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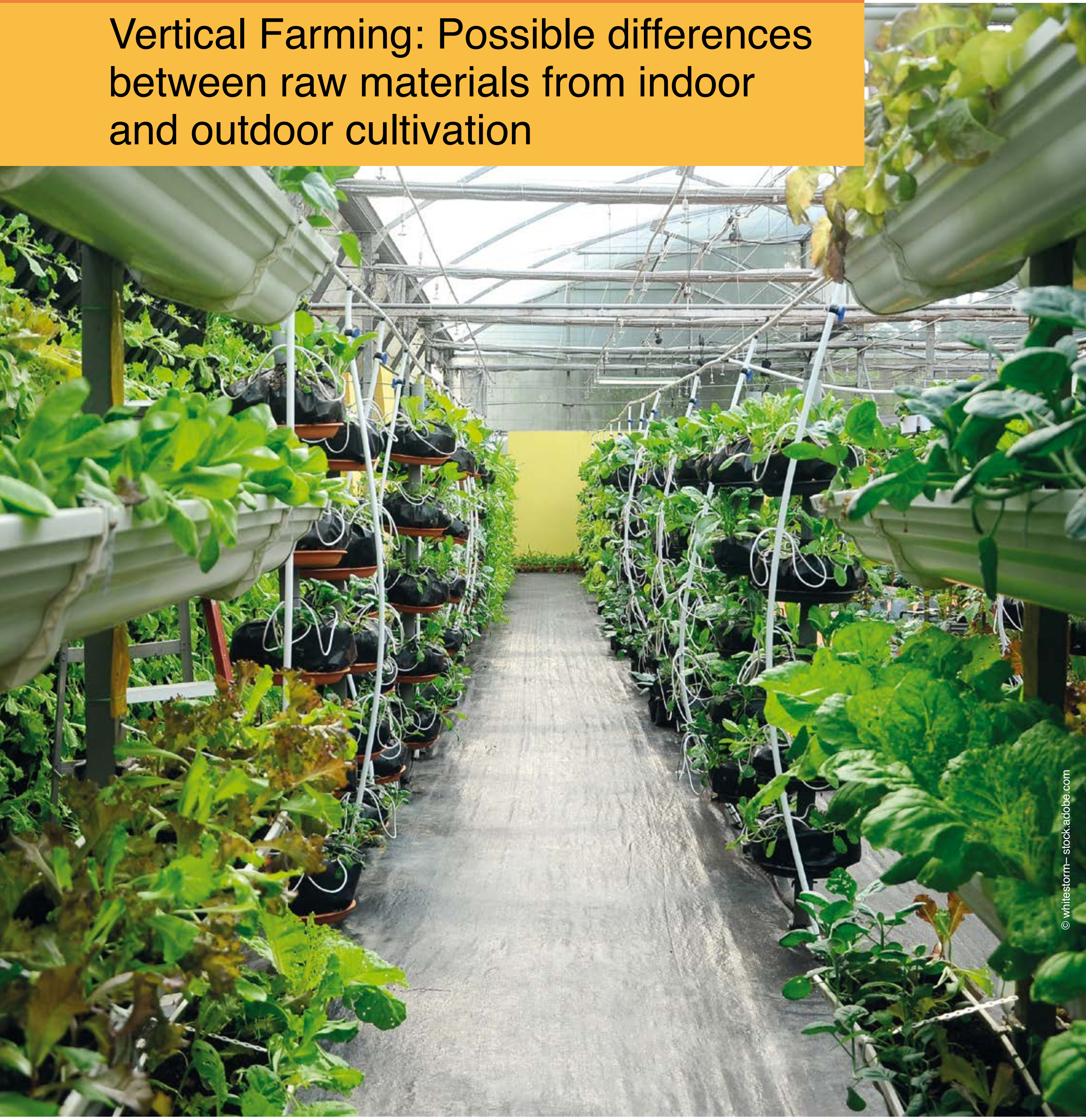
Vertical Farming: Possible differences between raw materials from indoor and outdoor cultivation



