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Current status and future challenges in implementing and upscaling vertical farming systems

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Vertical farming can produce food in a climate-resilient manner, potentially emitting zero pesticides and fertilizers, and with lower land and water use than conventional agriculture. Vertical farming systems (VFS) can meet daily consumer demands for nutritious fresh products, forming a part of resilient food systems—particularly in and around densely populated areas. VFS currently produce a limited range of crops including fruits, vegetables and herbs, but successful implementation of vertical farming as part of mainstream agriculture will require improvements in profitability, energy efficiency, public policy and consumer acceptance. Here we discuss VFS as multi-layer indoor crop cultivation systems, exploring state-of-the-art vertical farming and future challenges in the fields of plant growth, product quality, automation, robotics, system control and environmental sustainability and how research and development, socio-economic and policy-related institutions must work together to ensure successful upscaling of VFS to future food systems.

Rapid urbanization, climate change, land degradation, pandemics, biodiversity loss and extensive use of pesticides and fertilizers challenge our food supply chain. Consumers increasingly demand healthy, tasty, locally produced, plant-based food with low environmental impact. Furthermore, 24% of all food never reaches consumers—partially due to low quality and long supply chains[1]. Vertical farming has the potential to address these challenges and improve the production of high-quality products, such as fresh herbs, fruits, vegetables and flowers[2–4]. Additionally, vertical farming could boost the production of plant-based cosmetic and medicinal products. There are many forms of vertical farming systems (VFS), and the terminology is ambiguous (Box 1). This Review focuses on multi-layer indoor crop production systems without solar light, in which growth conditions are precisely controlled. These types of VFS enable a year-round guarantee on product quantity and quality, as production is independent of solar light and other outdoor conditions (Fig. 1). In turn, this allows location-independent production—from tundra to desert and from outer space to heavily urbanized regions on Earth.

Production can occur in a variety of structures such as repurposed high-rise buildings, cellars, growth chambers and shipping containers. The use of most resources (including land area, water, pesticides and nutrients) is extremely low compared with open-field and greenhouse production. Full control over the production process, including hygiene control, reduces pathogen contaminations and improves uniformity, nutritional value, taste and shelf life. VFS may allow for better resilience to catastrophic events such as extreme weather conditions, pandemics, supply chain disruptions and nuclear fall-out as in Fukushima in Japan in March 2011. Scientific findings from research conducted under lab conditions can be applied more readily in VFS than in the field or greenhouse[5].

Techniques used in modern vertical farming have their roots in human history, possibly inspired by hydroculture alongside the Nile in ancient Egypt, Chinese floating gardens (reported in the fourth century) and floating rafts (chinampas reported in the twelfth century) of the Aztecs (fourteenth century). In the nineteenth and twentieth centuries, soilless cultivation techniques (Fig. 2), artificial lighting and modernized greenhouses[6] assisted the development of indoor plant cultivation[7]. Towards the end of the twentieth century, the first structures resembling modern VFS appeared in the United States, Japan and the Netherlands[6,8]. Advances in light-emitting diode (LED) lighting technology fuelled a recent global expansion of VFS, while the spread of the concept among the general public is due partly to the pioneering and promotion work of industry icons such as Dickson Despommier and Toyoki Kozai[9,10].

This Review discusses the state of the art of vertical farming and its future challenges in the fields of plant growth, product quality, automation, robotics, system control, environmental sustainability, socio-economics and policy.

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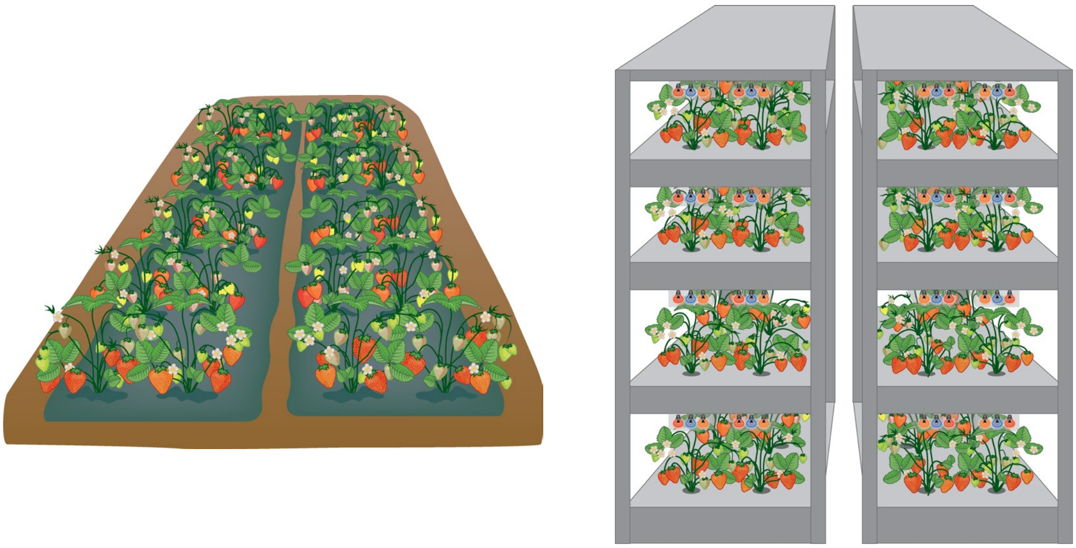
Box 1 | Examples of VFS located in a shipping container, a closed building and a warehouse

In this Review, VFS refer to multi-layer indoor crop production systems with artificial lights, in which growth conditions are precisely controlled. Plants can grow vertically (**a**) or horizontally (**b**,**c**). VFS exist in many different forms[2,4], and there is currently no consensus on terminology. For example, the large systems in **b** and **c** can be referred to as VFS, plant factories with artificial light (PFAL)[48], vertical farms with artificial light (VFAL)[2] or fully contained cultivation systems[131]. Moreover, the farm in **a** could be specified as a vertical farming unit (VFU)[131] or container farm[95]. When direct sunlight is used, as in high-tech multi-layer greenhouses, terms such as closed plant production system (CPPS), plant factory with solar lighting (PFSL)[117] or greenhouse–vertical farming unit hybrid[131] might be preferred by some but are not commonly used[3]. Conversely, there might be large system differences that are not captured by the terminology. For example, **c** differs from **a** and **b** in the type of fertigation system (hydroponic versus aeroponic), whereas **a** differs from **b** and **c** in the orientation of the system (wall-mounted versus shelf-mounted). Photos were supplied by Freight Farms (**a**), Sananbio (**b**) and AeroFarms (**c**).

