Guidelines for cultivation in a vertical farm

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Referaat
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. 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 are also reported, in anonymous form, showing that steps from the industry start to be taken toward openness and cooperation.

Abstract
Het ontwerpen van een teelt in een vertical farm is geen simpele copy-paste van kasinstellingen. In een indoor farm worden de teeltomstandigheden op een andere manier geregeld dan in een kas. Er is geen zonlicht en al het licht wordt dus geleverd door (LED) lampen met een andere spectrale samenstelling en een andere energiebelasting (geen stralingswarmte) in vergelijking met zonlicht; de lucht wordt voortdurend geconditioneerd (gekoeld en ontvochtigd) en circuleert met vooraf ingestelde windsnelheden, wat van invloed kan zijn op het vermogen van het gewas om latente warmte af te geven en daarmee op de opname van water en voedingsstoffen. Bovendien is een vertical farm niet of minder afhankelijk van buitenomstandigheden dan een kas en geeft dat meer vrijheid bij het toepassen van teeltrecepten (binnen systeemgrenzen) vergeleken met een kas. Met steun van de Club van 100 is dit rapport tot stand gekomen waarin richtlijnen worden beschreven die een teler handvatten biedt bij de start van een teelt in een vertical farm. Verschillende aspecten worden beschreven die in overweging moeten worden genomen, met opties, om tot een teeltontwerp te komen. Ook worden ervaringen van vijf Vertical Farming-bedrijven gerapporteerd, in anonieme vorm, waaruit blijkt dat er vanuit de sector stappen worden gezet in de richting van openheid en samenwerking.

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Summary

Several terms are used for an indoor cultivation facility without using sunlight (van Delden *et al.*, 2021). The term 'plant factory with artificial lighting' refers to a plant production facility with a thermally insulated and nearly airtight warehouse-like structure (Kozai, 2013). Multiple culture shelves with electric lamps on each shelf are vertically stacked inside. This term is used in Asia and does not always include indoor systems used in Europe. 'Container farms' can be shipping containers equipped with self-contained vertical farming systems, but can also be used with 1 cultivation layer for high wire crops (Butturini & Marcelis 2020). In this document the term 'vertical farm' (VF) will be used which includes all types of indoor cultivation without sunlight.

If you start to cultivate a crop in a vertical farm, many things need to be considered and decided upon. This document approaches several aspects of indoor production from a crop perspective: what decisions should be made to be able to cultivate a high productive and uniform crop in a vertical farm? Uniformity is important when cultivating a crop with minimum manual crop management. A VF is by definition suitable for techniques like vision and robotics which makes uniformity of the crop even more important.
Cultivation in a VF is not a simple 'copy-paste' of settings from the greenhouse. In an outdoor or greenhouse cultivation, some factors are set, like sunlight (intensity and spectral quality) and day length (when no assimilation lamps are used). In a VF all factors needs to be chosen - within boundaries of the system - because there is no relation with outdoor climate.
The aspects that needs to be considered are many: choosing the plant material, light, climate conditions, growing medium, watering, nutrients, CO_2, choosing sensors and level of automation. These aspects will then influence the sustainability of the production system.
All these topics are described in separate paragraphs and decisions that needs to be taken are summarized in tables at the end of each paragraph. In blue coloured boxes within the topics, experiences from practice are described. These information was gathered by interviews with 5 Vertical Farming companies present on the market in and outside the Netherlands (sources are kept confidential). In orange coloured boxes, experiences and input from members of the Club of 100 (see Appendix 1) are reported.

The purpose of the guidelines is to give support when it comes to decide how to set up or modify a cultivation in a vertical farm. Different fields of expertise are discussed in order to tackle every aspect of a controlled cultivation. Moreover, with the shared experience of companies we wanted to highlight the importance of open spirt of cooperation as a mean to learn from each other to support a (faster) development of the sector.

The guidelines are part of the project "Measure, Control, Grow" supported by the Club of 100 which decided to publish it in order for the whole sector to benefit from it.

1 Vertical Farm facility

These guidelines for cultivation in a vertical farm focus on the cultivation set up and therefore assume that the facility (vertical farm, VF) is already available.
Vertical farms are high-tech cultivation systems where all conditions, including light, are fully controllable. There are many different structural designs which make no one vertical farm equal to another. Compared to other high tech-facilities such as greenhouses, sunlight is lacking which implies that all light should be provided by assimilation light (see §3). And by lacking windows, like a greenhouse, more air exchange and forced air circulation is needed to create the desired climate conditions. Greenhouses have large volumes of air in relation to the cultivation area to realize a stable climate by avoiding large effects of the outside environment on the inside environment. This ‘buffering’ aspect of the large air volume is needed for example when radiation of the sun is fluctuating during the day. High light intensities will heat up the greenhouse because of the longer wavebands (heat radiation) contained in the sunlight spectrum. In a vertical farm the ratio between the volume of air and crop is much lower, which implies that the crop will influence more the cli mate conditions compared to a greenhouse cultivation, for example by transpiring (see §4).

Every VF system is different. Comparable climate settings in different VF results in different end products. Some companies have different cultivation modules (separate facilities) that are used for research and for production. In the research modules, tests are carried out to design the optimal cultivation recipe that is copied to the production module. But this will only result in comparable products if this module is the same.
Companies have their own data specialists working on finding relationships between sensor data and production data to understand the system.

Club of 100 members are positive about the potential of VF’s. They think VF are suitable for situations where execution in a greenhouse climate is challenging and/or precise light manipulation is required or beneficial. On the other hand, they are still discovering in what way it can be used profitable for their company.
An important advantage is the higher density of young plant material that can be cultivated in several layers which can be preferable over buying more greenhouse area.

2 Plant material

The first choice to make when starting a cultivation is the crop and, within this, the cultivar, to grow. The crop should fit in the system and since the individual plants may not be reachable by hand in a stacked system, crop management should not be needed or being automated (see §7). The most commonly grown crops in vertical farms are leafy vegetables and herbs. However, there is also some diversification with crops such as strawberry and tomato. Vertical farming might also be well suited for production of plants with specific metabolites, for use as pharmaceuticals, nutraceuticals, or skin care products (Butturini & Marcelis 2020) as well as for starting material (young plant production).

From interviews, we learned that the crops to cultivate are chosen based on the wishes of the clients. Several crops are tested in research modules to assess whether a profitable cultivation can be achieved that meets the requirements of the clients.
In practice most cultivated crops for production and selling are herbs and leafy greens. But some notice the challenge and opportunity to cultivate added value crops like berries.

VF are suitable for the propagation of high-value plantlets and for crops with high energy demands (e.g., heating in winter, cooling in summer), especially for species and cultivars with stringent quality requirements.
Companies use VF for a certain stage of the crop, for example production of young plants. The first phases in a cultivation like germination and rooting requires specific environmental conditions that can be easier achieved in a VF compared to a greenhouse.

When the crop is chosen, the next step is choosing the starting plant material. There are several options, such as seeds, young plants, unrooted cuttings or tissue culture. The advantage of starting with seeds or tissue culture is that the plant material is disinfected and the risk of bringing in pests and diseases in the system is diminished. However, disinfection of seeds will not guarantee that the plant material is virus free (Reingold *et al.*, 2014). But starting with seeds from reliable companies is a safe choice because the seed companies are keen on clean plant material and test the plant material on regular base. Organizations such as NAKtuinbouw in the Netherlands are also involved in testing material in order to provide reliable and high-quality propagated material for national and international trading.
Tissue culture material is genetically identical because of vegetative reproduction (clones). The disadvantage is that it is not always available and the material will be expensive.
Starting with seeds needs an extra selection step when the germination rate is not 100% or when germination is not uniform in timing. Selection of uniform seedlings will increase the uniformity of the crop.
Starting with young plants or unrooted cuttings has the advantage that uniform material can be ordered and selected. The material is not sterile so attention needs to be paid on preventing bringing in pests or diseases. Screening plant material on diseases (PCR or ELISA test on virus for example) is an option but it is expensive (especially when a broad spectrum is tested) and not common at the moment of planting. But when specific symptoms are observed during cultivation, tests can be done (communication Ineke Stijger, Wageningen University & Research).
Cultivars can be selected based on important aspects for cultivation in a VF. Uniformity is one of the most important criteria. Another aspect is the final plant height due the limited space available between 2 layers when a stacked system is used. A certain distance between top of the crop and the lamps is needed for a homogeneous light distribution on the plants. Plant architecture is critical in achieving uniform (vertical and horizontal) light distribution across the canopy. An open canopy with long internodes and narrow leaves is beneficial for uniform light distribution. However, in VF, compact plants are desired to fit in the system. The challenge is therefore to combine breeding efforts and growth recipes that result in a compact plant ideotype with uniform light distribution over all leaves (van Delden *et al.*, 2021).

The selected cultivars should perform well with artificial light without sun light. Moreover, the duration of the cultivation cycle can play a role in cultivar selection. Shorter cultivation cycles save time and is thereby cheaper. Another consideration links to the physiological processes in the crop: some processes are critical like photoperiod. Some plants are day length sensitive and need a certain photoperiod or period of darkness for critical processes like flowering.

For all interview VF companies, the first step to select the cultivar is done by screening several genotypes and selecting the most suitable ones regarding the requirements of the client. Most important for clients is quality, meant as taste and appearance, followed by shelf life. Appearance can be the size (maximum leaf length to fit in a box for the supermarket), perfect leaves without any spot (restaurants, herbs premium quality). Besides this selection criteria, the cultivation cycle should be relatively fast to be profitable for the VF company.

