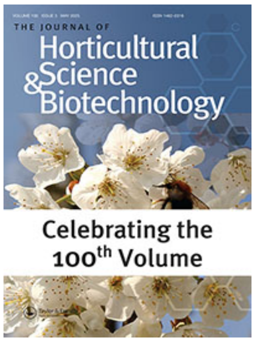

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REVIEW

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The future of vertical farming: necessary advances in precision technology, crop selection and market sector development

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ABSTRACT
Vertical farming in indoor controlled environments is increasingly recognised as an essential component of resilient and secure national-level food production, but varied challenges across technology and crop development, economic potential and market sector status conspire to prevent rapid adoption. Indoor food production in controlled environments, where the environment and production approaches can be optimised to enhance production outcomes, and which are unaffected by the negative impacts of extreme weather, offers a means to reinforce and future-proof traditional food production approaches, to ensure future food security, yet this sector has struggled to achieve economic parity with traditional field-based approaches and successful business models are rare. In this review we consider the status and developments needed across vertical farming technologies and crop options, to improve production efficiencies, and future market sector developments needed to address the economic challenges presented by this approach to food production, to ensure successful development of the essential indoor food production sector. We highlight four key areas that need to be addressed, namely: energy and production efficiency; delivery relative to economic scale; and deficit compared to traditional agriculture, whilst also suggesting potential solutions within each area.

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Introduction

Food security is a growing concern globally, as human populations increase and as the pressure from climate change affects traditional food production systems (Mirón et al., 2023; Ray et al., 2019; Searchinger et al., 2019). The UN has estimated that between 691 and 783 million people have already faced food shortage in 2022 and 29.6% of the world population are moderately or severely food insecure (FAO, 2023). Estimations of future demand indicate that edible crop and meat production will need to increase significantly in order to meet future demands (Berners-Lee et al., 2018; Hossain et al., 2020), but pressure on food production as a consequence of climate change, and from alternative land-use options considered necessary as climate change mitigation strategies, such as biofuel production, means traditional field-based agriculture alone is insufficient to guarantee future food security (Ahmed et al., 2021; Kornhuber et al., 2023; Oh & Lu, 2023).

Indoor plant production, also known as Controlled Environment Agriculture (CEA), is considered an essential part of future food production (Oh & Lu, 2023; Petrovics & Giezen, 2022). There are many forms of CEA, from glasshouse production systems typically (but not exclusively) utilising a single growing layer, to vertical farming (VF) systems where plants are grown in multi-layered soilless systems in controlled environments, creating a factory-style production process with high space-use efficiency. This review will focus on VF as the main approach to CEA, unless otherwise stated.

The expected benefits of VF have been widely noted: they include reduced land and water requirements and consumptions; greater precision in the use of agrichemicals; greater control over production outcomes (crop uniformity, time to harvest); and more harvests per year than is possible with field-based agriculture (varying per crop) (Beacham et al., 2019; Kabir et al., 2023; Van Delden et al., 2021). In addition to this, production using VF is inherently climate change agnostic, as the growing environment created is not subject to the vagaries of extreme weather, making this a technological option of significant potential to reinforce and future proof traditional food production approaches, to ensure future food security. Nevertheless, numerous challenges exist for this technology, in terms of widespread adoption, which typically centre on the inherent issues of high energy usage and potentially high labour and capital investment costs, which are problematic in the context of economic efficiency and viability, and the potential for commercial return on investment (Lubna et al., 2022). Yet, in future scenarios where extreme

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weather events occur with greater frequency as a consequence of climate change, and where field-based food production systems become less reliable (Kornhuber et al., 2023), the need for ensured food security may shift the balance in favour of controlled environment production systems (Kalantari et al., 2020; Oh & Lu, 2023). The potential for extreme weather events that cause crop losses in multiple regions simultaneously presents an increasing risk (Gaupp et al., 2020; Kornhuber et al., 2023; Tigchelaar et al., 2018). This study will focus on three key areas of necessary development for the future of the VF industry: precision technology, crop strategy and selection, and market sector identity and techno-economics, to quantify the challenges currently obstructing widespread adoption of VF, as well as highlighting the essential areas for further research necessary to enable the development of this sector.

Opportunities and challenges for current indoor production

In VF systems, plants are grown in indoor facilities. In these controlled environments the growing conditions and production factors, including temperature, lighting (intensity, duration, spectral composition), CO_2 content, humidity, nutrient availabilities, and others, can be carefully controlled to enhance production outcomes. These systems typically utilise artificial lighting, derived from LEDs, but can also work in combination with sunlight (such as in advanced glasshouse systems). Water and nutrients are most commonly delivered to the plants hydroponically or aeroponically, offering high potential for automation and control. These closed-loop systems limit the loss of fertilisers to the environment, reducing rates of nutrient pollution (Gruda., 2019), and use substantially less water than is the case in both traditional in-field and glasshouse production systems (Graamans et al., 2018; Perez, 2014). The controlled nature of these environments means that food can be grown independent of external environmental conditions, thus avoiding the potential impacts of extreme weather events (Moghimi & Asiabanpour., 2023), and annual/seasonal environmental variation which can affect yields and produce quality (including appearance and flavour profiles, as a result of environmentally mediated stress). Additionally, limited environmental exposure reduces the opportunity for damage and impact from pests and pathogens, improving production outcomes and limiting the need for pesticide usage (Zhang et al., 2021). VF also uses substantially less land per kg of food produced compared to traditional farming (Kalantari et al., 2018), though the estimates of the size of the reduction can vary greatly (Pennisi et al., 2019).

