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Vertical Farming: A Summary of Approaches to Growing Skywards

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Abstract

Pressure on agricultural land from a rising global population is necessitating the maximisation of food production per unit area of cultivation. Attention is increasingly turning to Vertical Farming (VF) approaches in an attempt to provide a greater crop yield per square meter of land. However, this term has been used to cover a broad range of approaches, from personal- or community-scale vegetable and herb growing to vast skyscrapers for commercial production of a wide range of crops. This article summarises the main categories of VF in order to help clarify this emerging but sometimes confusing area of agriculture and discusses how scientific investigation of the potential of VF is currently lacking and will be required to help determine its feasibility as a method to assist meaningfully in global food production.

Keywords

Vertical Farming, hydroponic, glasshouse, controlled environment, protected horticulture

Introduction

Agricultural production is experiencing increased pressure to generate larger yields as the global population rises and demand for food increases. By 2050, the global population is predicted to reach 9.7 billion, with 70% of people living in urban environments (United Nations, 2015). In addition, agricultural land may be lost through the expansion of urban areas and infrastructure development (Lotze-Campen et al., 2008), potentially leading to shortages of farmland (Corvalan et al., 2005; Healy and Rosenberg, 2013; Thomaier et al., 2015). This scale of change may necessitate the investigation of novel food production methods as both the amount of and yield achievable from conventional farming of agricultural land is limited.

With the aim of increasing crop yield per unit area of land, the concept of Vertical Farming (VF) is currently gathering momentum (Agrilyst, 2017). By farming upwards rather than outwards, this technique aims to reduce pressure on traditional agricultural land and, by incorporating soil-free growing systems, is particularly attractive for use in urban areas. However, the term ‘Vertical Farming’ has come to have a wide range of definitions that can provide confusion. Often, although not necessarily associated with urban agriculture, VF encompasses a range of growth systems of different scales, users, technologies, locations and purposes. It is particularly suited to the cultivation of horticultural crops such as leafy vegetables (Agrilyst, 2017). Here we try to provide a summary of some the main approaches to VF and highlight the characteristics of different VF growth systems.

Categories of Vertical Farming Systems

Vertical Farming systems can be broadly divided into two categories – those comprising multiple levels of traditional horizontal growing platforms, and those where the crop is grown

on a vertical surface. Rooftop glasshouses with conventional, single-level production, while belonging to the category of urban agriculture and having the potential for efficiency improvement through integration into e.g. urban heating and waste infrastructure, termed Building Integrated Agriculture (Caplow, 2009; Eigenbrod and Gruda, 2015), are not considered here due to their similarities to conventional rural protected horticulture facilities.

Stacked Horizontal Systems

This form of Vertical Farming (Figure 1A-B) frequently adapts existing commercial protected horticulture systems. Such systems comprise multiple levels of traditional horizontal growing platforms. Many horticultural crops, such as leafy vegetables including lettuce (*Lactuca sativa*) and herbs, tomato (*Solanum lycopersicum*) and pepper (*Capsicum* spp.) are grown in large scale glasshouses using hydroponic systems (Agrilyst, 2017). These can include substrate blocks formed of rock-wool or similar materials which provide a matrix for plant roots and are drip-fed with a precisely controlled mixture of water and nutrients. Alternatively, plants can be grown in rafts which float on the surface of beds of nutrient solution (deep water culture, DWC) or using a thin layer of nutrient solution in the rootzone (Nutrient Film Technique, NFT) (Beacham et al., 2017; Monaghan and Beacham, 2017). Such systems often incorporate recirculation of the nutrient solution to maintain optimum nutrient composition with additional sterilisation/sanitation steps to control potential pathogens. Alternative approaches include aeroponics where the rootzone is misted with nutrient solution, requiring relatively low volumes of water (Weathers and Zobel, 1992), and aquaponics (nutrient provision from waste from a fish farm built into the recirculation system; Rakocy et al., 2006).