A VF can be introduced by a greenhouse company as an extra facility. Crop, starting material, growing media and nutrient solutions are kept the same and only the facility is different and provides opportunities to steer and test.
An example of testing is creating a combination of (relatively) high light and high relative humidity which can be realised in a VF and is difficult to realize in a greenhouse. Tests in a VF are very promising with this high RH and light in the first phase of cultivation of young plants (germination, rooting).

Table 1 *Aspects regarding starting plant material.*

Plant material	Explanation
Crop	Client requirements Suitable for VF cultivation: crop management, size, physiology
Cultivar	Productivity Uniformity Morphology: height can be limiting to fit in the system Plant architecture: uniform light distribution Quality Duration cultivation cycle Good performance with artificial light
Physiology	Think of critical physiological processes for the crop like: day length sensitivity, period of dormancy
Starting material	Seeds (more clean, germination can be heterogeneous) Young plants (uniform, not sterile) Unrooted cutting (not sterile) Tissue culture (more clean, genetically identical, expensive)

3 Light

Light is one of the most important factors that regulates plant growth and development. The sun provides light with a specific intensity, cycle (day/night) and spectral quality, which all change during the day and season. Growth and development of plants are regulated by the 2 processes of photosynthesis and photomorphogenesis. Photomorphogenesis is the light spectrum-mediated development, leading to differences in morphology, colour and flowering of the plant. Photosynthesis is the process where CO_2, taken up via stomates, water and light energy are converted into chemical energy in the form of sugars.

In a vertical farm light is provided with lamps. Lacking the natural sun light, a lot of decisions need to made about factors like photoperiod, light intensity, light sum (daily light integral), spectral quality. All these factors, and the other factors that are described in the document, can be kept constant throughout the year which theoretically makes cultivation stable and predictable. However, in nature, no place on earth has a constant light regime, not even in summer at the arctic regions (Velez-Ramirez *et al.*, 2011). Plants have a circadian rhythm which coordinates plant physiological processes to specific times of the day or night, and thereby plant responses can be different than expected.

3.1 Photoperiod

The length of the photoperiod is important for day length sensitive plants. For example qualitative short-day plants like chrysanthemum need a certain critical duration of the dark period to induce flowering. Flowering doesn't occur when the dark period is shorter or when the period is interrupted. Crops are usually cultivated with a dark period which represents the natural situation. During the dark, assimilates are distributed; when this period is too short in relation to the amount of produced assimilates, plants can show symptoms like curled or thick leaves due to the accumulation of sugars into starch or purple stem.
Potentially, continuous lighting is a way to increase plant productivity. Prolonging the photoperiod increases the hours per day where photosynthetic organisms can assimilate CO_2 and prolonging the photoperiod towards 24 hours per day could translate into more biomass. A number of crops cannot stand continuous 24 hours lighting and symptoms like necrosis, chlorosis and lower photosynthesis capacity are reported (Velez-Ramirez *et al.*, 2011). Long term use of continuous light is detrimental for crops like tomato and pepper, although short term use of continuous light (5 to 7 weeks) improved vegetative growth and fruit production of both species (Demers & Gosselin 2002). Also Ohyama *et al.*, (2005) showed that young tomato plants performed well when under 24 hour light during 17 days with alternating temperatures of 28/16°C during 16 and 8 hours respectively. Using alternating temperatures following the 24 h pattern probably keeps the circadian rhythm during continuous lighting and prevents symptoms as mentioned before. Lettuce seems to be capable of growing under continuous light, although the optimal photoperiod might be lower than 24 h (Pennisi *et al.*, 2020).
Continuous lighting is – as far as we know- used in some cultivars of rose in greenhouse cultivation.

3.2 Light intensity and light sum

The amount of assimilates that plants produce is not only related to photoperiod, but to the total light sum that plants receive. A light sum is easy to calculate by multiplying the light intensity with the photoperiod. For example, when plants receive 300 μmol PAR m^{-2} s^{-1} during 16 hours per day, the plants receive 17.3 mol PAR m^{-2} d^{-1} (300 x 3600 x 16 (h) / 10^6 (to convert μmol to mol). A light sum is also defined as the daily light integral (DLI). When the crop shows symptoms of too much light, the photoperiod can be reduced or the light intensity can be reduced, resulting in a lower light sum per day.

Light intensity can be set as a fixed value and can be kept stable during the photoperiod. In a greenhouse the natural sunlight causes a dynamic light intensity pattern during the day with an increase during sun rise and a decrease during sun set. On a clear day the light intensity will peak at noon and the pattern during the day shows a sigmoidal curve. On a cloudy day the light intensity can be dynamic and fluctuate a lot. In the VF the pattern of light intensity can be chosen: sun rise can be mimicked by a slow increase of light intensity to a maximum value that will be kept during the day until a slow decrease at the end of the day mimicking sun set. These light transitions between light and dark periods are described as 'fading'. Dynamic patterns during the day can be chosen as well. Until now it is not clear if a stable climate during the day is favourable for all crops. Research was carried out in 2022 in 2 separate chambers in a VF at Wageningen University & Research to compare a stable and a fluctuating climate on the production of strawberry. After 21 weeks of cultivation, light and temperature sums achieved under fluctuating conditions were the same as those under stable conditions and no differences were found in strawberry production (personal communication C. Carpineti).

The light sum can be chosen as a fixed value during the whole growth cycle or can change during cultivation. When no plant spacing is applied during cultivation, light interception will increase in the first period of cultivation until the canopy is closed and most light is intercepted during the rest of the cultivation cycle. This implies that a lot of incident light is lost in the first phase of cultivation. It can be beneficial to start with a lower light sum at the start of cultivation and increase the light sum until maximum light is intercepted. Biomass of lettuce was highest at the end harvest when the light sum increased during cultivation compared to a stable light sum with comparable light sums during the whole cultivation (Jin *et al.*, 2023). Incident light will be used more efficient when plant density is adapted during cultivation by spacing the plants to maintain high light interception throughout the whole cultivation cycle. A dynamically managed plant density allows for continuous canopy closure throughout the growth cycle by gradually decreasing density as plants grow would be the optimal situation regarding light use efficiency (van Delden *et al.*, 2021).

All interviewed companies provide a light and dark period. Electricity is expensive; turning off the lamps is more financially viable compared to the financial gains that a higher biomass in an extended photoperiod can produce. Continuous lighting exhausted the plants, resulted in more tip burn and a shorter shelf life. All companies use the 24 h rhythms and some are testing other schedules like 6h rhythms (4 hours light and 2 hours dark).

Using a VF provides the opportunity to create climate conditions and companies test different combinations of light intensities and RH. Results are promising although optimalisation of light intensity is needed to prevent leaf damage.

3.3 Light quality

Spectral quality of assimilation lamps is different from sun light. Sunlight is the electromagnetic radiation given by the sun. This radiation is filtered by the atmosphere before it reaches the Earth as global radiation. Global radiation includes radiation with wavelengths between 300 and 3000 nm, which are grouped as ultraviolet radiation (UV), visible and infrared radiation. Radiation in the region 3000-100000 nm (3-100 μm) is referred to as heat radiation. Only 45-50% of the global radiation is PAR (Photosynthetic Assimilation Radiation) light and used for photosynthesis (Hemming *et al.*, 2004). The spectral quality of the photons (μmol/m^2/s) in the PAR region in sun light is around 30/35/35% blue/green/red assuming that the region 400-500 nm blue; 500-600 nm green and 600-700 nm red. The red: far-red ratio is sunlight is around 1.2 and decreases during sun set. This ratio can influence the morphology of plants especially at the end of the day. Far red at the end of the day led to increased stem length of tomato seedlings which improves grafting on a rootstock (Chia & Kubota et al 2010). When the amount of red at the end of the day was high, viola, petunia and fuchsia were more compact (Dieleman *et al.*, 2018).

In a VF the spectral quality can be chosen by combining different LEDs. The question arises what is the best spectrum to choose. There is increasing interest in manipulating light intensity and quality to improve biomass productivity and enhance concentrations of bioactive secondary metabolites in leafy herbs and vegetables. However, no single light solution fits all scenarios (Dou & Niu 2020).
Red light is most energy efficient because the energy content per photon is lowest (see also §10. Sustainability). Regarding the process of photosynthesis, red light is most efficient (McCree 1972; Snel *et al.*, 2011). But growing plants in red light will not result in healthy plants because other wavelengths are essential for a good development and functioning of plant. Research showed that the spectral quality can have big effects on plant morphology and growth. Effects of spectral quality can be different for different species and even for cultivars between a specie (Dieleman *et al.*, 2020).
To prevent problems regarding light quality a 'safe spectrum' can be chosen which includes the whole region between 400 and 700 nm, with sufficient blue (5-10%), green (around 10%) and most red (80%). Far red lamps can be installed and used separately. Dynamic and dimmable lamps will give the most degrees of freedom to play around with the spectral quality and effects on the crop can be monitored.

Most interviewed companies started with LED lamps with a fixed red and blue spectrum. Some companies still use this RB spectrum in the production area. Other companies also use fixed spectrum in the production area but included green, white and/or far red LED. In the research area different spectra, light intensities and photoperiods are tested to obtain the best light strategy for the desired crop.

Companies are aware that red light is most efficient regarding the photosynthesis process and also red and far-red light are most efficient when it is expressed in photons per Joule.
Tests with broad spectra and purple spectra were carried out and provided insight in effects of spectral quality on plant growth. Broad spectra resulted in better plant growth and indicates that finding the optimal spectrum of LED in a vertical farming environment is of great importance.