Due to these promising advantages, the VF sector has expanded rapidly over the past decade and has attracted hundreds of billions of pounds in investment (de Oliveira et al., 2022). However, the failure rate for businesses in this sector is concerningly high and it has been estimated that around 85% of VF ventures fail within a few years of startup without continued investment of funds (de Oliveira, 2022). This is the result of multiple factors, including the high energy requirements for production and the significant initial investment for the system design and build, coupled with difficulties in achieving economic efficiency and returns on investment with the crops produced.

The majority of current VF systems grow a small range of crops, primarily salad greens, herbs, microgreens, and other leafy greens, which are selected for their short growth cycles and relatively high retail value. These crops can have an extremely high vitamin content and potent flavour, but, importantly they are not classified as staple crops. The production of the four key staple crops (wheat, maize, rice and soybean), that make up two-thirds of all calories consumed by humans globally (Kim et al., 2019), is beyond the current economic potential of VF systems, due to the high energy cost required to grow the crops to maturity. As such, VF to date offers a contribution to the global food security of auxiliary crops.

Economics of VF

The economics of VF have hitherto been problematic. Numerous high-profile businesses and early technology adopters have struggled with profitability, and beyond the financial support levied from investment, have failed to realise successful business models (de Oliveira, 2022; Simos & Jordan, 2023). Many of the high profile failures have been large-scale systems, which have required significant investment to establish. Although these larger farms can hypothetically benefit from an economy of scale, several compounding factors limit their viability. Large-scale VF systems offer the potential for mass production of horticultural food items, sold to retailers for wider distribution. Yet, this advantage may in effect mean the produce outputted by larger systems achieves a lower price point than smaller-scale systems, which are selling direct to the consumer at a higher price point. The work of Almena et al. (2019) considers the benefits of centralised vs. distributed food production and demonstrates higher profitability potential in the latter, as smaller, distributed food production systems become profitable at much lower production rates than centralised, or large-scale, production systems.

Determining the optimum scenario for VF production is challenging. The potential profitability of VF systems has been modelled for different scenarios (de Oliveira et al., 2022; de Souza et al., 2022), but further work is necessary to determine optimum size and technology/control level in order to achieve profitable business models, and for effective integration with existing food production systems.

Market sector development

The differences in size and scale of VF systems can have a significant influence on initial profitability and potential success. Despite the media exposure of the large-scale technologically intensive VF systems, most vertical farms are smaller scale, single site operations, employing between one to three people (CEA census, 2021). In Northern America there has been a large increase in the number of small-scale farms in recent years with localised supply chains (de Souza et al., 2022). The decreased setup cost for smaller scale operations coupled with direct-to-consumer business models offers some obvious advantages. Establishing smaller farm systems lowers the initial cost to set up a VF system, reducing the risk exposure and offering more realistic return on investment (ROI) potential. However, this is often at the expense of more advanced technologies afforded with large investment. This presents an interesting dichotomy with regard to the advancement of this sector (Figure 1), whether sector and individual business development should be incremental (bottom-up), or whether development stages can be bypassed by larger scale investment and the establishment of large-scale systems (top-down). Considering the deployment of VF technology in this context could inform where support from agents such as government should be concentrated, and could allow more widespread adoption among the general public and from existing farm systems, as a diversification option, and may refine the objectives in terms of technology development from the very high-end extreme control philosophies to scenarios where less control is required in order to achieve economically viable production objectives.

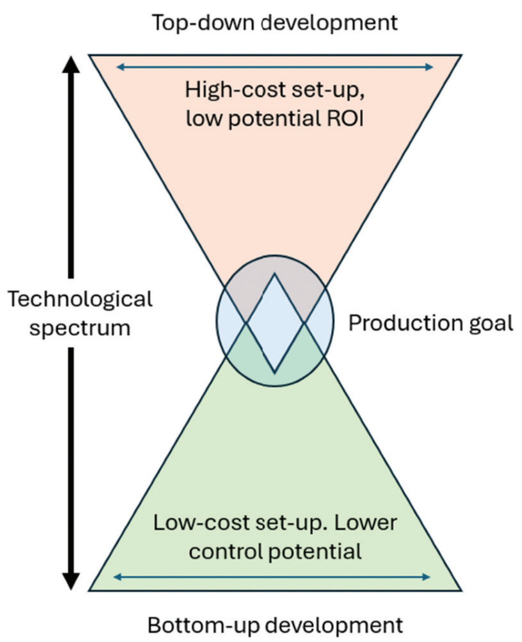

Figure 1. The industry development dichotomy. This typology describes the competing approaches to industry development, from businesses predicated on large-scale production and high investment from initiation (top-down) and businesses developed more incrementally, using VF technologies to enhance production as challenges are encountered (bottom-up), developing business opportunity in-line with supply chain demands.

Both large- and small-scale VF still faces several challenges in competition with traditional open field farming. The energy costs of VF systems can be many times greater than traditional farming per kg of food produced (Moghimi & Asiabanpour, 2023). Some allowance in this comparison must be made for the influence of subsidy, which supports traditional agriculture, with around one third of UK farms estimated to be loss making without support payments (House of Commons Committee of Public Accounts, 2022). Whilst VF has been subsidised in some cases (de Oliveira, 2022), public policy and investment in VF systems is often limited. Furthermore, VF and other urban agriculture projects have been found to 'fall between' the jurisdictions of urban and rural regulatory bodies in the EU (McEldowney, 2017) and thus are unable to access agricultural subsidies. Analysis of recent EU food and agricultural strategies has been shown to lack any consideration of novel methods of food production (Van Delden et al., 2021). Regardless, technological improvements to either improve the energy efficiency of lighting systems or the use of renewable energy to power vertical farms will be required to lower energy prices and the carbon footprint of vertical farms, and this will remain a key objective.

