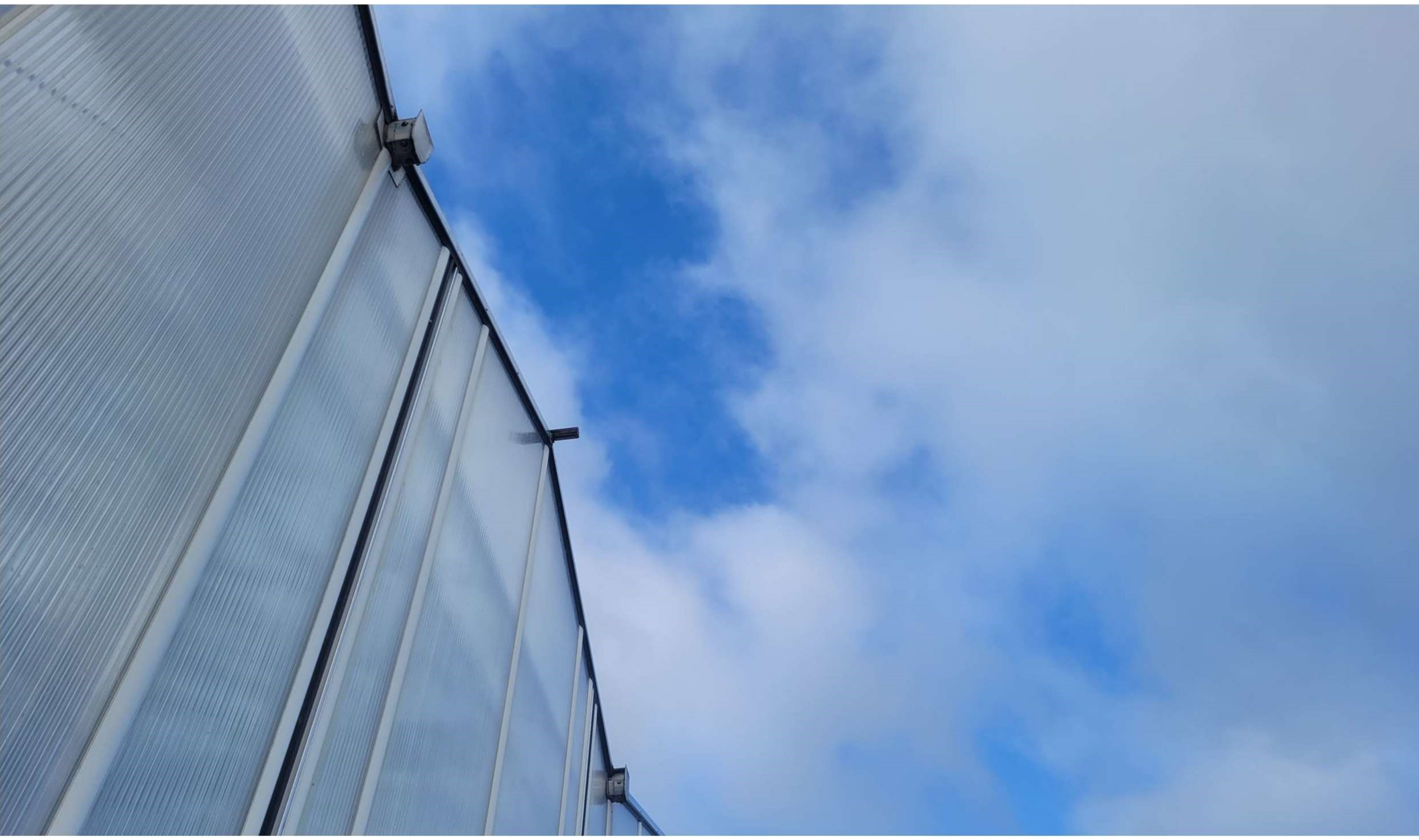
Controlled Environment Agriculture -

A review of technology utilisation

EXECUTIVE SUMMARY

"A lot of what we grow, we couldn't grow if we didn't have glasshouses."



This report reviews the technology currently utilised within Controlled Environment Agriculture (CEA) in the UK. Data was collected from trade data, scientific literature, industry interviews and questionnaires.

