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ORIGINAL ARTICLE

Does green vertical farming offer a sustainable alternative to conventional methods of production?: A case study from Scotland

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Abstract

Climate change is an existential global reality that is placing considerable stress on agriculture sectors. With the recognition of the impacts of climate change on food security, there has been a greater uptake of controlled environment agriculture (CEA) to provide climate-resilient and high-quality production. Vertical farming (VF) can allow primary production in urban locations as well as reducing seasonality and variability in produce. It is emerging as an alternative to traditional farming methods. This research aimed to explore the major environmental impacts of VF produce in comparison with conventional farming methods, using lettuce as an example crop. Life cycle analysis indicate that electricity consumption by VF account for 91% of the carbon footprint. Under the 2019 Scottish electricity mix, VF did not offer a viable competitor for UK open-farmed lettuce or Spanish imports in terms of low greenhouse gas emissions (at approximately 1.49 $kgCO_2$ eq. kg^{-1}). However, with increasing use of renewable electricity in the national mix, by 2020, this had dropped to 0.42 $kgCO^2$ eq. kg^{-1} making it comparable with UK open-field agriculture (at approximately 0.46 $kgCO_2$ eq. kg^{-1}). Under a 100% renewable electricity generation scenario, VF-related emissions drop further (to 0.33 $kgCO_2$ eq. kg^{-1}). This would potentially offer a low-carbon production method not subject to seasonality which is better than that reported by most other production methods and offers higher water and nutrient efficiency. This research highlights green VF as potential alternative for sustainable future produce especially under changing climate scenarios.

KEYWORDS

carbon footprint, environmental impact, life cycle analysis, renewable energy, sustainability, vertical farming

1 | INTRODUCTION

The ability to produce nutritious food safely and sustainably is crucial for human well-being and contributes to healthy economic growth. Given the widely accepted link between climate change and anthropogenic GHG emissions, the increasing evidence of extreme weather events and regional climate shift mean that our approaches to primary food production and produce, need to be reassessed and redesigned. Global food production contributes 21–37% of the total anthropogenic GHG emissions worldwide (IPCC, 2019). At the Scottish level, Lampkin et al. (2019) estimated that agricultural GHG emissions were 7.6 Mt CO_2e with 75% from livestock production alone. It is estimated by this 'business as usual' (BAU) scenario (i.e. that if nothing is changed) increasing demand to satisfy current food and feed consumption patterns could cause food-related GHG emissions to increase by up to 40% by 2050 (IPCC, 2019). Though there is debate as to the relative importance of increasing production versus improving distribution (Fouilleux et al., 2017), it is imperative that the world move away from the BAU scenario and instead focus on changing our behaviours, processes and products to circumvent GHG production.

A logical step to improving agricultural yield predictability via reduced environmental and chemical input dependence has been to move towards contained agriculture concepts like controlled environment agriculture (CEA) systems. CEA structures offer a way to remove the variables of pedoclimate and environment from crop production. By exerting controls over usages of light, heat and fertilisers, the production environment can be optimised, offering a stable environment independent of, or much less influenced by, any climate or extreme weather events. This can not only ensure the highest and most predictable yield possible (potentially as high as 10–100 times greater than more traditional agriculture systems; Engler & Krarti, 2021) but also potentially increasing the quality of the product. CEA systems are found worldwide, and it is estimated that the vertical farming sub-section alone will be worth approximately 33.02 billion USD by 2030 (Grand View Research, 2022). CEA can range from the classic polytunnels and glasshouses, through to the more modern concept of vertical farming. Vertical farming is an adaption of CEA towards increased productivity for a given footprint and often mooted as a production route for urban agriculture (Lubna et al., 2022). It poses a method of increasing the productivity of agricultural land by adding in a vertical element—using the same land use footprint, while adding in multiple growing levels (Dano, 2018). Though the definition of a vertical farm can cover a variety of set-ups from hydro- to aero- and aquaponics, to multilayer glasshouses and intensive plant factories with artificial lighting, where all inputs are controlled at all times (Engler & Krarti, 2021). Generally, it is accepted that vertical farming eliminates the need for herbicides, pesticides and soil-based fertilisers (Despommier, 2010) and improves the use of nutrients by up to 50% (Avgoustaki & Xydis, 2020). In addition, it recycles water, reducing use up to 95% (Avgoustaki & Xydis, 2020) and opens up the ability to produce crops within an urban setting, reducing transport time and impacts to points of onward sale or usage (Despommier, 2010). VF would also allow for the reclaiming of unused buildings in both a rural and agricultural setting and give the opportunity to produce crops year-round, not subject to seasonality. In addition, it has been suggested that VF could play a role in water purification (Despommier, 2010).

As well as colder and more changeable climactic conditions than is generally found in the rest of the UK and on many areas on the continent, Scotland also possesses limited suitable arable land (The James Hutton Institute, 2022a, 2022b). This constrains the ability of Scotland to increase food production, and unreliable weather conditions can lead to crop failures. Furthermore, post both Brexit and the COVID-19 pandemic, issues with food import and export (Freeman et al., 2022), as well as agricultural labour shortages (Environment Food and Rural Affairs Committee, 2022), highlight an increasing need to rethink our food production methods in order to continue to ensure a stable economy and the nation's future food security. This could argue for a shift towards vertical farming as a means of potentially mitigating these issues.

However, though numerous potential advantages of vertical farming have been highlighted (Avgoustaki & Xydis, 2020; Despommier, 2010), the potential negatives are less well agreed upon. In particular, the associated pros and cons in a Scottish context have not been fully explored. This raises questions about the impacts of required inputs such as energy (gas and electricity), infrastructure and substrate in a VF and wider CEA context. Given the current and ongoing improvements in the Scottish national electricity mix (Scottish Government, 2020), the newly developed and still evolving field of vertical farming, and the Scottish pledge to meet NetZero by 2045 (Scottish Government, 2019) it is imperative to address this knowledge gap in order to determine what role VF might play in a carbon neutral Scotland.