Table 2 *Aspects regarding light for VF cultivation.*

Light	Explanation
Photoperiod	Day length and period of darkness. Important for day length sensitive plants
Light intensity	What light intensity, stable or dynamic
Light sum	Light sum is determined by photoperiod and light intensity It influences photosynthesis and growth
Fading	Lamps from 0 to max or fading between light transitions
Spectrum	○ PAR: ratio blue, green, red ○ UV needed? colour, pollination, secondary metabolites ○ Far-red needed? Morphology can be influenced ○ Fixed spectrum, dynamic spectrum ○ Mimic sunset: changing R/FR ratio at the end of the day

4 Climate

4.1 Temperature

Temperature – within certain boundaries - influences the developmental rate of plants. In general, developmental rate increases with increased temperature with an optimum temperature. Some plant processes are determined by the temperature sum, for example the temperature of the apex influences the formation of new leaves. That implies that the period of a cultivation cycle can be influenced by the average temperature.

Plants respond to plant temperature and not to air temperature. Usually climate is controlled by controlling and measuring air temperature. Plant temperature can be different compared to air temperature. For example heat radiation supplies energy to the leaves which can result in an increase of temperature. Transpiration of leaves costs energy and as a result, leaf temperature will drop and can be lower compared to the air temperature. These dynamics between air and plant temperature are different in a greenhouse cultivation and VF. In a greenhouse, the sun has a big influence on plant temperature and also high pressure sodium lamps emit infra-red radiation which is heat radiation. In a VF sunlight is excluded and LED provides less heat radiation compared to high pressure sodium lamps. This implies that the plant temperature in a VF will be differently related to air temperature compared to a greenhouse cultivation. When air temperature is used for controlling the cultivation, effects on plant development in a VF using air temperature can be misjudged. Besides that, experience should be build up regarding controlling plant temperature and its effects on plant growth and development and asks for a different way of controlling the crop.
Temperature during the light and dark period can be set and the period in between can be faded during a certain period like discussed for light intensity. The difference in temperature between the light and dark periods is called DIF which can influence morphology. In general a positive DIF stimulated elongation and a negative DIF stimulated compact plants (Shimizu 2007). This knowledge can be used when morphology is an important aspect of the cultivation and of the final product.

4.2 Relative humidity and air movement

Leaf transpiration rate is determined by the vapour pressure deficit (VPD) between the air and the stomates. Therefor VPD indirectly affects nutrient uptake and thereby plant growth. Temperature and relative humidity (RH) together determines the vapour pressure deficit, because the amount of water that air can contain is depended of the temperature. Air with higher temperatures can contain more water compared to cold air. Vapour pressure deficit between open stomates and the air is the driving force for the transpiration of plants. For example, RH in a stomate is considered as 100% and the leaf temperature can be measured; vapour pressure can be calculated. The difference with the vapour pressure of the air (temperature and RH) determines the transpiration rate when stomates are open. Air speed influences the transpiration rate because removing the transpired water from the leaf will maintain the deficit between leaf surface and air. Air movement is necessary to avoid a stagnant climate and to create homogeneous conditions in the production facility. Air circulation inside a plant production system is often considered for achieving better spatial uniformity of air temperature. Too high air speeds (greater than 1 m s^{-1}) can give mechanical stress to plants and/or reduce internodes size and leaf size. Low air speeds can increase boundary layer resistance which can hamper CO_2 uptake. Transpiration and photosynthetic rate were reduced in potato leaves when air speed was low (0.01 m s^{-1}, Kitaya *et al.*, 2000). Growth and uniformity of tomato seedlings were enhanced at an air speed of 0.7 m^{-1} s^{-1} compared to 0.3 m s^{-1} (Yokoi *et al.*, 2008).

In VF the direction of the air flows are mostly horizontal. In a stacked VF, a relatively laminar horizontal air current is generated over the plug trays and through the transplant canopy in each shelf. By using fans with an inverter for controlling the fan rotation speed, the air current speed over the transplant canopy can be continuously controlled in a range between 0.2 m^{-1} s^{-1} and 1 m s^{-1}, depending on the transplant growth stage, planting density, transplant morphology, etc (Kozai 2020). With computational fluid dynamic models (CFDs), the effect of several design parameters have been simulated to investigate their effects on air flow and climate uniformity in vertical farms (Kang, 2024). The effect of vertical and horizontal air distribution on lettuce tip burn has been analysed in different studies (Kubota *et al.*, 2023) showing potential reduction of its incidence when vertical airflows (downward onto the canopy) are applied to different lettuce cultivars (Kaufmann 2023).

The number of air exchanges per hour (N, h^{-1}) is a measure of how many times the air within a defined space is replaced by new air, which is defined as the ratio of hourly ventilation rate divided by the volume of room air. For VF, ideally N should be small for the purpose of controlling the environment and preventing entry of pathogens and pests. However, a minimum air exchange rate can be maintained to prevent the accumulation of ethylene, which can cause damage to the plants. For relatively airtight, well-insulated VF, the N is approximately 0.01-0.02 h^{-1} (Kozai, 2013) and can even be 0 in a fully closed system like the VF at Wageningen University & Research Greenhouse Horticulture in Bleiswijk (Graamans 2020). The advantage of such a closed system is that it can function like a ‘plant chamber’ where the amount of supplied CO_2 is related to biomass production.

Tests were carried out to find the best temperature regarding yield and quality and also literature was used. DIF was tested (difference between temperature during light and darkness) to find the optimal yield and preventing tip burn.
From the interviews it was clear that there is need to understand the relationships between irrigation, nutrient uptake, transpiration and ventilation. Airflow is important to stimulate transpiration and thereby the uptake of water and nutrients. Knowledge is lacking on how to find the optimal settings for these parameters that results in a healthy crop.
In practice, directions of air flow are multiple (not only horizontal) and even under angles which influence the microclimate.

Ensuring an uniform airflow is the most challenging aspect, aiming to equalize climate parameters (temperature and humidity for proper seed germination) and transpiration for optimal growth.

Table 3 *Aspects regarding temperature, RH and air movement in a VF cultivation.*

Factor		**Explanation**
Temperature	Setpoint	Influence of plant temperature on development
	Fading	Transition from light period to dark period: fading or not, how long
	DIF	Difference temperature during light and dark period: influences morphology (elongation/compactness)
	Uniformity	Check **plant** temperature at several position in the VF. Experience is that local variation can occur. This will have negative consequences for uniformity.
RH irt temp	Setpoint	Vapour pressure deficit is driving force for transpiration when stomates are open
Air movement	Speed	Influence on homogeneous conditions Influence on boundary layer/ transpiration
	Direction	Horizontal, vertical or under an angle at each shelf
	Exchange/capacity	Number of replacement of the air by ‘new’ air per hour. Advantage of high exchange: get rid of pollution. Disadvantage of high exchange: less control and not usable for estimation of photosynthesis rate.

5 Irrigation and substrate

To optimise the irrigation strategy in a vertical farm, two factors are closely linked to each other: irrigation system and growing medium. Once an irrigation system is chosen, the range of growing media to choose from becomes smaller. As a result of this choice, it needs to be decided how to deal with fertigation and treatment of irrigation and drain water.

5.1 Irrigation system

Plant roots need to be provided with water, nutrients and oxygen. A variety of methods is available to provide the first two elements to the plant roots and the way of application has an effect on the available amount of oxygen.

Below a list of irrigation systems with main characteristics is provided:

- Overhead irrigation: has a huge effect on air humidity. Normally used in full field cultivation (chrysanthemum, lily) or cultivation of potted plants (phalaenopsis, kalanchoe). In general large volume of water are provided leading to over-irrigation. Water is always saturated with oxygen before plants are reached and of course the crop itself gets wet. For the right distribution of water on the whole cultivated area, a distance between the irrigation line and the top of the crop is required. The supply lines are quite long, which affects timing of arrival, changes in nutrient composition. Standstill time can affect pH.
- Drip irrigation: small irrigation events are possible which makes it relatively easy to control the drain percentage. Dripper capacity decides on frequency and duration of irrigation events, choice is also connected to type of growing medium used (water holding capacity). Long supply lines, which affects timing of arrival of changes in nutrient composition and standstill time can affect pH and oxygen concentration.
- Ebb and flow: low frequency with large volume irrigation. Only small percentage of irrigation water is taken up by the crop, large volume of drain water to be recycled. Often used for potted plants and nursery stock production. Capillary force of growing medium is transporting water from the table/floor to the entire volume of the root zone. Diseases can spread easily from one plant to another. Heavy construction is needed because of the high volume of water applied to the system.
- Nutrient film technique (NFT): continuous irrigation, large volume of drain water to be recycled. No water and nutrient buffer around the roots of the plants in case of electrical failure. Changing composition of the nutrient solution towards the end of the cultivation gutter. Easy spread of root diseases. Covering of the water flow from light is important to prevent algae growth.
- Deep flow technique (DFT): continuous availability of water. Oxygen transport to the roots is an important point of attention. Easy spread of root diseases, difficult to clean the system in between cultivation cycles. Heavy construction needed to support the weight of the water. Covering of the water flow from light is important to prevent algae growth.

In practice different systems are used: NFT, drip irrigation, ebb and flow depending of the preference of the company. Also different systems are used within 1 company depending of the crop. For example ebb and flow system for tray crops or pot crops, NFT for growing head crops and drip irrigation for growing long-grow-cycle crops.

Combining ebb and flow with overhead irrigation provides flexibility to steer the crop through its different growth phases. Irrigation in VF is easier due to predictable drying (provided climate uniformity is ensured), requiring much less correction (edge watering) compared to high-tech greenhouses.

