutrients such as calcium which is usually linked to smaller leaves, less light interception and less crop photosynthesis as well as fruit quality issues such as blossom end rot. High humidity also hampers pollination (unless bumble bees are used), gives a higher disease risk (e.g. botrytis) and a higher risk of fruit "disorders" (cracking). A too low humidity means a VPD higher than 1 kPa (higher than 7.5 g/m^3) which means an RH lower than 70% at 25°C. A too low humidity results in water stress in the plant, closure of stomata, reduced cell elongation and hence smaller, thicker leaves. Closure of stomata and thicker leaves results in less crop photosynthesis. Furthermore, low humidity will reduce fruit water content (reduced fresh weight) and stimulates blossom-end-rot (BER).
- **CO_2**: it is required for photosynthesis and in general the higher its concentration, the higher the crop growth and production. A general response of crop yield, summarizing experiments with several crops including tomato, sweet pepper and cucumber, has been published indicating an increase in production with increasing CO_2 concentration until a saturation effect appears, which depends on other climate conditions such as light intensity (Nederhoff, 1994).

There is a fundamental difference between greenhouses and VFs in the way the indoor climate is realized and controlled. Greenhouse climate is largely affected by the outside weather conditions while in vertical farms the realised climate is purely the outcome of the climate control equipment. Therefore climate measurements in vertical farms basically ensure that climate control equipment delivers what it is supposed to rather than adapting the operation of the climate control equipment to fluctuating conditions. As an example, radiation measurements in a greenhouse can be used to control the operation of artificial lights based on the radiation provided by the sun on a specific moment. A vertical farm could operate without light measurements as the light levels can be known only by knowing the status of the artificial lights. However, measuring is still useful as an additional control of the functioning of the equipment.
Advances in the field of technology and electronics have resulted in the development of sensors that accurately monitor climate parameters as well as equipment that can be used to control the climate. Typically in CEA systems multiple parameters (Van Henten, 1994) related to the climate inside and outside the greenhouses are measured by sensors. Sensors are widely available in the market and present in every modern growing system can measure air temperature and humidity of the air with an accuracy of 0.1°C and less than 1% respectively. This accuracy is only achieved when the sensors are ventilated; otherwise overheating of the sensor by radiation causes overestimation of temperature and underestimation of relative humidity. However, these sensors have a major drawback: they are located in rather big housing and they require wire connections both to transmit the measured data to the climate control computer and to be powered. As a result they are installed in limited numbers. Therefore, they provide hardly any information about spatial climate distribution. Research has shown that, in commercial greenhouses, temperature differences of up to 5°C and humidity differences of up to 20% are common between different location where sensors are installed (Balendonck et al., 2014) but in closed growing systems this spatial climate differences should not occur. Numerous research projects have proven that information on spatial climate distribution can serve as the starting point for more accurate climate control that results in higher climate homogeneity (Balendonck et al., 2014, 2020; Tsafaras et al. 2018; Vanthoor et al, 2017). Climate homogeneity can be measured by a dense grid of sensors that should meet at least two basic requirements: (i) small size and wireless connection that allows to be placed in multiple places close to the crop without interrupting common work actions (e.g. crop management) and (ii) sufficient ventilation to ensure accurate measurements. In a closed growing system where the effect of outside weather is minimised, climate homogeneity studies can be performed a limited number of times e.g. at the beginning of the operation of the facility and if well designed the results should not change over time.

Weather stations located in close proximity to the greenhouse facilities are equipped with temperature, humidity, and CO_2 sensors pyranometers, anemometers as well as precipitation sensors. In addition to outdoor weather stations, indoor climate sensors are located in a plastic housing (measuring box) that protects them from water, dust or direct radiation (Table 6). The measuring boxes include temperature, CO_2, humidity and radiation sensors and they are equipped with fan and air filters to provide reliable registrations. Additionally, to climate sensors, sensor on the irrigation and drain tanks, allow continuous monitoring of the volume, EC and pH levels of the supplied and drain water. Information on water quantity and quality is integrated in fertigation process control units to define the watering strategies.

These aforementioned measurements serve as input for a control system that regulates the use of the climate control equipment. The latter is governed by "if... then..." rules set by the user and depending on the configuration of the equipment, it can operate through actuators the climate control equipment such as heating, cooling, (de)humidification, natural or mechanical ventilation, lighting, CO_2 supply.

Table 6 *Overview indoor environment parameter for monitoring and available sensors*

Indoor environment (non-destructive)			
Parameter	*Method*	*Status-Limitations*	*Available sensors*
Climate			
Temperature Relative Humidity CO_2	Measurement boxes containing sensors measuring temperature, (electronic) relative humidity and CO_2	Available. More spatial measurements are required	Hoogendoorn Priva Ridder 30MHz Technolution Air Pro LI-830-LI-850 CO_2 H_2O
Photosynthetic Active Radiation (PAR)	PAR sensor	Available. More spatial measurements are required	Hoogendoorn Priva Ridder 30MHz Technolution Air Pro Li-250Q
Light spectrum	Spectrometer	Available. More spatial measurements are required	LI-180 WavGo
Net Radiation	Pyranometer and pyrgeometer	Available. More spatial measurements are required	CNR4
Flue gas composition	Gas analyser (NO, CO, NO_2, C_2H_4)	Available	MACView
Air speed	Anemometers	Available	WindMaster 3D Anemometer Airflow sensor
Water tank			
pH	Digital pH meters	Available	
EC	EC meters	Available	
Macronutrients (N, P, K, Ca, Mg, Cl, NH_4, NO_3, SO_4, PO_4, HCO_3, Fe, Zn, B, Cu, Mo, Mn)	Multi ion electrode (8 elements)	No online sensing- Lab analysis	CleanGrow Auto CG200
	Multi ion electrode (6 elements)	No online sensing- Lab analysis	CleanGrow Multi-ion Nutrient
	Capillary electrophoretic meter	No online sensing- Lab analysis	Capilix
Root zone			
Water content EC Temperature	Substrate moisture EC and temperature sensors (WET)	Available. More spatial measurements are required	Cara-Met GS3 Teros-12 GroSens WET-2 Soil Pro
Nutrient composition in slab (N, P, K etc.)	Ion selective measurements	Proposed trait- Currently missing	CleanGrow Multi-ion Nutrient (not online)

4.2 Crop monitoring for control

While climate measurements are widely used for control of the growing environment, that does not apply yet for crop monitoring since crop sensing information (3D structure, physiological aspects) is currently missing. Plant monitoring or phenotyping is a set of methodologies and protocols used to accurately study plant performance, growth, architecture, and composition at different organization scales, from organs to canopies; it is a non-destructive and non-invasive way of analyzing plant trait dynamics or the time course of plant phenotypes. Ma et al., (2022) grouped crop traits in two categories:

- Morphological traits: such as plant height, stem diameter, canopy cover, leaf length/width/angle/area, colour
  Useful for plant development monitoring but they do not fully represent plant status as information like water and sugar status is missing.
- Physiological traits: such as biomass, chlorophyll content and fluorescence, water uptake and transpiration, nutrient uptake.
  Useful to monitor plant growth and status. Compared to morphological traits, the detection process is more sophisticated and sensing technology is usually more expensive.

A third important category can be added to this:

- Crop health: such as leaf damages due to pests and diseases (biotic stress) or due to, for example, nutrient deficiencies.