To address this information shortfall, this study seeks to compare four major procurement pathways for popular seasonal produce in order to contrast VF production to traditional farming methods. Using lettuce as an example crop, the following production pathways were identified for Scottish consumption: grown in traditional open-field agriculture in Spain and transported to the UK for onward sale; grown seasonally in traditional open-field agriculture in the UK and transported to point of onward sale; grown out of season in regional glasshouses in Scotland and transported to the point of onward sale; grown locally in vertical farms in Scotland and transported to the point of onward sale. In order to do so the following questions were proposed:

1. What are the relevant environmental impact values found in literature for lettuce production in these four production pathways
2. How do these values compare with a modelled vertical farm based in Scotland utilising:
   a. The current Scottish energy mix
   b. In a full renewable electricity production scenario

2 | METHODS

2.1 | Literature analysis

Peer-reviewed and grey literature were searched for and analysed on the topics of lettuce production. Priority was given to studies focused on production of lettuce in open-field agriculture in Spain or production in the UK under any format. Studies on lettuce production by means of vertical farming were scarce so the search was widened to include global production of lettuce in a vertical farm. As the term vertical farm is somewhat non-specific, covering any in a range of agricultural systems (including those with supplemental lighting, sole source lighting and intensive plant factories), in this study it was taken to reference intensive plant factories where all environmental aspects are fully controlled. Studies that included aquaponics were discounted from the analysis due to the more complicated nature of the set-up and the intertwined production of both plant and fish. Estimating the accurate environmental footprint of the lettuce production was only made more difficult and subject to allocation influence.

The identified literature was then searched for the following key impacts determined to be most appropriate to allow for comparison across the four product pathways:

- Global warming potential (GWP)/carbon footprint (CF)
- Water usage (WU)/water footprint (WF)
- Land usage (LU)/land footprint (LF)

These values were extracted and where necessary converted for later comparison using the functional unit of 1 kg of lettuce and the following metrics: GWP = $\mathrm{kgCO_2}$ eq. $\mathrm{kg^{-1}}$; WF = $\mathrm{m^3\ kg^{-1}}$; LU: $\mathrm{m^2\ yr^{-1}\ kg^{-1}}$. In addition, any information on component analysis (whereby the relative contribution to the impact figures is detailed in per cent), absolute values for electricity use, pesticide use, fuel use, fertiliser use, heating, lighting, transport, water use, refrigerants and any other contributor deemed relevant were also gathered for comparison and use in the modelling stage of this study. Finally, a brief review was undertaken to explore potential for nutrient decline in transport.

2.2 | Model analysis

Data were drawn from the literature to develop a life cycle analysis (LCA) model to estimate likely impacts. The low instance of reporting of raw figures limited options for extraction, however, the paper Pennisi et al. (2019) was identified as a template. Though it did not offer absolute figures for all aspects of the proposed model, it did give detailed figures for electricity consumption. As this was identified in the literature as contributing the largest proportion of a VF's CF (Burgos & Stapel, 2018; Tennant, 2019), and because preliminary results found that the Pennisi et al. (2019) figures yielded results in line with that of anecdotal evidence from discussions with industry within Scotland, it was considered appropriate to use electricity consumption as a proxy based on the Pennisi et al. (2019) figures. The use of energy usage as a proxy for CF has been suggested as acceptable in other aspects of food production showing a similarly strong contribution analysis (Parker, 2012; Sandison et al., 2021). Similarly, while the study itself took place in the USA, it was felt that raw energy use was more representative of system efficiency than of country of origin when applied to an electricity production mix tailored for Scotland.

SimaPro 9.2.0.2 was utilised for the modelling portion of this study. Guinée et al. (2002) CML-IA methodology was used for the CF investigation portion, and Boulay et al. (2018) AWARE 2.0 for the exploration of water footprint of electricity production.

2.2.1 | Energy mix

Electricity options were identified using the Ecoinvent 3 database. Pre-mixes were identified for Great Britain (GB) at high voltage, mid voltage and low voltage. However, due to the discrepancy between renewable usage between Scotland, England and Wales (Scottish Government, 2018) a Scotland-specific electricity mix was created (Table 1) utilising breakdowns of grid mix in the years 2017, 2019 and 2020 (Scottish Government, 2018, 2020). In 2017 renewables made up 53% of the electricity mix, dominated by onshore wind production, though

TABLE 1 Percentage electricity mix for Scotland, based on data from (Scottish Government, 2018, 2020, 2021)

	Scotland 2017	Scotland 2019	Scotland 2020	Scotland fully renewable scenario
Coal	0	0	0	0
Gas	8.6	0	0	0
Nuclear	35.6	0	0	0
Oil and Others	2.8	0	0	0
Hydro	11	15.8	19	21.1
Onshore wind	34	56.5	60.2	67.0
Offshore wind	0	9.4	10.7	11.9
Other renewables	8	8.4	8.6	0
Others	0	9.9	0	0

TABLE 2 Carbon footprint and water footprint of 1 kW h electricity produced by different methods, with carbon footprint measured in kg CO_2 eq. and water usage measured in m^3

	Water usage of 1 kW h	Carbon footprint of 1 kW h
Oil	0.00166	1.28000
Gas	0.00361	0.51300
Nuclear	0.00614	0.00710
Wind onshore <1 MW turbine	0.00626	0.01110
Wind onshore >3 MW turbine	0.00973	0.02060
Wind onshore 1–3 MW turbine	0.00491	0.01160
Wind offshore	0.00788	0.01440
Hydro	0.00167	0.00378

hydroelectricity also featured. Non-renewable electricity was largely nuclear, though gas and oil both also featured. In sharp contrast, the 2019 mix had achieved 90.1% renewable electricity production, still dominated by onshore wind production, though hydro and offshore wind also contribute. In 2020, the renewable electricity consumption had risen to 98.6%, showing the same contribution patterns as 2019.

In all of the year mixes looked at, a percentage of renewable energy has been represented as 'other'. This has ranged from 8% to 8.6% between 2017 and 2020. As the breakdown of this category cannot be known, this has been represented in the models by allocating this section proportionately to the other named renewable electricity production types. Similarly, post 2017, the breakdown for non-renewables is not clear, labelled only under 'other'. In this instance a general electricity mix for GB provided by Ecoinvent 3 was used as a proxy. A sensitivity analysis was undertaken to explore the effects of this assumption on the results, whereby (a) renewable other was allocated instead to the GB mix, (b) other non-renewables was allocated between non-renewable production methods proportional to named non-renewable electricity production from 2017.

