Vertical Farming 2023: research topics

Inventory of relevant topics for Fieldlab Vertical Farming

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Referaat
Binnen het Fieldlab Vertical Farming is een inventarisatie gemaakt van de onderzoeksvragen, waaraan de komende jaren gewerkt moet worden om Vertical Farming verder te ontwikkelen. Dit is gedaan middels een webinar en in een vijftal focus groepen. Uit de rapportage van de uitkomsten zijn met behulp van tekstanalyse de meest genoemde onderwerpen voor onderzoek en ontwikkeling gehaald. Dit zijn: (1) marktonderzoek, (2) het onderzoeken en ontwikkelen van systemen, standaarden, besturingsconcepten en groeirecepten; (3) het verbeteren van resource use efficiency, (4) onderzoek naar het klimaat in een Vertical Farm en (5) de respons van planten daarop, en de successievelijke gevolgen voor productie en kwaliteit.

Abstract
Within the Vertical Farming Field Lab, an inventory has been made of the research questions that need to be worked on in the coming years to further develop Vertical Farming. This was done through a webinar and in five focus groups. The most frequently mentioned topics for research and development were extracted from the report of the results, using text analysis. These topics are: (1) market research, (2) researching and developing systems, standards, control concepts and growth recipes; (3) improving resource use efficiency, (4) climate research in a Vertical Farm and the plant response to it, and (5) the successive consequences for production and quality.

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1 Introduction and objectives

At the start of Fieldlab Vertical Farming in 2019, Vertical Farming was a fast developing industry, with start-ups, commercial companies, and research facilities popping up like mushrooms after the rain all over the world. Vertical farms (VFs) and other closed production systems have given researchers and industry a tremendous opportunity to fine-tune the production climate to the specific needs of each crop. They allow for (almost) full control of light, temperature, plant nutrition, et cetera. People around the world are looking for the perfect growth recipes for VFs, opportunities to grow new crops and feasible business cases. Their search, however, was often limited by a lack of relevant information. A clear strategy on how to develop knowledge was missing. Within the field of Vertical Farming, even the basics were still lacking, such as standardised methods for measuring and quantifying different aspects of the production process, which renders many research results incomparable.

Because the knowledge institutes and most industrial partners in the consortium of Fieldlab Vertical Farming are familiar with knowledge development strategies in greenhouse horticulture, we have inventoried relevant topics to formulate a strategy for the next 10 years of research on Vertical Farms, based on greenhouse horticulture experience. The listed questions should give direction to the research within Fieldlab Vertical farming as well.

This inventory was made by Wageningen Plant Research business unit Greenhouse Horticulture within Work Package 2 of the Fieldlab Vertical Farming project. The Fieldlab Vertical Farming project is sponsored by EFRO Kansen voor West, Province of South Holland and Topsector for Horticulture & Starting Materials. Within this project, Wageningen Plant Research collaborates with Greenport Horti Campus, Wageningen Economic Research, Delphy BV, Delphy Improvement Center, Philips Horticulture LED Solutions, Logiqs, Vertify, Inholland, Own Greens and Future Crops.

2 Methodology

The collection of research questions for Vertical Farming 2030 was started by organising a webinar with researchers of Wageningen Plant Research Greenhouse Horticulture (WPR). Since a clear definition about Vertical Farming was needed to facilitate good discussions, we used the definition from the Association of Vertical Farming:

"Vertical farming is the practice of growing food and/or medicine in vertically stacked layers, vertically inclined surfaces and/or integrated in other structures. The modern idea of vertical farming uses Controlled Environment Agriculture (CEA) technology, where all environmental factors can be controlled. These facilities utilize artificial control of light, environmental control (humidity, temperature, gases, ..) and fertigation. Some vertical farms make use of techniques like greenhouses, where natural sunlight can be augmented with artificial lighting."

The webinar was used to collect a first set of ideas and questions partly directly for the (commercial) industry, and partly for plant research (indirect contribution to the development of Vertical Farming research). We used open and (semi-) closed questions, and structured the answers accordingly.

The results of the webinar were used as input for brainstorm discussion in (four) 'focus groups' with experts from WPR as reported in the table:

Focus group topic	Number of participants	Date
Water and product quality	5	12th April 2022
Breeding and beneficial insects	6	4th May 2022
Technology and circularity	6	9th May 2022
Sensing and crop handling	8	19th May 2022

Additionally we organized a brainstorm session with the partners of Fieldlab Vertical Farming (27th July 2022, with 10 participants).

The definition of Vertical Farming was 'fine-tuned' in the discussions in the focus groups and rephrased to a definition which covers the subject of the Fieldlab.