5.2 Irrigation strategy

The total volume of water supplied to the crop should replace the volume of water taken up by the crop (transpiration + biomass production) and is normally calculated using transpiration models with data on total irradiation. Any additional supply of water will become drain water to be collected, treated and reused. By adapting the frequency of irrigation events and the volume per irrigation event circumstances around the roots can be controlled: water content, dissolved oxygen concentration, nutrient composition, pH. This can be controlled by measuring water content in the growing medium (ebb and flow, drip irrigation), amount of drain water (drip irrigation, NFT), water level (DFT) and oxygen content (DFT). Water content can be used as a leverage to steer generative or vegetative growth of the crop.

Irrigation can be done with an automated system where gutters are irrigated based on a weighing gutter twice per day. It is possible in this way to dynamically change the amount of watering based on plant growth stage and cultivar.
Irrigation strategy was designed through testing different frequencies and monitor biomass.

5.3 Water treatment

Water quality is of outmost importance for optimal production. Incoming water needs to be of high quality (low in salts, no disease). Depending on source quality, it can be important to apply water treatment technology (e.g. desalination, disinfection). After collection of drain water, water treatment can play an important role to be able to recycle/recirculate drain water:

- particle removal (filtration); prevention of clogging, improve working of water treatment.
- prevention of diseases spreading through the crop (disinfection).
- breakdown organic molecules (oxidation); dissolved organic matter from growing media, root exudates.
- Selective removal of elements (ion-exchange, selective membranes); prevent concentration build-up (e.g. sodium, heavy metals).

It is important to keep in mind that some technologies only have an effect on the spot (point treatment; e.g. UV, heat treatment) and other technologies have an effect throughout the entire irrigation system (system treatment; e.g. ozone, hydrogen peroxide). Chemical remainings or reaction products of water treatment can have a negative effect on crop production.

Some companies apply water treatments: UVC disinfection and others ozone.

5.4 Growing media

A growing medium, or horticultural substrate, is a porous material other than soil in which plants are grown. In soilless cultivation, the growth of plant roots is limited within the container volume; therefore, growing media (GM) must be effective in capturing adequate irrigation solution, maintaining a buffer medium in between irrigation events, and supplying a sufficient amount of air and nutrients to plant roots. Importantly, growing media must be free from phytotoxic substances, plant pathogens and weeds.

In VF, selecting the right GM is of crucial importance, particularly in the propagation stage from seeds to transplants. To aid in the selection of appropriate GM, materials are characterized in the lab based on key parameters, including particle size distribution, bulk density, water holding capacity, air-filled porosity, easily-available water, pH, pH buffering capacity, electrical conductivity (EC), nutrients, microbial stability, and phytosanitary testing (Table 4).

Following the assessment of the tested materials' properties, measures should be taken to improve substrate performance. This can be achieved by blending the materials with other GM and/or additives (lime, base fertilizers, clay, wetting agent, etc.) to bring them within the recommended range, as well as adjusting the fertilization and irrigation regimes to create optimal conditions in the root zone.

Regarding the nature of the material, growing media can be classified into three classes including inorganic, organic and synthetic growing media.

- Inorganic GM: natural unmodified materials (sand, tuff and pumice, etc.) and processed materials mainly through high heat application to transform the texture of the materials (stone wool, perlite, vermiculite, expanded clay granules, zeolite, foamed glass, etc.).
- Organic GM: peat, coconut coir, bark, wood fibre, plant fibres (hemp, flax, jute), composts, and biochars, etc.
- Synthetic GM: oil-based material (such as polyurethane) and emergent biodegradable polymers from innovative producers like GROWFOAM® and Nygaia.

Growing media can exist in loose form, which can be filled into the containers like trays and pots or in pre-shaped form such as stone wool in plugs, cubes and slabs or pre-shaped bio-based substrates. Inorganic GM offer advantages like inert materials, free of plant diseases, ease to handle (for controlling pH and nutrient availability in the root zone). However, inorganic materials come with high environmental impacts due to the energy-intensive processing and challenges in disposal. For organic GM, peat and coir are commonly used. They are easy to dispose of after use. However, as being organic material, each comes with certain limitations in their performance properties, necessitating pre-treatments to improve their performance. For example, white peat has acidic pH (typically around pH 3-4) and low wettability, which requires lime addition to raise the pH, along with amendment of wetting agent or clay to improve wettability. Coir has high cation exchange capacity for Ca and Mg, which requires buffering substrate with $Ca(NO_3)_2$ to ensure an adequate supply of these elements in the root zone. It is worth noting that selecting certified growing media, such as RHP and CEN certification, is crucial for ensuring the proper properties of GM. A list of certified GM and suppliers can be found on the RHP website (www.rhp.nl/en/).

Depending on the cultivation systems and irrigation strategies in VF, certain factors must be taken into consideration when choosing a growing medium to ensure an even distribution of nutrient solution and proper aeration. It is very important that if more than one planting stage is involved, consistent GM must be used between the propagation (in plugs) and transplant system (in cubes), meaning that GM with similar hydration properties must be employed. The nature and size of the particles should be considered to avoid clogging of the irrigation. Pumice, known by equivalent names such as tuff, pozzolana, or pouzzolane, is preferred over perlite, as small perlites can run into the irrigation systems and disrupt the irrigation.

Adding plant biostimulants to cultivation systems has recently gained attention as an eco-friendly way to boost crop growth. According to the European Fertilizer Regulation (EU) 2019/1009, plant biostimulant means a product stimulating plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (i) nutrient use efficiency, (ii) tolerance to abiotic stress, (iii) quality traits, (iv) availability of confined nutrients in soil or rhizosphere. In general terms, plant biostimulants have no fertilizing and plant protection effects. Non-microbial biostimulants include, but not limited to chitin, keratin, algae extracts, humates, vinasse, amino acids, etc. Microbial biostimulants include, but not limited to Trichoderma spp., mycorrhizal fungi, Rhizobacteria, etc. It is important to note that the effects of biostimulants are generally qualitative, not quantitative. They may not work the same way for all crops or in all conditions. Plant species crop stage, plant nutrition, fertilization and abiotic conditions of the root-zone are critical factors.

- Frequency: it is recommended to add small amounts regularly to maintain stable microbial activities and microbial composition.
- Placement: applying biostimulants whether on top of GM or mixed within GM can make a significant difference.
- Irrigation systems: ensure that biostimulants is evenly distributed in the root-zone by water flow.
- Abiotic conditions: maintain constant abiotic factors such as water content, pH and temperature in the root-zone.

Companies use different types of growing media: mixtures of coco coir and peat, biostrate, stone wool and customized substrate mixes.
Biostimulants are tested and some companies use them because results are positive. Other companies don't use biostimulants or are not allowed regarding the system design.

Companies use same media and fertilizer recipe in VF and greenhouse

5.5 Nutrient solution

Vertical farms use mainly (only) soilless cultivation systems as described above. All nutrients therefore need to be supplied throughout the cultivation. As for open field cultivation, nutrients are apported to the system via fertilisers. Most of the fertilisers used in soilless culture are water soluble and are therefore supplied to plants via the water (so called "fertigation"). The water enriched with nutrients is called nutrient solution (NS). Differently from open field cultivation, the concentration of nutrients in the NS is more important than the total supplied quantities of fertilisers (Kg/ha). The electrical conductivity (EC) is often used as indication of amount of ions dissolved in water, and therefore is also used in soilless systems as indicator of the concentrations of nutrients in the NS. There are 12 elements which are considered essentials for the plants and that must all be supplied via the NS in soilless system. These can be distinguished between Macronutrients, N-K-Ca-Mg-P-S, which are often present in the NS in the order of mmol/l, and Micronutrients, Fe-Mn-Zn-B-Cu-Mo, often dissolved in the order of µmol/l. Beside these essential elements, there are others which are debated to have beneficial effect on the plant as Si and Cl. All these elements become available for plant uptake when dissolved as ions. The absorbable ionic forms are NH_4^+ and NO_3^- for N, K as K^+, Ca as Ca^{+2}, Mg as Mg^{+2}, P as $H_2PO_4^-$, and S as SO_4^{-2}. The upper case indicates the valence of the ion. For trace elements, the valency is less important because their contribution to the EC is almost null.
Nutrients uptake is primarily influenced by the concentration of ions in the root solution (RS). According to the system that is used, RS can be very similar or very different from the supply solution (SS) and the drain solution (DS). For instance, in DFT or NFT the RS is also DS and SS. In drip irrigation with substrates slabs, the RS is similar but no equal to DS, and it is quite different from SS when drain rate are correctly maintained around 20-40%. The RS (and DS) can get closer to SS with high drain rate (i.e. 70-80%). In ebb and flow, SS and DS are the same, and this solution is often called "recirculating solution"; but RS is the average condition in the substrates between 2 ebb and flow cycles.
Therefore, we could conclude that RS concentration is defined as the average (24h) nutrients concentration around the roots. Each crop has its optimal RS concentration. This is both in terms of total ion concentration (EC), but also in terms of ratios between elements (i.e. K:Ca and NH_4:NO_3). These two parameters are not linked. You can have the same nutrients ratios at EC 2 and 5 dS/m. You can have different rations at the same EC. On top of this, the optimal RS depends on growth stage, type of substrates, growing condition (i.e. radiation), and production target (yield and quality). Crop type, growth stage and type of substrates mainly determine the nutrients ratios. For example, a fruity crop will require more K than a leafy green. A cucumber requires more Ca over K in the first weeks of cultivation and much less during the heavy fruit load. A woodfibre slab requires more N fertilisation compared to a peat slab due to N immobilisation, cocopeat needs more Ca and Mg due to the high CEC (cations exchange capacity) of its fibres. The growing conditions and the growing targets mainly determine the EC level. For instance, at high radiations the water use will increase and the EC in the root solution (RS) will tend to increase due to a low uptake EC (ratio between nutrients uptake and water uptake). The EC affects water uptake by root pressure due to the osmotic potential. High EC decrease the root pressure. "Low EC" (not below minimum requirement) maximizes the yield, high EC increases the fruit quality. This is true for each crop, but for each crop at specific thresholds.
Last but not least, the pH of the RS must be maintained around 5.5 for most crops. Specific crops like blueberries prefer even lower pH but it is an exception. pH determines availabilities of micronutrients and P. pH is primarily influenced by root respiration (release of CO_2), and the equilibrium between cations and anions uptake. pH can be regulated with NH_4:NO_3 ratio in the root solution.