An estimate was created for a full renewable scenario based on the 2020 electricity mix. In this scenario, the relative proportions of the main contributors were scaled up from 2020, allocating the 'other' non-renewable electricity production proportionally between renewable electricity production from the 2020 mix.

Data were taken from the Ecoinvent database regarding the relative carbon footprint and water footprint of each of the different methods of electricity production (Table 2). Onshore wind was seen to have three alternatives in terms of turbine size, each with their own associated CF and WF costs. In each case the largest wind onshore turbine was found to have the highest values. In order to produce a conservative estimate in the model, the largest wind turbine size was selected to represent on shore impacts. A second sensitivity analysis was undertaken to explore substituting this decision with turbines of alternate sizes.

2.2.2 | Allocation sensitivity analysis

To explore the effects of different allocation scenarios on the results, a sensitivity analysis was run where each year category was run under three scenarios: unallocated; adjusted; and the base scenario utilised in the rest of the analysis. In this the base scenario (indicated by the year of the data) represented a scenario where the 'other' category of renewable fuels was re-allocated proportionally among already represented renewable electricity production types. Non-renewable 'other' electricity production was represented simply with the UK general electricity mix provided by Ecoinvent (high voltage). In the unallocated scenario all 'other' category of fuels (renewable and non-renewable) was represented using the general UK high-voltage energy mix provided by Ecoinvent. Finally, in the adjusted mix, all other categories were proportionally allocated among existing electricity production types, with renewable other allocated to renewable production sources, and non-renewable to non-renewable production sources. In years where no existing non-renewable production sources was available (2019, 2020), it was split proportionally as per 2017 non-renewable usage. As no other category was recorded in 2017 for non-renewable fuels, no adjusted 2017 scenario was run.

2.3 | Transport analysis

Finally, the expected duration, distance and effects of transport were explored. Distances for travel across the UK and from Spain to the UK were identified in literature (Canals et al., 2008; Hospido et al., 2009), with an assumption made of 30 km for local transport to calculate relative speed. Average speeds were assumed, with 60 mph over long distances, and 30 mph within city transport. The necessity of an 8.5 h rest stop overnight was also assumed in when travelling from Spain due to the long commute.

Nutrient decline was calculated using Vitamin C as a proxy, due to its importance as a key nutrient in lettuce. Utilising data from Konstantopoulou et al. (2010), assuming a refrigeration temperature of 5°C, nutrient decline was calculated for open and closed packaging over all nitrogen application rates (20, 80, 140, 200, 260 mg L^{-1} N) as per each of the transport scenarios. No delay between harvest and transport or transport and point of onward sale was assumed.

3 | RESULTS

3.1 | Literary comparison

3.1.1 | CF ranges

A range of CF's were found in literature corresponding to each possible farming method. These are represented in Figure 1. Ranges found for each of the open farm systems were low, with median values similar between the UK-based open farm agriculture and Spanish agriculture (values 0.30 and 0.45 respectively, Table 3). Consistency was found in the CF ranges for unheated glasshouse produce in the UK, however, the number of observations for this was low ($n = 2$) and restricted to a single study (Hospido et al., 2009). A greater range was found in values for heated glasshouse produce in the UK, and a higher median value at 3.00, though this was still lower than that found for vertical farming (median value 3.67, though it dropped to 2.72 if the extreme value of 37.19 was removed). The minimal value found for CF was attributed to a particularly efficient VF system, though VF systems also were responsible for the highest value by some margin. This remains true regardless of whether the outlying value of Tennant (2019) is removed from the analysis.

3.1.2 | Contribution analysis

The relative contributions of inputs to the system were calculated (Figure 2). For open farm systems in Spain, the dominant contributor was transport responsible for 42.5%

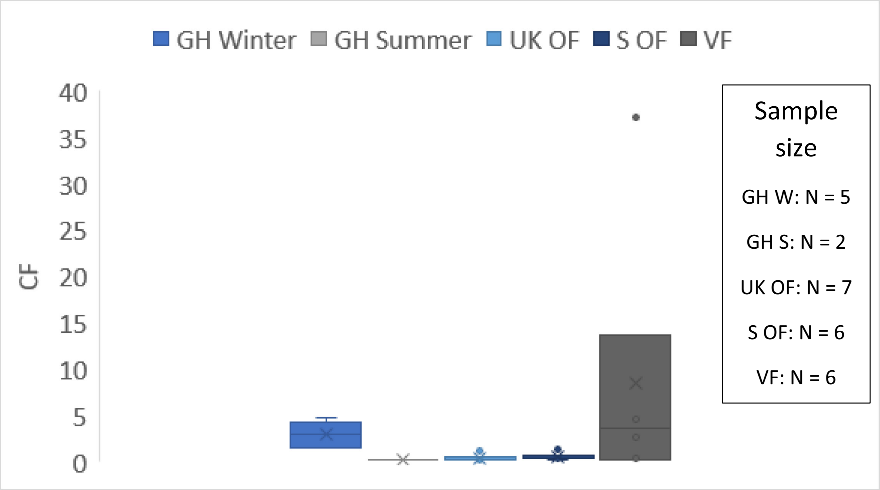

FIGURE 1 Comparative carbon footprint ranges (kg CO_2 eq.) found in literature for producing 1 kg lettuce, where GH W, glasshouse grown in winter; GH S, glasshouse grown in summer; UK OF, open farm grown in the UK; S OF, open farm grown in Spain; VF, vertical farm grown. Whiskers on plot represent the range, *X* the average value, and dots representative of outliers. Based on data from literature (Bartzas et al., 2015; Burgos & Stapel, 2018; Canals et al., 2008; Hospido et al., 2009; Nicholson et al., 2019; Tennant, 2019).