These horizontal growing systems have the potential to be stacked on top of each other within taller structures to form a vertical farm. This can be achieved either in glasshouses (Figure 1A)

or in self-contained controlled environment (CE) facilities, sometimes referred to as 'Plant Factories' (Takatsuji, 2010; Figure 1B). Glasshouses have the benefit of being able to utilise sunlight for plant growth with supplementary levels of lighting being required during periods of low light, for example during winter or cloudy conditions, or for areas of the system distant from the glasshouse periphery or shaded by higher levels of planting. CE units, however, being fully-enclosed, require all lighting to be provided, thereby increasing the energy costs of these systems compared to glasshouses, although the ability to insulate the CE facility as the walls are not required to transmit light could offset the cost of heating a glasshouse structure. In order to minimise energy consumption, increasingly efficient light-emitting diode (LED) illumination can be used, with the spectrum of light output tailored to the individual needs of particular crops (Bourget, 2008; Massa et al., 2008). Reduced heat output from LED lights versus high pressure sodium lamps (Massa et al., 2008) should allow closer positioning to the crop, ideal for stacked growth levels in VF facilities.

The choice of glasshouse or CE will also dictate the location of the VF system. Glasshouses need to be situated in locations providing adequate irradiance. In urban settings, this could comprise a free-standing structure with a glass or polycarbonate shell, built from the ground up. However, with the high cost of land in urban areas (Benke and Tomkins, 2017), a more cost-effective approach may be to build on top or side of existing structures and place the glasshouse on the roof of city buildings or alternatively as a 'green façade' (Köhler, 2008). CE facilities carry no such location restrictions and can be placed anywhere with adequate space. A number of enterprising companies are using a range of unusual urban sites for food production using CE systems, such as Growing Underground, a company producing micro greens and salad leaves in an unused London Underground tunnel (Growing Underground, 2018). In addition, CE systems remove issues of seasonality by maintaining controlled growing conditions year-round and can therefore potentially increase yield by allowing additional

harvests of short-period crops during an annual cycle or by preventing the influence of seasonal change.

Heterogeneity of growing conditions between levels in Stacked Horizontal Conditions Systems is a potential concern. Gradients of temperature, light and other factors (Jarvis, 1992) across the different growing levels may result in unwanted crop variability. A study of a soilless four tier strawberry (*Fragaria* spp.) glasshouse system found significant differences in a number of growth parameters between levels, with plants on the top tier showing higher yield and quality than those on lower levels, thought to be due to the greater availability of photosynthetically active radiation (PAR, Murthy et al., 2016). In glasshouse-based systems, to attempt to ensure that each level of the stacked system receives an equal share of light, supplementary artificial lighting or a rotating mechanism that moves each level in turn to the top of the stack can be used to reduce shading of lower levels and maintain homogeneity of growing conditions for each level (Massa et al., 2008; Morrow, 2008). Sky Greens, a company based in Singapore, use a gravity-assisted rotating growing system with multiple tiers of troughs in an attempt to reduce supplementary lighting need and overall energy consumption (Sky Greens, 2018).

Stacked horizontal systems tend to be used in large-scale commercial enterprises, growing relatively large volumes of one or several types of crop (for example, lettuce, spinach (*Spinacia oleracea*) and tropical leafy vegetables by Sky Greens (Sky Greens, 2018)). Crop choice in Stacked Horizontal Systems can be dictated by the space available between each level, with shorter crops allowing for a higher number of levels and so potentially greater yield per unit height of the growth system. For this reason, smaller crops such as microherbs and spinach (*Spinacia oleracea*), which also benefit from fast growth, in turn maximising turnover and profit, are often favoured for their compact growth habit (Agrilyst, 2017; Table 1). Use of

stacked levels for taller crops such as tomato and pepper may require changes to cultivation methods and crop varieties to achieve high yields from shorter plants.

Multi-Floor Towers

A variation on the concept of Stacked Horizontal Systems is that of Multi-Floor Towers (Figure 1C). In this scenario, rather than the multiple levels of plant growth occurring in the same chamber (glasshouse or CE), the different levels of planting are located on different floors of a tower structure and so are isolated from each other. This allows different conditions to be maintained for each level of planting which can allow a wider range of crops to be grown by tailoring the conditions of each level to best suit each crop. By using a physical division between each level of planting this approach is most suited to CE systems. However, despite numerous designs (Mok et al., 2014), no Multi-Floor Tower systems are currently in existence.

Balconies

An alternative to indoor growth in Multi-Floor Towers is the use of balconies for growing produce (Figure 1D). This approach is more suited to production on an individual or community basis rather than commercial enterprises but may prove useful for the personal production of low volume crops such as herbs.