UK CEA sector

1. CEA is defined here as Greenhouse production and vertical farming.
2. The UK CEA sector is diverse, ranging from large scale greenhouse producers to vertical farming start-ups and technology providers. Growers produce a wide range of crops including fruits, vegetables, herbs and ornamentals.
3. The UK fresh produce and horticulture sector utilises CEA technologies for high value cropping. The greenhouse sector is small relative to outdoor cropping with 1.5% - 2% of production area but accounts for approximately 15% of the vegetable value, 9% of the soft fruit value and 33% of the ornamental value.
4. More data is needed to assess the area and value of vertically farmed vegetables, fruit and ornamentals but there is substantial investment in this area with at least 7 commercial VF businesses in the UK with production areas 5 - 25,000 m^2.
5. The majority of CEA producers and technology suppliers thought that the volume of CEA crop produced in the UK would increase over the next 5-10 years.
6. Technology suppliers were more optimistic about increasing CEA crop production and VF growers were also more optimistic than greenhouse growers.
7. The main reasons behind predictions for a decrease in greenhouse grown crops were high energy costs, labour availability and barriers for new entrants.

Current Technology in CEA

8. The single most important reason given for technology prioritisation was to reduce cost and improve efficiency with energy being the costliest item for CEA production.
9. All growers use some form of heating, ventilation and air-conditioning (HVAC) environmental control system.
10. The use of LED lighting is increasing, with some growers investing up to £11 million in LED illumination.
11. Automation was the most frequently mentioned priority for improvement by both growers and technology suppliers but those trialling robots suggest they are not yet outperforming humans.

Future Technologies

12. Research activity regarding CEA technology is increasing with the number of publications increasing 300% in 10 years.
13. The greatest research efforts in CEA technology appear to be directed towards modelling and simulation (which could benefit the development of automated control systems), energy and lighting, which ties well with the needs of producers.
14. Carbon dioxide management, highlighted as a key concern for growers, nutrition, robotics, waste management and vertical farming were under-represented in academic research. These areas therefore represent potential future research priorities.
15. The key barriers to the take up of new technology are operational costs, capital costs and technology not being fully developed.
16. Two thirds of respondents felt that current UK CEA grower advice and support was insufficient to support technology uptake.

Future Priorities

17. There was complete consensus on alternative energy sources and automated harvesting and packing as priority areas for improvement.
18. However, capital and operational costs were seen as the two strongest barriers to technology adoption.

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THE UK CEA SECTOR

CEA production value and volume

The main source of trade data is the Defra Horticulture Statistics database reporting data from the 2021 season (Defra, 2022). There are currently no data recording the volume or value of crops produced using vertical farming in the UK.

The overall area of UK protected fruit and vegetables in 2021 was 2,275 ha, accounting for 1.5% of the total cropped area. CEA production is of high value and the area of CEA vegetable production in 2021, described as protected vegetables, was 798 ha (excluding mushrooms) with a value of £256m. This accounts for approximately 15% of total UK-produced vegetable value.

The figures for CEA fruit production are less clear, as soft fruit grown under plastic is not quantified and it can be assumed that the great majority of soft fruit is grown in protected structures for a significant period of the season. The area of glasshouse fruit production has not been recorded since 2016, when it was 217 ha, the equivalent of ~2% of soft fruit production in that year. The value of glasshouse fruit in 2021 was £54.1m, accounting for 9% of the total soft fruit value of £575.3m.

CEA ornamental production has a limited dataset. The area was not recorded in 2021 and was last recorded as 118 ha of protected crops in 2004. An estimate of the value of CEA production can be derived from the categories of flowers, bulbs and pot plants (excluding Hardy Nursery Stock) and was valued in 2021 at £444m of a total of £1,580m, accounting for approximately a third of production.

Key CEA businesses

Key businesses including both growers and technology suppliers are summarised in this section to give an indication of the range and scale of CEA production. This list is not an exhaustive list of all businesses involved in CEA.

Greenhouse salad producers

The top 20 CEA salad growers in the UK turned over £689m in 2021 (HortWeek, 2021). The sector is dominated by a few large businesses and the top 5 growers accounted for 60% of the turnover in 2021.

1. APS Produce - £131m (tomatoes, peppers, cucumbers and aubergines)
2. Thanet Earth - £103m (tomatoes, cucumbers and peppers)
3. Springhill Farms - £71m (tomatoes)
4. Glinwell – £69m (tomatoes, cucumbers, peppers, aubergines)
5. Abbey View Produce - £60m (cucumbers)

Key salad producers

Greenhouse production of salads is divided between salad fruits, including tomatoes, peppers, cucumbers and aubergine. There are ~20 tomato nurseries in the UK that produce in total 100,000 tonnes a year for UK consumption and two large businesses, APS, on multiple sites and Thanet Earth in Kent, that produce roughly 50% of the UK crop. Smaller producers include Flavourfresh salads in Lancashire and R&L Holt in Worcestershire.