Plant monitoring studies have recently focused on developing accurate, high throughput, and rapid phenotyping systems and image-processing algorithms. Common plant traits studied with imaging technologies include color, size, texture and shape for different plant organs such as flowers, leaf, stem, fruit, canopy and roots. Top canopy cover area can be related to plant fresh and dry weight and can be used to evaluate growth rate and estimate yield as well as making decisions on when to apply management actions such as spacing or transplanting. However, imaging also has its challenges due to complex crop features and backgrounds. For this, deep learning visual pattern recognition is a promising avenue for real-time applications in cultivation systems; however, a large number of datasets is necessary to train it (Kozai et al., 2023). Crop sensors should be explored for continuous collection of relevant crop performance indicators, both physiological and morphological traits, with the associated (micro)environment conditions to increase the application of data analytics and/or AI in crop management. To achieve this it is thus necessary to know which sensor information is required and can be implemented in cultivation control.

In recent years, there has been quite some interest in crop monitoring. Although systems like infrared camera’s (to determine plant temperature) and weighing gutters already exist for decades, they are still hardly used in control of greenhouse climate. Recently, new versions of existing sensors or new plant sensors are commercially available, such as sensors to measure sap flow, stem diameter, chlorophyll fluorescence, plant stress, plant weight, water uptake and crop status. In general, for all sensors, a number of questions should be answered:

- Which plant process do they determine?
- With which accuracy and reliability?
- How sensitive are the sensors for fluctuating climate conditions (noise)?
- What would be a “normal” value for this plant process, and at which value would the grower need to take an action?
- What action could be taken to bring the value of this plant trait back to “normal”?
- How long would this take?
- How many plants/which area does the sensor measure?
- Via which platform are the data visible for the grower?
- Can the system be linked directly to the climate computer and used for control?
- What is the price of the sensor and data collection infrastructure?
- Etc.

However, the main question to install crop sensors in a CEA system is what the implication of the sensor is for control. An example could be photosynthesis: if a sensor would be available that measures instantaneous rate of crop photosynthesis, and could be compared to a calculated rate of crop photosynthesis, a discrepancy between the two might imply that the crop does not perform to its full capacity. That might mean that lighting should be reduced, irrigation should be adjusted or that the crop is suffering from pests or diseases. That implies that even a sensor that would be quite advanced does not give an unequivocal signal to the control which action to take. This (unfortunately) holds true for many plant sensors.

Thus, to select crop sensors that can be used for control, the questions listed above should be answered, and based on these answers, the relevant crop traits, and sensors to measure those could be selected (Table 7).

Table 7 *Overview crop traits for monitoring and available sensors*

Crop status (non-destructive)			
Parameter	*Method*	*Status-Limitations*	*Available sensors*
Morphological trait			
Number of formed leaves/ fruits/ flowers/ buds (plant load)	RGB camera 3D cameras and image processing techniques on counting instances of the desired parameter	Available. Ongoing research	Rob2Pheno (Phenobot) GearSense Phenoeye LUNA
Formation rate fruit/flower/bud/truss development	3D cameras and image processing	Available. Ongoing research	GearSense Phenoeye
Internode length	Digital caliper	Hand operated	Schouten et al., year
	RGB camera- Machine learning		Yamamoto et al., year
	Light-based modelling		Kahlen et al., year
Leaf Area Leaf size (width length)	Portable device measuring area, length, average and maximum width of each leaf	Hand operated	LI-3000C
Leaf angle distribution	Trigonometric relationship using smartphone	Hand operated-patent	Ahmes
Physiological traits			
Photosynthesis on crop level	Chlorophyll fluorescence camera or laser (ETR)	Available. Ongoing research	CropObserver, CF2GO, Gardin
	Photosynthesis chamber	Available. Ongoing research	PlantData
	Photosynthesis monitor (gas exchange whole greenhouse)	Monitor. sensitive to changes in window opening and CO_2 supply	
Photosynthesis on leaf level	Chlorophyll fluorometer or gas exchange measurements	Handheld	Mini-PAM II CI-340 CID Bio-Science Li-Cor LI-6800 Sendot photosynthesis sensor
Crop growth Weight gain	Weighing gutter systems	Sensitive to surrounding perturbations	Hoogendoorn Aquabalance Ridder ProDrain Trutina DrainVision Paskal Wireless Value wireless scale Aranet weight sensor with tray
Evaporation of the crop and stomata status	Watering-drain measurement and calculation	Sensitive to surrounding perturbations	Aquabalance Moisture balance Ridder ProDrain Trutina DrainVision
Juice flow and stem thickness/firmness	Imaging, or clip that could be attached which expands and tests firmness by applying pressure	Available. Ongoing research	Phytosense 2Grow Aranet sap flow sensor kit
Plant/Leaf temperature - Condensation on plant/fruits	Infrared cameras Thermal cameras	Plant specific	Hoogendoorn Thermoview Topcrop monitor Pointed Microclimate Sigrow stomata camera Aranet IR plant temperature sensor
	Artificial fruits	Fruit specific	Artificial tomato
Ripeness of harvest	RGB and hyperspectral camera	Available. Ongoing research	Plantalyzer Metomotion

			Root AI
Sugar content at a given time	Hyperspectral	Ongoing research	Rahman et al., 2018 Research PerClass-WUR
Dry matter at a given time	Hyperspectral, Image Analysis	Ongoing research	Tackemberg
Gene expression	Nanopore	No online sensing	Nanopore CD Genomics
Proposed traits			
Plant balance (switch from vegetative to generative)	Imaging, Artificial Intelligence	Proposed trait-currently missing	
Thickness and colour of the head of the plant		Proposed trait-currently missing	
Assimilate partitioning	Hyperspectral Technique can be similar to sap flow but then for phloem	Proposed trait-currently missing	
Temperature of plant parts as shoot apex, leaf, whole plant	Infrared imaging	Proposed trait-currently missing	
Colour of leaves and flowers	Imaging	Proposed trait-currently missing	
Flower diameter (continuous, gerbera)	Imaging	Proposed trait-currently missing	
Bud size and shape	Imaging	Proposed trait-currently missing	
Fruit size	Hyperspectral	Proposed trait-currently missing	
Position and length of the truss stem	Imaging	Proposed trait-currently missing	

5 Towards the integration of plant feedback in cultivation control

Due to the dynamic character of crop processes, climate optimization constitutes an optimal control problem. An optimal control problem is a type of mathematical problem where the goal is to determine the control inputs for a dynamic system that will optimize a certain performance criterion. This involves finding a control strategy that minimizes or maximizes an objective function over time, subject to the system's dynamics and any constraints. Studies on such optimal control have been conducted for CEA systems, especially in greenhouse control already in 1991 by Van Henten and Bontsema. However, it is difficult to realize optimal control for physiological processes which are characterized by complexity and uncertainty (Morimoto et al., 1994).
In a vertical farm, optimal control techniques to obtain higher yields and better quality of plants are essential from the viewpoint of cost-performance. Application of optimal control theory offers an opportunity to identify control strategies in which the benefits associated with the marketable produce and the costs associated with its production are balanced. This approach requires, among others, an appropriate model of the crop evolution in time as a function of the indoor climate. The development of such models requires insight into the biological processes.

To achieve a biofeedback system (integration of sensing technology for plant traits and environmental monitoring to support models to optimize growth recipes, thereby enhancing the resource use efficiency of vertical farming systems), it is crucial to identify the plant and environmental parameters for canopy monitoring on a weekly, daily, or hourly basis and the related sensing technology. In order to identify the relevant plant traits, a conceptual framework of plant processes is presented to identify the main morphological and physiological traits affecting plant biomass production (dry weight) and fresh yield (Figure 14; Dieleman et al., 2025).