TABLE 3 Descriptive statistics of carbon footprint ranges in kg CO_2 eq. found in literature for producing 1 kg lettuce where GH W, glasshouse grown in winter; GH S, glasshouse grown in summer; UK OF, open farm grown in the UK; S FO, open farm grown in Spain; VF, vertical farm grown; VF corrected, VF scores with outlier excluded from analysis

	GH W	GH S	UK OF	S OF	VF	VF corrected
Median	3.00	0.25	0.30	0.45	3.67	2.72
Standard Deviation	1.23	0.00	0.31	0.38	13.01	2.11
Range	3.25	0.00	0.95	1.20	37.03	5.59
Max	4.75	0.25	1.20	1.38	37.19	5.74
Min	1.50	0.25	0.25	0.17	0.16	0.16
Mean	2.94	0.25	0.46	0.56	8.46	2.72

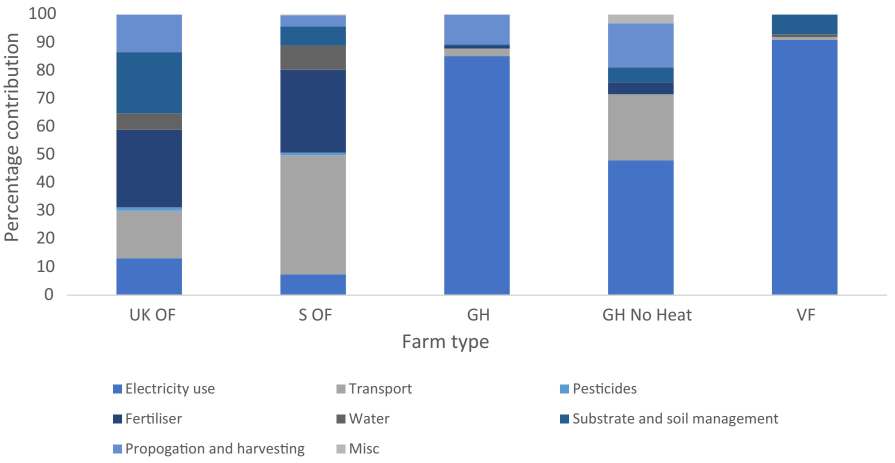

FIGURE 2 Analysis of relative contributions towards overall carbon footprint score for selected farming methods, where UK OF, open farm in the UK; S OF, open farm in Spain; GH, heated glasshouse; GH no heat, unheated glasshouse; VF, vertical farm. Based on data from Hospido et al. (2009) and Tennant (2019).

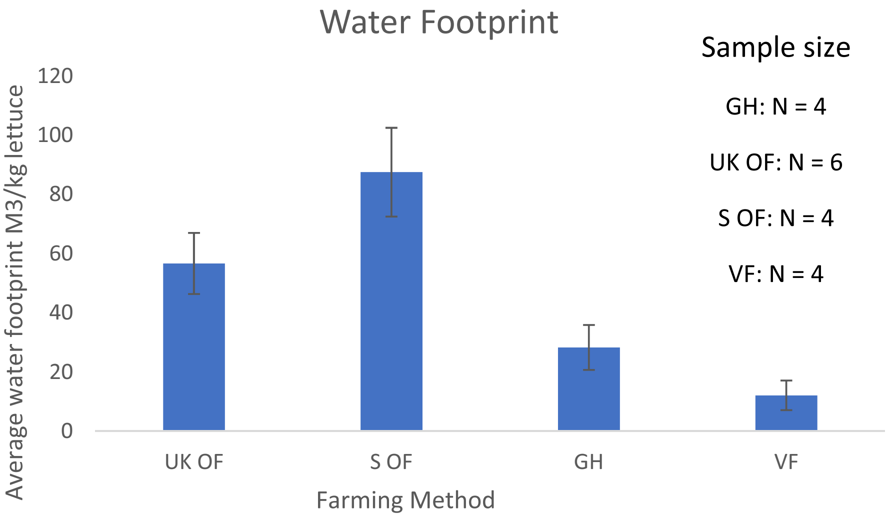

FIGURE 3 Comparison of water usage scores for selected farming methods found in literature where UK OF, open farm in the UK; S OF, open farm in Spain; GH, glasshouse; VF, vertical farm. Bars indicate statistical error. Based on data from literature (Burgos & Stapel, 2018; Canals et al., 2008; Hospido et al., 2009; Nicholson et al., 2019; Tennant, 2019)

of the overall CF, and the secondary factory was fertiliser use at 29.5%. This is not the case with UK OF, which shows a much more even scattering of inputs, though transport (16.9%) remains notable along with fertiliser use (27.6%), cooling (13.2%), harvesting (12.3%) and general soil management (21.8%). Heated GHs for winter produce are dominated by inputs from heating and lighting (81.7%), with the next biggest contributor the propagation phase at 10.6%. In the case of unheated GHs in summer, cooling and transport are the largest contributors (36.0% and 23.5%, respectively). In VF, the dominant contributor by a large margin is electricity use at 91.0% with the second largest that of substrate at 7.0% (Figure 2).

3.1.3 | Literary WU comparison

Comparison of water footprints reported in literature show OF systems were the least efficient, with those in Spain showing a 55% larger water footprint than those in the UK. GH in the UK (based on heated/winter figures only) had notably lower water demands than the OF agriculture (at 28.25 m^3 compared with 87.5 m^3 for Spanish OF and 56.3 m^3 for UK OF). VF shows the highest level of efficiency at 12.05 m^3 (Figure 3).

3.1.4 | Literary LU comparison

Land use in farming systems closely follows the pattern found with water demands, with OF agriculture in Spain requiring the largest area per year to produce lettuce at 0.57m^2. This is followed by OF in the UK at 0.34 m^2, GH in the UK at 0.23 m^2 and finally VF at 0.09 m^2 (Figure 4).

3.2 | Modelled results

3.2.1 | Modelled GWP results

Data from Pennisi et al. (2019) were amalgamated to produce the following descriptive statistics regarding electricity usage for production of 1 kg of lettuce on a modern vertical farm (Table 4).