Techno-economics

The principal challenge for VF currently is the cost of energy for production. Other forms of growing, such as traditional greenhouses and open field agriculture, have lower energy burdens, relative to VF. Most types of VF, conversely, must provide artificial lighting and environmental control, incurring energy costs. A potential solution to the energy consumption and subsequent costs of VF is to seek to align production with electrical supply (such as in Figure 2). Integrating renewable energy derived from solar, anaerobic digestion, wind turbine, and geothermal energy generation into the supply for VF production could be one of the steps in overcoming the energy barrier. An energy-yield-cost model has been proposed as a method of evaluating the clean energy supply for VF to ensure food production in a more commercially viable scenario (Keyvan &

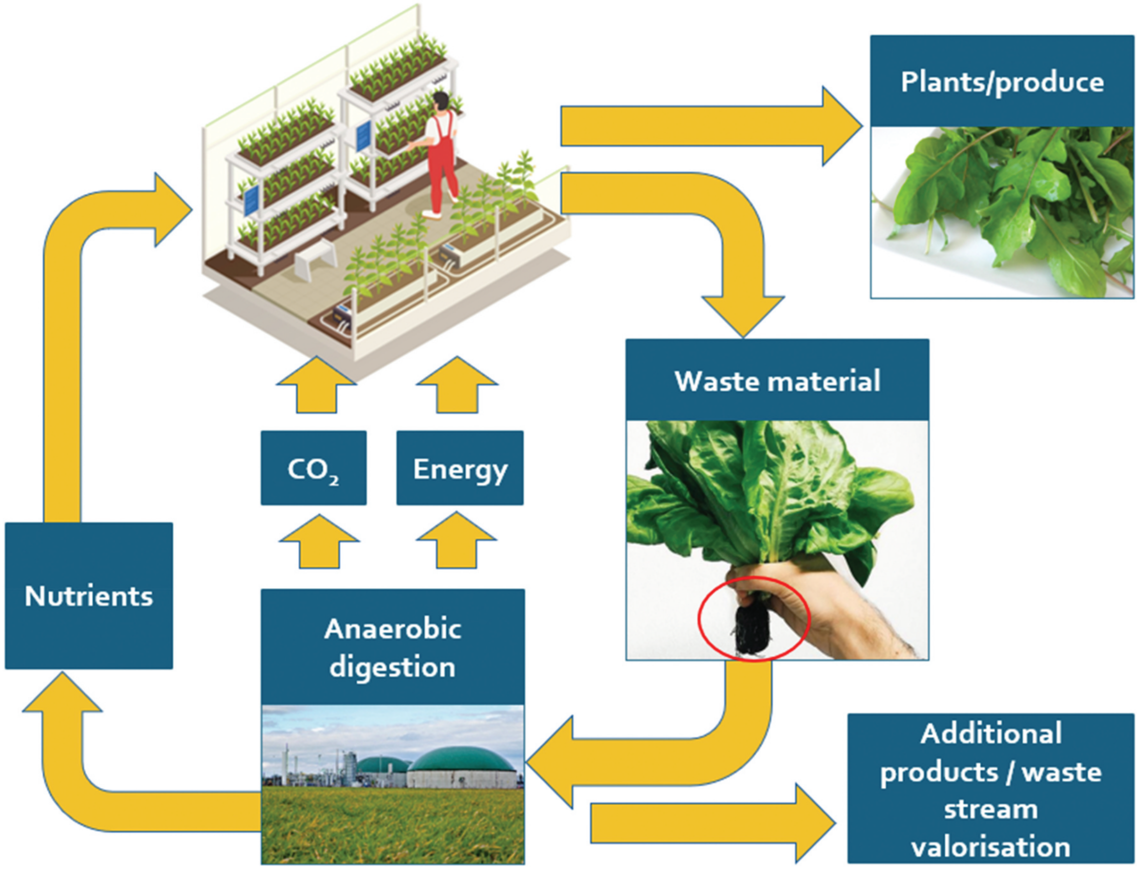

Figure 2. Circular economy solution for VF systems utilising anaerobic digestion (AD). In this model, horticultural production waste is managed via co-location with AD, and resources including energy, nutrients and CO_2 (and for certain systems, heat) can be reclaimed and re-used, for maximum efficiency.

Roshandel, 2024). This intriguing, yet theoretical model, suggested that, for lettuce (*Lactuca sativa*) grown under VF conditions, 2.35 m^2 of solar panels is needed for every 1 m^2 of crop production. A similar study in Malaysia suggested savings of 8–11% on electricity consumption could be made by linking solar panel electricity production directly to VF production (Teo & Go, 2021). The link between clean energy production to the electricity supply required by VF is tantalising in overcoming the potential energy cost barrier the sector faces. Further work, and potential government support (as was the case for the study in Malaysia: Teo & Go, 2021) will be needed to develop a location-based commercially viable model.