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Vertical farming (VF), i.e. the commercial and vertical cultivation of plants indoors and under often controlled environmental conditions, is an innovative cultivation method that offers numerous ecological but also economic advantages over traditional arable farming methods. These include, among others, a high, standardised quality of the cultivated products, easily plannable and secure yields due to a lack of environmental influences and a reduced need for water and crop protection products. In addition, the local production of formerly imported foodstuffs enables short transport routes to the consumer. All in all, VF appears to offer a sustainable solution to some of the current challenges, such as anthropogenic climate change, increasing urbanisation, soil degradation and the growing loss of biodiversity. This expert knowledge is dedicated to this new cultivation method. The focus here is on VF in Europe and the comparison between conventional cultivation and VF.

Basically, the VF system describes the arrangement of plants within a vertically arranged infrastructure. Two different categories can be distinguished: Vertical systems that only use artificial light (plant factories with artificial lighting (PFAL)) and systems that (additionally) use sunlight (indoor farms (IF)).

PFALs are mostly characterised by the cultivation of plants with control of all environmental factors (Controlled Environment Agriculture (CEA)). In this context, the vast majority of systems have the following characteristics (Kozai, 2019):

- All walls and roofs are opaque and only (LED) lamps are used as light sources in the cultivation room;
- The cultivation room is almost airtight;
- The walls and floor are well insulated;
- A hydroponic cultivation unit is used;
- The cultivation room (sanitary area) may only be entered by persons wearing disinfected clothing who have previously passed through a hygiene air lock;
- The reproduction and growth of pathogens, insects and harmful rodents is strictly monitored, recorded and reduced to a minimum.

Lighting with LEDs creates day and night cycles, which are important environmental signals for the plants. This allows to control the development of the plant and consequently the yield, ingredients and quality of the products with the help of the set light intensity, light spectra and photoperiods. How well the plants can absorb the energy of the photons depends not only on the light settings but also on other environmental factors. The light settings at the beginning of plant growth and before harvesting also influence the shelf life, taste, appearance and nutrients of the products. That results in optimal growing conditions, high production efficiency and crop quality, as well as year-round food production. Leafy vegetables are the most popular crop grown commercially in PFALs worldwide, with lettuce accounting for the largest share of total production here (Zhuang et al., 2022).

In addition to PFALs, other CEA cultivation systems are used in Europe. These include:

- Container farms: modular vertical farm located in a shipping container;
- In-store farms: vertical farm located at the point of consumption or distribution, such as in grocery retail;
- Appliance farms: vertical farm integrated in a house.

The term indoor farm (IF) covers production systems that produce plants indoors by (co-)using natural sunlight. Vertical systems in greenhouses mainly include columnar and pyramidal constructions. These arrangements allow the plants to be relatively evenly exposed to the light. In addition to sunlight, assimilation light is often used (Pflanzenfabrik, 2022). Examples are greenhouses, foil tunnels and umbrella houses. IF is mostly used for the cultivation of high-quality vegetables. Especially in the technology of greenhouses, there has been great progress in development in recent years. The most commonly used cultivation methods in IF are:

- Hydroculture or hydroponics: Here, cultivation takes place without soil. Instead, the plant roots are immersed directly in a nutrient solution or find a foothold in gravel, sand or mineral wool. Hydroponic systems can be operated continuously or statically. Hydroponics is the most common method used in IF;

- Aeroponics: The plant roots are in a chamber with 100 % humidity and are sprayed with water or a nutrient solution. Advantages include high nutrient efficiency and yields up to ten times higher than in soil production. However precise sensor technology is required;
- Drip irrigation: Drip irrigation is mostly used for perennial crops. Here, hoses or drippers direct the nutrient solution to the base of the plant in a controlled manner. Closed or non-circular systems are also possible here;
- Nutrient Film Technique (NFT): The nutrient solution flows continuously in a container with a slight gradient through a mostly closed system, wetting the plant roots hanging in it;
- Aquaponics: This is a combination of indoor fish farming and hydroponics. The excrement of the fish serves as a natural fertiliser for the plants.