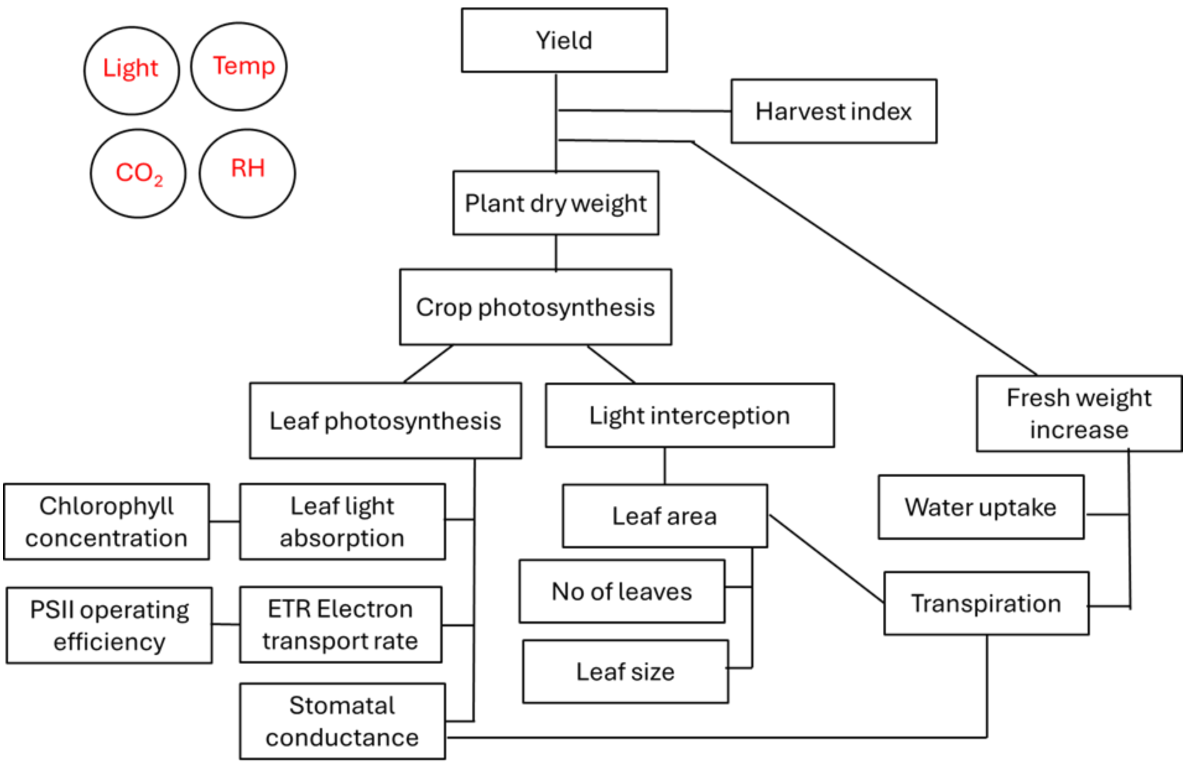

Figure 14 *Schematic overview of plant processes affecting crop production (from: Dieleman et al. 2025)*

In the following sections, plant traits and related sensing technology are proposed for the three case-study crops: lettuce, strawberry and young tomato plants.

5.1 Plant feedback in a lettuce cultivation

For a lettuce cultivation, Figure 15 shows the tailored overview of plant processes and traits of interest that affect the production of commercial lettuce.

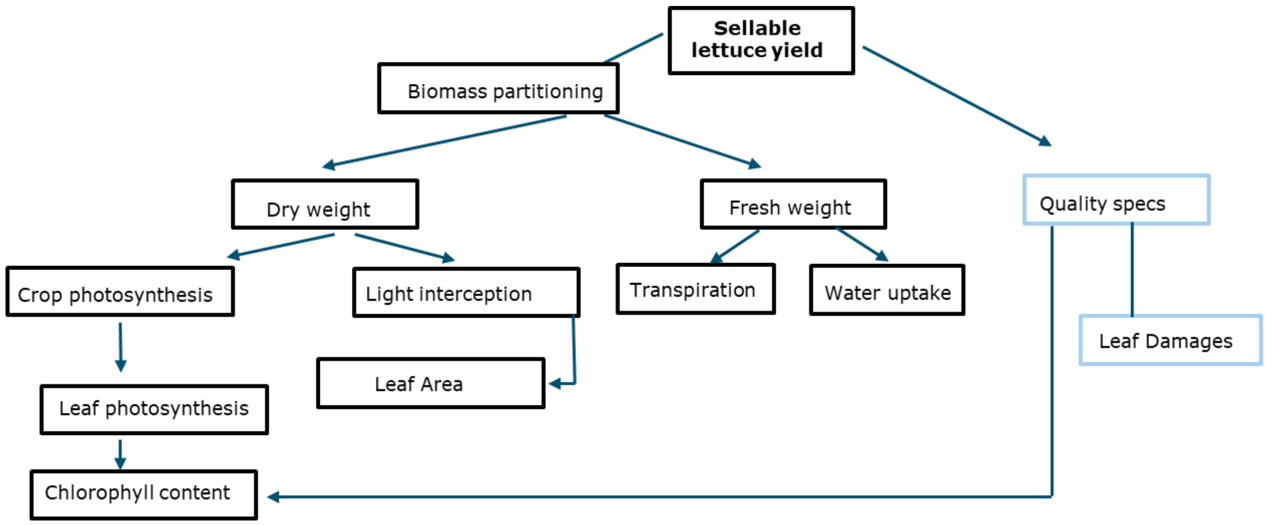

Figure 15 Overview of plant processes and traits of interest for a lettuce cultivation.

In lettuce, fresh weight of the head is an important plant characteristic. Monitoring the water uptake and transpiration provides insight in the fresh biomass weight of the crop (Figure 16). All these elements can contribute to a simple model or flow chart to monitor, control and predict yield of lettuce.

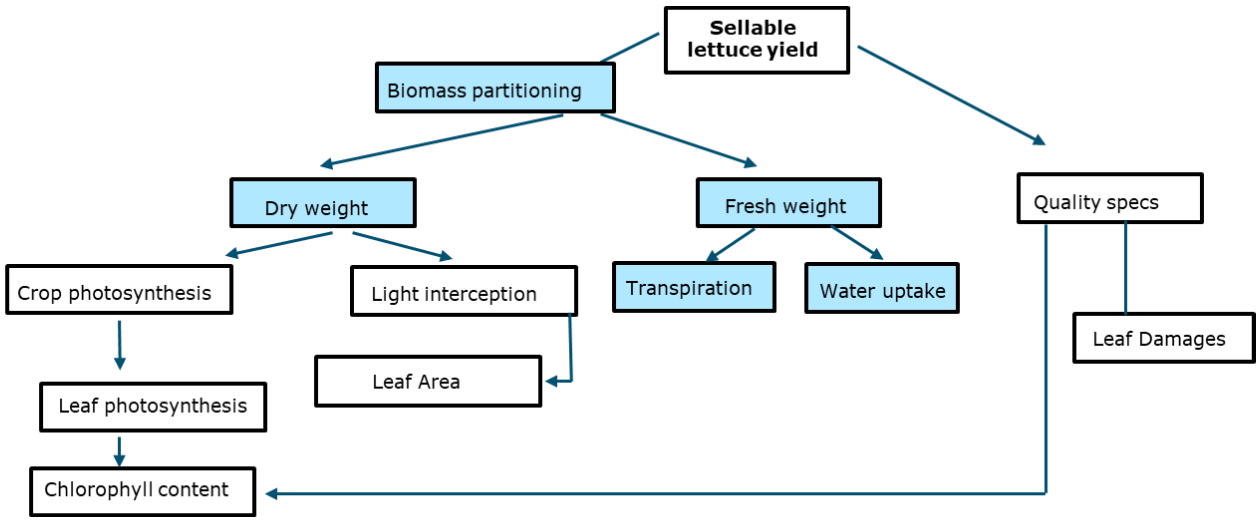

Figure 16 Weight accumulation processes of lettuce measured by a weighing device and coupled to an algorithm for water uptake and transpiration