Crop growth

The key challenge for improving yields and resource use efficiency (RUE) (key terms defined in Box 2) in VFS lies in the iteration of Liebig's law of the minimum—that is, repeated identification and optimization of the most limiting growth factor. Fortunately, VFS allow for control over many environmental variables that determine plant behaviour, including light quantity and spectrum, water and nutrient availability, temperature, relative humidity, airflow, and carbon dioxide (CO_2) concentration. This control allows for a more predictable plant composition and growth rate—a substantial advantage of VFS over other farming techniques[11]. Precise control may be achieved by combining advanced decision-making software and sensor data derived from the plant and its environment. Sensor-informed artificial intelligence (AI) can be used to update self-learning dynamic growth prediction models that are partially process-based and partially data-driven. Such models can, in turn, control systems for illumination, fertigation, and heating, ventilation and air conditioning (HVAC), allowing for real-time integrated regulation of the growth environment to ensure consistent productivity and product quality. 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. AI can lower labour costs through reducing the need for expert farmers to determine optimal growing conditions (see section 'Automation and robotics').



Open-field farming	Vertical farming
Uncontrolled sunlight (day length, spectrum and intensity), temperature, [CO_2], water and relative humidity	Controlled light (day length, spectrum and intensity), temperature, [CO_2], water and relative humidity
Low and unpredictable productivity per unit area	High and predictable productivity per unit area
Unguaranteed and non-uniform quality of produce	Guaranteed and uniform quality of produce
High water use	Low water use
High pesticide use	No or low pesticide use
Low energy use	High energy use
Substantial food miles	Potential for minimal food miles

Fig. 1 | Key differences between open-field farming and vertical farming. Note that the many forms of greenhouse horticulture could be regarded as intermediate cultivation systems. At one end of the spectrum are multi-layer high-tech glasshouses, with high control over temperature, light, photoperiod, fertigation and CO_2 concentration, regarded as vertical farming by some[3] (Box 1), and at the other end are low-tech plastic tunnels, which are closer to open-field farming. Created with BioRender.com.

VFS energy use is strongly determined by the need to deliver photosynthetically active radiation (PAR) to the plants (see section ‘Environmental sustainability’), which is very costly, both economically and environmentally. Maximizing light use efficiency (LUE) is therefore crucial. Below, we discuss four strategies to maximize LUE.

Increasing the fraction of light intercepted by the crop. In VFS, much light is lost to walls, aisles or the floor between plants. Reducing light losses between plants may be achieved by continuous canopy closure achieved by, for example, variable plant density, intercropping or optimized lighting strategies. A dynamically managed plant density allows for continuous canopy closure throughout the growth cycle by gradually decreasing density as plants grow. Laser diodes that shoot photons onto specific leaves could be used for more precise illumination, reducing light losses between plants[12]. Maximum light interception is typically reached when the leaf area index (m^2 leaf area per m^2 floor) is 3–4, with little gain at higher leaf area index values. Environmental cues such as far-red light trigger fast leaf outgrowth and stem elongation, increasing whole-canopy light capture in early growth phases[13,14]. However, far-red light tends to reduce leaf thickness, which might be undesirable from a quality standpoint. Simultaneous growing of multiple crops (intercropping) is underexplored in VFS but may improve whole-canopy light interception[15].

Improving light distribution within the crop. 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[16]. However, in VFS, compact plants are desired[17]. The challenge is therefore to combine breeding efforts and growth recipes that result in a compact VFS plant ideotype with uniform light distribution over all leaves. Functional–structural plant models can simulate three-dimensional plant architecture and identify plant ideotypes for VFS[18] while accounting for light positioning and reflection by walls and floors. Lighting applied from underneath lettuce leaves has been shown to preserve the photosynthetic capacity of lower leaves by delaying their senescence, thereby increasing yield[19], but whether this strategy increases LUE and the quality of fresh products is unknown.

Optimizing leaf photosynthesis. Light intercepted by leaves can be used to drive photosynthetic reactions. Maximizing