Commercially, mainly leafy vegetables, micro greens, i.e. young, edible seedlings and flowers are produced. Organic certification of the products is currently not possible in Europe, as plants must grow in soil for certification. Exceptions are plants that grow naturally in water.

Comparison of vertical farming and conventional farming

One of the greatest strengths of vertical farming is the controllability of the environment in which the plants are raised. Environmental factors such as humidity, lighting, temperature, ventilation and CO_2 concentration can be controlled and therefore also the growth and yield of the plants. Moreover, indoor cultivation results in independence from the climate and weather conditions of the location. In addition, the quality and ingredients of the products can be influenced by vertical farming.

Studies have shown, for example, that the proportion of health-promoting antioxidants in beetroot is significantly increased in vertical farming. It was also possible to reduce the total cultivation time of marjoram from 101 to 136 days in field cultivation to 46 days in vertical farms (Mempel et al., 2021, p. 291ff) and also to increase the content of health-promoting glucosinulates in watercress by adjusting environmental factors. However, it is important to consider the composition of the plants as a whole when specifically influencing ingredients, as nutrient imbalances or an accumulation of unwanted groups of substances such as nitrate can also occur.

Another advantage of vertical indoor cultivation is the high and also year-round yield of vegetables, fruit and herbs on a small area, which makes this production system particularly attractive for cities and metropolitan areas. For example, a ten-layer vertical farm can produce a yield of 80-120 kg of lettuce per square metre per year, while conventional open field cultivation can only produce 3.9 kg/m²/year (Table 1) (Avgoustaki & Xydis, 2020, p. 7, 27). However, especially crops with longer generation times and staple crops have so far shown poor profitability in vertical cultivation. Nevertheless, the cultivation of these products could become more important in the future, because cultivation on small areas in cities can stabilise supply chains, especially by shortening transport routes.

Due to these short transport routes, but also due to the possibility of enriching antioxidants in the plants, the shelf life of products from vertical farming is usually longer. Another advantage of vertical farming, especially in terms of sustainability, is a reduction in food waste. Because of the longer shelf life, but also the more uniform morphological characteristics of the raw materials and short transport distances, there is also less food waste at the food retail level than with comparable products from conventional agriculture. Moreover, in vertical indoor cultivation, further processing steps such as washing before packaging are not necessary due to the absence of pesticides and soil and could be eliminated.

An additional advantage of indoor cultivation in vertical farming is that the controlled and enclosed environment can prevent, or at least limit, the entry of pests. Although this also fundamentally reduces the possible introduction of microorganisms and viruses, the risk of microbial contamination of agricultural products remains. In the closed environments of vertical farming, pathogens can easily spread if proper hygiene measures are not taken. Bacteria, viruses and fungi can multiply on plants, surfaces and in the air or be transmitted through these media and affect the health of the plants. Improper handling or contamination of the nutrient solutions can also lead to a rapid spread of pathogenic microorganisms. The same applies to humidifiers or ventilation systems, especially if the filter and cleaning routines are insufficient. In addition, growing substrates such as coconut fibres or hydrogel, which are not completely germ-free, can serve as reservoirs for pathogenic microorganisms. Finally, humans can also contribute to the spread of microorganisms. If workers do not follow proper hygienic measures or use contaminated clothing or tools, they could transmit pathogens from one plant to another.

The risks can be counteracted with air filters and airlocks, the automation of work processes, as well as UV treatment. It is also important to note that pathogens and pests spread mainly through the nutrient solution, which makes recirculating systems especially susceptible to contamination in this way. This danger can also be prevented, for example, with ultrafiltration, hydrogen peroxide, heat treatment and UV radiation. In addition, the nutrient solution should frequently be checked microbiologically and replaced regularly, as the microbial load of the nutrient solution increases the longer it is used. If contamination does occur, the systems should be emptied and cleaned. Furthermore, modular systems can help to counteract proliferation. A well thought-out and implemented quality management system is, regardless of the cultivation method, the most important condition for ensuring food safety and quality. However, quality management in vertical farming is not to be compared with that of conventional farms, but rather should be seen as a combination of agricultural and food-processing quality management. This is also the reason why some companies operating vertical farms have quality management certifications for both agricultural production (e.g. GAP) and food safety (e.g. BRC, ISO 22000). Many companies already have high quality standards with a HACCP concept, but further research is needed in this area.