In the VF cultivation described in Chapter 3, biomass was monitored intensively by destructive harvests, which is commonly done in research. In a production system destructive harvests are not an option so biomass increase should be monitored using sensors. A tray weight sensor has recently being developed (https://pro.aranet.com/products/aranet-weight-sensor-with-tray/) and can be used in ebb and flow irrigation systems (Figure 16). This sensor is measuring weight of the whole tray placed on it so substrate and plant together. When combined with an algorithm that calculated water uptake and evapotranspiration, a more accurate measurement of plant weight (fresh mass plus dry mass) increase can be obtained. Given the size of the frame, this sensor was designed to measure potter plants and seedling trays of 51 cm x 31,7 cm as shown in Figure 17.

Figure 17 Tray weight sensor used in an experiment during lettuce and basil propagation phase

Another option to have an estimate of development and crop performance in lettuce is to measure the increase of the lettuce head size in time by using camera's from above (Figure 18).

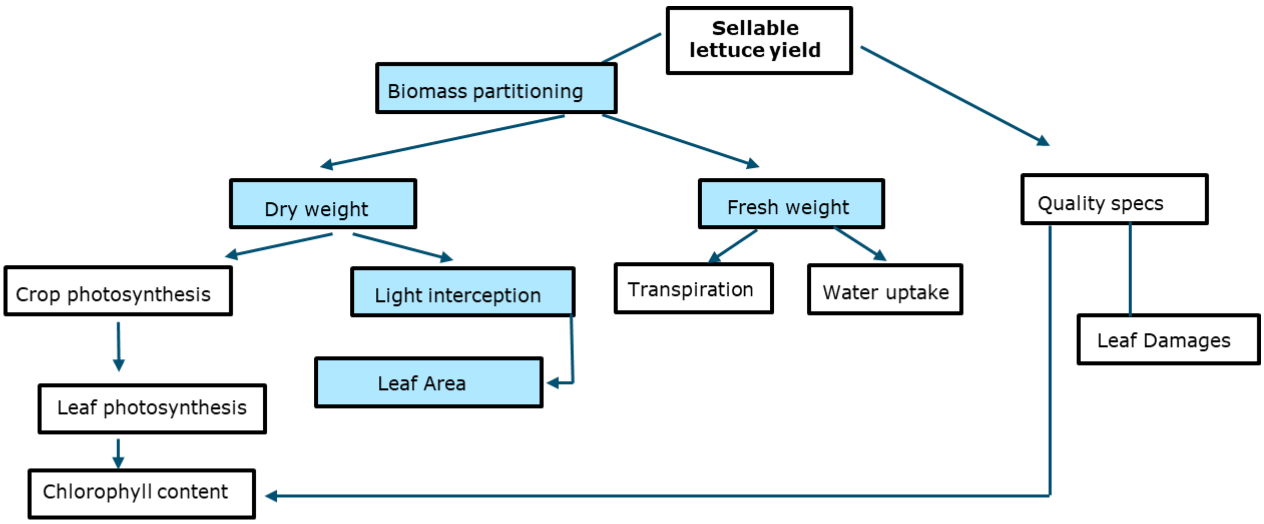

Figure 18 *Weight accumulation processes of lettuce calculated starting from a top view RGB camera to assess projected leaf area and/or volume (with a depth camera) and coupled to an algorithm for weight accumulation*

Software is needed to distinguish the pixels between plant and background (segmentation) and the increase of plant area in time can be calculated. Research done in an EDEN ISS space greenhouse at Antarctica showed that the harvest day can be predicted with an accuracy of 2 days 1 week after transplanting by fitting a logistic curve through the daily number of pixels classified as leaves by the segmentation and recognition algorithm (Zeidler et al. 2019). Limitation of this method is that accuracy decreases when the canopy is closed.

A more advanced system was developed by Zhang et al. (2020). Different lettuce types (flat and curled) were monitored in a greenhouse by digital imaging and a convolutional neural network (CNN) model was used. The model was trained to make estimates of growth related traits: leaf fresh weight, leaf dry weight

and leaf area. The results indicated that a CNN with digital images is a robust tool for the monitoring of the growth of greenhouse lettuce, better for flat type leaves than for curled leaves.
In the 'Autonomous Greenhouse Challenge' executed at Wageningen University & Research in Bleiswijk depth cameras (RealSense) were used to obtain information about crop growth (Petropoulou et al. 2023). Images were analysed by computer vision algorithms (Deepabv3+ implemented in detectron2 v0.6) and lettuce was separated from the background. The height and width information were very accurate and the lettuce head volume was estimated reasonably. The traits height and coverage were used to develop a light loss and harvest indicator to support remote decision-making. The light loss indicator could be used as a decision tool for timely spacing. However, the computed volume showed to be not suitable to predict the end crop weight. First reason is that the fact that overlapping leaves do not contribute to coverage or volume. Secondly, the height over time flattens during the last 2 weeks, and related to that, also the volume flattens during the last days. At the same time, destructive measurements showed that the fresh weight grows especially in these last days. As neither the coverage nor the height and volume indicated this fresh weight growth, it can be concluded that in the final stage, growth takes place from the central point of the head, resulting in more compact lettuce heads. Several traits were combined for the harvest indicator, ultimately resulting in a fresh weight estimation with a mean absolute error of 22 g.

Images can also provide information about the crop status: for example to detect anomalies like wilting, discolouring or pests and diseases.

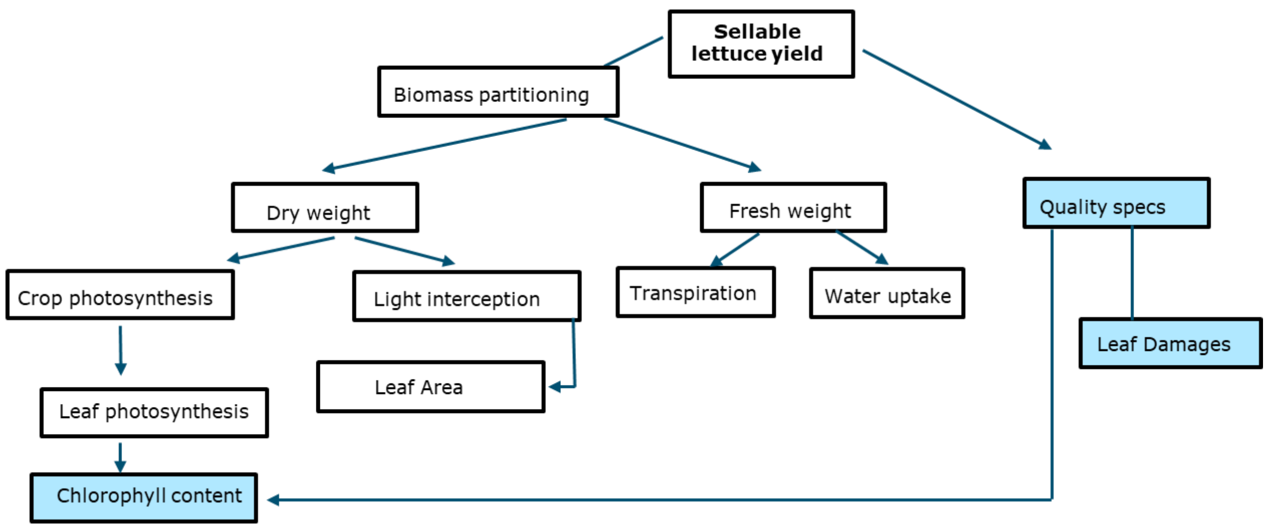

Figure 19 *Visual quality as measured by a RGB camera. With spectral imaging, compounds such as chlorophyll can be quantified*