Cucumber and pepper production utilise the same technology as tomatoes. The Lea Valley has a concentration of growers who sell cucumbers and Abbey View Produce were previously producing approximately one third of the cucumber crop, although production has been hit hard in 2022/23 due to the effect of high energy prices. GrowCo is a group of 6 businesses growing cucumbers in Humberside and Essex. The largest grower of peppers in the UK is Tangmere nurseries in West Sussex who produce approximately 30% of the UK crop

Leafy salads are grown in both soil and soil-less production systems under protection. Key businesses include producers of traditional greenhouse-grown flat lettuce such as Snaith Salads, Yorkshire and Countryfresh, Lancashire. A large area of polytunnel production has been established at Agrial farms in East Anglia. Shockingly Fresh is a new business in Worcestershire producing leafy crops using Saturn Bioponics towers in multitunnels, and is developing production at other locations. JepCo, Lincolnshire is utilising deep water hydroponics to produce lettuce in a protected system.

Greenhouse systems are also used commonly to produce herbs for the UK market and the key players include Vitacress, West Sussex; Lincolnshire herbs, Lincolnshire and Langmead herbs, West Sussex.

Greenhouse fruit producers

The majority of soft fruit in the UK is produced under polytunnels where the level of control of the environment is limited to basic ventilation through manual movement of the polythene skin to increase or reduce air movement. More advanced technologies are also utilised in polythene multitunnels and glasshouses. This is particularly useful for early and late season production where additional heat is required for crop development. Nearly all fruit businesses produce a range of crops, with many not being produced using CEA systems. As an indication, the top 5 UK businesses in 2021 (HortWeek, 2022a) producing soft fruit are reported as:

1. S&A Produce (UK) - £85m (strawberries, raspberries, blackberries, blueberries)
2. Wilkin & Sons - £42m (strawberries, raspberries, plums, apricots, rhubarb)
3. Winterwood Farms - £41m (raspberries, blackberries, blackcurrants, redcurrants, blueberries, gooseberries)
4. Hall Hunter Partnership - £38m (strawberries, raspberries, blackberries, blueberries)
5. EC Drummond - £36m (strawberries, apples, cherries)

Key fruit producers

Key fruit producers that are utilising more advanced greenhouse technology include EC Drummonds, Herefordshire; Wilkin & Sons, Essex; The Summer Berry Co., West Sussex; The New Forest Fruit Co. Hampshire and Hugh Lowe Farms, Kent. There are also some key producers in Scotland including, Sea Hills Farm, Angus and John Hannah Growers, Lanark.

Greenhouse ornamental producers

The ornamental sector is the most difficult to summarise. Growers are producing a very diverse range of crops, with most businesses growing a wide range of species and types, utilising open ground (particularly Hardy Nursery Stock), polytunnels and greenhouse systems. The top 5 ornamental nurseries in 2021 (HortWeek, 2022b) were:

1. Flamingo Flowers (now the Butters Group) - £216m
2. Newey Varfell - £38m
3. Ball Colegrave - £29m
4. Double H Nurseries - £28m
5. Bridge Farm Group - £27m

Key ornamental growers

Key ornamental growers producing crops in CEA technology, including greenhouses or multitunnels include: Butters Nursery, Lincolnshire; Ball Colegrave, Oxfordshire; Double H Nurseries, Hampshire; Bridge Farm Group, Lincolnshire and Craigmarloch Nurseries, Glasgow.

Vertical farming producers

The UK Urban AgriTech collective (UKUAT) completed a stakeholder mapping of CEA production in 2022, with an emphasis on vertical farming (ukuat.org). They identified 44 technology suppliers and 49 growers. Amongst the growers were both greenhouse producers and vertical farming businesses. At the time of writing there are at least seven vertical farming units ≥ 5000 m^2 being built or in operation in the UK.

Key vertical farming businesses

Fischer Farms have units in Staffordshire (3,200 m^2) and Norfolk (25,000 m^2); GrowUp Farming are building a production unit in Kent (size not stated); Growing Underground have utilised redundant London underground tunnels in Clapham (~6,000 m^2); InFarm have opened a new production unit in Bedfordshire (5,500 m^2); Jones Food Company are producing crops in Lincolnshire (5,000 m^2) and Gloucestershire (15,000 m^2); OneFarm have a unit in Cambridgeshire (6,500 m^2); Perfectly fresh (APS-owned) have production in Cheshire and North Yorkshire (5,000 m^2).