The results of the different focus groups were listed. The text was analyzed by automated word counting with online software tool www.online-utility.org/text/analyzer.jsp, extracting the most mentioned relevant words and combination of words.

3 Results

3.1 Definition

In the different groups, the definition of Vertical Farming used by the Association of Vertical Farming (as mentioned in Chapter 2) was jointly discussed and reformulated into:

"Vertical Farming is a crop production system which features extensive climate control and which relies solely on artificial lighting (no sunlight). The term can be considered as the common (popular) name by which indoor farming systems are called. The adjective "Vertical" is indeed not binding as it relates to the stacked structure of the multilayer indoor facilities which do not represent the whole Vertical Farming technology. Closed to multilayer production systems, also high wire and/or single layer facilities are present in the market. The most comprehensive term would indeed be "indoor farming" or "plant factory" although the latter can have a negative connotation as it recalls industrial processes. The degree of control is in general very high with a tendency towards "sterile" production with growing media different from soil and a very low and controlled degree of openness and ventilation with the outside."

Questions still remain about the minimum production area that would differentiate a vertical farm from a growth chamber and a container.

3.2 Webinar results

In total 43 researchers of WPR Greenhouse Horticulture joined the webinar. The webinar was organized in 2021 and held online because of Covid-19 restrictions. The main aim of the webinar was to gather an initial set of ideas and perceptions directly for the (commercial) industry and from the research on VF's opportunities and challenges.

3.2.1 Where will VF contribute most in the future of plant production systems?

Respondents could choose one or more of the following answers to this question:
- Value: produce high added value crops
- Location: produce food locally (in cities)
- Transport: minimize transport
- Quality: produce fresher, tastier crops
- Diet: produce healthy, nutritious food
- Independence: produce food without the (changing) climate
- Quantity: produce more food for more people
- Continuity: produce consistent crops
- Sustainability: produce with less energy / water/ CO_2
- Nothing: greenhouses are better

Figure 1 *Number of times an answer was mentioned (multiple answers allowed).*

3.2.2 How can Vertical Farming enhance future plant research? (Open question)

The answers to this question were grouped into clusters. Listed in no particular order:

- Better reproducibility of results
- Investigate insight in crop physiology mechanisms
- Obtain a more accurate quantification of resource use (e.g. water, CO2, energy) compared to open or semi-closed cultivation systems
- Test all kind of relevant (extreme) climate conditions to build robust and versatile crop models
- Conduct research with a smaller risk of pest and diseases
- Increase the adoption of sensing and AI to collect, organize and interpret data

3.2.3 What are the most important or challenging data to track in Vertical Farm research? (open question)

The answers to this question were listed in no particular order:

- Product quality
- Microclimate
- Plant transpiration
- Nutrient uptake
- Root zone environment and development

3.2.4 What are the most important developments in industry up to now? (open question)

The answers to this question were listed in no particular order:

- Breeding
- Growth recipes (crop-specific)
- LED lighting
- Autonomous growing

3.3 Results focus groups

A total of 25 WPR experts, divided in 5 working groups, participated in brain storm sessions. The main aim of the focus groups was to inventory the most pressing research questions within VF. Eventually, this will help to formulate a strategy for the next 10 years of Vertical Farms research.

The following abbreviations are used in the text below:
- VF: Vertical Farm
- GH: Greenhouse
- OF: Open Field

3.3.1 Pros and Cons of Vertical Farming as a worldwide cultivation system

Control

The fully closed characteristic of Vertical Farms makes the system independent from location and external fluctuating climate. This also makes the system quite fragile as it has no buffer in case of disruptions (ex. no electricity supply). Being independent from outdoor conditions means that such system can be in theory implemented everywhere around the world and, at the same time, can guarantee high reproducibility. In addition, multiple farms can be controlled in a centralized way. Their advanced climate control systems enable the realization of tailor-made growth conditions leading to homogeneous production in terms of yield and quality and a "just-in-time" production which meets the needs of the market and of the consumers. This high-tech facility shows great possibilities for autonomous growing which means that less labor, especially lower skilled people, are needed. This fits well with the interests and job preferences of the new generations and with the aging population.

By being independent from sunlight, Vertical Farms can be dynamically operated and take advance of the energy price fluctuations.
Vertical farms do require, on the other hand, more high-skilled personnel compared to greenhouses due to the high technological level and the fact that manual crop labor is ideally automated. Vertical farming is though still at the level of a novel technology with little experience and unproven benefits. No standards or good practices for system design and for production are yet well established.
- We need to be able to differentiate between proper and dubious research / production numbers (both in scientific papers and from companies)
- Growing in a VF balances between having total climate control and not knowing how the plant will actually react to a closed environment
- Diseases are still a large issue in VF, but are not talked about
- How can we adapt the production/product to the available systems?