Vertical Growth Surfaces

Green Walls

Green Walls comprise vertical or inclined growing platforms sited in locations such as the façades of buildings (Figure 1E) (Köhler, 2008). Potential issues with green walls include the ease of harvest of plants high above ground level, exposure to urban pollution in walls not covered by a protective surface and maintenance of an equal provision of water from the top to bottom of the wall. Another consideration for the location and dimensions of green walls is that of light availability. A recent study (Song et al., 2018) sought to evaluate the availability of PAR along building surfaces in an urban environment, in this case a high-density residential area of Singapore. Based on estimates of plant light requirements calculated from leaf physiological traits of seven leafy vegetables, the study found that façade areas exposed to direct sunlight for a minimum of half the day provided sufficient PAR for plants with high light requirements. The amount of available PAR increased with building height but was also influenced by façade orientation and configuration, with east-west orientated buildings considered to be better for continuous cultivation by avoiding the effects of north-south oscillation of the sun. The study also highlighted a risk of excessive and perhaps deleterious PAR levels during the middle of the day in some areas. These findings prove promising for the cultivation of vegetables in green walls but will need to be reassessed to determine growing conditions in temperate cities and different latitudes.

Cylindrical Growth Units

In this type of system, plants are grown one above another around the surface of upright cylindrical units housing a nutrient supply (soil or hydroponic substrate) and located within a glasshouse or CE facility (Figure 1F). A comparison between a Cylindrical Growth Unit and a conventional horizontal growing surface has been made using lettuce (*Lactuca sativa* cv. ‘Little Gem’) (Touliatos et al., 2016). Both systems used hydroponic culture and artificial lighting.

The study found that although photosynthetic photon flux density (PPFD) and lettuce shoot fresh weight decreased significantly from the top to the base of the cylinder unit, the Cylindrical Growth Unit was still able to produce more crop per unit floor area than the horizontal growing surface. Additional artificial lighting could help to increase crop uniformity in such systems (Touliatos, et al., 2016). Cylindrical Growth Units have been used to grow lettuce, strawberry and a range of herbs (Saturn Bioponics, 2018).

Considerations for Vertical Farming

One of the major issues currently facing Vertical Farming is that of a paucity of scientific studies of the yield potential, crop quality, energy efficiency and other parameters of VF systems in order for their potential to be properly assessed (Al-Chalabi, 2015; Eigenbrod and Gruda, 2015; Mok et al., 2014; Pinstруп-Andersen, 2018). However, here we summarise some of the key considerations for VF systems and their implications on its potential future success.

Crop Choice

Crop range in VF systems is currently limited, with most producers predominantly favouring salad leaves and other small leafy vegetables (Agrilyst, 2017; Table 1). These crop types are well suited to cultivation in VF systems for a number of reasons. Their small size allows them to be grown in facilities such as stacked horizontal systems or cylindrical growth units where space, particularly in the vertical dimension, is at a premium. Small plant size also allows a higher number of plants, and so potentially increased income, per unit area horizontally. These crops also tend to show rapid growth and a short timeframe from germination to harvest, increasing the number of crops that can be produced in a season, further maximising

profitability. A rapid turnover of crops also allows increased flexibility in planting regime in terms of crop choice and allows growers to better cope with problems such as crop loss due to disease or pest damage.

Whilst some small leafy crops such as culinary herbs and salad greens would be expected to experience reasonably consistent demand year after year, growers of more 'trendy' vegetables such as micro greens may need to be amenable to rapid changes in crop choice if such crops experience a rapid decline in demand, in order to be replaced by others. Again, the short production cycles of such crops will prove helpful in this regard.

Investigation of the suitability of VF for the production of other crops may help to expand produce range and income, with some growers already using VF for crops such as strawberry (Table 1). Fresh produce crops including leafy vegetables and soft fruit represent higher value than commodity crops and can help to maximise income from a limited amount of growth unit surface. Other crops that are frequently produced in protected horticulture systems in Northern Europe, such as tomato and pepper, could in theory be grown in VF systems, however their large plant size and relatively long growth cycles make them less appropriate candidates. In addition, VF systems could potentially be used for the production of non-edible crops such as ornamental flowers.

Economics

The start-up costs of VF systems are seen as a major constraint, with site selection of high importance (Benke and Tomkins, 2017). While VF is usually discussed in relation to farming in urban areas, and therefore must allow for higher land prices than in rural settings, there is no reason VF systems, particularly those that adapt conventional commercial glasshouse agriculture, cannot be used in rural locations. This can take advantage of land that is otherwise unsuited to outdoor (unprotected) agriculture and which otherwise may remain unused for food

production, such as waste, depleted or heavy metal-contaminated ground containing poor or unsuitable soil, or ex-industrial sites where the ground surface has been replaced with concrete or brick.