An acceptable pH range in the root solution is between 4.5-6.5. pH below or above this levels for prolonged time can cause damages to the crop and the system (i.e. clogging of drippers and stonewool disaggregation). For target recommendation of RS and for the advised SS to reach those RS targets, we advise the consultation of the manual BemestingAdvisebasis.

From the interviews we learned that all companies use an A and B unit and mix them. Micro elements are separately dosed. EC and pH are monitored.

Table 4 *Aspects regarding watering in a VF cultivation.*

Factor		**Explanation**
Irrigation strategy	Frequency	Number of irrigation events during the day
	Total volume	Total volume based on transpiration (measured in $mL/J/m^2$), divided over multiple irrigation events in case of drip irrigation. Decides on volume of drain water.
Irrigation system	Type of irrigation	Continuous or discontinuous. Decides on the volume of water to be transported, treated, etc.
Water treatment	Goal	Particle removal, disinfection, breakdown organic molecules, selective removal of elements.
	Point of engagement	Point vs. system treatment: Is the effect of a technology only on the spot, or does it also have an effect on water quality in the buffers, irrigation lines, etc.?
Growing media	Particle size distribution	Chose proper size fraction to ensure porosity and prevent the blockage of irrigation.
	Bulk density	The ratio of solid mass to bulk volume of substrate. GM materials have low bulk density.
	Water retention	Water holding capacity refers to the maximum amount of water that can be held in the pore volume of the GM. Air-filled porosity implies aeration in the root-zone (desired range 10-20%, v/v). Easily available water indicates water available unhindered growth.
	pH, pH buffering capacity	Recommended pH range 5.5-6.5. Each growing media has different buffering capacities.
	Electrical conductivity (EC)	EC indicates soluble salts in the solution. Normal EC range 1.0-2.5 dS/m, depending on the crop and growth stage lower or higher EC can be adjusted.
	Nutrients	Macro and micro nutrients released from the GM (using the 1:1.5 water extraction). This information helps to adjust fertilization.
	Biodegradability	Saprophytic microorganism feed on the fibres of growing media and nitrogen from fertilizer solution, resulted in less nitrogen available to the plant roots. Low microbial activities indicate greater substrate stability. Biodegradability of GM is assessed through measurements of oxygen uptake rate (OUR) and/or N immobilization.
	Phytosanitary	Several testing depending on material sources to identify potential risks of phytotoxic substances, weeds, pests and diseases.
Fertigation	EC	Important for determining the yield/quality ratio. It also affects water uptake by root pressure (less relevant during day, more important for night).
	pH	Important for micro and P availabilities, clogging and substrate integrity. Depend on root respiration, water quality, cation/anion uptake balance.
	Nutrients Ratios (NH_4:NO_3), K:Ca	Important for proper nutrients uptake and avoid problems like fruit abortion and tip burn. Depend on crop type, growth stage, growing medium.

6 CO_2

CO_2 is an important component in the photosynthesis process: it is taken up by the plant via stomates and is converted into assimilates. Water and light are necessary for the photosynthesis process which takes place in chloroplasts in the plant. The photosynthesis rate can be increased by increasing light intensity and CO_2. That means that the optimal CO_2 concentration should be maintained in the VF during the light period given the applied light intensity.
The outside air CO_2 concentration is around 400 ppm. In a VF the air is supplemented with CO_2 because its concentration drops when plants take it up. CO_2 comes from fossil sources or from a biogenetic source (see also chapter sustainability). In a VF, CO_2 is used very efficiently compared to a greenhouse because of the more airtight system. In such a closed system, CO_2 uptake is directly related to increase of biomass.

CO_2 is applied from tanks or cylinders from industry. Setpoints come from in-house test and from literature.

Table 5 *Aspects regarding CO2 in a VF cultivation.*

Factor		Explanation
CO_2	Setpoint	Optimal concentration during photoperiod
	Source	Fossil, biogenetic

7 Crop management, beneficial insects and hygiene

7.1 Crop handling

Crop handling includes all tasks performed at crop level from start until harvest. This is strongly dependent of the crop type, but it always starts with seeding or planting the plant material. How to decide about the optimal plant density? Seeds can be positioned at high density to minimize the needed area. After germination, seedlings need to be spaced for optimal light conditions for each seedling. The optimal plant density regarding optimal use of space declines when plants are growing and light interception per plant increases. Seedling growth is delayed and saturated after the percent projected area reaches 100%. If the transplanting is conducted after this moment, the productivity decreases. In addition, the work hours for transplanting increase because of overlapping with surrounding plants (Kozai 2020). On the other hand, applying the final plant density already from the start will reduce the production per m^2 of cultivation area. This shows the dilemma between optimal plant growth, use of area and labour that is needed for transplanting.
For some crops no extra crop handling is needed until harvesting like the cultivation of micro greens, herbs, leafy greens, radish. For this reason VF are nowadays used mostly for cultivation of these crops since they grow fast and can be harvested quickly.
Also ornamentals like bedding plants or propagation material (chrysanthemum cuttings, young fruit vegetables) don't need crop handling before selling. Other crops like fruit bearing crops tomato and strawberry need to be pollinated which can be done mechanically or by using insects (§7.2). Fruit vegetable crops like tomato, pepper and cucumber need several repetitive actions during cultivation like pruning, removing old leaves and harvesting. In a greenhouse cultivation these actions, except pollination, are carried out manually. In a high wire cultivation system without sunlight these management actions can be done manually as well since the canopy structure is comparable with a greenhouse cultivation. In a VF with a stacked system, individual plants can hardly or not be managed by hand which means that crop management activities need to be automated (§9).

> Companies that cultivate herbs, microgreens and leafy greens don't carry out crop handling in the period between sowing and harvesting. Other companies transplant 1 or 2 times after sowing and each phase of the plants has their own requirements regarding plant density and climate settings.

7.2 Pollination

For fruit bearing crops such as strawberry and tomatoes, pollination is necessary to ensure good fruit development. In some cases, pollination can be performed by dispersing the pollen via vibration of the plant stem but this is time consuming and not always as efficient as with insects. This process is called "buzz pollination" and it is used also in greenhouses for the pollination of tomato flowers. In traditional greenhouse settings, *Apis mellifera* (honeybees) and *Bombus terrestris* (buffalo-tailed bumblebees) are commonly used pollinators. Pollinators rely on their excellent colour vision to identify flowers. The vision of hymenopteran species (like *A. mellifera* and *B. terrestris*) has been studied extensively, and shows that they are able to discriminate between different colour and use the contrasting colours (including UV) for the recognition of flowers (target versus background) (Peitsch *et al.*, 1992; Kevan *et al.*, 2001). This characteristic presents a challenge when attempting to employ commercial bumblebee hives for crop pollination within vertical farm facilities that lack UV light and further investigation in this area is undergoing.

Recent research conducted at Wageningen University and Research in Bleiswijk has shed light on the foraging behavior of the hoverfly species *Eristalis tenax* (http://polyfly.es/en/) in strawberry cultivation. It has been observed that this species can forage on strawberry flowers even in the absence of UV light, although its foraging activity is reduced compared to the control treatment with UV light (Figure 1).
Another recent study (Nashimoto *et al.*, 2023) explored the feasibility of robotic pollination as compared to hand pollination and found no differences in percentage of marketable strawberries, weight, volume and sugar content.
To enable the cultivation of plants requiring pollination in vertical farm environments, further exploration of diverse insect pollinators and adjustments in the composition of light spectra and ques to help the pollinators orient are necessary.

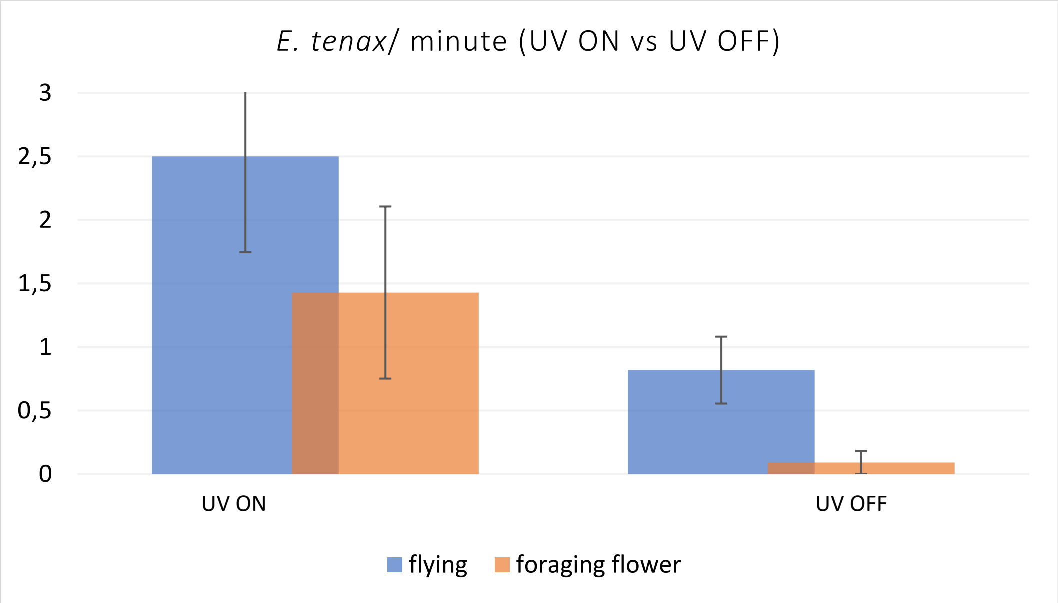

Figure 1 *Number of E. tenax per activity in the strawberry crop during one minute observations.*

For pollination of tomato and strawberry bumblebees and polyflies are used and also manual pollination is done.