Where other forms of electrical supply must be considered, a load-shift or fluctuating electrical demand model has been considered. By aligning the operating procedure of the lighting in a VF with times of low-demand and thus low-cost energy supply, savings of between 16–26% could, in theory, be achieved (Avgoustaki & Xydis, 2021). The study highlights the benefits of developing operating models for individual VFs in specific countries drawing upon the region-based advantages of the fluctional price of electricity.

Targeting the use of VF to localised consumption scenarios, such as within offices or domestic situations, has also been evaluated. Both ideas rely on harnessing the niche interest of the 'users' of the urban space to promote and fund the costs of a VF system for local growing of leafy greens and herbs. In an office setting the cost for VF production of crops remains higher than greenhouse or open field agriculture, but there is a reduction in overall CO_2 emissions through reduced transport costs and food miles (Cichocki et al., 2022). Intriguingly there is a suggestion that VF crops are more efficient than ornamentals in reducing CO_2 concentrations and increasing oxygen levels interior spaces like offices, potentially offering synergies for the human workforce present. In urban family settings, VF systems are maintained and managed by the people living in the domestic setting. Case studies in Shanghai (Shao et al., 2022) and Poland (Sroka et al., 2021) demonstrate that they can offer a locally sourced, high quality, low cost, and production resilient edible crop, with a low carbon footprint when coupled with renewable energy sources.

The techno-economic assessment of VF aligns with the 'common sense' observation that is the core of the challenge for this technology: it is necessary to pay to recreate the energy input given 'free' from the sun in other food production systems. The advantage of this burden is that VF systems are removed from the increasingly dramatic nature of the weather, as climate change brings greater unpredictability to seasonal weather patterns. Coupled with geopolitical uncertainties, the food security and resilience VF can bring is a significant offsetting to the energy input considerations. It could also be concluded from the techno-economic assessment that the lower the price paid for energy, the greater the profit margin of produce derived. It is therefore essential at the planning stage of any VF enterprise to build-in the quantum of energy required per the scale of the VF to be undertaken. This may result in a modest scale VF system being the most desirable techno-economically (Figure 1). Through a more considered approach it should be possible to deliver economically viable crops to market through judicious selection of VF system, energy use, and crop scale.

Precision technologies

One of the most appealing factors of VF, from a production perspective, is the ability to incorporate automation and control technologies which can enhance the factory-style production of food and limit the need for human labour and input. Using such approaches could, in principle, result in more favourable outcomes such as reduced labour costs, and more consistent yields through reduced human error, which is a commonly reported risk factor by VF operators (de Oliveira, 2022). A range of advancements in technology and approach are needed in order to truly exploit the theoretical opportunities.

Robotics, control and automation

The incorporation of robotics into VF systems, for actions such as seeding, transplanting and harvesting, has been previously discussed (Chitre et al., 2023; Jayasekara et al., 2021; Van Delden et al., 2021). This could offer some appealing advantages, such as the optimisation of cultivation space where humans are not required to move around, or the production of crops in environments potentially harmful to humans (i.e. high UV, humidity, and CO_2 levels) (Van Delden et al., 2021). However, the benefit added requires further evaluation in terms of economic and technical efficiency. Much of the promise offered by robotics in VF is as yet unrealised, with the cost, energy, and versatility requirements proving prohibitive for many horticultural operations (Chitre et al., 2023; Wichitwechkarn et al., 2023). Additionally, as robotic systems are currently experimental, low success rates and damage to crops is potentially an issue (Koostra et al., 2021). For widespread deployment, robotic assistance will need to be adaptable to a range of production environments and be reconfigurable to allow application to variable tasks, in order to avoid procurement of multiple machine types. Modular, reconfigurable robotics systems could be beneficial in this regard, as a single machine could be adapted to fulfil multiple tasks across different farm layouts (Chitre et al., 2023). This could also help to make robotic assistance accessible to smaller-scale vertical farmers in the future, an essential factor in the development of a competitive and robust industry sector. As such, research needs to focus on automation which is reasonably (relatively) cheap, easy to install in small-scale farms and which requires minimal training or technical knowledge to operate, relative to benefits in labour reduction.

In order to have automated robotic labour, quantification of environmental variables and cues is needed through the incorporation of sensory systems (Figure 3), with suitable control software. The development of the 'Internet of Things' (IoT) has advanced significantly in recent years and is applied in various applications across commercial and domestic environments, including VF (Kaur et al., 2023; Putri et al., 2023; Ullah et al., 2023). Where this is linked to artificial intelligence (AI) driven control systems, this can offer opportunities for full system automation. This could be used to generate a mixture of data driven and mechanistic models (i.e. using a mixture of existing knowledge about plant growth and machine learning) to enable real-time monitoring and control over key processes in VF systems (Van Delden et al., 2021). Other potential uses of AI technology include scheduling farming operations to maximise harvests (Abukhader & Kakoore, 2021) and identifying potential plant diseases in crops (Siropyan et al., 2022). However, many automated systems are custom-made for VFs and not open source, which is potentially disadvantageous (Wichitwechkarn et al., 2023).