If vertical farming is to provide an answer to the challenges of climate change and the global food crisis, the most important question is the resource efficiency of the farming method. Vertical farming has the potential to make very efficient use of the resources employed. This enables vertical farming to achieve high, predictable productivity for the space it occupies. In addition, there is very low water consumption and a non-existent to low use of pesticides. There is also the possibility of minimising the miles travelled for food by locating the farms close to the consumer or processing industry. This is, for example, the case for lettuce, where a transport distance of 43 km instead of 3,200 km is possible, as shown in Table 1 (Avgoustaki & Xydis, 2020, p. 50). Closed cycles in production also allow resources that have already been used and are not required, such as nutrients, to be recycled. In addition, vertical farming allows for higher light utilisation efficiency (plant dry weight per incident photosynthetic photon flux density in g/mol) than greenhouse or open field cultivation due to the ability to easily adjust environmental factors.

However, a major disadvantage of vertical farming is the high energy consumption of the cultivation method. The high energy input, mainly for lighting but also for air conditioning, results in a larger carbon footprint than for greenhouses and outdoor cultivation (Figure 1). Starting points for lowering energy use or reducing the carbon footprint are the use of renewable energy, the integration of farms into district heating systems, combined heating and power plants and the maximisation of light utilisation efficiency. However, even if the entire energy of a vertical farm is generated from renewable energy sources, which greatly reduces the carbon footprint, it is still greater than that of greenhouse and open field cultivation. Greenhouses in Europe are therefore still more efficient than vertical farming in terms of energy use, which makes a combination of the two types of cultivation attractive for breeding and raising young plants. As high energy consumption is also the largest cost factor of vertical farms, there is a great deal of research aimed at reducing the high energy input.

Compared to vertical farming, conventional farming has, among other things, the disadvantage that it is location-dependent. Site-specific factors such as climate, soil quality or weather can therefore not be changed or influenced, or only to a very limited extent. This also increases the risk of crop losses. In addition, conventional cultivation requires a large amount of water. As many plants only grow in certain regions, long transport distances to the consumer can also result. The advantage, however, is that little energy is required for cultivation. Contrary to the assumption that vertical farming results in less microbial contamination due to the closed environment, a study by experts in food hygiene found no statistical differences in the microbial profile of raw materials from conventional and vertical farming. As a result, contamination with pathogenic microorganisms can occur in both types of cultivation.

Resource efficiency	**Vertical indoor farm (10 layers of lettuce)**	**Conventional outdoor cultivation (lettuce)**
Efficiency of water use	1 l/kg/year	250 l/kg/year
Water consumption	Usually hydroponics or aeroponics Approx. 11 l/head	Irrigation and precipitation Approx. 250 l/m²
Energy use/consumption	250 kWh/kg/year	0.3 kWh/kg/year
CO_2 emissions	158 kg/t lettuce	540 kg/t lettuce
Light source	Artificial lighting operating 10-24 h/day	Sunlight
Use of crop protection products	Indoor cultivation Sterilised environment	Use of EPA-approved pesticides, herbicides and fungicides, as well as traditional methods such as ploughing, weeding and mulching
Yield	80-120 kg/m²/year	3.9 kg/m²/year
Land use	365 days/year	275 days/year
Efficiency of land use	0.3 m² for 1 kg/day	93 m² for 1 kg/day
Harvests per year	8-12 per year	2 per year
Transport distances	43 km	3,200 km