A model was run utilising the energy mixes provided as default for the region in Ecoinvent 3, and the energy constructs created using data from Tables 2 and 3. Based on the energy demands identified in the Pennisi et al. (2019) paper, the output found in Table 5 was obtained. Results were found to be substantially higher for any of the default mixes for the region, suggesting these to be outdated. It is noted that Scotland, England and Wales all possess different electricity mixes (Scottish Government, 2018). The steady improvement in CF can be seen between years 2017 and 2020, due to the increase in renewable usage (from an average figure of 2.22 kg CO_2 eq. to 0.424 kg CO_2 eq.). Moving towards a full renewable scenario shows a further drop in CF (down to 0.329 kg CO_2 eq.).

3.2.2 | Modelled WU results

Using the same energy mixes and assumed energy usage as Table 5, water footprint was also calculated for each (Table 6). Once again, the default energy mixes for GB showed the highest water demand, though in this case the 2017 Scottish energy mix proved to have a lower water footprint that the 2019 or 2020 mixes (an average of 0.145 m^3 compared to 0.163 m^3 and 0.157 m^3). The fully renewable scenario and the 2020 scenario provide the same estimate for WF at 0.157 m^3.

3.2.3 | Sensitivity analysis

By referring to the results in Tables 7 and 8, a trend can be seen, with unallocated scenarios (scenarios in which unknown energy production marked as 'other' in data were represented using a general GB mix) showing higher impacts in both CF and WF than the study scenario (2017, 2019 and 2020 energy mixes, where unknown percentage of renewable energy production was allocated proportionally between already represented renewable energy production, and unknown non-renewable energy production was represented using the general GB mix). The study scenario was higher in turn than the adjusted scenarios (where both unknown renewable and unknown non-renewables were re-allocated proportionally among already represented renewable/non-renewable energy production). The effect of assuming energy use represents only 91% of the CF was also explored in the renewable

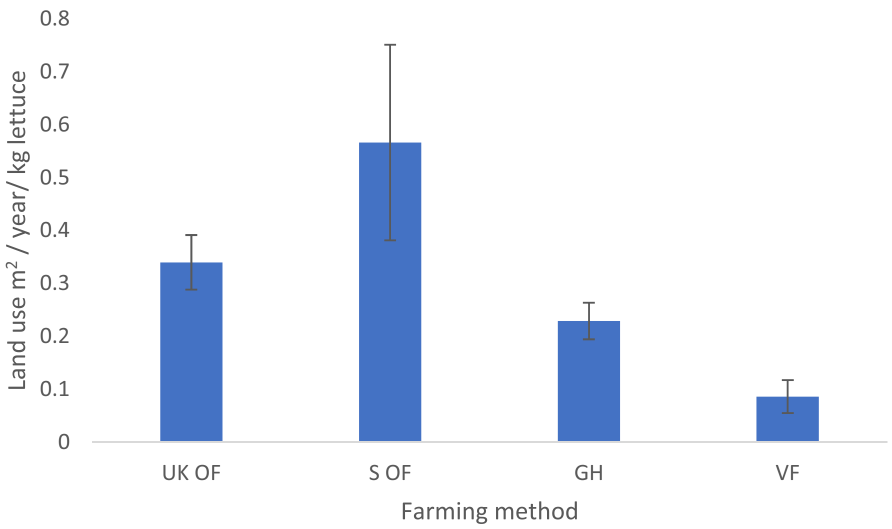

FIGURE 4 Comparison of land usage scores for selected farming methods found in literature where UK OF, open farm in the UK; S OF, open farm in Spain; GH, glasshouse; VF, vertical farm. Bars indicate statistical error. Based on data from (Burgos & Stapel, 2018; Canals et al., 2008; Hospido et al., 2009; Nicholson et al., 2019; Tennant, 2019)

TABLE 4 Descriptive statistics for electricity consumption in a vertical farm, based on data from Pennisi et al. (2019)

Statistic	KWh/kg
Average	20.12
Median	20.3
Max	25.5
Min	14.8

TABLE 5 Carbon footprint (in kg CO_2 eq.) of production of 1 kg lettuce in a vertical farm in Scotland utilising selected electricity mixes, where GB HV, high-voltage mix for Great Britain provided by Ecoinvent 3, where GB MV, medium voltage mix for Great Britain provided by Ecoinvent 3, where GB LV, low voltage mix for Great Britain provided by Ecoinvent 3, 2017 = electricity mix for Scotland based on data from Scottish Government (2018), 2019 = electricity mix for Scotland based on data from Scottish Government (2020), 2020 = electricity mix for Scotland based on data from Scottish Government (2021), and a potential scenario utilising full renewable electricity.

CF/energy mix				
Electricity mix	Average	Median	Max	Min
2017	2.22	2.24	2.81	1.63
2019	1.49	1.51	1.89	1.1
2020	0.424	0.428	0.537	0.312
Fully Renewable	0.329	0.332	0.417	0.242
GB HV	6.66	6.72	8.45	4.9
GB MV	6.71	6.77	8.51	4.94
GB LV	6.85	6.91	8.68	5.04

+9% scenario in Table 7. This showed only small increases in CF between renewable scenarios and renewable +9%, ranging from 0.024 to 0.041.

3.3 | Transport

The likely time and distance of transport was estimated based on results in literature for transport from each of the different farm options. A figure of 2600 km for transport from Spain to the UK, and 200 km for transport within Scotland for both OF and GH systems were taken from Canals et al. (2008) and Hospido et al. (2009). An estimated figure of 30 km was used for localised transport between VF systems and their point of onward sale. Table 9 details the distance, expected time and assumptions of the estimated travel.

Utilising the information from Table 9, vitamin C loss was explored during transport for each of the farm systems (Table 10), under the conditions of open or closed polyethylene packaging. Though a greater decline was seen in transport from Spain (approximately 5%), as an absolute decline in nutrient content, all instances are low. This is likely a consequence of the use of cold supply chains for fresh produce transportation (Tort et al., 2022).