Production and quality

The stable and highly controllable growth environment sets the premise for a predictable production with a predictable quality. The option of tailor-made recipes in addition to the undergoing development of new varieties allows for the production of high value crops where quality parameters such as shelf-life, taste and nutritional composition are improved. This also supports the creation of a higher level of food safety and security as it allows for the production of virtually any crop, anywhere and at any time with high quality and hygiene standard. Relevant topics are:
- Research tool for every crop
- Hybrid solutions: only part of production cycle in VF (i.e. propagation)
- Plant processes not fully understood
- Varieties have been created for GH and OF
- Can the knowledge actually be translated to GH?
- Huge gap between plant knowledge and technical capacity for control
- Limited experience with growing other products at the moment

Sustainability
The positive aspects of controlled and closed system are linked to the high water, nutrients and CO_2 use efficiency and, in case of stacked systems, to a high land area use efficiency. Moreover, the high hygiene protocols allows for little to no use of pesticides or chemicals. Having little or no influence from exterior climate makes it possible to produce crops in places with extreme climate conditions allowing for local and fresh production. This supports the creation of a food system where less transport is needed and less food loss is generated along the food chain.

Energy wise, Vertical Farming is not yet a sustainable production system. To support this transition, companies are investing in the production of clean energy and are assessing the option of integrating this production system in energy systems with other buildings or industries.
In terms of circularity, the material flows are quite similar to those of a high-tech greenhouse.

Market
From an economic stand point, Vertical farming production systems require high investments (CAPEX) and have still relative high operational costs (OPEX) making it still difficult to be economically feasible for many crops. As it is today, the feasibility of such production system depends on the geographical area: climate, resources availability and cost, fresh vegetable and high-end market.

- Market needs to be suitable (financially affluent markets)
- Hype from private equity, resulting in high expectations (that may not be met soon)
- Investments are becoming more difficult to receive
- Difficult to monetize the different in quality in certain markets (i.e. the Dutch market)
- How much are customers willing to pay?
- Over engineered: interest for research not for market
- Added value of VF compared to advanced greenhouses:
  - GH achieves also high efficiency of production
  - GH achieves lower initial investments

3.3.2 Most important developments in VF industry up to now

- Growth recipes
- LED lighting
- Autonomous growing
- Price of the LED decreasing
- Efficacy of LED increasing
- System integration: sum of the parts is greater
- Crop monitoring
- Massive private investments
- COVID: interest in local food production
- (International) Market interest
- Consumer consciousness; origin and sustainability of product
- Interest in food safety
- Producer consciousness; sustainability of production
- New players entering the market
- Interest from popular media
- Interest from students, young people in high-tech aspects
- Interest in a ‘new’ field; room for exploration

3.3.3 Next necessary developments to support Vertical Farming

Disease and pest management

- Diseases (they will enter VF; how to manage)
- Hygiene standards
- Disease prevention: minimize diseases and pests entering the system
- Biological control: perfect hygiene is unrealistic, which measures need to be taken in VF?
- Minimize people entering VF cells required for production: hands-free production

Cultivation and quality

- Breeding crops specific for vertical farms: temperature range, resilient to pest and disease, smaller crops, adapt to LED lighting, compounds
- New crops for production in VF: medicinal, pharmaceutical crops, high-caloric, protein-rich, livestock feed
- Hybrid systems: From VF to GH during cultivation cycle (propagation vs production)
- Crop handling vs automation; what is possible?
- Focus on production beyond IP, currently following private finance system
- Optimal production recipes
- Timing of lighting throughout day/cycle
- New cultivations that are manageable in VF, not in GH
- Determine which cultivations can benefit from (the control of) vertical farming?
- More extensive measurements of the plant (responses) to integrate in the "internet of plants": spectral imaging, sap flow, fluorescence, etc.
- Processing: How to optimize harvesting and other logistical issues for different (new) crops in VF?
- Advanced automation for (new) crop in VF
- Understand better crop climate interactions
- Being able to control the system (climate, fertigation, disease detection and management, etc.) based on sensing crop related parameters
- Understand the sources of variability between different trials or VF facilities and minimize them
- Understand the effect of growing conditions and management decisions on crop quality, nutritional value and product shelf-life
- Measuring / communicating quality clear prediction of nutritional value
- Promote knowledge exchange instead of inventing the wheel over and over and over again
- Advance in automation and robotization (crop handling, harvesting, scouting, etc.)