Table 1: Resource efficiency of lettuce cultivation in vertical farming and conventional farming in comparison (modified by Snigur according to: Avgoustaki & Xydis, 2020, Pg. 7, 27)

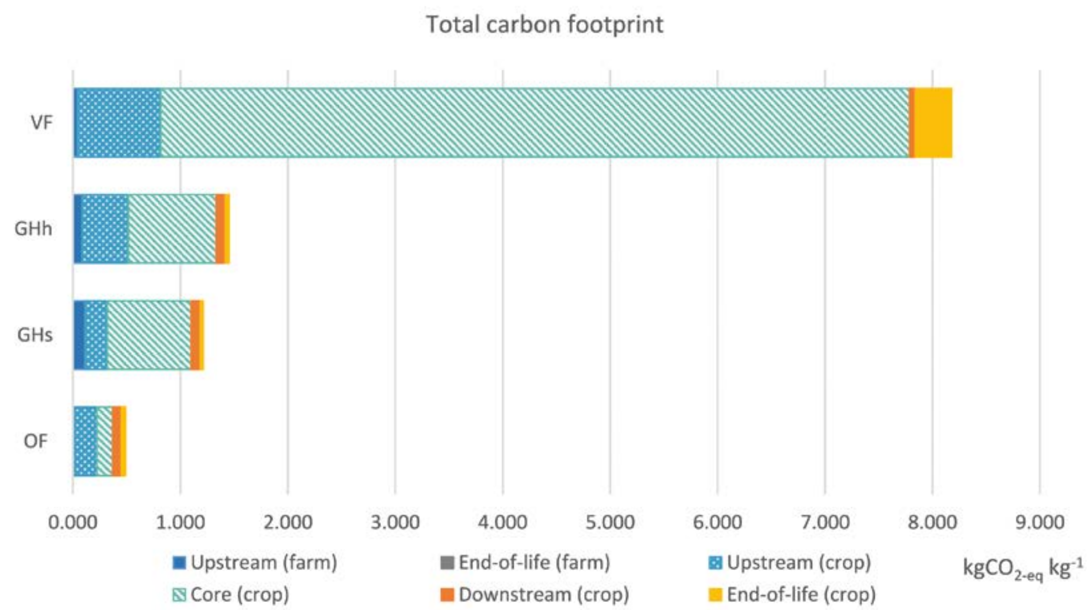

Figure 1: Total carbon footprint of the production systems considered (Blom et al., 2022, Pg. 6)

This makes good personal and operational hygiene necessary in both types of cultivation, irrespective of the cultivation method (Mohammad et al., 2022).

A holistic view of all the advantages and disadvantages of vertical farming and conventional agriculture is therefore necessary. In Europe alone, there are many different approaches to sustainably implementing vertical farming and conventional cultivation. For this reason, the special cases must be examined as holistically as possible in all considerations in order to be able to make a well-founded statement about the use of vertical farming.

Market and future developments

In 2020, the global market for vertical farming was worth 5.5 billion US dollars. It is expected to grow by 24 % over the next few years (GlobeNewswire, 2021, p. 1). Currently, the United States of America is the largest market player worldwide (Statista, 2022, p. 10). Examples of international companies using vertical farming can be seen in Table 2. In the last five years, however, there has also been a strong development in this segment in Europe, accompanied by increasingly fierce competition. The Netherlands is considered a pioneering country in the field of modern agriculture, including vertical farming. There are numerous companies, research institutes and educational institutions here that specialise in vertical cultivation. Dutch expertise extends to technologies such as hydroponic and aeroponic cultivation, LED lighting and automated systems. But in other European countries as well, an increasing number of large-scale farms (> 15,000 m²) are being built. In the UK, for example, there are a growing number of vertical farming businesses that grow high-quality produce in urban areas. The proximity to urban markets and the interest in sustainable farming methods have contributed to the rise of vertical farming in the UK. Companies in Scandinavia, Switzerland and Germany have also specialised in innovative indoor growing methods to promote local food production.