This can function as an early warning system. Spectral imaging can provide information about water content (Polder et al. 2023), which is an important trait in lettuce. In practice some growers have camera's and images are made from the top on regular basis, but not used in a decision support system. Images can also be used to judge the colour of the crop. Other growers use chlorophyll fluorescence cameras that calculate the efficiency of the photosynthesis with the use of an algorithm. Based on the data decisions can be made about the lighting strategy for example (Staalduinen, 2024).

Another plant characteristic that provides information about the developmental rate is plant temperature. In almost all cultivation systems air temperature is measured and used to control the crop. Not the air temperature but plant temperature (of the growing point) determines developmental rate of the plant. When different cultivations are compared, comparison of plant temperature will provide more direct information about development to be able to understand differences between cultivation and to be able to steer the cultivation.

In Table 8 several processes or characteristics are listed that would be helpful to monitor the cultivation of lettuce.

Table 8 *Traits that provide insight in plant performance and sensors that can be used for monitoring lettuce (leafy greens).*

Process/characteristic	Trait	Essential	Sensor	Frequency
Growth	Diameter head (increase in time)		camera	day
	Projected leaf area	yes	camera	day
	Light interception (to calculate crop photosynthesis)			day
	Height		camera	day
	Biomass (increase in time)	yes	Scale, load cells	hour/min
	CO_2 uptake (to calculate crop photosynthesis)			hour/min
Development	Plant temperature		IR camera	hour
Water relations	Transpiration			hour
	Water content	yes	Hyper spectral camera	hour
Warning and quality	Tip burn		camera	hour
	Glassiness		camera	hour
	Wilting/anomalies	yes	camera	hour
	Colour		camera	day

5.2 Plant feedback in a young tomato plant cultivation

For a cultivation of young tomato plants, Figure 20 shows the tailored overview of plant processes and traits that affect the production of commercial young tomato plant.

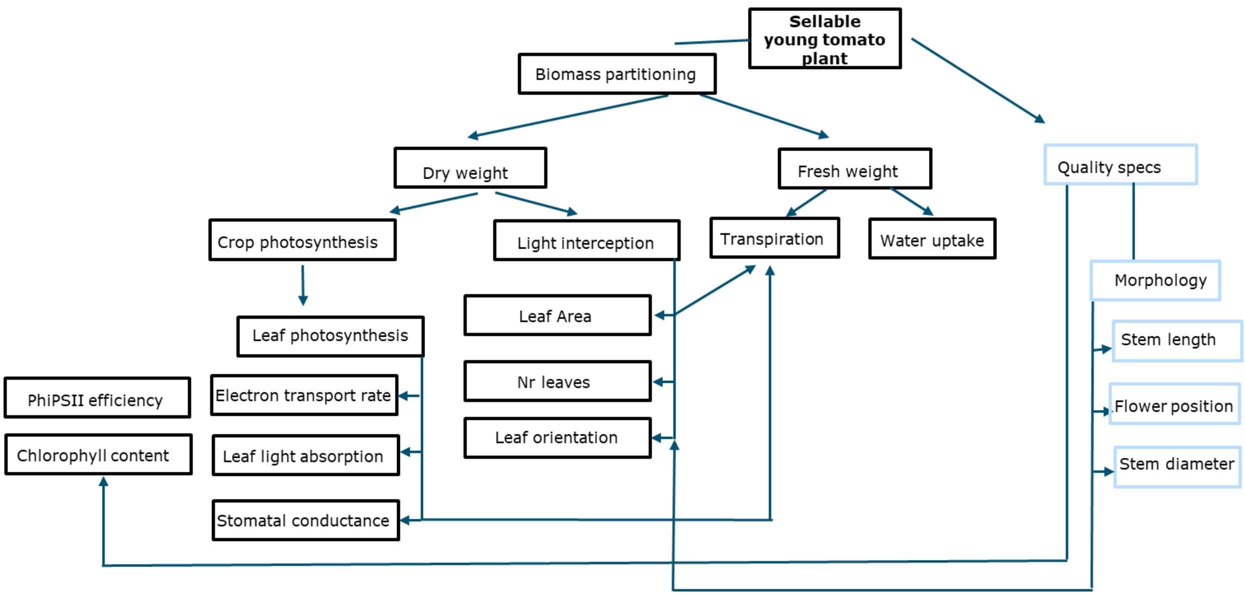

Figure 20 *Overview of plant processes and traits of interest for a young tomato plant cultivation*

In the VF experiment, climate (temperature and RH) was monitored per layer. The crop was monitored by visual observation and characteristics were measured after 15 days and at the end harvest.

In greenhouse horticulture tomato growers start the cultivation with young tomato plants provided by propagators. Growers can be specific regarding characteristics of the young tomato plants like, height, number of leaves below the first truss, fresh weight of the plant, stem diameter (Figure 21).

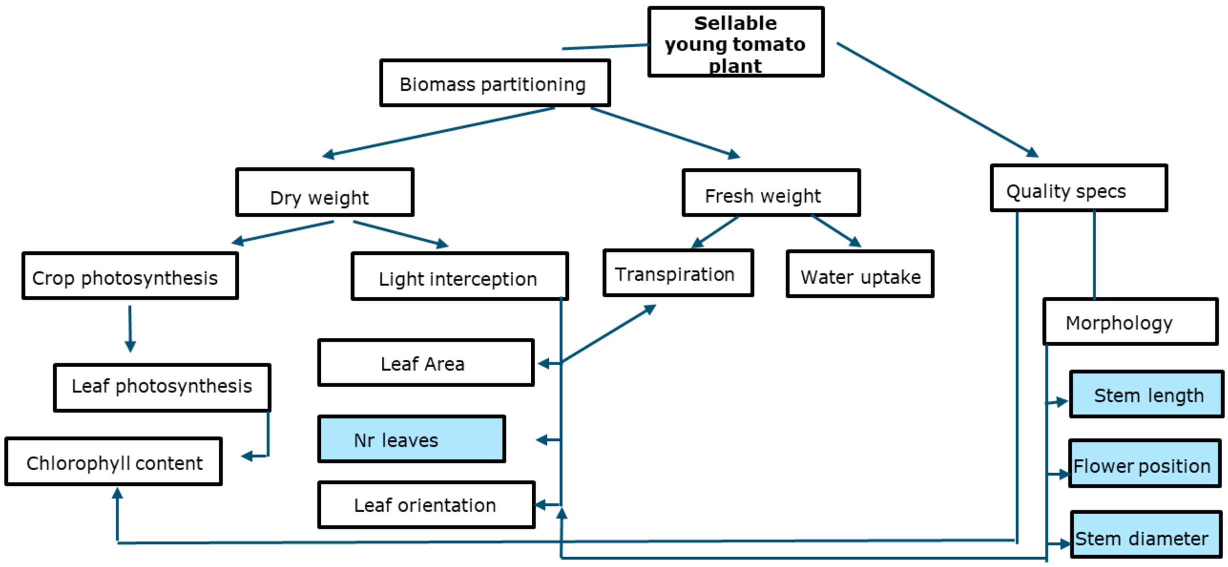

Figure 21 *Visual quality as measured by a RGB camera coupled to a processing algorithm to extract traits of interest for young tomato plants*

Uniformity between stems and between plants is also an important aspect. Also characteristics are mentioned that are hard to quantify like 'a strong truss', or a certain 'generative/vegetative balance' (Kromdijk & de Gelder, 2011).