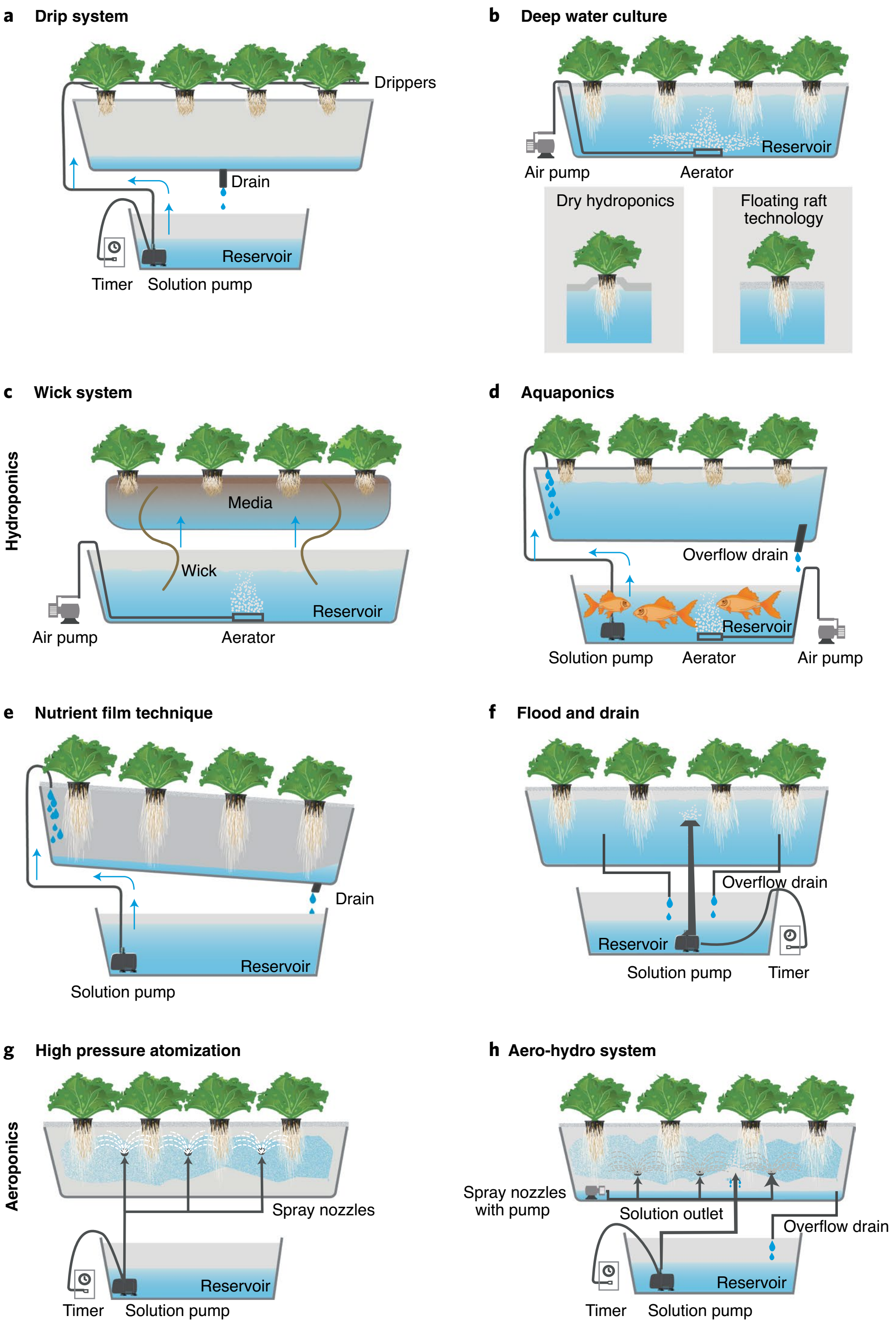


Fig. 2 | Schematic drawings of hydroponic and aeroponic soilless cultivation systems. a–h, In hydroponic systems, plant roots grow in direct contact with water; in aeroponics systems, plant roots grow in air or mist. Key systems are presented here, although the terminology is ambiguous and hybrid forms exist. In drip irrigation, plants in a stonewool block or substrate-filled pots are fertigated using one dripper per pot (**a**). In deep water culture (also termed 'true hydroponics'), plant roots are fully immersed in an oxygenated nutrient solution (**b**). Wick systems use a thin hydrophilic material that provides water from the nutrient solution to the pots (**c**). Aquaponics is similar to deep water culture, but the nutrients are partially derived from fish culture (**d**). The nutrient film technique partly exposes the rooting system to a thin layer of flowing nutrient solution (**e**). Flood-and-drain systems (also termed 'ebb and flow' or 'ebb and flood') periodically immerse the root system in a nutrient solution (**f**). High-pressure atomization nebulizes the nutrient solution in very fine mist that deposits onto the root surface (**g**). Aero–hydro systems are hybrids between hydroponics and aeroponics, where most of the roots grow in air or mist, and one end of the roots (the root bed) is emerged in nutrient solution (**h**). This figure was inspired by Eldridge et al.[44].

photosynthetic quantum yield (μmol CO_2 fixed per μmol photons absorbed) is an important factor for improving LUE. The high degree of environmental control in VFS can be used to maximize photosynthetic quantum yield by integrally tweaking photoperiod, light spectrum, photosynthetic photon flux density (PPFD) (that is, irradiance in the range of 400–700 nm (μmol $m^{-2} s^{-1}$)), CO_2 concentration, relative humidity and leaf temperature. However, even in a completely stable environment, diurnal photosynthetic

Box 2 | Glossary of terminology and abbreviations used in the context of this paper

Term	Explanation
Anti-nutrients	Substances that block mineral uptake by humans (for example, glucosinolates, lectin or phytate).
Artificial intelligence (AI)	Computer-based intelligence that is able to acquire and apply knowledge. Capable of performing tasks in dynamic real-world situations that typically require human intelligence or beyond.
Biofertilizers	Microbial biostimulants that enhance nutrient uptake. Biofertilizers increase nutrient use efficiency and open new routes of nutrient acquisition by plants. Examples include mycorrhizal and non-mycorrhizal fungi, bacterial endosymbionts (for example, *Rhizobium*) and plant-growth-promoting rhizobacteria[78].
Biofortification	A method to increase the concentration or bioavailability of (micro)nutrients in plants during cultivation, as opposed to ordinary food fortification, which entails adding nutrients during food processing. Can be achieved by conventional breeding, genetic modification or environmental modifications.
Biostimulant	Any substance or microorganism applied to plants that can enhance nutrition efficiency, abiotic stress tolerance or crop quality traits, regardless of the nutrient content of the substance. By extension, plant biostimulants also include commercial products containing mixtures of such substances or microorganisms (see biofertilizers)[78].
Codex Alimentarius Commission	An international forum of 188 individual countries and the EU. This forum develops international norms for food production, aiming to protect public health and warrant honest trade and food production. The Codex is a United Nations organization, involving both the FAO and the WHO.
Forgotten crops	Crop species that are neglected by mainstream breeders, growers, food manufacturers and retailers—also referred to as underutilized or orphan crops.
Fortified foods	Foods with added nutrients that do not naturally occur in the food or do not naturally occur in high doses. Fortification aims to increase nutritional value, prevent deficiencies and provide health benefits.
Heating, ventilation and air conditioning (HVAC)	Climate systems for regulating the indoor climate by heating, by exchanging or replacing air (ventilation) and by cooling and/or humidity control (air conditioning).
Light use efficiency (LUE)	The mass of marketable fresh product per unit of incident light ($\mathrm{g\,mol^{-1}}$).
Long-tail business strategies	The selling of low volumes of hard-to-find items to many customers instead of selling large volumes of a limited number of mainstream items[128,129].
Novel foods	Foods or food ingredients that have not been consumed to a considerable degree in the EU before 1997. The Novel Food Regulation (EU) No. 2015/2283 states that these novel foods cannot be sold on the EU market unless they have undergone a thorough novel food safety assessment to prove that the food is safe for human consumption.
Phytochemicals	Here referred to as chemicals produced by plants. Sometimes a narrower definition is used: bioactive compounds present in plants.
Resource use efficiency (RUE)	The amount of marketable product per unit of supplied resource.
Tip-burn	A plant physiological disorder that causes the onset of necrosis on the margins of leaves. Typically observed in leafy vegetables such as lettuce.

quantum yield may periodically change, due to slow photosynthetic induction and stomatal opening at the beginning of the photoperiod[20,21], incomplete carbon utilization (feedback) and decrease in photosystem II operating efficiency (photodamage) throughout the photoperiod[22], and circadian rhythms (for example, repair cycles of photosystem II (ref. [23]) and diffusional limitations by stomatal conductance[24]). Environmental factors, such as PPFD, could be adjusted dynamically to react to diurnal changes in quantum yield. Such an approach would require continuous sensing and prediction of quantum yield, a currently underexplored but highly promising avenue.

Apart from light, LUE depends on other environmental factors, such as temperature and air composition. For example, a high CO_2 concentration can substantially increase LUE in C_3 plants by suppressing photorespiration, boosting yields up to 40% (ref. [25]). In VFS, high CO_2 concentrations can be maintained with low input, since nearly all CO_2 supplied is absorbed by plants. However, maintaining uniform temperature, relative humidity and CO_2 concentration profiles inside VFS remains challenging, due to incomplete air mixing. Vertically stacked production layers with limited head space hinder the delivery of conditioned air to crop canopies. Stagnant areas result in a non-uniform growth environment and high relative humidity and temperature, with a large leaf boundary layer that reduces gas exchange between leaves and the environment[26]. Stagnant air may reduce plant growth and cause physiological disorders such as tip-burn[27]. A localized air distribution system can deliver conditioned air at each production shelf to improve growth environment uniformity and ensure sufficient airflow. Computational fluid dynamics can be used to study airflow patterns (and their effects on plants) in silico. This can assist in determining optimal specifications of the airflow distribution system designs (for example, the locations of air inlets and outlets[28]). Areas of stagnant air could also be avoided using conveyor belts or dynamic spacing (see section 'Automation and robotics').