System

- Standardization of dimensions and lay-outs, similar to GH, to develop robotics or other installations. dimensions and capacities of installations, trays, etc.
- Flexible systems to produce different crops or optimized systems for specific crops?
- Integrated systems: single supplier, one-stop-shop
- Reduce energy use / carbon footprint (embodied energy)
- Integration into buildings/cities for reducing footprint of the system as a whole
- Build VF for purpose, as opposed to a standard system
- Climate homogeneity
- Close nutrient cycles: circular approach to cities, as local as possible
- Resilience: How can the system increase its resilience?
- Substrate: improve hygiene further (inorganic > organic)

Market and consumers

- Market development/ market positioning of VF products / which markets are suitable for VF?
- Global market vs Dutch market
- Consumer perception: How do consumers perceive VF production / what is added value / how is it valued / what are they willing to pay?
- Political situation; independent from other countries
- Optimize price of products from VF
- Market and consumer perception of vertical farming and greenhouse production and their respective benefits?
- Accessibility to low-cost, renewable energy sources
- Integrate VF in the energy networks for peak shaving (added value)
- CAPEX and OPEX need to be reduced; standardization, modularity, simplification, smart
- Organic/ biological? Other specific quality marks/label
- Then standardize and point out the benefits in the aspects of the previous point that one can gain when growing a product in VF compared to a greenhouse.

Sustainability

- Local production
- Optimize energy use in VF
- Sustainable energy/electricity production
- Research: environmental footprint / health
- Consumer education: advance the critical view and understanding of consumers

3.3.4 Market development of Vertical Farming in the next 10 years

Netherlands/Europe

- The investments will keep pushing the development of VF forward, not necessarily in NL. Knowledge may continue to be developed in NL, we should have a central position in that
- NL will probably not focus on local production in VF, we will focus on advising other locations
- Hybrid model will become more interesting
- Realistic picture crystallized: what can we expect from production in VF?
- Netherlands as central player in international markets (similar to greenhouse)
- Netherlands as developer of systems/knowledge
- Supply of resources (energy and water) in danger following climate change/management
- Price as main motivator between GH and VF consumer preference
- Minimize Nitrogen production linked to crop production

International

- Availability of water becomes stringent; increased interest in saving water
- Labels/identification of VF product -> market as high-quality crop/no pesticide/organic/etc.
- Perspectives on food may evolve: i.e. what is 'natural' production of crops?
- Extended knowledge on crop types and production recipes will allow for wider variety
- A few large players vs smaller players: number of farms will be lower, but with higher production capacity… (?) There will be very few commercial companies growing in VF. It will not be used for mass production of food but mostly for propagation, cuttings, rare and valuable crops, crops with high nutritional value, medicinal crops. VF will also allow crop production in places that now there is hardly any plant grown
- More location, more players …(?)
- Easier to scale than GH following economy of scale (VF is like a factory)
- Even fewer supermarket chains; demand-driven market in the hands of few players… (?)
- Personalized food: produced/made to order (food production supports this model)
- Customization of food: grow on demand, attuned to the human body (increase knowledge on human requirements)
- Obesity as a crisis will continue: improve healthy living at a reduced cost
- Which locations present the earliest growth markets: regions at risk of climate change, affluent areas, regions in search of food independence
- Labor interested in open field work decreases
- Labor: higher skilled labor required following automation, less labor in total
- Soil degradation inhibits open field production
- War for control over food production (locations, resources) -> promote local production?
- Produce nutritious crops
- Food prices will increase
- Relative price of plant-based products will decrease (alternative protein sources)
- Urbanization/derealization keeps increasing; more opportunities for local production
- Smart solutions for living and working promote smart solutions for food production

Climate change

- Rain water and transpiration influenced by climate change -> poor situations for GH
- Extreme climate situations more frequent -> reduced reliability of OF/GH
- CO_2 emissions may become regulated / costs may be increased for CO_2
- Extraterrestrial food production; food production for space colonization
- Global food system overhaul; minimize dependence on international food trade

4 Analysis

4.1 Text analysis

The list of topics as collected in the focus groups, presented in the previous chapter, was analyzed using the online text analysis tool https://www.online-utility.org/text/analyzer.jsp. The most mentioned relevant words (nouns, no articles and prepositions) and combinations of words are listed in Table 1. Combinations of words have a higher position in the table than single words.

Words with related meanings are grouped together. A bold word describes the cluster of words and phrases in question.