7.3 Pest control

It was assumed that indoor grown crops were free from diseases and pests. Today we know that keeping them in such a condition can be quite challenging as it requires high hygiene procedures for control of staff, equipment and any other material entering the production units. In greenhouse horticulture, growers implement IPM (Integrated Pest Management) to control pest outbreaks (Barzman *et al.*, 2015). Also for Vertical Farming it is possible to enhance the control of pest and disease by the adoption of IPM-based strategies (Roberts *et al.*, 2020). The major role in the IPM strategies is played by biological control agents (BCAs). There are two ways of working with them, preventively (building a standing army of natural enemies that are already present in the crop before the pest appears) or curatively (when BCAs are introduced when the pest appears). The third option is to rely solely on chemical plant protection products. Due to the risks associated with this type of pest control (danger for human and plant health, residues and pest resistance) it is not recommended for use in closed systems as vertical farms and will not be discussed further.
IPM strategies are tailored to specific crops and depend on: cropping system, abiotic conditions (temperature, relative humidity) and pest occurring. In the table below (Table 6) we provide an example of implementing a preventive/ curative strategy in tomato cultivation based exclusively on biological measurements.

Table 6 *An example of utilizing biological measurements for pest control in tomato greenhouse cultivation.*

Biological control agent/ measurement		
Pest	**Preventative**	**Curative**
Greenhouse whitefly (Trialeurodes vaporariorum)	Parasitoid Encarsia formosa, predatory bug Macrolophus pygmaeus	Beauveria bassiana (PPP)
Sweet potato whitefly (Bemisia tabaci)	Parasitoid Eretmocerus eremicus, predatory bug Macrolophus pygmaeus	
Spider mite (Tetranychus urticae)		Predatory mite Phytoseilus persimilis
Potato aphid (Macrosiphum euphorbiae)		Parasitoids Aphidius ervi, Aphelinus abdominalis
Tomato pinworm (Phthorimaea absoluta or Tuta absoluta)	Predatory bug Macrolophus pygmaeus	Pheromone trap, Bacillus thuringiensis (PPP)

In general companies work clean and disinfect to prevent introducing any kind of pests and diseases. For example by cleaning the water with an ozon system.
Some companies don't use any insects; other companies use beneficial insects for pollination of strawberry and tomato or integrated pest management using beneficial insects and microorganisms.
Some companies use UV against powdery mildew and/or $H2O2$ in low dosage against algae.
Generally these measured were successful to prevent pest and diseases. One company had issues with spider mites; bio pest control worked for a while and after that pesticides had to be used.

Companies have positive experiences using beneficials in VF (nematodes, mites and insect).

Table 7 *Aspects regarding crop management and beneficial insects in a VF cultivation.*

Factor		**Explanation**
Crop management	Plant density	Choose a plant density and keep in mind the need of transplanting/spacing, optimal plant growth and optimal use of space
	Transplanting	Reduce plant density by spacing or transplanting How many times during cultivation?
	Pruning	Remove unwanted plant material like side shoots, leaves
	Harvesting	Harvest of the product during cultivation. How?
Pollination	Strategy	Choose correct pollination strategy, more research required
Pest control	Strategy	Preventative/ curative introduction of biological control agents depending on crop and abiotic factors

8 Sensing technology

Data in indoor cultivation systems is growing in importance as a means of optimizing plant growth and development. Terms such as data driven horticulture, use of Artificial Intelligence (AI) and data analytics become more and more popular. Decisive factor for understanding the cultivation processes and developing AI technologies is the availability of relevant data that represent the growing climate and crop conditions. To address the dynamic behaviour and complexity of crop production systems and integrate the long-term accumulated experience and intuition of growers, the digital information measured with sensors should be qualitatively and quantitatively sufficient for employing data driven decision making approaches.

One of the main characteristics of VFs as growing systems is the high level of accurate control of all growth parameters. In contrary to greenhouses or open field production, VF systems are mostly independent from fluctuations of external weather which allows precise climate control. The latter implies also accurate measurements of climate or other growth parameters. The use of sensors is essential for both control and collection of data that will be useful for optimising or monitoring the growth and development of the crop. So far, the available climate and irrigation sensors measure necessary growing information. Nowadays there is a wide variety of sensors available from commercial companies, especially for climate measurements. However, their installation and use should be always done with care. Always the sensors used should be calibrated and maintained well. High light intensities and humidity can push electronics to their limits. Furthermore, the positioning of the sensors is a topic to consider. Creating a homogeneous climate is usually a challenge, even in VFs, so wrong positioning of the sensors can potentially lead to non-representative recordings. VF growing systems vary a lot among different companies and the control or sensors' positioning varies as well. For example, climate measurements can take place at crop level, at the inlet of climatised air or at the outlet or at all those positions. Each choice could lead to a number of advantages and disadvantages without being right or wrong as long as the users are aware of what they are doing.

In general, climate measurements can be characterised as indirect measurements aiming to estimate the performance of the plant based on known (or assumed) plant response to different climate conditions. Under that perspective, the closer those measurements are to the plant level, the more representative they can be considered. In any case, sensing the climate is an indirect method yet the one still widely use. Going one step further, from a plant perspective; sensing the crop itself could be an alternative more direct way for controlling the cultivation.

Nonetheless, that does not apply for crop monitoring where crop sensing information (3D structure, physiological aspects) is currently missing in the essential digital crop data. Additional crop sensors should be explored for continuous collection of crop development and performance indicators with the associated climate conditions to expand potentials of emerging technologies, data analytics and/or AI in crop management. Information from sampled data captured by novel sensors to perform diagnostic, predictive, prescriptive and cognitive analytics, can accelerate scientific discovery, bridge current knowledge gaps that cannot yet be explained and facilitate decision making.

That implies first the replacement of commonly used measurements of the environment (such as air temperature) with perspective crop related measurements (such as crop temperature) and secondly the development of new sensors. Including new parameters in the control loop would also require the establishment of reference values and optimal/desired range for those parameters.

The recent developments in the fields of image analysis and machine learning create great possibilities to replace manual crop observations with automatic recording of crop traits. In that field a lot of research is currently in progress results are promising without reaching yet the level of commercial available products. The combination of sensing, AI, production-systems operation and plant physiological knowledge in near-airtight VFS may substantially increase RUE: crop-specific requirements can be met precisely by dynamically adjusting environmental variables to optimize RUE (van Delden *et al.*, 2021).

All interview companies use sensors and record climate data like temperature, relative humidity, CO_2, light intensity. Air temperature is measured at different locations inside the VF; for example measurements at the inlet and at the outlet position of the air or using a measuring box in the cell. The temperature measurement point for controlling the system is different among the companies. Sometimes on the average, sometimes on the return air.
Regarding the water part, date on pH, EC, water temperature, drain, dissolved oxygen are monitored.
Measurements on plants are less common and less frequent compared to climate measurements and some never thought of the importance of monitoring the plants instead and/or together with the climate. Plants are observed by eye and checked on anomalies. Plant temperature is sometimes monitored by hand-held equipment or thermal camera's. It was not clear how these data can be used.
Some companies, on the other hand, measure already a lot at plant level. They installed camera's and images are taken regularly from the top and/or from a sideview. Pictures are stored but not all companies use the images in an automated system for early warnings or detection of anomalies. Some companies have scanners for 3D images, hyperspectral camera's and they use the data in 'big data sets' to try to find relations between crop performance (harvest prediction) and sensor data by machine learning.

In the interviews we asked for a 'wish list' for monitoring the system: what more would you like to know or measure at system or at crop level?
Some companies would like to know the micro climate: is it too humid inside the crop, should we change the ventilation? Another 'wish' is to have insight in 'stress' of the plant or in the efficiency of light use by measuring fluorescence.
Discussions with the companies made clear that it makes sense to monitor the crop instead of or as a supplement to monitoring the climate, but for them it is not clear what should be monitored. Things that were mentioned: it would be good to have plant parameters like weight, height during cultivation to be able to monitor crop performance.

A company has a 'traditional' sensor package. They are exploring ways to measure plant transpiration to actively steer the VF.

Table 8 *Aspects regarding sensing technology in a VF cultivation.*

Factor		**Explanation**
General	Installation	Calibrate and maintain especially at high humidities
	Measurement position	Representative point(s)
Sensor	Monitor climate	Temperature, relative humidity and CO_2 is quite standard; can be measured in the cell, at inlet (supplied air) or outlet (return air). Light Indirectly measuring crop performances; the closer to the crop, the more informative
	Monitor crop	Most informative for crop responses Few sensors available such as fluorescence sensors, crop temperature, stem thickness and sap flow.
Camera	Monitor crop	RGB, hyperspectral or multispectral, thermal cameras Can be used for early detection and crop development Under development for field application

9 Automation and robots

There is growing interest in process automation for indoor farming in order to reduce operational costs relative to labour. For example, when the production costs by component were analyzed for an indoor Japanese farm producing 7000 heads of lettuce per day, labor costs account for 26% of the total production cost (Kozai *et al.*, 2015. Figure 2).