TABLE 6 Water footprint (in m^3) for production of 1 kg lettuce in a vertical farm in Scotland utilising selected electricity mixes, where GB HV, high-voltage mix for Great Britain provided by Ecoinvent 3; where GB MV, medium voltage mix for Great Britain provided by Ecoinvent 3; where GB LV, low voltage mix for Great Britain provided by Ecoinvent 3, 2017 = electricity mix for Scotland based on data from (Scottish Government, 2018) 2019 = electricity mix for Scotland based on data from (Scottish Government, 2020) and fully renewable = a potential scenario utilising full renewable electricity

Energy mix	Average	Median	Max	Min
2017	0.145	0.146	0.184	0.107
2019	0.163	0.165	0.207	0.12
2020	0.157	0.159	0.199	0.116
Fully Renewable	0.157	0.159	0.199	0.116
GB HV	0.176	0.178	0.223	0.13
GB MV	0.184	0.186	0.234	0.136
GB LV	0.314	0.317	0.398	0.231

4 | DISCUSSION

4.1 | Carbon footprint

Various studies have highlighted VF as having both the highest (Tennant, 2019) and lowest (Burgos & Stapel, 2018) CF impact. This is likely due in part to the variation in energy mixes, with (Burgos & Stapel, 2018) reporting a range of associated CFs (5.74–0.16 kg CO_2 eq.), with the lowest reported from 'improved VF', that is those utilising renewable energy sources and improved energy usage. In contrast, the VF reported in Tennant (2019) was still in its research and development phase, prior to commercial launch. This indicates that it is likely it had not yet found best practice for production efficiency and highlights how important methodological decisions are in vertical farming with regards to both environmental impact and economic turnover.

The VF industry is relatively youthful and is still generally in a technological development phase with true commercialisation in its infancy (Van Gerrewey et al., 2021). Nonetheless, no correlation was seen between the year of the study and CF values, suggesting that the efficiency of the individual setup is more relevant than the age of the industry. Several papers have explored relative efficiencies and have found relationships with crop growth rate and, amongst others, nutrient solution concentration (Foster, 2018; Hosseini et al., 2021), rate of harvest, ratio of red/blue spectral components in the lighting (Pennisi et al., 2019), LED light distance between plants and photoperiod interval (Foster, 2018). Unfortunately, this wide range of parameters, limited studies and variety in reporting detail made it impossible at this stage to detangle the methodological influence on CFs found for VF and identifies this as a topic for further attention. Similarly, though the correlation between size of production and sustainability has been documented in other systems (Schlich & Fleissner, 2005), and there is a customer association about this effect in VF (Jürkenbeck et al., 2019), the authors are not aware of any existing study which offers a specific like for like comparison to prove this to be the case. Given the relative contribution analysis, however, it is safe to assume that energy efficiency is the most fundamental aspect to environmental sustainability within a VF (Burgos & Stapel, 2018; Nicholson et al., 2019; Tennant, 2019).

Exploration of the effect of electricity mix on the modelled results highlight the strong effects that this plays on the results. As all default GB mixes were found to be unrepresentative, it is imperative that Scotland specific energy mixes only be used in LCAs with such a high dependency on electricity. Further investigation proved the GB mixes to likely be outdated as they were based on 2014 data, though given the relative mix differences between countries within GB (Scottish Government, 2018), caution is still advised when relying on generic GB figures.

Data were not available from existing Scottish VFs, but examination of the purpose-produced energy mixes for Scotland allowed exploration of a hypothetical VF in Scotland. While the modelled data were restricted to electricity use only, and this is not comprehensive as a full LCA, given the relative contribution analysis (at approximately 91.0%), it is likely to be representative of a CF for potential vertical farming in Scotland. The correlation between increased renewable usage and lowered CF is clear when mapping between the 2017 and 2020 and hypothetical fully renewable scenarios. The current energy mix (assumed to be as 2020) shows a much lower CF than any of the mixes for GB. Under the 2020 scenario, CF for fresh produce in a VF (here lettuce) is found to be on par with the median and mean values for Spanish OF, and only slightly higher than that for UK OF. It is however noted that this scenario is still higher than the GH values for summer fresh produce production. The modelled 2020 scenario already provides an environmentally friendly option for the production of leafy greens from a point of view of current carbon emissions, though there is no real current savings or incentive from a GHG emission point of view to utilise it over other existing methods.

TABLE 7 CF (in kgCO_2 eq.) results for 1 kg of lettuce under different allocation scenarios for electricity mix.

	2017 unallocated	2017	2019 unallocated	2019	2019 adjusted	2020 unallocated	2020	2020 adjusted	Fully renewable	Renewable +9%
Min	1.61	1.34	1.1	0.701	0.471	0.639	0.312	0.281	0.242	0.266
Median	2.21	1.84	1.51	0.961	0.646	0.876	0.428	0.385	0.332	0.365
Mean	2.19	1.83	1.49	0.953	0.641	0.869	0.424	0.382	0.329	0.362
Max	2.77	2.32	1.89	1.21	0.812	1.1	0.537	0.484	0.417	0.458

Note: Unallocated = 'other' fuel categories represented using general proxy mix for UK electricity, 2017/2019/2020 = other renewable fuels allocated between existing renewable categories, other non-renewables represented using general proxy mix for UK electricity, adjusted = other categories allocated proportionally among existing renewable/non-renewable fuel categories. Renewable +9 = fully renewable scenario taken to be 91% of the overall CF, with an additional 9% added to represent 100% of a CF using renewable energy.

TABLE 8 WF results (m^3) for 1 kg of lettuce under different allocation scenarios for electricity mix.

	2017 unallocated	2017	2019 unallocated	2019	2019 adjusted	2020 unallocated	2020	2020 adjusted	Fully renewable
Min	0.106	0.106	0.12	0.116	0.112	0.115	0.116	0.116	0.116
Median	0.146	0.145	0.165	0.159	0.154	0.158	0.159	0.158	0.159
Mean	0.145	0.144	0.163	0.157	0.153	0.156	0.157	0.157	0.157
Max	0.183	0.183	0.207	0.199	0.194	0.198	0.199	0.199	0.199

Note: Unallocated = 'other' fuel categories represented using general proxy mix for UK electricity, 2017/2019/2020 = other renewable fuels allocated between existing renewable categories, other non-renewables represented using general proxy mix for UK electricity, adjusted = other categories allocated proportionally among existing renewable/non-renewable fuel categories.