Directing photosynthates into harvestable products. VFS typically require short plants with a small rooting system and a high harvest index—that is, partitioning of assimilates to marketable organs. For leafy greens, high partitioning of the leaves is desired; for other crops, flowers (for example, medicinal cannabis), fruits (for example, strawberry) or underground parts (for example, radish) are marketable products that need high partitioning of assimilates. This could be achieved by plant breeding and the manipulation of environmental variables[11]. For example, in tomato, far-red light supplementation has increased the partitioning of assimilates to the fruit from 33% to 40% (ref. [29]).

Although root biomass and respiration should typically be minimized, root functioning should be sufficient to invigorate shoot growth. Soilless cultivation techniques (Fig. 2) allow for high control over the root environment (rhizosphere), enabling optimal root function. For instance, the concentration of mineral salts in VFS rhizospheres is typically ten times higher than in rhizospheres of open-field crops[30]. In other words, the regulation of rhizosphere nutrient concentration, pH, water availability, oxygenation and temperature ensures high plant nutrient content and high growth rates. Growth-stage-specific or diurnally timed nutrient application can improve product quality and quantity (see section 'Product quality'). An additional benefit of soilless cultivation techniques (Fig. 2) is the ability to grow clean (for example, no soil residue and fewer pathogens), high-quality below- and aboveground plant organs (roots, rhizomes, tubers and leaves) for consumer markets and breeding companies.

A potentially overlooked growth factor is the release of volatiles by plants and materials in VFS. Plastics, for example, can emit toxic fumes (such as phthalates and formaldehydes), which can cause chlorosis but in some cases can go unnoticed and result in unexplained yield differences between VFS. Plants themselves also emit many volatiles, and impurified air may lead to growth retardation while increasing pathogen resistance[31]. Moreover, high volatile concentrations may cause allergic reactions or diseases in VFS workers. Not only volatiles are important; if small plastic particles end up in the rhizosphere, they may be taken up by the roots and can influence yield and product quality[32].

Product quality

To be truly successful, VFS should create products with a high market value, which can be achieved by high-level environmental control that guarantees uniform high-quality products. Quality is an umbrella term covering many aspects, which in turn depend on specific morpho-physiological properties such as water and mineral content, tissue texture and phytochemical levels. Phytochemical levels affect taste and aroma (for example, carbohydrates and volatiles), appearance (for example, colours and pigments), shelf life (for example, carbohydrates and antioxidants), nutritional value (for example, vitamins) and pharmaceutical value (for example, carotenoids and cannabinoids). Environmental control can not only increase phytochemicals that positively impact product quality but also reduce phytochemicals that negatively impact quality, such as phenolics involved in tissue browning and anti-nutrients (for example, glucosinolates, nitrite, lectin or phytate), as reviewed previously[33]. However, the challenge remains to translate these findings into management practices (growth recipes) that can target specific quality attributes. For example, the application of light recipes targeted at specific quality aspects can easily lead to unpredictable outcomes: responses to light treatments are often species and cultivar specific, and the light treatment may interact with other environmental factors (such as the nutrient supply), affecting several quality attributes simultaneously. Regardless, VFS have great potential to optimize quality.

Most promising interventions to improve the nutritional status (for example, more fibre and less nitrite) focus on the application of increased light intensities. High PPFD increases photosynthesis and causes a stress response that induces the production of carotenoids[34], vitamin C[35] and phenolic compounds[33] (for example, flavonoids such as anthocyanins) (Fig. 3). In addition to nutritional value, elevated concentrations of these phytochemicals can improve quality attributes such as taste, appearance and shelf life[33,36]. Sometimes, too much light causes bitterness (due to high anthocyanin and chlorophyll concentrations, for example) and tip-burn. However, these effects also depend on variety, airflow, humidity and temperature[11,27].

In addition to PPFD, the light spectrum can affect product quality through its considerable impact on phytochemical content (anthocyanins, carotenoids, chlorophylls, flavonoids and phenolics)[33]. For example, blue and ultraviolet A (UVA) light can selectively stimulate the production of phenolic compounds in the phenylpropanoid pathway, such as sinapate ester sunscreens[37], which might increase nutritional value. In leafy greens, concentrations of β-carotenoids and lutein are elevated by blue and red light, respectively[33]. The red:blue ratio also affects phenolic compound levels, antioxidant activity, nitrate content, firmness and crispness in some products[38–40]. Green light increases phytonutrient concentrations (vitamin C, tocopherol and phenolic compounds) and inhibits anthocyanin biosynthesis[41,42].

The regulation of rhizosphere pH, water availability, oxygenation, temperature and nutrient concentration may enhance growth and quality. For example, it is relatively simple to increase mineral content (biofortification of, for example, K, Fe, Zn, Se or I) or reduce anti-nutrient concentrations by modifying the nutrient solution composition without sacrificing growth[43,44]. However, increasing or decreasing specific plant mineral concentrations does not necessarily increase nutritional value, as nutrient availability results from the cocktail of phytochemicals—that is, the food matrix. For example, serum iron in humans is drastically reduced by phytate and in turn considerably increased by antioxidants[45,46].

Increased quality should ideally not reduce productivity or energy use efficiency. Therefore, the concept of end-of-production treatments was developed[36], where during the last days of cultivation, factors such as PPFD, light spectrum and nutrient solution composition are changed from maximizing growth to maximizing quality. For example, increased PPFD applied several days before harvest extends the shelf life of lettuce[36].

The environmental control of VFS thus allows for a consistent supply of uniform and high-quality products. End-of-production treatments are especially promising, as they have relatively little effect on yield and morphology but can boost visual appearance, phytonutrient content, flavour, cold tolerance and shelf life[33,36,47].

Automation and robotics

Due to high labour costs, the scarcity of skilled workers and the need for high efficiency, there is a strong demand for automation in VFS. Labour constitutes a large part of the total production costs (25–30%; ref. [48]). Notwithstanding their fixed and operational costs, robots can perform different tasks efficiently, consistently and with high precision. A fully automated production environment without humans entering the facility has additional benefits: workplace health, safety and welfare regulations become less relevant, and plants can be grown under UV radiation, high humidity and increased CO_2 concentration (>1,000 ppm)[49]. Robots can lead to greater cultivation space, as plants can be grown without walking aisles and at heights that would be considered unsafe for workers. In addition, the absence of humans entering the VFS lowers plant disease pressure.