In the VF cultivation some of these parameters were measured manually at the end harvest. It would be useful to monitor the plant characteristics during cultivation to be in control of the 'end product'. As far as we know these characteristics are not monitored automatically in practice. On the internet companies advertise with monitoring the crop by imaging, data analysis, and predict plant development (for example: https://gearboxinnovations.com/en/gearsense/). At a research stage, effort is being made in imaging crop by 2D and 3D cameras and accurately segmenting the different organs (Figure 22). Next steps will be to use the segmented point clouds to reconstruct plant architecture and determine height internode length and branching angles of young tomato plants (Van Marrewijk et al., 2025)

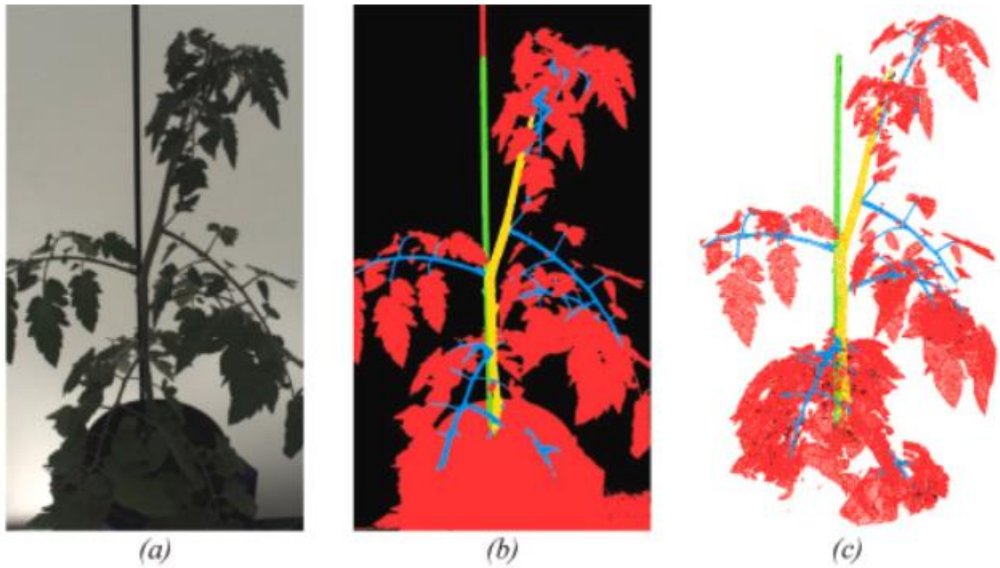

Figure 22 *Real RGB image of young tomato plant (a); segmented image (b); segmented point-cloud (c). Source: Van Marrewijk et al., 2025*

To make optimal use of the provided (expensive) light, it is useful to monitor light interception or projected leaf area and use this for dynamic spacing to realize optimal production with good quality.
Biomass accumulation over time can be measured by scales or by having tables on load cells. This measurement, similarly to the lettuce case (Figure 16), can be coupled to an algorithm for water uptake and transpiration for an accurate measurement of plant weight accumulation.

In Table 9 several processes or characteristics are listed that would be helpful to monitor the cultivation of young tomato plants.

Table 9 *Trait that provide insight in plant performance and sensors that can be used for monitoring young tomato plants (propagation).*

Process/characteristic	Trait	Essential	Sensor	Frequency
Growth	New leaf formation	yes	camera	day
	Light interception (to calculate crop photosynthesis)		PAR sensors	day
	Height		camera	day
	Projected leaf area (to calculate spacing)	yes	camera	day
	Biomass (increase in time)	yes	Scale, load cells	hour/min
	CO_2 uptake (to calculate crop photosynthesis)		Closed system	hour/min
Development	Stem diameter		Camera side view	day
	Detection truss/flower, position	yes	Camera: color detection	day
	Uniformity: position apexes of shoots per plant and between plants	yes	In-depth camera	day
	Plant temperature		IR camera	hour
Water relations	Transpiration			hour
	Water uptake			hour
Warning	Wilting/anomalies		camera	hour
	Color		camera	day
	Pests and diseases		camera	day

5.3 Plant feedback in a strawberry cultivation

In the strawberry VF experiment described in Chapter 3, morphology of the crop was monitored by manual measurements. Different climates can influence morphology and with that light interception, crop photosynthesis and fruit production. During cultivation the number of leaves, petiole length, crop height and width and truss length were measured. In the fluctuating climate, the crop height and width were significantly smaller compared to the stable climate, which could have a negative effect on total light interception. But the total light interception between the 2 treatments were comparable (Carpineti et al. 2024) which did not explain the differences in fruit production.

Fruits were harvested bi-weekly which provides actual information about crop performance. Fruit production harvest is the results of many processes during the cultivation before harvest. In an everbearer strawberry (and also in fruit bearing crops) assimilates partition between sinks which can be generative sinks (flowers and fruits) and vegetative sinks (new leaves, roots) (Figure 23).

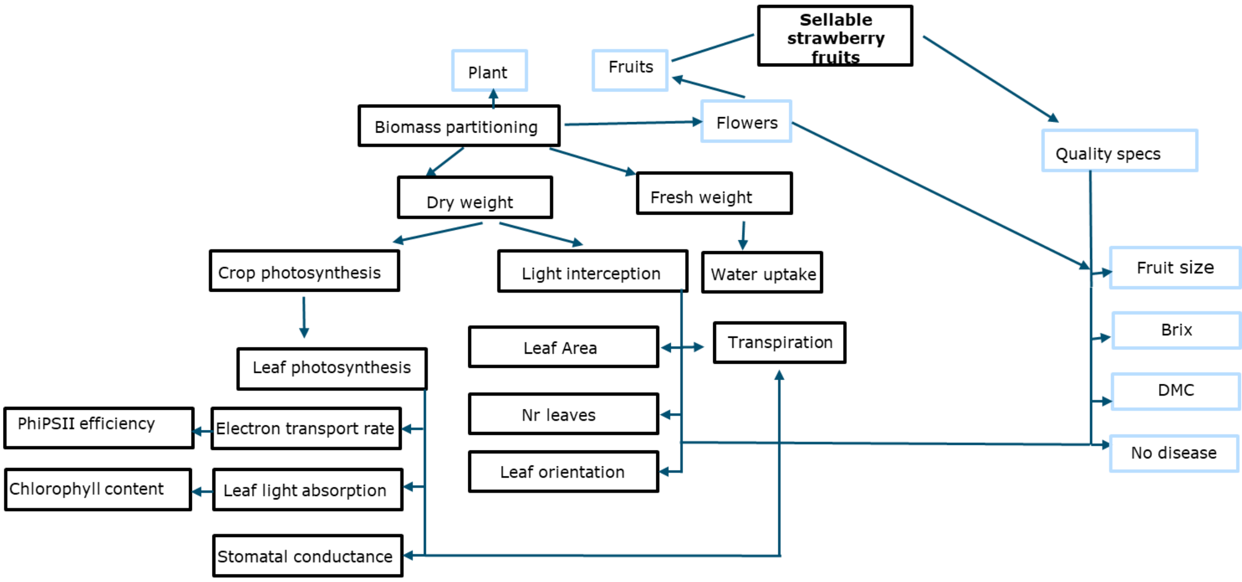

Figure 23 *Overview of plant processes and traits of interest for a strawberry cultivation*