Microclimate sensing

Controlled environment growing in principle offers a paradigm where the environment is stable and consistent. However, subtle variations in the near-crop environment, including differences in temperature, humidity and CO_2, can drive sizeable differences in production outcomes. Factors idiosyncratic to VF systems, including the physical layout or heat emittance potential of lights, can result in 'hot spots' or 'stagnant air', which can result in uneven growth or the potential for increased risk of pest/pathogen development (Van Delden et al., 2021). Insufficient ventilation can also result in undesirable outcomes such as tipburn, a visible necrosis in the leaves of plants which can impact crop value (Kauffman, 2023). Understanding the grow-environment in the near vicinity of crop plants is increasingly important (Figure 3), as air flow patterns can be drastically changed by the location of inflows and outflows within VFs (Lim & Kim, 2014), and by heat sources and distribution with a grow space. Additionally, feedback mechanisms

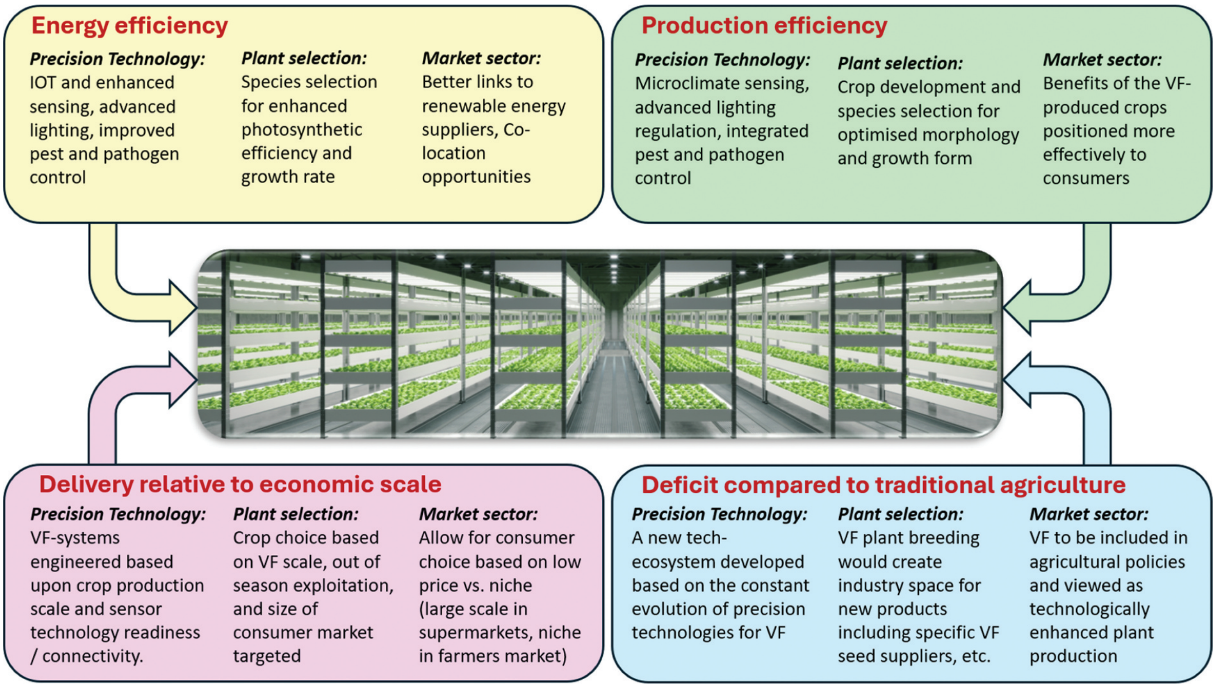

Figure 3. Future challenges and opportunities for VF systems. The challenges and opportunities across energy use, production approaches, economics and industry-centred characteristics are considered and summarised in the context of necessary developments for the technology, biology and market sectors.

between the crop plants and the environment, such as transpiration rates, which both influence and are influenced by the characteristics of the growing environment, will drive variation in environmental characteristics. This can be monitored using multivariate sensor systems, coupled with IOT technologies (Ullah et al., 2023), to offer detailed information at numerous points in the near crop area, from across the VF system.

One production advantage of this approach, beyond crop growth potential and harvest/development uniformity, is the opportunity for automation and localised interventions in larger systems, as opposed to factory-wide interventions. This may serve to enhance the precision of management, and allow parsimony in environmental management technology needed, both in terms of equipment use, allowing energy savings, and in capital purchasing requirements. HVAC systems are the second largest energy consumers in vertical farms after lighting (Arcasi et al., 2024) and have a high initial capital cost.

Cleaning/sterilising technologies

The nature of hydroponic growing systems and the presence and availability of water and nutrients for growth can make the management of pests and pathogens a problematic challenge. In the absence of management, the development of algae or biofilms in irrigation liquid is highly likely and, in systems without sufficient humidity management or air movement, the development of moulds or mildews on plants or substrates presents a production challenge requiring constant monitoring and management intervention. Current approaches for management are varied and include chemical sterilisation (i.e. hydrogen peroxide (H_2O_2) or ozone (O_3) treatment) or physical degradation (i.e. UV light or heat treatment) (Roberts et al., 2020). Each method presents difficulties in terms of energy efficiency, ease of automation or the maintenance of a hospitable growing environment for the target production organisms. Establishing technological options that are fully integrated, self-activating and which are energy efficient is therefore a necessary technological advancement.