There are differences in the level and form of automation in current VFS, depending on the scale, type and available capital—but some general trends can be observed. The entire growth environment is closely controlled; this control will progress towards fully autonomous systems through innovations in sensing, modelling and AI technologies. Smart environmental control necessitates online sensing and modelling of key physiological processes. Although model-assisted decision-making[50] can increase yield in greenhouse crops, it is yet to be generalized in VFS. The computer models used may be mechanistic (knowledge-based, using key processes known to determine plant growth) or data-driven (applying machine-learning techniques to infer patterns in the data). A substantial limitation of existing mechanistic models is the need to adjust parameter values depending on genotype, which requires expert knowledge. Barriers for industrial applications may be removed by using data-driven parameter estimation and sensors that monitor plant behaviour in real time. Although data-driven models are

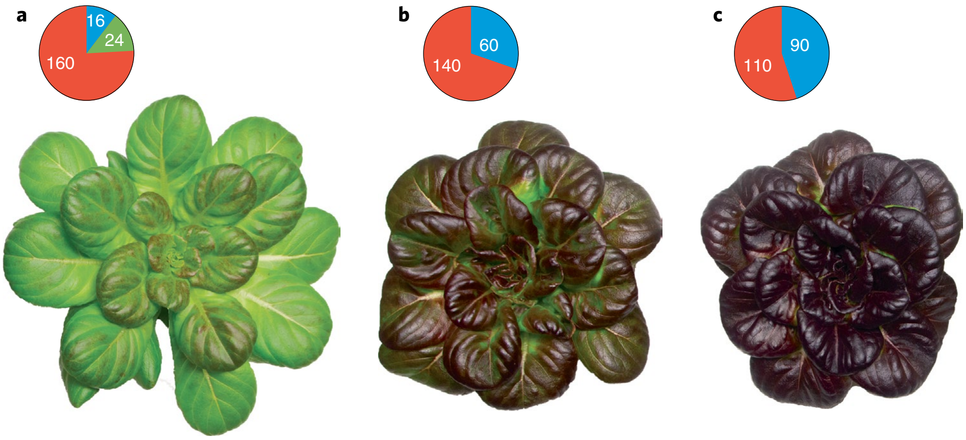


Fig. 3 | Light quality influences lettuce coloration. a–c, Plants (*Lactuca sativa* 'Capitata'; Rijk Zwaan, De Lier, the Netherlands) were grown in a climate room with a 15/9 hr day/night rhythm, an air temperature of 20 °C and a PPFD of 200 μmol m^{-2} s^{-1} supplied by either white (400–700 nm) LEDs (**a**) or a combination of red (660 nm) and blue (450 nm) LEDs (**b**,**c**). The numbers indicate the intensities of each light colour (μmol m^{-2} s^{-1}).

powerful, they have limited interpretability and require large datasets for training. A combination of mechanistic and data-driven models may create an ideal blend of interpretability and predictive power. For both model types, sensors measuring biologically relevant traits are essential and need to be mobile or small and cheap to accurately cover canopy responses over large cultivation areas.

Robotic systems for seeding and transplanting exist[51] and can be applied in VFS. Material transport and handling of fixed-size containers can be fully automated, using technologies developed in greenhouses and in autonomous warehouses. Automated plant transport between compartments can increase RUE, as conditions in each growth compartment can be optimized for a specific developmental stage. While the harvesting of leafy greens is automated in some commercial VFS, the majority of VFS relies on manual labour for harvesting, crop scouting and other management tasks. Robotic operation in greenhouses is an active field of research, and many systems have been proposed (for instance, for harvesting sweet pepper[52,53], tomato[54] and strawberry fruits[55], and for de-leafing cucumber plants[56]). However, despite decades of research[57], no commercial systems exist, as current robots have a low success rate, are slow and cause mechanical damage to crops. Robots face several challenges in crop handling[58]. Fruits and vegetables vary strongly in appearance, shape, size and material properties. The plant canopy is highly cluttered and complex, which complicates perception—recognizing all ripe fruits within a canopy is difficult. Robots need to interact safely with human co-workers and handle delicate plant organs without product damage or human injury.

Recent developments in agricultural robotics alleviate these challenges, further facilitating the ease of transferability to vertical farming. Advances in deep learning have greatly improved robots' abilities to perceive fruits and vegetables, despite variation in appearance[59], and active perception allows robots to deal with complex surroundings[60]. Robots and grippers are being developed for gentle handling of crops[61], and developments in human–robot interaction will allow for collaborative robots that safely interact with human co-workers[62]. Apart from technological innovations, the VFS environment can be simplified for robotic operation. In the short term, the level of standardization could be improved by standardizing the size of cultivation panels to simplify automation and reduce costs of robot development[63]. In the long term, breeding for crop architectural characteristics that simplify robotic handling could be undertaken. For example, breeding for cucumbers with longer peduncles or growing sweet pepper cultivars with distributed instead of clustered fruit position[57] can improve robotic handing.

Currently, the automation of environmental control, illumination and fertigation is to some degree utilized in VFS, but it could greatly benefit from combining innovations in sensor technology, crop modelling and AI. Robots handling fixed-sized containers for transplanting, harvesting and transportation are available and can be integrated in VFS. Further research is required to allow robots to come in safe contact with plants and humans. Meanwhile, autonomous VFS should be built from modular building blocks that facilitate upscaling.

Environmental sustainability

Agriculture has been at the origin of the evolution of societies[64] but is not without environmental impact[65,66]. The global and regional environmental impact of agriculture is typically a weighted assessment of factors including air, water and soil pollution; soil erosion; deforestation; biodiversity loss; and the use of resources such as land, water, minerals and energy[67]. Such scientific analysis is currently absent for VFS. The closed nature of VFS seems to limit their direct impact on the environment[68], but crop production in VFS requires more energy input[69] than open-field agriculture[70]. Additionally, VFS are currently economically unsuitable for producing staple foods in practically all markets[71]. They mainly serve markets that demand high-quality crops otherwise produced in greenhouses, such as fresh leafy greens, herbs and ornamentals. Accordingly, we primarily compare the environmental impact of VFS with that of greenhouses.

The closed environment of VFS allows for multi-layer soilless cultivation, high production density and extensive control. This facilitates local production, prevents environmental pollution and reduces the land footprint, opening the potential for revitalizing soils and increasing biodiversity. Additionally, the closed construction of VFS prevents artificial light from polluting its environment—a concern for biodiversity in dense greenhouse areas[72]. The closed construction and advanced HVAC systems of VFS minimize water use, allowing transpired water to be recycled. Eventually, water may leave VFS only as part of the harvested product, which would reduce water use by ~90% compared with greenhouses[69] and by ~99% compared with the open field. However, VFS are not unique in their potential for water recycling, as closed greenhouses with active cooling can achieve similar efficiencies[69]. High-level water treatment should theoretically allow for near-indefinite reuse of nutrient solutions. In this case, all fertilizers leaving the system would be in the crop itself, and fertilizer use efficiency would approach 100%. In turn, nutrients in green waste and sewer water from cities could be recycled in VFS. However, despite societal interest in this concept, the current variability in composition and potential contaminations with pharmaceuticals, toxins (for example, heavy metals) and pathogens are technological hurdles for the recycling of such waste streams.