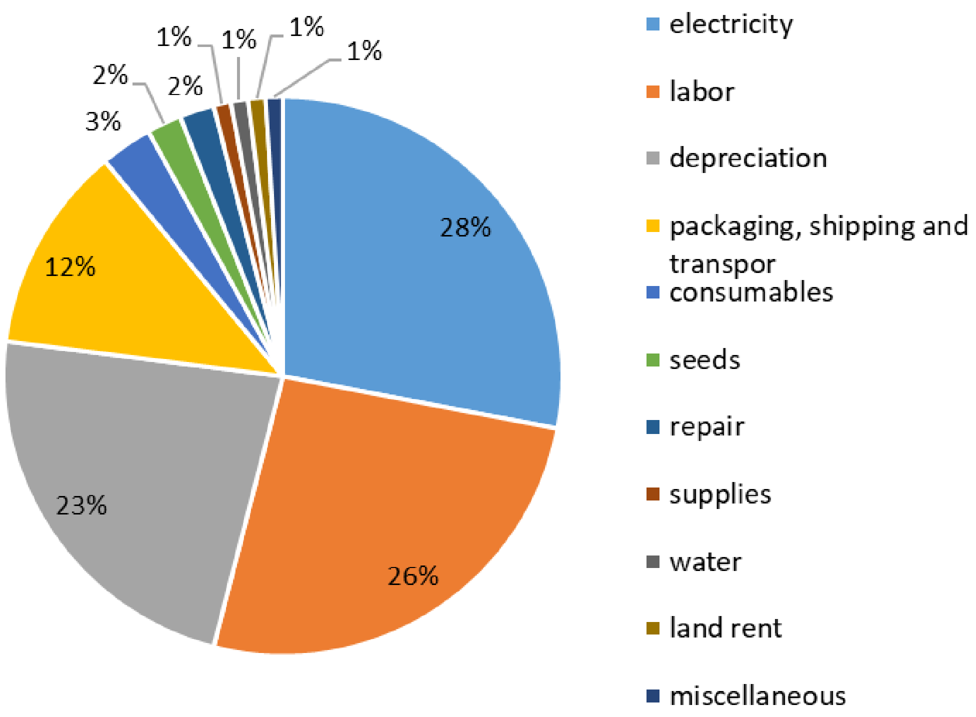

Figure 2 *Relative operational cost of a Vertical Farm producing lettuce in Japan (Kozai et al., 2015).*

When leafy vegetables are cultivated, almost no labor is necessary between transplanting and harvesting. The work that can be automated includes seeding, transplanting, moving cultivation panels, harvesting, weight checking, packaging, metal inspection, and panel cleaning (Shimuzu *et al.*, 2020). Some of these operations such as seeding, packaging and cleaning panels are already automated in other cultivation systems such as high-tech greenhouses which means that a market for these type of general machine is already present.

Also capital expenditure of VF systems can be higher compared to other forms of protected cultivation. High initial investment is primarily associated with the development of the infrastructure. Large-scale vertical farms, generally automate transporting, loading, and unloading of crops, utilizing dedicated conveyor belts and robotic systems which requires specialized hardware similar to those used in warehouses and is therefore very costly (Wichitwechkarn *et al.*, 2023).

Several processes are automated in companies, like seeding, transplanting, harvesting, quality control of harvested product, packaging, cleaning gutters. Some companies still have manual handling like tray movement, harvesting.
All interviewed companies emphasize the potential of a higher degree of automation and see this as the key to a viable and efficient indoor farming business. It is the way to reduce costs by reducing labor costs. Processes that are mentioned: soaking the seeds, spacing, transportation of growth trays. This will require a higher level of automatic infrastructure. But the intensive space in a VF unit might make it difficult to develop a higher level of an automated system.
Also a more intelligent system for climate control has potential, where setpoints can be determined based on real-time growing conditions and strategies. Such a system needs models and algorithms and this should be developed.

Table 9 *Aspects regarding automation in a VF cultivation.*

Factor		Explanation
General	Process automation	Balance between labour savings (operational costs) and investment costs

10 Sustainability

Ecological sustainability covers two broad aspects: environmental impact and resource depletion. Vertical farming involves various energy- and material flows. All are linked to both environmental impact and resource depletion, depending on where these flows come from, how they are used on the farm, and where they end up afterwards. This chapter outlines such considerations.

10.1 Energy

Light is energy: the energy carried by each photon increases as the wavelength gets smaller. For instance the energy of a blue photon is about 150% the energy of a red one. The processes used within LEDs to convert electricity into photons are different for each colour LED, so that electrical energy is used with varying efficiency (the third column in Table 10). Finally: white light is produced by coating blue LEDs with a fluorescent layer that spreads the blue light into various wavelengths, an additional conversion that decreases the efficiency (the last two rows of Table 10). As photosynthesis reacts to the number of photons rather than to their energy, LEDs used for crop production are usually indicated by their efficacy, the number of photons you get for a given amount of energy (the rightmost column of Table 10).

Table 10 *A compilation of the efficacy attained by the best LEDs presently available, at the optimal operating temperature. Source: Kusuma et al., 2020.*

LED	Peak wavelength or correlated colour temperature	Efficiency ($W\ W^{-1}$)	Photon efficacy ($\mu mol\ J^{-1}$)
Blue	450 nm	0.93	3.5
Green	530 nm	0.42	1.9
Red	660 nm	0.81	4.5
Far-red	730 nm	0.77	4.7
Cool white	6500 K	0.76	2.9
Warm white	2700 K	0.69	2.6

The fixtures used in horticultural application are much more complex than just a LED diode, the quality of which does vary among manufacturers. In addition to the efficacy of the selected LEDs, fixture efficacy is determined by four additional factors: LED drive current; LED junction temperature; driver efficiency and optical losses in the fixture. In their comprehensive review, Kusuma *et al.*, 2020, estimated a "theoretical maximum" of about 4.7 µmol J-1 (efficiency 87%) that the technology may gradually approach over the next 15-20 years, whereas the very best systems are currently around 3.5 µmol J-1 (efficiency 65%).

One issue sometimes overlooked is that a vertical farm is a closed system, which means that the energy one pushes in has to be removed, if the temperature is not to inflate. Graamans *et al.*, 2017, demonstrated that most (radiation) energy is converted into vapour in the process of transpiration, that has to be removed through cooling. It is well-known that the Coefficient Of Performance of an air conditioning system is highly dependent on operating conditions, that is: the cooling/dehumidification ratio; ambient temperature and temperature difference between sink and system. For the present purpose, the estimate of Kozai *et al.*, 2016, will suffice, that air conditioning adds some 25% to the electricity bill.

Altogether, a system providing 300 µmol $m^{-2}\ s^{-1}$, including climatization would require a power of about 110 W per m^2 production area. So DLI of 17.3 mol m^{-2} day^{-1}, as discussed in §3, has an electricity bill of 6.2 MJ (or 1.7 kWh) per day per m^2 production area.

In summary, producing one mol of PAR light in a vertical farm with the present LED systems requires about 0.36 MJ, which is 100 Wh. With LEDs attaining the "theoretical maximum" efficiency 4.7 µmol J^{-1} this could be reduced to 70 Wh, also accounting for the fact that increasing the efficiency of the LEDs will slightly reduce the need for climatization.

10.1.1 Options for electricity supply to be sustainable

From the numbers above, one can calculate that the electricity requirement for a vertical farm is at least 0.6 MWh per square meter crop area, per year. What would be the area of a PV system able to produce that electricity? The webtool available on-line (JRC, 2022) allows to calculate that 1 square meter PV optimally installed (slope and azimuth) in Amsterdam would deliver about 0.2 MWh per year: that is, even in optimal conditions one needs 3 m^2 PV panels for each m^2 crop area. But then, one would still need the grid to act as a buffer between supply and demand of electricity. Quite a similar reasoning would apply to wind-powered electricity. Unfortunately the electricity provided by the grid in The Netherlands is still largely produced by burning gas and coal: the present carbon footprint of the Dutch electricity mix is 321 g (CO_2 eq) per kWh (EEA, 2023). Through the webtool mentioned above, it is possible to dimension the battery capacity that would be needed in order to become independent of the grid.

Table 11 *Aspects regarding automation in a VF cultivation.*

Factor	Considerations
Energy source	Carbon-intensity of grid Area taken up by renewable energy generation Battery capacity can be dimensioned using webtool
Lighting	Crop response has to do with photon efficacy (determined by number of photons and photosynthetic response) rather than the photons' energy (determined by light wavelength)
Air conditioning	Most radiation energy is converted to water vapour; removing this through air conditioning increases total energy consumption by about 25%
Crop	Crops with a high harvest index and low dry matter content produce the most fresh yield (and therefore profit) per unit energy input

10.2 Material flows

Vertical farms involve various material flows, both consumable and in their construction. Which considerations should be made for the sustainable material use in vertical farms, and which solutions exist? To better understand this, it is important to understand the principles behind the circular economy. We then apply these principles to vertical farming.

The world is moving from a 'linear' to a 'circular' economy. In a linear economy, resources are extracted from natural reserves, used, and eventually disposed. On one side, this depletes finite natural reserves, whilst on the other, resources are lost to the environment, where they are difficult to recover and cause harm. A circular economy uses fewer virgin materials and keeps existing materials in use, minimising waste and using any waste that cannot be avoided as an input elsewhere in the economy. By closing the loop for material flows, circularity aims to eliminate problems caused on both sides of linear chains.