Filtration technologies for water management

Filtration technology has advanced significantly in recent years and offers a reliable, mechanical option for the management of irrigation materials, particularly in recirculatory hydroponic systems. A liquid phase traditional filter can remove particulate materials that are greater in size than the pores within the filter, with pore sizes generally ranging from 1–200-mm. Membranes are an advanced filtration technology that utilise polymer films or ceramics to achieve separation. In this process, feed solutions are passed through the membrane (permeate) with material too large to pass captured (retentate or concentrate). Membranes are classified by the pore size of the filter and are generally defined as microfiltration (MF, 0.05–10 mm), ultrafiltration (UF, 5–100 nm), nanofiltration (NF, ~1 nm) and reverse osmosis (RO, nonporous) (Oatley-Radcliffe, 2017). In the case of traditional filtration and MF, the generally accepted mechanism of action is simple sieving. However, with the other membrane processes the separation is achieved by a combination of steric, electrostatic and dielectric effects.

Vertical farming systems often employ closed-loop recirculating irrigation which can facilitate the spread of pathogens within the system. These systems require a network of drains that collect and treat the water within (Wichitwechkarn et al., 2023). The typical materials flowing in such a recirculation loop will be particulates and microorganisms (mould and algae). Micro filtration is an effective physical barrier to such organisms and will provide near 100% reliable removal. At the small scale, such a process will use a cartridge style frontal filter (similar to a car fuel filter) and will need periodic replacement. At larger factory scale this set-up will consist of a tangential flow filtration process with either hollow fibre, tubular, or a spiral wound membrane (Stanojević et al., 2003). This would result in the production of around 90% cleaned water and a slurry containing the resultant particulates. If further water recovery is to be made then this slurry would need to be processed, typically in a pan filter, which would remove the remaining liquids that could then be sent back to the water reservoir. The particulates would then be available as a damp cake for disposal to an anaerobic digester. Any residual salts and nutrients in the liquid phase would be retained in the permeate and recycled back to the farm. This approach has been discussed and demonstrated in several works to date (Mir et al., 2022; Saengsuk et al., 2024; Wiegmann, 2023).

So far, water has been considered as recirculating within VF and leaving via products. However, fresh water must be introduced into the system as well, and consideration must be given to where this water comes from. Where there is an abundance of fresh water in the local environment then this feed stream is of little concern other than that of sterility requirements that can be achieved using MF, already discussed. However, VF in the future are potentially likely to be based in large metropolitan areas (Al-Kodmany, 2018). Many cities around the world are already struggling for fresh water and water scarcity is expected to increase significantly by 2050 in most areas of the globe (He et al., 2021). Grey or black water sources present a water recycling and extraction opportunity for cities of the future, with locations such as Singapore already employing a 'four national taps' strategy, which includes: Desalinating seawater; indirect potable and direct non-potable reuse of reclaimed water; the storage of rainwater; and imported water (Bai et al., 2020). In this context MF can be employed to remove particulates and contaminants, followed by RO, which removes small organics and salts. The result is a water source that would be clean enough to supply VF systems without onerous burden on existing freshwater resources.

In addition to water management, filtration technologies could be employed to reclaim nutrients from a range of waste streams. These materials could then be employed in the cultivation of horticultural products. This has been demonstrated for cheese whey (Hidayat et al., 2023) and a range of anaerobic digestates (Zacharof et al., 2019) including digestate derived from dairy manure (Gerardo et al., 2015). Filtration technology could therefore offer an opportunity for enhanced recycling or circular economy solutions to be applied to VF system waste streams, where organic horticultural wastes could be processed via anaerobic digestion and the derived energy and nutrients reutilised in the production process, significantly enhancing efficiency (Figure 2).

Electrochemical sterilisation

As an alternative to mechanical interventions, such as filtration, it is possible to apply the principles of electrochemistry for sterilisation and pathogen removal (Kerwick et al., 2005; Lévesque et al., 2020). Electrochemical disinfection, where electrical currents are passed through irrigation liquid to convert chloride ions in solution to free chlorine and perchlorate ions (Cl2(aq), and OCl(aq), respectively), at levels below phytotoxicity, is not a new process but is typically applied as a separated function rather than integrated directly into the hydroponic setup (Lévesque et al., 2022). Dissolved chlorine gas is an oxidising agent in aqueous solutions that can eliminate microbial life present in irrigation liquids. Once the electrochemical stimulation is stopped, the chorine gas converts back to chloride ions, but can be transformed to free chlorine again by the repetitive application of the electrochemical stimuli (Lévesque et al., 2019). Integrating this technology into VF systems offers considerable opportunity for automation, reducing the need for multi-stage irrigation management, as well as saving on space, equipment, and management input. Furthermore, in situ treatment of fertigation liquid in re-circulating hydroponic systems can reduce production material wastage, pest and pathogen contamination and management intervention requirements.

Crop selection and strategy

Currently the plants grown in controlled systems differ little from organisms employed in traditional field-based agriculture. These organisms are the product of hundreds to thousands of years of selective breeding, for characteristics that are useful in field-based systems. For VF in the future, the selection of what would be considered desirable phenotypes, genotypes, morphologies and potentially phenologies will need to be reconsidered (Figure 3).