Table 1 *Occurrence of most mentioned phrases and words in the combined focus groups report.*

Phrases / words	**Occurrences**
Crop climate interaction	3
Crop response	3
Optimal **production recipes**	2
How to grow	3
How to manage	2
Added value	6
High quality	3
Shelf life	3
Nutritional value	4
Quality	31
Value	13
Production system	5
System/systems	46
Climate control	5
Control	21
Production climate	3
Climate interactions	3
Climate	41
• Temperature	12
• Light	11
• CO_2	10
• Air	8
(**Resource**) Use efficiency	4
Energy use	3
Energy	14
Water	14
Crop/crops	81
Varieties	8
Breeding	8
Production	69
Market/markets	35
Standards/standard/standardize/standardization	17

When we analyze the relationship between the most mentioned words, we can draw a scheme as presented in Figure 2. The presented relationships are cause-effect relationships (for instance: a certain crop reaction results in a certain product quality) or interactions (the market asks for certain production volumes; deviations from this lead to disruptions and price fluctuations).

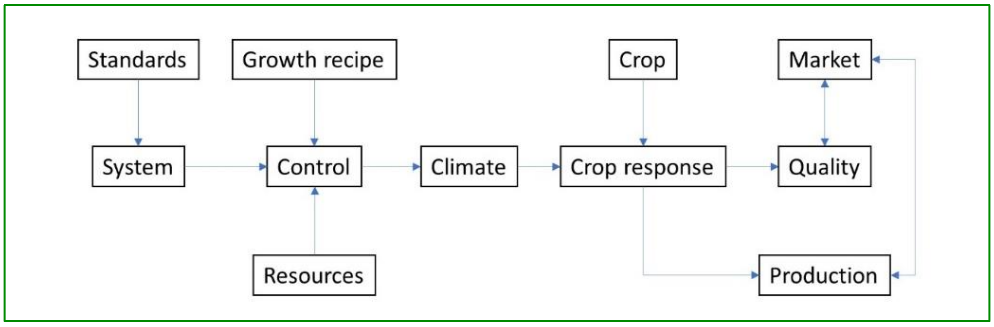

Figure 2 *Relations between most mentioned words in focus groups.*

4.2 Recommendations for research in Fieldlab Vertical Farming

Given the project structure of Fieldlab Vertical Farming, R&D contributions to several topics described above, can be addressed to certain work packages. Others do not fit in with the pre-competitive nature of the Fieldlab, and should be taken up by commercial activities outside the Fieldlab. A concept for assigning topics to the different work packages in Fieldlab Vertical Farming is described in Table 2.

Table 2 *Assignment of R&D activities on relevant topics to Fieldlab work packages.*

Topic	Aims	Fieldlab Vertical Farming	WP	Type of research activity
Market	How do consumers perceive VF products?	Consortium	1	Market research
Standards	Which differences in technical set-up cause differences in production performance?	Consortium	2	Comparative trials
System	Further development and optimization of VF systems.	N/a	-	Design and construct by companies outside Fieldlab
Growth recipes	Develop and improve growth recipes for different crops in VFs.	Partly, by individual partners	2	Cultivation experiments
Control	Furter development of control systems.	N/a	-	Development and implementation by companies outside Fieldlab
Resource use	How to improve resource use efficiency?	N/a	-	Maybe interesting for follow-up
Climate	Optimize climate in VF cells	Consortium, individual partners	2	Comparative and individual trials
Crop response	How do measure and interpret crop response?	Consortium, individual partners	2	Comparative and individual trials
Crop	Breeding and selection	Partly	2	Partly: selection of varieties. Breeding by companies outside Fieldlab
Quality	Quality assessment, quality improvement	Consortium, individual partners	2	Comparative and individual trials
Production	Optimize production (quantity, timing)	Consortium, individual partners	2	Comparative and individual trials

5 Conclusions

Within the Vertical Farming Field Lab, an inventory has been made of the research questions that need to be worked on in the coming years to further develop Vertical Farming. This was done through a webinar and in five focus groups, involving researchers and commercial partners as well. The most frequently mentioned topics for research and development were extracted from the report of the results, using text analysis. The main topics of interest are:

- Insights in markets, consumer perception of products grown in a Vertical Farm
- Research and develop:
  - VF systems;
  - Standards for VF systems. At first find out how different set-ups lead to different production performances;
  - Concepts for control systems (measure, decide, execute);
  - Growth recipes for different crops
- Improve resource use efficiency, especially for energy
- Research the optimal indoor climate in a Vertical Farm cell
- Determine the plant response to the climate and the successive consequences for production and quality

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