The choice of rural versus urban location is an important one. For instance, it has been estimated that the installation of a rooftop glasshouse requires a minimum investment three times higher than that for a conventional ground-based glasshouse due to the required building adaptation (Brin et al., 2016). Similarly, the choice of glasshouse versus CE systems will affect requirements and so costs for artificial lighting and structure construction. Use of pre-existing buildings for CE facilities should however, reduce setup costs versus dedicated VF structures (Brin et al., 2016). Banerjee (2014) analysed the economics of a hypothetical carbon-neutral 37-floor VF facility containing a mixture of agricultural and aquacultural production. Due to the degree of stacking and multiple harvests, the facility would be predicted to provide yields many times higher than expected from its footprint with an estimated food cost of between € 3.50 and € 4.00 per kilogram. The study concludes that extensive research is needed for the optimisation of the production process in such systems in order to reduce costs and that their use 'might be feasible', particularly in large cities with very high purchasing power. Unlike many other food sources, including commodity crops, the prices for fruit and vegetables have tended to rise (Wallinga, 2009), which could reflect limited technological advancements and economy of scale compared to other crops. High fruit and vegetable prices could allow VF schemes to recoup costs more rapidly but also, when combined with start-up and running costs may risk prices of produce ultimately being too high for many consumers, relative to other food sources.

Environmental Effects

Vertical farming systems are frequently suggested to offer reduced environmental impacts compared to existing supply chains, for example by reducing transport requirements through locating production in urban sites. However, it has been calculated that of the total greenhouse gas (GHG) emission of food systems, production accounts for 83%, while transport only accounts for 11% (Weber and Matthews, 2008). Furthermore, as predominantly smaller scale producers, VF enterprises may lack the increased transport energy efficiency provided by larger scale and so energy use per transportation unit may be higher (Schlich and Fleissner, 2003; Schlich et al., 2006). In contrast, transport distances will be greatly reduced through urban localisation and may lead to a net reduction in transport-associated energy requirements (Pretty et al., 2005). Construction of VF facilities will also generate GHGs via building construction and energy use. Studies of the energy use, GHG production, yield and water use of VF systems are scarce. One study of the dimension optimisation of a hypothetical Multi-Floor Tower design for lettuce production with artificial lighting, water circulation and solar panels on the roof and one façade calculated that the solar panels could provide sufficient energy for the lighting and water pumping requirements of the system (Al-Chalabi, 2015). However, the carbon footprint of the system (CO_2/kg lettuce) was five times higher than for conventional field-grown crops in the summer and two times higher in the winter when conventional energy sources were used. Increased adoption of renewal energy infrastructure may therefore increase the viability and adoption of VF systems.

While not a VF system in the truest sense, a simulation-based environmental analysis workflow has also been used to model GHG production in three urban farming scenarios – a rooftop glasshouse, a partially-enclosed rooftop farm with skylights and side windows and a completely enclosed urban farm with no natural light (Benis et al., 2017). The simulation considered a large number of production factors including site, crop, operation model, supplemental lighting, thermal considerations, plant growth and water use. The results

indicated that when producing tomatoes, the rooftop glasshouse and partially-enclosed system could reduce GHG emissions by half and two-thirds, respectively, versus the existing supply chain, but the fully-enclosed system was considered to have the highest Global Warming Potential (GWP) due to the amount of supplementary lighting required. These factors will need to be taken into consideration when choosing VF systems.

Energy Requirements

As VF necessitates the use of a glasshouse or controlled environment facility, so energy use may be expected to be higher than for field-grown crops. Indeed, 58% of the energy input for UK horticulture is used for protected edibles production in glasshouses, whilst only 9% is used for field crops (Warwick HRI, 2007). It has been found that glasshouse production of lettuce uses 0.08 GWh/ton compared to just 0.0014 GWh/ton for field-grown salads (Warwick HRI, 2007). A model of yield, water and energy use for lettuce production in a hypothetical 815 m² temperature-controlled NFT hydroponic glasshouse with supplementary lighting and water circulation has been calculated using engineering equations based on available data (Barbosa et al., 2015). When compared to results calculated for conventional field production, the hydroponic glasshouse had a 10 times greater yield and 10 times smaller water requirement compared to conventional production. However, the energy demands of the hydroponic glasshouse were around 80 times higher. Maximising efficiency in VF systems, which also frequently employ hydroponic culture, will therefore be key to their success, although it should be noted that soil-free cultivation can potentially increase yields up to ten times compared to soil-based systems (Burrage, 2014; Savvas et al., 2013). CE systems, with a higher artificial lighting requirement will likely require even further optimisation for their use to be widespread.