In the described VF cultivation, 69% and 65% of the biomass portioned to the fruits (stable and fluctuating climate respectively). It would be interesting to get insight in the assimilate partitioning during cultivation to control the production pattern. As far as we know, no sensors are available to get insight in these processes like destructive harvests do. A derivative option is to monitor the generative/vegetative balance by detecting flower formation in time (Figure 24). A flat pattern in flower number in time will lead to a flat pattern in fruit production as well. A camera with detection software could be helpful to monitor flower formation, and images can also provide information about anomalies and pest and diseases. Korean research used images of the strawberry crop and were able to detect fruit clusters and divide it into 7 growth stages of the flower/fruits using a pretrained model (Oh et al. 2023).
Sensing techniques can be helpful in detecting pests and diseases (Figure 24). Images can provide information when symptoms occur, or pests are detected. Research is carried out to detect for example powdery mildew using image recognition or with the help of olfactory sensors which measure odor emitted by the crop after infection (Recognizing powdery mildew with cameras or olfactory sensors - WUR).

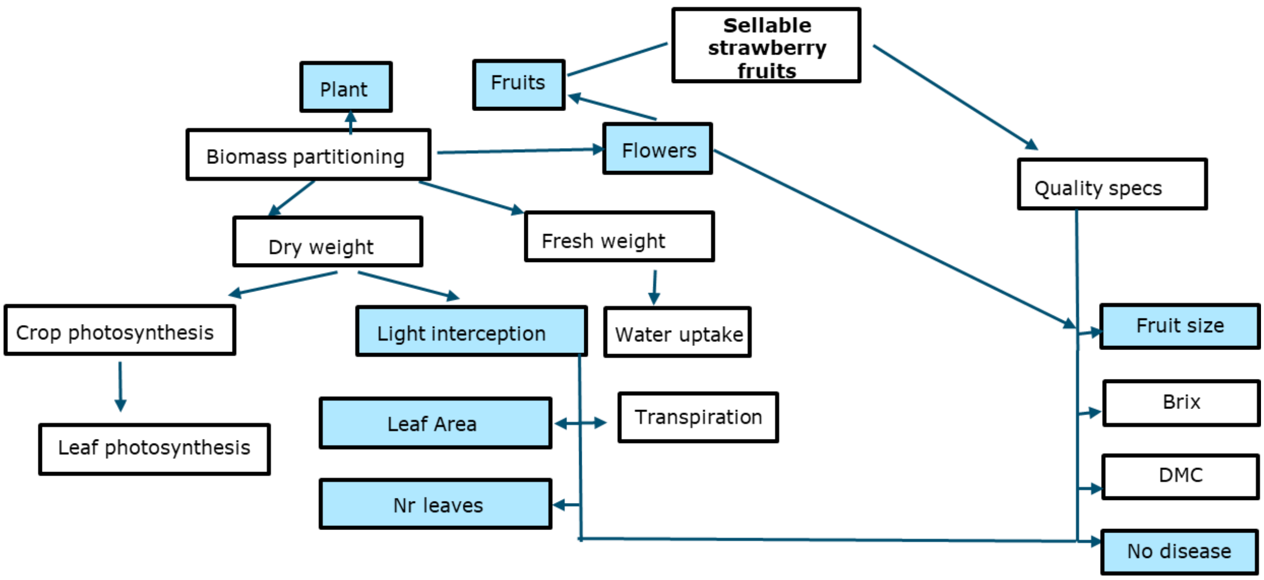

Figure 24 *Generative and vegetative balance and disease detection as measured by top and side view RGB camera coupled to software*

In practice growers use sensors to monitor the climate and soil moisture. Mildew can expand when RH is high, so also microclimate is monitored. Monitoring the crop is in practice done mainly by visual observations.
There is interest to monitor the crop; Fragaria Innova (cooperated strawberry growers) started with testing ‘biosensors’ (from Vivent, Swiss) that detect electric signal of plants (van Lier & Koopmans 2023). The hypothesis is that the signals of the plants in combination with climate data can generate information about the plants using AI and machine learning.

Another crop performance parameters that are difficult to determine, but that might help in understanding the crop physiology and can provide instantaneous feedback on the plant status is the crop transpiration. Crop transpiration is part of crop and cultivation system mass and energy balance; therefore being able to estimate it allows more precise climate control as well as irrigation. Furthermore, it could be used to detect deviations from the expected optimal performance of the crop caused by stress factors. Frequently it is linked with the term “crop activity”.
Within the AGROS II project, a method to compute transpiration based a combination of mathematical algorithms and commonly available data from the greenhouse is tested. This combination forms a software based tool that meets the requirements to be called a “soft-sensor”.
Crop transpiration can be estimated based on the calculation of the total resistance to transpiration through the simulation of boundary layer and plant stomata response to climate parameters (namely light, temperature, CO_2 and humidity) (Stanghellini, 1987). More recent studies have suggested simplified version of the transpiration model described by Stanghellini (1987). In the described method, the transpiration model described by (Van Beveren et al., 2013) is used. In this model, a crop-specific parameter (c) is incorporated, which acts as a scaling factor to make the model adaptable to the different crop architecture and stomatal properties of varieties and plant species.
The suggested approach uses commonly available irrigation and drain data to run a self-calibration procedure of the transpiration model which allows the estimation of the aforementioned crop specific parameter as well as other model parameters (boundary layer resistance, leaf area index of the crop) making the computation algorithm flexible to be used for different crops, providing that measured irrigation and drain data are available.
The algorithm reconstructs the drain profile by using the (measured) supplied water via irrigation, the estimated transpiration and crop growth in fresh weight. The behavior of the substrate is also included to account for filling or emptying of the substrate which affects the drain profile. In an iterative way, the parameters related to transpiration are estimated in order to achieve the best match between the simulated and measured drain profile of the last two days. Then the defined parameter values are used to simulate the transpiration of the current day (Figure 25).