However, the scenario with full renewable electricity generation with a median value was only slightly above that of the value for UK OF (0.032 kg CO^2 eq. higher). Furthermore, the minimum value estimated (0.242 kg CO^2 eq.) is marginally lower than that of UK OF (0.250 kg CO^2 eq.) and all other farming methods, including summer grown glasshouse produce. Even if the results of the model were not used as a proxy but instead taken as 91% of the overall footprint (Table 7), this results in only marginal increases, (e.g. the minimum value rising to 0.266 kg CO^2 eq. bringing it just above the UK OF value) keeping the results much in line with those reported here.

Regarding the sensitivity analysis, without further information on electricity break down, a more exact estimation cannot be made. In this model, the base allocation scenario was chosen as a conservative estimate that offered more accuracy than unallocated and compensated for the lack of information about non-renewable break down in 2019 and 2020. Similarly, the exact mix of renewable energy production in a fully renewable scenario cannot be known at this point, and the mix used here is simply one option of multiple possible mixes. However, given the relatively small unknown allocation, the suggested mix is highly likely representative of the impacts that can be expected. This highlights that there is strong potential for VF in Scotland to offer a viable and consistent method for fresh produce under a full renewable scenario. This would offer indoor, local produce, all year-round. Whilst not explored as a part of this study, converting to a full renewable system would also likely have a marked reduction on the CFs for Scottish or UK grown produce in glasshouses, given the dominance of heating and lighting in the contribution analysis of GH produce.

4.2 | Water footprint and land use

As expected, given the hotter climate in Spain that allows lettuce growth during the winter seasons in an OF environment, there is a requirement for greater water input. In a closed environment such as a glasshouse or a vertical farm, water loss in minimised, often via closed loops, where unused/recycled water is saved and re-used. In the case of VF, anecdotal evidence even suggests that rainwater can be utilised rather than mains water, further reducing environmental impacts.

Unlike CF, improving the electricity mix by increasing renewable energy production increased the water footprint between the electricity scenarios of 2017 and 2019 (up by 0.018 m^3). This however remained below the WF of the GB mixes. The WF also drops slightly comparing the 2019 and the 2020 mix (down by 0.003 m^3). The differences seen are likely to be due to the relative water footprints associated with different types of wind generation (Table 2) and are somewhat subjective at this stage, as no precise outline for what the desired fully renewable energy mix should look like has been defined. Changing from the 2020 mix to the fully renewable scenario shows no further change. Nonetheless, while there is potentially some apparent trade-off with regards to water footprint and renewable use, the values are still low in all three Scottish scenarios and an improvement on the generic GB mix (Scottish range from 0.145–0.163 m^3, compared with the GB range from 0.176 to 0.314 m^3). Therefore, this aspect is unlikely to be a cause for major concern regardless of the chosen energy mix scenario.

In this study, land usage was considered only for the geographic area occupied by the farm relative to the crops produced as this was felt to be a fair measure. Others have argued that area per crop should include the square meterage of growth trays, thereby accounting for the third dimension of VF and a better indication of relative efficiency/productivity. However, literature values are in line with the former expectation, with OF requiring more area to produce crops than the more intensive VF and GH options. Due to the three-dimensional stacking available in VF systems, it is logical that it offers the lowest LU per kilogram of lettuce produced when measured in this way. In addition, OF requires access to areas traditionally farmed, while VF is not bound by such limitations and can operate across the rural-(peri)urban scale.

TABLE 9 Estimated transport time for lettuce produced under different farming methods for onward sale in Scotland.

	UK OF	UK GH	Scottish VF	S OF
Transport distance (km)	200	200	30	2600
Transport time	2 h 4 min	2 h 4 min	37 min	35 h 5 min
Assumptions	Assuming an average of 60 mph	Assuming an average of 60 mph	Assuming an average of 30 mph	Assuming an average of 60 mph. Inclusive of 8.5 h rest period rather than continual driving

Note: UK OF, grown in open farm in the UK; S OF, grown in open farm in Spain and Scottish; VF, grown in a VF in Scotland. Based on data taken from Canals et al. (2008) and Hospido et al. (2009).

4.3 | Transport

Though refrigerated transport was substantially further for Spanish OF produce (Canals et al., 2008; Hospido et al., 2009) and was a dominant contributor to the component analysis for Spanish grown lettuce, the CF values indicate that it is of low concern in terms of GHG emissions. Spanish OF lettuce offers one of the lowest CF options for lettuce production, second only to UK OF, which can only produce seasonally. Similarly, though the transport duration was substantially longer than that of any UK produce, exploration of potential nutrient decline did not highlight major losses. Though loss of vitamin C was unarguably higher in the Spanish lettuce scenario at approximately 5% in open packaging (4.6%), this is relatively minor overall (at approximately 5.5 mg 100^{-1} g f.w). This could still be an issue if further delays in delivery of produce from abroad became common, particularly given Brexit restrictions and this could affect the lifespan of the vegetable pre- and post-sale. However, the other nutrients (such as carotenoids, Vitamin K, A and folate) are more labile than vitamin C and therefore can suffer a greater proportional reduction with transportation, predominantly due to dehydration. Allied to this, extensive transportation and storage can also impact deleteriously on shelf life, mineral loss and consumer attractiveness via wilting and discolouration (Managa et al., 2018). Closed packaging can reduce the nutrient loss by approximately 2.5%, suggesting this to be the best-case scenario for this aspect in transport, though it is likely to increase overall CF of the product via packaging embedded footprints.

4.4 | The future of Scottish fresh produce production

Hand in hand with a pledge to meet NetZero by 2045 (Scottish Government, 2019), Scotland is committed to moving towards fully renewable energy production and use. Currently, there is a mismatch between the two, with Scottish energy use close to 100% from renewable sources (98.6% in 2020), but with Scottish renewable energy production dragging behind at 61.8%, though this remains higher than in England and Wales (Scottish Government, 2021). With the current renewable electricity use and intended achievement of fully renewable energy usage within Scotland the closer goal, this increasingly highlights the possibility of VF as a viable and environmentally sustainable option for Scottish agricultural produce. Further improvements may also be delivered by the increase in microgrids and local renewable and relatively low-cost energy (Martin, 2020).