Despite the developments of the last few years, it is above all the high energy and investment costs that are putting pressure on companies. As energy costs are the most important cost factor due to the high electricity consumption of the farms, several farms have already had to close. As a result, companies are focusing even more than before on cost-saving measures and process optimisation. Already today, there are companies that use 100 % renewable energy, cloud analytics, the Internet of Things and Big Data to improve their processes through automation etc. and save costs.

The industry in Europe is currently focusing mainly on the cultivation of leafy greens such as lettuce, spinach, rocket, chard and various types of cabbage. Added to this are herbs such as basil, coriander, parsley, mint and oregano, as well as microgreens such as radish sprouts, cress, mustard sprouts and broccoli sprouts. Some vertical farms also grow edible flowers such as marigolds, violets or nasturtiums, which can be used as decorative and flavourful elements in dishes.

Company	**Country**	**Growth system**	**Products**	**Sales**	**Other**	**Source**
AeroFarms	USA	Aeroponics, Horizontal beds Sensors, machine learning	BabyGreens, microgreens	LEH	B-Corporation CEA Food Safety USDA GAP	(AeroFarms, 2023a, 2023b, 2023c, 2023d)
Bowery Farming	USA	Hydroponics Horizontal beds AI, sensors	Leaf lettuce, leafy vegetables, herbs, strawberries	LEH	-	(Bowery Farming, 2022, 2023)
Crop One	USA	Hydroponics, Modular farms with horizontal beds Sensors	Leafy vegetables	LEH	Cooperation with Emirates Flight Catering	(Crop One, o.J.a, o.J.b; Energy Monitor Worldwide, 2022a)
Kalera	USA	Hydroponics, Horizontal beds AI and Cloud Analytics	Leaf lettuces, microgreens	LEH	-	(Kalera, 2023a, 2023b)
Plenty Unlimited Inc.	USA	Hydroponics, Vertical plant towers Robots, sensors, AI	Leafy vegetables	LEH	-	(Plenty Unlimited, 2023a, 2023b)
Spread	Japan	Hydroponics, Horizontal beds Automation	Leaf lettuces	LEH	R&D: Strawberries	(Spread, o.J.a, o.J.b)
Sky Greens	Singapore	Hydroponics, Rotating plant towers, Sunlight	Leafy vegetables	LEH	-	(Sky Greens, 2014)

Table 2: Vertical farming companies worldwide with systems used, products and country assignment (Snigur, 2023)

Depending on profitability, strawberries, peppers, tomatoes and protein-rich plants could also be grown in the future. The main customers for these products are the retail food trade, hotels, restaurants and catering, but also the processing industry such as the perfume, cosmetics and pharmaceutical industries. The latter are mainly interested in the uniform quality of the plants and the possibility of enriching certain substances in the plants by adapting the environmental conditions during cultivation.

Due to the great potential that lies in vertical farming, but also the equally great challenges that exist in this context, many institutions and companies are conducting research on a wide range of topics related to vertical farming. On the one hand, research is being conducted into the cultivation of plants that are currently cultivated rarely or not at all. These include products such as staple foods, protein-rich plants, vanilla, various herbal medicinal raw materials, pointed peppers, but also herbal and aromatic plants. The influence of growing substrates and light conditions on the quality, safety and ingredient profile of plants is also being researched. In addition, research is being conducted on cultivation systems, e.g. the use of automation to enable standardised processes up to just-in-time production, as well as the measurement, recording and optimisation of material flows and energy consumption.

Even though vertical farming is still in its early stages in Europe, the industry has the potential to gain importance for the production of vegetables, fruit and herbs, especially in urban centres. In the future, production will probably continue to focus on herbs and salads, but strawberries could also become relevant in urban areas. The trend in vertical farming is towards special varieties and flavours. Vertical farming also has potential in the production of special food ingredients, medicines and cosmetics, or in the cultivation of young plants that are transplanted into greenhouses. With the advancing automation of operations, the requirements profile for the know-how of the required skilled workers will also increasingly shift. Above all, however, it will be important to educate consumers about the cultivation method.

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