Selective plant breeding for VF

The key plant traits for food crops that are highly productive in VF systems are a compact root architecture, compact aerial parts, normally manifested in a short stem and bushy leaf system and a high cropping yield of small fruit in the case of fruiting plants. Whilst their cultivation is technically possible, root or fruiting crops of large dimensions are not yet commercially viable to be produced in VF systems. Furthermore, production challenges, such as the requirement for pollination to instigate fruit set, must be considered. For these reasons, commercial VF have predominantly focused on leafy greens, herbs and other non-fruiting crops, as their major plant species targets. Yet, the morphology of these crops is potentially still sub-optimal. For instance, the rosette formation for crops such as lettuce may confer advantages to the plant in outdoor systems where there are variations in temperature, climate, etc., but in a controlled system this represents a sub-optimal formation for optimal space usage. The goal for any selective breeding endeavour will focus on plant structures optimised for compact cropping environments, for both root and aerial parts, to reduce the production of non-target biomass. Moreover, high capacity for nutrient uptake, rapid maturation and tolerance or favour for artificial forms of lighting would also be favourable characteristics (Singh & Kombo, 2024; Teo & Yu, 2024). These plant traits should lead to limited production of 'unwanted' biomass, reducing the production of surplus biomass enhancing production efficiencies. Additionally, reducing the requirement for primary input materials (e.g. nutrients, photons) which are usually the costliest in VF systems, will also lead to operational efficiencies. Thus, combining these gains should lead to a more profitable VF production system.

One technique that has yet to be applied widely in VF crop development is genetic modification. Advanced tools such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) may accelerate the potential for genetic modification of existing crops, to alter or augment existing characteristics for application in VF systems, but only where the genetic makeup of an organism is sufficiently well defined. The work of Teo and Yu (2024) considered the untapped potential of genetic engineering for VF systems and highlights three breeding targets for plant traits which could be optimised for VF. These included: Traits to maximise production (achieved through optimising the equilibrium between growing inputs, such as photosynthetic efficiency and growth rates, versus harvest outputs, such as increased yields and decreased untargeted biomass); traits to enhance resource management (compact plant architecture, self-pollination for fruiting crops, potential for integration with automation for harvesting); and traits aligned with consumer preferences (targeting genes for enhanced nutrition, desirable flavours or favourably altered appearance, i.e. purple or orange leaves instead of green).

Yet, whilst genetically modified (GM) crops are a controversial but essential part of current open-field agricultural production, the application of this approach may present an alternative issue for VF, in that indoor production is already considered by some to be concerningly artificial (Yano et al., 2021). This may be further compounded by the application of genetically modified crops. Additionally, whilst GM crop research for VF is already underway, it is unclear how quickly advances using this approach will be made. It is possible that commercially viable and available GM VF-specific plants could take years to develop. Nevertheless this approach is expected to make significant differences to the applicability and efficacy of VF and is likely to be a vibrant area of future research and development activity.

Plant-based production of non-food products

While economic constraints limit the current selection of food crops grown in vertical farms, an alternative market may be the cultivation of plants for pharmaceutical, nutraceutical or phytochemical production. Such products are often sold in market sectors with potentially higher profit margins per mass of product. The target plant species may also benefit, or even require, the specifically controlled growth environments offered by VF production systems, allowing the standardised production of the targeted phytochemical (Huebbers & Buyel, 2021). A key feature of VF production is the ability to specify the growing conditions desired to maximise the biochemistry within the plants, resulting in the phytochemicals/secondary metabolites of interest. Similarly, this desired biochemistry can be achieved by manipulating the growing environment to elicit a specific stress response in a plant, leading to the production of phytochemicals of commercial importance (Yeshi et al., 2022). Various factors can be used to induce stress, such as nutrient solution composition, temperature, irrigation frequency, light intensity and composition, applied either singularly or in combination to elicit the necessary plant stress response (see Table 1). For example, galantamine is an alkaloid found in daffodil plants (genus *Narcissus*) which is used to help alleviate the symptoms of patients with mild-to-moderate Alzheimer's disease (Santos et al., 2020). The concentration of galantamine is increased in daffodils when grown in upland environments, due to the potentially

Table 1. Known plant species targets for high value chemical compound production.

Plant organism		Compound	Purpose/treatment	Ref
Daffodil	*Narcissus* spp.	Alkaloid - galantamine	Alzheimer's disease	Santos et al. (2020); White et al. (2019)
Madagascar periwinkle	*Catharanthus roseus*	>100 alkaloids including ajmalicine, serpentine, vincristine and vinblastine	Circulatory conditions. Treatment for cancers including lymphoblastic leukaemia, Hodgkin's and non-Hodgkin's lymphomas, Ewing's sarcoma, breast cancer	Kalidass et al. (2009); Sharma et al. (2022)
Lesser periwinkle	*Vinca minor*	>50 alkaloids including vincamine	Neuroprotective agent for cerebrovascular conditions	Amiri et al. (2020); Patyar et al. (2011)
Foxglove	*Digitalis* spp.	Cardenolides including digitoxin and digoxin	Heart rate regulation for patients with compromised cardiac function	Verma et al. (2016)
Lavendar	*Lavandula* spp.	Therapeutic or essential oils	Stress, anxiety and depression alleviation. Aid for sleep	Cardia et al. (2021); Jafari-Koulaee et al. (2020)
Aloe vera	*Aloe vera*	Anthraquinones, polysaccharides, chromones	Topical ointment to treat skin-conditions, wounds and burns. Antiseptic and antimicrobial	Saleem et al. (2022)
Cannabis/ marijuana	*Cannabis* spp.	Tetrahydrocannabinol, cannabidiol, cannabinol, tetrahydrocannabivarin, dronabinol, nabilone, CBD, nabiximols	Painkiller. Treatment of psychological conditions such as PTSD and anxiety	Hameed et al. (2023); Legare et al. (2022)

challenging growth conditions (e.g. high rainfall levels, exposure to wind, cold temperatures and poor soil) (White et al., 2019). Understanding this 'recipe' for stress could allow the prescription of growing environments utilising VF that are optimised for the production of phytochemicals such as galantamine.