The ongoing balance between agricultural land availability and energy use will likely dictate the extent of adoption of VF in the future.

Conclusion and Recommendations

Vertical Farming is an emerging technology aiming to increase crop production per unit area of land in response to heightened pressure on agricultural production. By utilising protected horticulture systems such as glasshouses and controlled environment facilities in combination with multiple levels of growth surface and/or inclined production surfaces, VF is a technically-demanding and expensive approach to crop production. VF therefore necessitates a combined technical approach to factors including lighting, growing system, crop nutrition, energy efficiency, construction and site selection. Whilst VF has been shown to have potential for the production of a wide range of crops, the technical and economic optimisation of VF requires further attention with additional research into maximising productivity and reducing system costs being required. Furthermore, VF is currently industry-led, with a large number of independent start-up companies. Funding for research regarding VF at academic institutions is limited. This hinders optimisation of the efficiency of VF growth systems and supply chains through a lack of standardisation of systems as each VF enterprise develops its own approach. It also means that much of the data available for determining VF feasibility, such as crop yield, is either based on commercial marketing material or conjecture rather than scientific investigation or is unavailable in the public sector (Pinstrup-Andersen, 2018). This situation necessitates further research into the viability of VF for useful scales of food production. As a sector, VF would benefit from additional collaboration with academia in order to realise its potential and determine the likelihood of VF sector expansion in the future as a durable source of food production.

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Declaration of Interest

The authors declare no conflict of interest.

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Tables

Table 1. Examples of crops grown in VF systems in commercial enterprises and academic studies.

Crop	Source
Micro greens	Growing Underground, 2018; VertiCrop, 2018
Salad leaves	Growing Underground, 2018; AeroFarms, 2018; VertiCrop, 2018
Strawberry (<i>Fragaria</i> spp.)	Murthy et al., 2016; Saturn Bioponics, 2018; VertiCrop, 2018
Lettuce (<i>Lactuca sativa</i>)	Sky Greens, 2018; Touliatos et al., 2016; Saturn Bioponics, 2018
Spinach (<i>Spinacia oleracea</i>)	Sky Greens, 2018
Tropical leafy vegetables	Sky Greens, 2018
Assorted leafy vegetables	Song et al., 2018
Culinary herbs	Saturn Bioponics, 2018; VertiCrop, 2018

Figures

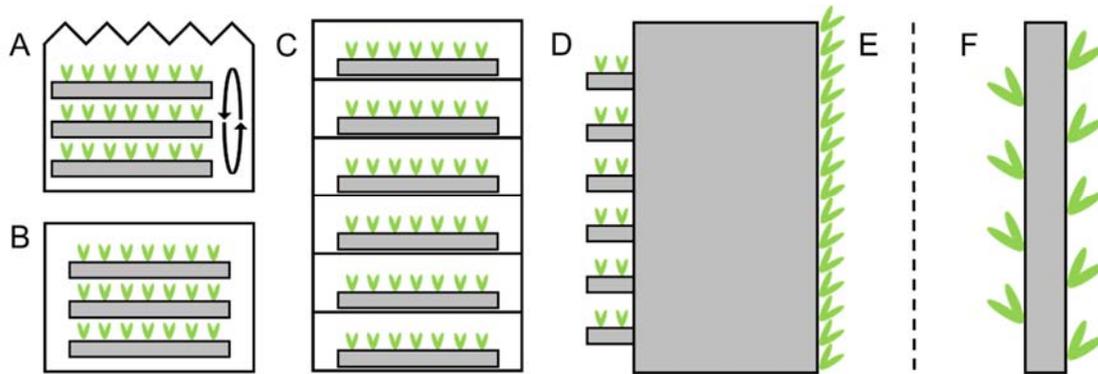


Figure 1. Representation of vertical farming (VF) types. Stacked Horizontal Systems comprise multiple levels of horizontal growing surfaces and can be located in glasshouses (A), sometimes with level rotation incorporated, or controlled environment (CE) facilities (B). A variation of this approach is that of Multi-Floor Towers (C) where each level is isolated from the surrounding levels. The use of balconies (D) for crop production is another example of VF using stacked horizontal growing surface. Vertical growing surface include Green Walls (E), which can be positioned on the side of buildings and other vertical surface and Cylindrical Growth Units (F) with vertical arrangements of plants.