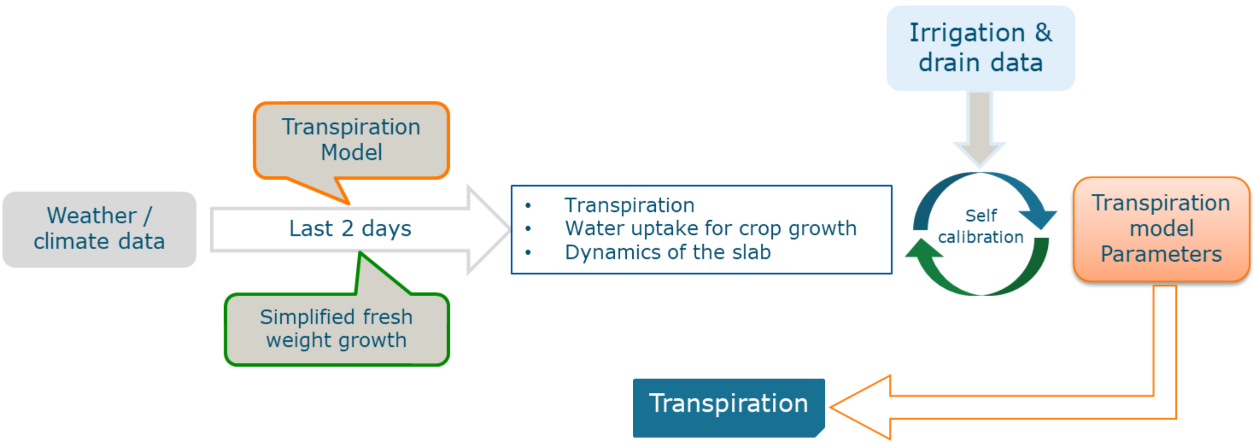

Figure 25 *Overview of soft-sensor method for transpiration, water uptake and slab water content calculation.*

When this soft sensor calculation is coupled to weighing gutter or a scale it can be used to monitor fresh and dry biomass accumulation (Figure 26).

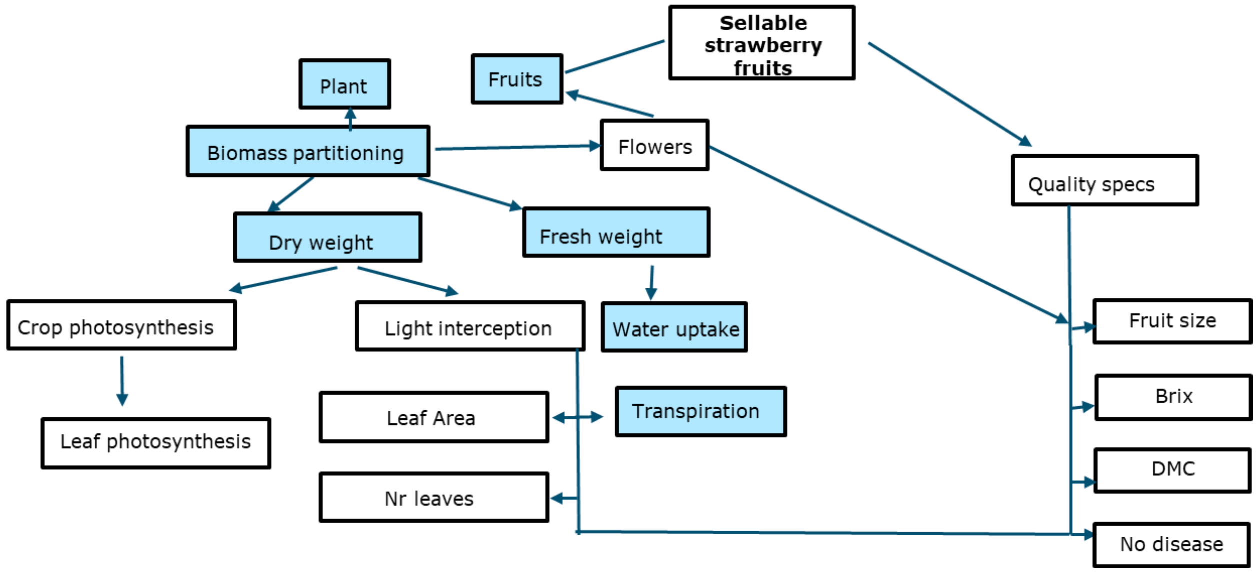

Figure 26 *Weight accumulation processes measured by a weighing device and coupled to an algorithm for water uptake and transpiration for strawberry*

In Table 10 several processes or characteristics are listed that would be helpful to monitor the cultivation of strawberries.

Table 10 *Trait that provide insight in plant performance and sensors that can be used for monitoring strawberry (fruit bearing crop).*

Process/characteristic	Trait	Essential	Sensor	Frequency
Growth	New leaf formation	yes	camera	day
	Projected leaf area or diameter	yes	camera	day
	Light interception (to calculate crop photosynthesis)		PAR sensors	day
	Height		camera	day
	Biomass (increase in time)	yes	Scale, load cells, tray weight sensor	hour/min
	CO_2 uptake (to calculate crop photosynthesis)		Possible in closed system	hour/min
Development	Plant temperature		IR camera	hour
	Detecting truss/flower		Camera: colour detection	day
	Number of flowers	yes	camera	day
	Number of fruits	yes	camera	day
	Ripening seeds/fruits		hyperspectral	day
Water relations	Transpiration		Prodrain	hour
	Water content			hour
Warning	Mildew		camera	day
	Wilting/anomalies	yes	camera	hour
	Color		camera	day
Quality	Color fruit		camera	day
	Brix			day
	Dry matter content		Hyper spectral camera	day

6 Discussion and conclusion

In all three case studies, both common processes and monitoring techniques were identified as well as dedicated traits which are specific to the quality requirements of the final product.
Monitoring growth as biomass accumulation over time offers opportunities for better planning of management actions such as spacing and planning the end of cultivation or harvest. Development is a strongly temperature driven process and, within boundaries, can be slowed down and sped up by lowering or increasing temperature, respectively. For all three cases, a monitoring system consisting of either a weighing sensor positioned below the plants or an algorithm to compute water uptake and transpiration from the total measured weight has been proposed. Both approaches have their pros and cons. The first approach is the only way to measure water uptake, but it requires close attention and maintenance of the system while the latter is a software based method that can be applied in any case given that basic greenhouse data (climate, irrigation, drain) are available. The self-calibration option of the soft-sensor allows its application to different crops (high wire or not) while the weighing gutter can only distinguish transpiration from water uptake when crop weight is also measured.
Close to this, a wide variety of application for cameras (RGB, depth, spectral) has been proposed, in combination with detection software, for biomass calculation, phenotyping and anomalies detection (due to quality issues or pests and diseases). Cameras are widely available now, but the greenhouse remains a difficult environment to operate in. Occlusion remains the main difficulty in extracting crop traits from images. However, developments in the field of AI are speeding up the process and research progresses towards the extraction of crop traits and it will soon be available in more commercial applications.

In general, these data- and process-driven models for crop growth are in their infancy, but some recent work has shown promise in greenhouses. Examples are AGROS project and Autonomous Greenhouse Challenge as well as the growing size and number of companies providing decision support systems such as Source.ag, Koidra and Blue Radix.

Research is still required to improve sensors and algorithms to maximize profits and energy efficiency in CEA. With this, the cultivation system can be optimized for efficient production, high yields, and maximum quality. Once these algorithms are connected, resource costs predictions (for example, electricity prices), these inputs can be incorporated in the algorithms to make sure that efficient use of resources is also done from a cost perspective allowing for the reduction of operational costs of vertical farming plant production where energy use can represent up to 20-40% of it (Appolloni et al., 2022).

To conclude, the objective and digital characterization of crop traits is the essential step for a biofeedback control system. For that, meaningful sensors have to be developed and tested in (semi-)commercial CEA systems, and large datasets are needed to train models. Digital twins of cultivation system and crop combined with machine learning can help to interpret information and finally autonomously control indoor crop production. This project contributed to the identification of relevant plant traits and technologies to monitor them in CEA cultivation of lettuce, young tomato plants and strawberry.

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