In addition to pharmaceutical products which occur naturally within plants, genetic engineering could also be used to grow crops that have been modified to produce certain compounds. In comparison to the previous section, this form of GM often involves inserting genes into a plant's DNA, that encodes a response for the plant to produce a specific chemical of interest. Usually, these chemicals are designed to accumulate in the leaves or fruiting bodies of the plant (Li et al., 2010). Genetically engineered crops, including those used for pharmaceutical chemical production, face heavy legal restrictions in many countries, which limits their potential for cultivation on a commercially viable scale (Marone et al., 2023). This potential issue may be reduced when applied in VF systems, as the potential for biological control is significantly greater than traditional agriculture. The risk of contamination can also be further reduced by the adoption of increased automation, as this limits the degree of contact between humans and plants (Huebbers & Buyel, 2021).

Although pharmaceutical compounds and other phytochemicals can potentially be sold at a higher price per mass of biomass produced, a possible limitation is the cost of extraction and purification of the targeted phytochemicals. For pharmaceutical proteins grown in GM crops, downstream processing can make up to 80% of the production cost (Fischer et al., 2013). For some pharmaceutical phyto-based products, this could be resolved by GM engineering the plants so they could be consumed orally (Ayan et al., 2022). However, this will likely not be feasible for all pharmaceutical products produced by GM crops. Moreover, this is not the case for many compounds found naturally within certain plant species. In the case of the latter, the desired compounds are often produced in trace amounts by the plant. For example, the anti-cancer alkaloids in *C. roseus* make up just 0.0003% of the plant's dry weight (Kalidass et al., 2009). Nevertheless, the phyto-pharmaceutical industry was estimated to be worth €214 billion in 2018 (Huebbers & Buyel, 2021) making this a key area of focus for crop production choices for VF systems.

Plant desirability index for vertical farming systems

Based on the plant traits, engineered or otherwise, proposed herein, a Desirability Index has been compiled for plants specifically for use in VF systems (Table 2). These desirable factors are not only commercially driven or linked to profit-driven agriculture. As mentioned in Section 2.2, governments or non-profit organisations have and should play a role in maximising the benefits of VF systems in urban regeneration and social well-being.

Knowledge sharing, education and training

One of the most prominent challenges is a lack of data and information sharing. Several authors have noted that vertical farming companies are often reluctant to provide information regarding operational costs, profitability and production approaches, most likely due to fear of competition (de Oliveira et al., 2022; de Souza et al., 2022; Lubna et al., 2022). This lack of data sharing and collaboration means that industry wide standards and best practices have not developed and, as such a large amount of time and money is devoted to research and development among new startups.

Table 2. Conceptual desirability index for plant characteristics suited to vertical farming.

VF Desirability Factor	Considerations
Plant structure	• Compact and high yielding aerial parts to maximise. • Compact and highly efficient root system for nutrient and water uptake. • Increased or targeted phytochemical production.
Consumer demand	• Improved aesthetic quality, consistence of shape and size or unusual shapes or colours. • Enhanced nutritional benefits.
Commercial value	• Lower prices when providing crops out of season. • Enable supply chains de-fossilisation and FMCGs to meet NetZero goals by using plant-based raw material sources.
Plant production resilience	• Reduce impact of extreme weather or geopolitical events. • Maximise use of raw material inputs, ensuring longer-term profitability of operations.
Socio-economic benefits	• Installation of VFs in office/residential spaces for increased connectiveness to nature and origin of food. • Re-purposing and rehabilitation of derelict buildings for new commercial ventures.

This often occurs while the companies are constructing their facilities or attempting to run them to make a profit (de Oliveira, 2022). Additionally, with every business failure, the information and insights derived are often lost, resetting the bar of development back to zero. Furthermore, this lack of information is likely exacerbated by the large proportion of VF founders and operators who have no experience in agriculture, which was consistently over 40% from 2019 to 2021 according to the CEA Census (2021). Similarly, finding staff with existing VF skills or expertise is also challenging. Mistakes caused by employees, such as improper seeding or incorrect nutrient dosing, can also substantially lower crop yield, and a survey across 18 vertical farms showed human error as the mostly commonly reported risk (de Oliveira, 2022). The development of education resources to support the developing VF sector is required, and this approach to food production should become a component of agricultural and horticultural studies, alongside the existing learning of open field or greenhouse growing.

Conclusion

Vertical farming is a key future component of food security and resilience that will be needed to feed a growing population against a backdrop of significant environmental change as a consequence of climate change. Whilst the principle of VF is sound, the current state of the industry and marketplace make the widespread implementation of this technology problematic from a business efficiency perspective. Issues with implementation and delivery are highlighted by the tension created between the bottom-up versus top-down VF industry development. Recognition of the importance of the development of this sector from the bottom-up and as a normalised production technique within the agricultural sector, backed by government in the same and equal fashion, would create a firm identity and equal opportunity for VF as an industry. This would allow new business ventures within the VF sector to identity the most suitable approaches to maximise returns on their target crops and successful business models to evolve accordingly, whilst maintaining decentralised and diversified food production. Finally, the implementation of precision technologies and VF-specific plant varieties will bolster the emerging VF industry, as targeted technological and biological advances combined to maximise outputs and business opportunities. The potential for VF in food and plant production is sky-high, but the possibilities need to be built from the ground up.

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No potential conflict of interest was reported by the authors.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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