It is unknown how sensitive the closed construction of VFS is to plant pests and diseases in their day-to-day operation. Biocide use could be eliminated using beneficial organisms, continuous monitoring and very strict hygiene measures, including protective clothing and non-chemical disinfection of incoming air, water, seeds and other materials. Although these measures are beneficial to a certain degree, striving for a completely sterile environment is neither desirable nor realistic, as a pathogen-vulnerable environment might emerge[73,74]. In contrast to popular belief, soilless cultivation does not provide a sterile rhizosphere[75,76]. Care has to be taken to prevent pathogenic infections and build-up of toxic root exudates (autotoxicity[77]) and salinity (that is, NaCl build-up from polluted water or fertilizer sources). Biological control and biostimulants are in their infancy in vertical farming but could help in this respect[78]. There are many examples of biostimulants[79], including growth-promoting substances such as humic acid or silicium and beneficial microorganisms such as biofertilizers, that enhance plant resilience and alleviate adverse conditions[75]. However, there is little evidence that biostimulants are beneficial under optimal growth conditions. Light-spectrum manipulation could be another method to modulate plant immunity, as this can also enhance resistance against pathogens and insects. For example, UVB radiation partly kills off pathogens, and a high red:far-red ratio can activate defence signalling (for example, the jasmonic and salicylic acid pathways), improving plant resilience[80,81]. Altogether, for crop protection within VFS, there are many considerations for system optimization and areas for future research[74].

Local production may shorten supply chains, reducing the period between harvest and purchase. This could reduce food waste by minimizing transport spoilage due to inconsistent cooling practices and perturbation damage. Short transport distances result in a longer and more reproducible shelf life, helping curb household waste. While zero-km is often considered a major advantage in reducing emissions, current data suggest this to be an overestimation[82]; transport has a relatively small contribution to the total carbon footprint of most products (<10%; ref. [83]) and entire diets (~6%; ref. [84]). The construction of new buildings for VFS may cause substantial environmental impact, but to our knowledge this has not been quantified. Additionally, the transient nature of VFS start-ups may exacerbate this impact through frequent bankruptcies wasting invested resources[85].

The advantages of VFS primarily come at the expense of energy, mainly determined by the need to deliver light energy to plants and later extract that energy as sensible and latent heat, using HVAC. There is no way around the physics of this issue, but projected enhancements in lighting efficiency, environmental control strategies, production system designs and crop improvements may reduce energy use and improve VFS profitability[86]. The environmental impact of VFS energy expenditure depends on the method of electricity generation. For instance, in 2016, Sweden and France produced electricity at 13 and $30\,\mathrm{g\,CO_2\,kWh^{-1}}$, respectively, by using renewables and nuclear energy[87]. The Netherlands produced around $500\,\mathrm{g\,CO_2\,kWh^{-1}}$, due to a high fraction of coal and gas-fired power plants. The European Union (EU) average in 2016 was $296\,\mathrm{g\,CO_2\,kWh^{-1}}$. The share of renewables in electricity generation is increasing slowly but steadily and will pervade the future energy mix. However, using solar panels to power VFS requires a considerable amount of land area (Fig. 4).

In summary, the closed nature of VFS allow a circular systems approach, lowering the impact caused by the use of pesticides, water and fertilizers, compared with open-field and regular greenhouse production. However, maintaining high hygiene standards typically increases the turnover rate of disposables with negative environmental impact[85]. The actual environmental sustainability of vertical farming will depend greatly on local methods of energy production and resource availability. VFS have great potential in locations where energy production is sustainable, ecosystems are fragile, water and land are scarce, and consumer demands for consistent product quality are high.

Socio-economic impact

Reports are mixed on the socio-economic impact of vertical farming. Positioning VFS in urban areas as 'techno-local food' producers[88,89] may increase transparency and awareness of food production for urban consumers[89–91]—but this food may be accessible mainly to elite and gentrified groups of consumers, thereby not contributing to broader access and food justice[89,90,92]. However, VFS perception and acceptance varies, with large regional and cultural differences occurring between Europe, the United States and Asia[93]. Besides some Asian countries (for example, Japan and South Korea), societal acceptance of vertical farming has been relatively low globally compared with outdoor forms of urban agriculture, such as rooftop gardens[90,93]. This may be due to terms such as 'plant factories'[94,95], which could leave the impression that VFS products are 'Frankenstein foods'[96]. Nonetheless, VFS also have positive connotations, such as aesthetic integration within the built environment[97,98], product aesthetics (clean, high-quality, fresh products), food safety and high levels of health-benefitting compounds[99]. VFS have created new opportunities for venture capitalists and start-ups, enabling the growth of a new generation of urban food producers and indoor farmers, who may not be seen as 'real farmers'[89,91,93]. However, this new generation of farmers will probably be early adapters of promising technologies, such as using blockchain for quality guarantees in VFS[100].

Vertical farming carries economic risks and hurdles, due to prohibitive start-up costs, unaffordable properties in urban areas (especially in expensive cities in developed countries) and lack of investment capital (though this is increasing steadily)[91,94,96]. Moreover, current economic conditions, partly driven by venture capital, can result in VFS being able to raise capital but seldom to run profitable operations[92]. Yet, VFS offer the possibility of reinvigorating industrial estates with low housing costs and are generally suitable for densely populated megacities[96,97]. In terms of employment creation, VFS offer possibilities for urban populations, but they can have displacement effects on rural areas[96]. The focus of vertical farming on locally produced food may affect current value chain set-ups, potentially leading to short chains driven by start-ups and absorption by agri-food conglomerates[101,102].

For further development and scaling of VFS, institutional and infrastructural work is required, while technological optimization is needed to reduce costs and create sustainable business models[94,96]. Optimal locations, regulatory trajectories, and shared standards and methods thus need to be defined. This requires the construction of cross-sectoral innovation ecosystems that unite stakeholders, including vertical farming entrepreneurs, urban planners, real estate, agri-tech companies and non-governmental organizations[94,103]. Such innovation ecosystems should address values and ethics[104] and assess sustainability and environmental impact once vertical farming increases in scale[85,91]. For upscaling, different geographical locations may require different vertical farming models appropriate to their specific socio-economic realities (for example, infrastructural costs, farmer motivations and consumer habits)[85,96].