Although a circular economy results in a closed loop, it involves more than just redirecting the end of the linear economy back to its beginning. Other strategies exist, together known as the 'R-strategies' (depending on the source, anywhere between 7 and 10). Far better strategies exist before recycling and recovery should be considered. The most desirable R-strategy is to 'refuse', which is about avoiding the use of a material in the first place, usually by finding radically new ways to achieve the same end goal. For example, it is better to send an email than it is to send a physical letter on recycled paper. Other strategies include 'reduce', which is about increasing the efficiency of existing processes, or 'repurpose', where unwanted by-products from one process are used as inputs for another. It is important to note that whilst efficiency (e.g. on a farm level) can slow resource depletion and environmental impact, it does not eliminate these things the way circularity does. Being more efficient with finite resources still depletes them, albeit at a slower rate.

Unlike currently with energy, vertical farms are exceptionally efficient with consumable material flows. That said, whilst efficiency is helpful in slowing environmental impact and resource depletion, it does not fully eliminate it. Where materials come from and where they end up has to be considered as well. In this chapter, we comment on six main consumable material flows, which each have their own considerations. These are very similar (if not identical) to considerations made in high-tech glasshouses.

10.2.1 Water

Vertical farms are the most water-efficient way of growing crops. This is especially the case when water is recaptured from the air after transpiration, which represents 90% of water losses in greenhouses. Water vapour that does leave the system has no negative environmental impact. Furthermore, in regions such as north-western Europe, nearly all the water used in controlled-environment agriculture is rainwater. No matter how efficient, this makes vertical farming a harmless participant in the existing natural water cycle. In regions where the rainfall pattern is less consistent over the year, or where there is a mismatch between supply and demand, larger water storage basins can help increase the proportion of rainwater used. In regions with insufficient rainfall, groundwater or water from desalination may be alternatives. However, groundwater may not be sustainable long-term if it is used at a faster rate than it can be replenished. Also, these sources are usually of worse quality than rainwater due to their higher sodium content, leading to reduced nutrient efficiencies.

10.2.2 Nutrients

The most well-known sustainability challenge related to nutrients is emissions to the environment, which leads to problems such as eutrophication. Closed-loop soilless irrigation systems, where water is recirculated, have the lowest nutrient emissions of all plant production systems, even if irrigation water is still regularly leached into the environment. In the Netherlands, nutrient emissions must be virtually zero by 2027. The challenge lies with the supply of these nutrients. The mineral fertilisers used in soilless growing systems come from mined reserves spread out across the globe, with the exception of nitrogen, which is fixated from the air using the (energy-intensive) Haber-Bosch process. This means that vertical farms contribute to resource depletion. Alternative sources do exist, but are often less soluble and contain more impurities, making it more challenging for growers to use them efficiently and avoid emissions.

10.2.3 Substrate

Growing crops on substrate rather than soil enables a greater degree of control and efficiency. The most commonly-used substrate in vertical farms, stone wool, comes with sustainability challenges. Although the basalt rock it is made of is plentiful, the stone wool left behind at the end of the crop cycle is a big waste stream.

Following the abovementioned R-strategies, various solutions exist. By using smaller plugs or by going fully hydroponic and using no substrate at all, the amount of substrate used can be reduced or even eliminated. Some stone wool manufacturers collect the stone wool and recycle it, though virgin materials are always still needed. Failing that, stone wool can be used to make bricks. In this last case, this does mean that new stone wool will still have to be made from virgin materials.

10.2.4 Carbon dioxide

Like with other flows mentioned so far, vertical farms are extremely efficient with CO_2, nearly 100% if the farm is completely airtight. The issue is that most of the time, this CO_2 comes from fossil sources. Not only does this lead to the depletion of a finite resource, but it also contributes to net increases of CO_2 in the atmosphere, since CO_2 is released after the crop is consumed or decomposes. Therefore, controlled-environment agriculture cannot be seen as a form of carbon sequestration. To be sustainable, 'short-cycle' CO_2 must be used, that is, from biogenic- or atmospheric sources (direct air capture). With biogenic CO_2, contaminants is a point of concern. Since vertical farms are virtually airtight, these can accumulate to toxic levels. Scrubbers or other devices to remove NOx, SOx, ethylene or aromatic compounds may be required (often necessary for compounds produced by the plants themselves).

10.2.5 Plastics

Plastics have many functions in vertical farms. Not only do they come from crude oil and do they become a waste stream; they also get mixed with residual biomass, making it a less pure material flow and therefore harder to use. Like with substrates, the first question is whether plastics use can be reduced or eliminated altogether. Where plastics are indispensable, recycled plastics or bioplastics may be a more circular option. Not all bioplastics are biodegradable, and many biodegradable plastics come from crude oil. There may also be challenges related to biodegradable plastics degrading during the crop cycle.

> Companies are aware of the importance of sustainability/circularity for saving costs and re-use of materials. Some companies take steps like, using less water by using a biofeedback system, or recycling of irrigation and HVAC water. Some companies re-use (parts) of the substrate.
> Some companies source energy from renewable resources, solar panels or they use green energy. Other options that are mentioned in the interviews are the use of dynamic watering and nutrient amounts to limit losses and are working on building a biodigester from which one can use energy, water and nutrients. Companies are also interested in use less light energy by adopting dynamic lighting.
> Regarding circularity: knowledge about the origin of used materials and what happens afterwards is not always clear. One company sends the remaining substrate for further use to other growers.

Table 12 *Aspects regarding automation in a VF cultivation.*

Material flow	Consideration
Water	Quality to control nutrient emissions Storage when rainwater supply is inconsistent
Nutrients	Zero emission growing Circularity of source of nutrients
Substrate	Reduce or eliminate substrate Recycling or repurposing options at end of life
Carbon dioxide	Short-cycle CO_2: biogenic or atmospheric
Biomass	Cultivars producing less residual biomass Repurpose elsewhere in the economy
Plastic	Eliminate using plastic-free solutions Alternative materials: recycled plastic, bioplastics, biodegradable plastics Mixing with biomass makes repurposing it difficult

11 General remarks

11.1 Electricity -> light -> yield -> €

The energy use of the chain of processes leading to crop growth (from photosynthesis to fixation) is affected both by environmental conditions (for instance oxygen and carbon dioxide concentration) and the nature of the crop. Bugbee and Monje, 1992, reviewed the processes that affect the final conversion efficiency and estimated that even in an optimal environment (that would reduce need for both root growth and maintenance respiration) the achievable conversion efficiency for C3 crops would be 1 g dry matter mol^{-1}. For instance Carotti *et al.*, 2021, determined lettuce productivity in a VF experiment with 48 combinations of light intensity, air and root temperature. The combination with the highest light productivity (which was also the lowest light intensity) yielded indeed about 1 g dry weight per mol light.
The conversion from dry weight of biomass to fresh weight of yield, makes it immediately obvious why it is almost exclusively leafy crops (including seedlings) that are commercially grown in vertical farms. Indeed, consider for instance 1 g total crop dry biomass, that requires at least 1 mol PAR light (100 Wh). In the case of wheat, the harvest index (the fraction of harvestable biomass, out of the total plant biomass) is 51%, and the water content of the seed is 15% (AHDB, 2023), resulting in 0.6 g grain seed. Lettuce, in contrast, has a harvest index of 85% and a leaf dry matter content of 3.5% (Carotti *et al.*, 2012), resulting in 24 g lettuce. Add to this the ratio between the market prices of lettuce and grain (upwards of 30) and then it is clear that the revenue on one mol light in leafy crops is about 1000 times higher than in cereals (see also Pattison *et al.*, 2018). Righini *et al.*, 2023 reached a similar conclusion about protein crops, after a VF experiment with soy beans.

General remarks stated by the companies are listed below:

- In a VF most of the employees are working in the technical field; the importance of plant specialists is not obvious
- There is interest in finding relations between cultivation factors and all factors and the end product
- There is interest in a model to calculate the effect of an action expressed in €
- There is need for a smart system that integrates input-output and helps in decision making (like a digital-twin).

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Appendix 1

The Club van 100 – Leading in Horticultural innovation
The 'Club van 100-leading in horticultural innovation' is a collaboration between Dutch suppliers in the horticultural industry which develop knowledge together with the Business Unit Horticulture and Flower Bulbs of Wageningen University & Research in a way that promotes business for the members. We inspire and create solutions that contribute to a more sustainable cultivation and future which fit entrepreneurship for growers worldwide.

Creating impact
The Club of 100 has four strategical roadmaps. Each roadmap has a clear vision and ambitions towards sustainable solutions. Together we initiate research projects that contribute to the roadmap ambitions in a way that it becomes applicable for the members and/or for the growers in the sector. This method provides the possibility to create impact and shows the added value of collaboration towards a sustainable and economical viable sector.
The for strategical roadmaps are:

- Healthy and productive plant
- Emission free cultivation
- Circular horticulture
- Autonomous cultivation

Our Members
The Club van 100 has around 80 members that collaborate in a equivalent way. Whether the partner is smaller or larger, all members have 1 vote. All members are leading in the horticultural sector. The unique collaboration of the full supply chain makes it possible to be leading in sustainable innovation with the possibility to apply the knowledge nationally and internationally.
The members are representatives of the full supply chain in the horticultural sector. They represent:

- Greenhousebuilders
- Installation companies in the fields of energy, climate and water
- Suppliers of growing media
- Suppliers and producers of nutrients, crop protection means and consumables
- Banks, insurers and accountant agencies
- Energy suppliers
- Suppliers of propagation materials
- Trade, distribution and storage

More information and overview of the members:
https://www.wur.nl/nl/onderzoek-resultaten/onderzoeksinstituten/plant-research/glastuinbouw/club-van-100.htm

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The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,600 employees (6,700 fte) and 13,100 students and over 150,000 participants to WUR's Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.