As well as the benefits of vertical farming highlighted in the introduction (decreased nutrient requirement, decreased water footprint, removal of need for pesticides, decreased transport time and decreased nutritional loss), by moving food production into a more urban environment, vertical farming offers the potential for increased jobs in cities and convenience for retailers and consumers of the produce. This in turn could free up farmland for production of other crops less suitable for vertical farm produce or intended for export. Nonetheless, there is a limit to what can currently be offered by vertical farming. Production is currently concentrated on fast-turnaround crops such as leafy greens and herbs (Artemis, 2020). Other, high-value crops are also beginning to be produced as well such as strawberries, tomatoes and ornamentals with research on going to other produce both for consumption as well as pharmaceutical/nutraceutical use, for example saffron (Crop Health and Protection, 2022). However, slow growing, heavy crops that typically require more space (e.g. potatoes and rice) are not likely to be suitable for vertical farming with the current technologies. VF systems offer the potential for speed breeding and creation of the new of varieties as it allows multiple generations of a crop to be produced within a calendar year. This would reduce breeding costs and resource use (Hickey et al., 2019; Samantara et al., 2022). On the other hand, by taking up presence in the urban environment, VF puts food production in direct competition with other claims for the space, such as housing which is already in short supply in some areas. Also,

TABLE 10 Calculated percentage loss of vitamin C in lettuce based on expected transport times for lettuce production options for Scotland (2 h and 4 min across country transport for greenhouse grown and UK open field produce, 37 min for locally grown vertical farm and 35 h and 5 min for inter country transport from Spain) at 5 degrees centigrade.

% loss of vitamin C during transport								
N concentration applied (mg N L^{-1})		20	80	140	200	260	Average % loss	Average Vit C decline from harvest (mg 100^{-1} g.f.w)
UK produce	Closed packaging	0.01	0.05	0.15	0.20	0.20	0.12	0.15
	Open packaging	0.36	0.27	0.26	0.26	0.22	0.27	0.33
Vertical Farm produce	Closed packaging	0.00	0.02	0.04	0.07	0.06	0.04	0.05
	Open packaging	0.11	0.08	0.08	0.08	0.07	0.08	0.10
Spanish Produce	Closed packaging	0.15	0.88	2.48	3.65	3.36	2.10	2.54
	Open packaging	5.99	4.53	4.39	4.39	3.65	4.59	5.53

Note: Based on vitamin C decline data under 5 different fertiliser application conditions and two different packaging conditions from Konstantopoulou et al. (2010).

existing infrastructure might not easily allow for VF to be undertaken at points of maximum benefit, but instead be relegated to the outskirts of a city, decreasing convenience and increasing required transport and by extension GHG emissions.

This study explored VF in the context of Scotland, though extrapolations can be made to a wider global environment. It is clear that for VF to become a sustainable and viable option for produce, the electricity mix is crucial. Our findings argue that for any country with fully renewable or low GHG producing energy production, VF is likely to offer a low CF production method for selected local food. However, even when fully renewable, VF has not yet achieved carbon neutral produce and would still require offset in order to meet NetZero. As this is still a new, and quickly evolving area, undoubtedly the next few years will see further increases in efficiency and establish best practice methodologies.

4.5 | Further research

The study gives an overview focussing on relevant comparative production streams in Scotland to allow for the potential of VF to be judged in context. The issue of risk of crop loss (increased waste) in OF agriculture is one that could potentially play a significant role, but at this stage has not been accounted for in any of the discussions or calculations. Similarly, while restricting the modelled results to electricity usage still represents the vast majority of the CF of a Scottish, it is important to produce a full LCA to assess all potential impacts in future examinations.

In particular, the contributions of substrate and nutrient solution have been highlighted in literature (Nicholson et al., 2019) as potentially high inputs to CF. Due to the range present in literature, expanding the LCA to include several farm set-ups, concentrating on comparative efficiencies, should shed more light on what to expect and highlight best practice from a sustainability point of view. The advantages of VF in areas where localised renewable energy is either being constrained or generated pre-grid, and the scale of VF systems on their efficiency offer additional points for future investigation, as does the effect of scale on sustainability. Though it was not possible to obtain data to explore for this study, the current willingness of VF industries to collaborate indicates that they may be receptive to future work. With the industrial input, the issues around relative contribution to supply chain losses (and CF) could be elucidated and solutions identified. The cost implications of vertical farming are a potential obstacle, both in implementation and in production and should be better explored in the Scottish, and wider global context. Finally, a similar in depth LCA should be undertaken for GH options, exploring the effects of changing electricity/energy options holds for them.

5 | CONCLUSION

This study has highlighted VF as having strong potential for future sustainable food production. Though a large range was found in literature, and the modelled results indicate that with the current electricity production mix for Scotland VF is comparable to existing production methods. Furthermore, by moving to a full renewable electricity production scenario, VF lowers its potential CF to on par with that of UK OF agriculture. This is lower than the options for Spanish produce, or that of heated glasshouses. Furthermore, it would allow for minimum time between harvest and onward sale, and offer consistency in production year-round, not subject to seasonality or adverse weather conditions.

There is a trade-off between CF and water footprint under both the current system and the possible future systems. Under current levels, Spanish OF closely followed by UK OF require the most water inputs, and in a full renewable scenario, where VF becomes much more viable, there is a slight increase in water usage caused by some renewable electricity options. These are deemed relatively minor in comparison with the requirements by OF agriculture, however, the importance of the trade-off must be something better explored and considered in a case-by-case scenario. Land use was also found to be highest in the OF systems and lowest in the VF system highlighting another potential trade-off in the current scenario. While potentially VF offers more effective land usage in terms of output, the issue of desirability and location must be considered may offer other considerations on this topic.

This work offers an initial insight into a complicated and highly region-specific topic and should be taken as such. Its intent is to develop a conversation around agricultural potential for Scotland and highlight potential areas of interest for further research with regard to environmental sustainability. Furthermore, it offers an insight into the potential for VF on a more global scale by exploring the importance of low-carbon energy production in VF produce.

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CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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