Public policy

So far, public policy around vertical farming has been fairly limited and scattered. Pioneering technologies can develop in a policy vacuum[105], but the scattered attention to VFS in innovation and

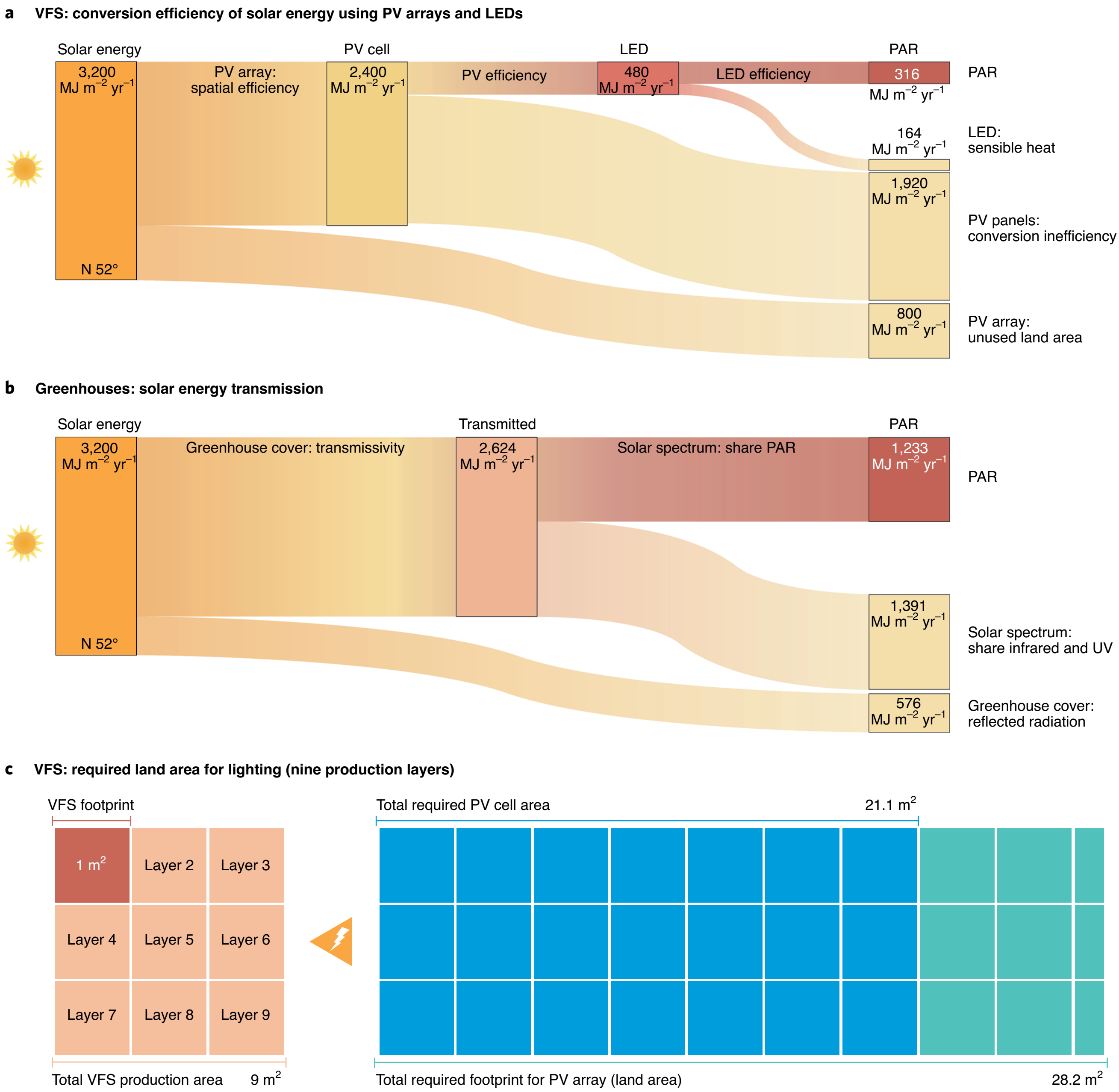


Fig. 4 | Sankey diagrams of the conversion of solar energy to PAR. a, Energy conversion in VFS using photovoltaic (PV) cells and LEDs. **b**, Energy conversion in glass greenhouses. **c**, The resulting ratio between a nine-layered VFS footprint, production area and the required land area for PV cells. Please note that the three panels pertain only to lighting energy: the energy requirement for the climate system (for example, cooling) has been excluded, as it depends too much on location and context. The assumptions for the energy conversion in VFS are that the PV cells have 75% land area efficiency and 20% energy conversion efficiency, and the LED efficacy is set at 3.5 µmol J^{-1} (projected industry standard). The assumptions for the energy conversion in greenhouses are that the greenhouse location is at 52° N latitude, the greenhouse transmissivity is 82% and solar energy contains 47% PAR. Additional parameters for the VFS include nine stacked production layers, with each layer operating at a PPFD of 250 µmol m^{-2} s^{-1}, a photoperiod of 16 h d^{-1} and a schedule of 365.25 d yr^{-1}, resulting in an LED electricity requirement of ~1,502 MJ m^{-2} yr^{-1}.

agricultural policy is surprising, given the potential contributions of VFS to resolving social and environmental issues[2,85,96]. Similarly to the socio-economic impacts of vertical farming, variation exists between regions regarding public policy. In Europe, public policy involvement is limited to research and development (R&D) support at the national and EU levels. Research investments in themes related to science-based, indoor crop cultivation systems increased considerably over the past few years (Supplementary Information 1). Interestingly, efforts in encouraging VFS-related innovation in the EU are not coupled to a broadening of the scope of agricultural policy. In 2016, a paper preparing a strategic approach to EU agricultural research and innovation mentioned vertical faming as potentially relevant[106], and in 2021, the production technique was discussed in the context of forging a climate-resilient Europe[107]; but neither the 2018 Common Agricultural Policy strategic plans[108] nor the recent Green Deal[109] and its Farm to Fork Strategy[110] bears witness to a change in agricultural policy to include novel forms of food production (Supplementary Information 2). In contrast, the

United States recently included vertical farming in federal agricultural policy, dedicating funds (US$2 million until 2023 (ref. [111])) for the "development of urban, indoor, and other emerging agriculture"[112,113]. The US Department of Agriculture also formed a National Committee on Urban Agriculture, which will provide guidance on policy formulation and outreach for urban, indoor and other emerging agricultural production practices and address obstacles to urban agriculture. Generally, public sector spending on agricultural R&D in the United States has decreased over the past two decades[114] in sharp contrast to Asia, where public and private sector spending on agri-food R&D has increased considerably in the same period[115]. Singapore's policy on procuring food self-sufficiency builds on trust in the potential of VFS. The city-state's involvement has gone from funding R&D in the 2010s (taking an active role in the development of private farming) to considering tax barrier adjustments[116] that would spur investments in vertical farming. Likewise, the Japanese government subsidizes high-tech companies that can no longer compete in traditional markets to invest in vertical farming development[117]. In an effort to ensure food security, China's agricultural policy—which traditionally emphasizes stimulating the production of staple foods[118]—now also includes investing in indoor farming[119].

Regional differences in the availability of arable land and other natural resources, as well as consumer demands, probably explain part of the observed variation in public policy attention to vertical farming. Adding to this is the ambivalent identity of vertical farming as a policy theme: vertical farming cuts across traditional institutional boundaries, which separate rural from urban planning[120] and innovation from agricultural policymaking. This ambivalence also disrupts the 'symbolic order'[121] by which to distinguish what is 'natural' and what is 'artificial', also complicating the regulation of vertical farming products. The discussion on whether to label vertical farming products as organic is a case in point: in 2019, Singapore's Food Standards Committee granted organic certification to a vertical farming company[122], whereas US, Canadian and EU labelling standards for the production, handling and processing of organic agricultural products are dissimilar and ambivalent regarding VFS depending on factors such as soil and substrate use in various stages of cultivation. Biofortification of crops (see section 'Product quality') may cause interpretational challenges in product regulation, raising questions over their status as fortified foods, foods for special medical purposes or novel foods. The Codex Alimentarius Commission set to work on this in 2014, but at present neither the World Health Organization (WHO) nor the US Food and Agriculture Organization (FAO) plans to define the concept or set guidelines on how to deal with the issue[123].

Currently, the suitability of VFS to address food supply chain challenges such as the supply of fresh, nutrient-dense food to local networks and raising consumer awareness about food is underutilized. To realize the full potential of vertical farming for addressing these food supply-chain challenges, policy blind spots and ambiguities must be addressed. An integral focus on food policies—rather than an institutional separation between innovation support interventions and agricultural policies—may present a proper embedding for assessing the merits of VFS.

Challenges and outlook

Given that VFS have the potential to be secure and sustainable sources of fresh food in urban areas[92], vertical farming is gaining momentum and expanding globally[124]. VFS have a low environmental impact, nearly no pesticide or nutrient emissions, minimal water and land use, and low food mileage, compared with other agri-systems. However, to contribute to the food supply chain, the high starting capital and operation costs of VFS will need to be mitigated. This can be done by advancing the system design, thereby lowering cost, increasing RUE and using a circular systems approach. Different VFS typologies with novel business models are needed, aiding economic viability and potentially overcoming current upscaling issues. However, there is almost no scientific literature on the economic feasibility of VFS, making speculation on future economics of VFS uncertain. Moreover, many novel vertical farming technologies postulated here require optimization—revealing new research questions ranging from fundamental plant physiology and applied physics to social science.

R&D supporting VFS should be aimed at reducing (or coping with) operational costs and the high demand for electrical energy. Operational costs and carbon footprint can be substantially reduced by the projected global transition towards renewable energy. Furthermore, projected improvements in LED efficacy[71,125] and LUE will result in cost reduction, as they simultaneously reduce energy use for lighting and cooling. Developments in online plant sensing, to monitor LUE continuously, will impact how light is delivered to the plant over the day and during its development, further reducing electricity use. Additional reductions in cost and energy can come from pioneering developments such as the use of vertical racks under direct sunlight[86,126] and wavelength-selective films that have energy-producing capabilities[127].

The number of profitable crops produced in VFS is currently limited, and breeding for specifically designed genotypes for vertical farming is in its infancy. We anticipate substantial gains in RUE and product quality from plant breeding. Fully controlled conditions and anticipated low disease pressure in VFS allow for the introduction of novel food crops or pharmaceutical crops or the re-introduction of forgotten crops to serve niche markets and employ long-tail business strategies[128,129]. VFS allow for changing the focus from genetic to environmental modification[11], adapting the environment to the genotype at hand. This approach would be especially beneficial for regions where genome editing is strictly regulated, such as the EU. Yet, in large parts of the world[130] where genetic modification techniques are permitted, this approach allows for entirely new genotype × environment effects. VFS can lower the risk of transgenic contamination—an ecological threat and ethical barrier for the use of genetic modification[131]. Genetic modification and full environmental control, especially when combined, are potent tools for enhancing the concentrations of specific compounds. Care therefore must be taken to keep concentrations of particular potentially harmful compounds below toxic levels[99].

The socio-economic impact of VFS is still unclear, as potential benefits and drawbacks for society are currently theoretical. However, vertical farming could form part of a technological remedy for environmental challenges that have arisen from a political economy causing these environmental challenges in the first place. Hence, as explored previously[92], we argue that it is useful to place VFS in a broader theoretical landscape than only the current political economy—to objectively scrutinize the assumption that VFS are a long-term solution for many challenges. For example, the heat produced by VFS and its disposal in urban areas might present new opportunities and challenges, depending on season, location and scope of the impact assessment. Little is known about the health effects of working in VFS with potentially frequent exposure to high light intensities from artificial light sources[125], the light spectrum of which may be very different from that of sunlight. Indoor production under fully controlled and safe conditions is preferred by consumers in several regions and cultures, whereas others might associate non-natural production with unhealthy food. Although VFS generally aim for higher nutritional value, negative impacts on specific plant mineral and phytochemical concentrations cannot be ruled out[33]. Moreover, paradoxically, the high hygiene standards in VFS could give rise to pathogen development, although biostimulants[78] and polycultures[132] could partly mitigate this hypothetical risk.

Suitable public policies could aid the acceptance and upscaling of VFS so that they can become a substantial part of current food supply chains. However, current institutional separation creates policy boundaries (urban versus rural planning and innovation versus agricultural policymaking), hindering high-yielding attention to the topic. An integral focus on food policies would help upscale VFS. Upscaling in itself will probably increase complexity, further emphasizing the need for vertical farming R&D. To speed up R&D and unfold the potential of data aggregation and meta-analysis, substantial investment in developing and adhering to data standardization, transportability and distribution[133] is needed. Importantly, VFS allow for fast transfer of scientific findings from labs to cultivation areas, or from VFS to VFS, taking away a considerable hurdle encountered in open field cultivation[134].

In conclusion, VFS could meet consumer demand for nutritious food, with a guaranteed and consistent quantity and quality every day of the year independent of soil, weather or climate change. Nevertheless, major challenges still exist regarding energy efficiency, economic profitability, automation and consumer acceptance. If these challenges can be overcome, vertical farming has great potential as a guaranteed source of high-quality food, providing a practical and resilient solution to present-day food system challenges.

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S.H.v.D., M.S., M.B., R.S.K. and L.F.M.M. defined the structure and topics of the Review. S.H.v.D. led the writing and reviewing process together with M.S., M.B., E.K. and L.F.M.M. The main contributors for each section are as follows: for the Abstract and Introduction, S.H.v.D.; for 'Crop growth', M.S., E.K., E.H., S.V.-C. and S.H.v.D.; for 'Product quality', E.J.W., J.C.V., R.E.S. and S.H.v.D.; for 'Automation and robotics', G.K., R.v.d.Z., M.B. and S.H.v.D.; for 'Environmental sustainability', L.J.A.G., W.v.I., R.S.K., C.S. and S.H.v.D.; for 'Socio-economic impact', L.K. and S.H.v.D.; for 'Public policy', A.L., M.B. and S.H.v.D.; for 'Challenges and outlook', M.B. and S.H.v.D.; for the parts on climate control, L.J.A.G., C.S., Y.Z. and M.K.; and for the parts on crop control, S.V.-C., E.H. and E.K. M.S. created Fig. 1. M.S. and S.H.v.D. created Figs. 2 and 3. L.J.A.G. created Fig. 4. M.B. conceived Box 1, M.S. and M.B. gathered the photos, and R.K. and S.H.v.D wrote the text. All authors proofread and approved the submitted work.

Competing interests

The authors declare no competing interests.

Additional information

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