The UKUAT stakeholder mapping also identified a number of smaller vertical farming businesses. Examples of these small and medium-scale businesses include: Harvest London, London; Crate to Plate, London and Vertegrow, Aberdeenshire.

CEA technology providers

Greenhouse technology

There are a number of businesses providing greenhouse technology to UK producers. These businesses can build or upgrade structures and are also increasingly offering vertical farming technologies. Key greenhouse technology providers include CambridgeHOK, Bridge Greenhouses, Ebtech Glasshouse Systems, Haygrove tunnels and Northern Polytunnels (HortWeek, 2022c).

Vertical farming technology

There are numerous businesses, including small tech start-ups and large multinational businesses, involved in developing and providing technology for the vertical farming sector. A number are providing turnkey solutions with ready-to-go units including Bridge Greenhouses, CambridgeHOK, Innovation Agri-Tech group and GroTainer. Other technology suppliers include LettUsGrow (aeroponics & container systems), Bristol; Vertical Future (hardware and software), London/Essex; and Saturn Bioponics (hardware), Birmingham. LED lighting is a fundamental requirement for vertical farming and key providers include large multinational businesses such as Signify, GE, KropTek and Valoya, as well as smaller UK businesses such as Vertically Urban, West Yorkshire.

CURRENT TECHNOLOGY IN CEA

Scope of the study

This study employed a Delphi method approach (Appendix 1) to gather views from sector producers and technology providers. Interviewees were selected in order to represent a range of different crop sectors (e.g. fruits, leafy vegetables, ornamentals), production systems (conventional greenhouses, vertical farming) and operation sizes. This led to the identification of 40 potential CEA experts in the UK who were initially contacted during October and November 2022. Twenty-five experts agreed to take part in the Delphi study, giving an initial response rate of 62.5% for the first round of interviews. All of those who were interviewed were then asked to complete an online questionnaire survey as a 2nd round of the study. Of the 25 experts who took part in the 1st round interviews, 18 completed the 2nd round of the survey. All round one interviews were conducted on Microsoft Teams and recorded. Full transcriptions of the recordings were used for data analysis. Thematic content analysis was carried out in NVivo. Round two of the Delphi study looked at nine areas related to CEA technologies. Options for each area were identified from 1st round interviews. Where ranking was appropriate, the weighted ranking for each list was presented and explained in the survey instruction. Therefore, the questionnaire survey functioned as both a platform to share round one results as well as gaining collective opinion and investigating the strength of consensus amongst the experts.

To facilitate the consensus assessment, for the first two areas, experts were asked to select top four rankings whilst options for the remaining seven areas were all measured with a 5-point ordinal scale or Likert scale. Data analysis in round 2 aimed to identify convergence of experts' judgements or opinions. In this situation, high frequencies of responses are seen as an appropriate indicator of consensus, i.e. the higher percentage of respondents selecting the same answer, the stronger the consensus.

For this review CEA was defined as Greenhouse production (fully enclosed transparent growing structures, including glasshouse and multitunnel structures, but excluding open sided polytunnels such as Spanish tunnels) and vertical farming (fully enclosed, sunlight excluding structures typically lit with LED lights).

Sample profile

The sample is largely representative of the CEA sector in the UK across a range of operation sizes, crops produced and systems used (Figure 1, Table 1 and Appendix 2). Six respondents were technology suppliers (four completed the 2nd round of surveys) and 19 were growers (14 completed the 2nd round). Of the six suppliers, one supplies conventional greenhouse systems with a single layer table top structure and five supply vertical farming systems (two aeroponic and three hydroponic). Three of these provide both technologies and services (e.g. agronomic advice, lighting recipes, technology support) to their customers.

Of the 19 growers, five use vertical hydroponic farming systems and 14 use conventional greenhouse single layer systems. In terms of the size of operation, of the 19 growers, three were micro growers with production areas under 1 ha (mean = 0.3 ha), all using hydroponic systems. Four were large growers with operation sizes ranging from 21 ha to 46 ha (mean = 30.6 ha). The 11 small growers' production areas ranged from 2 to 14 ha (mean = 6.1 ha).

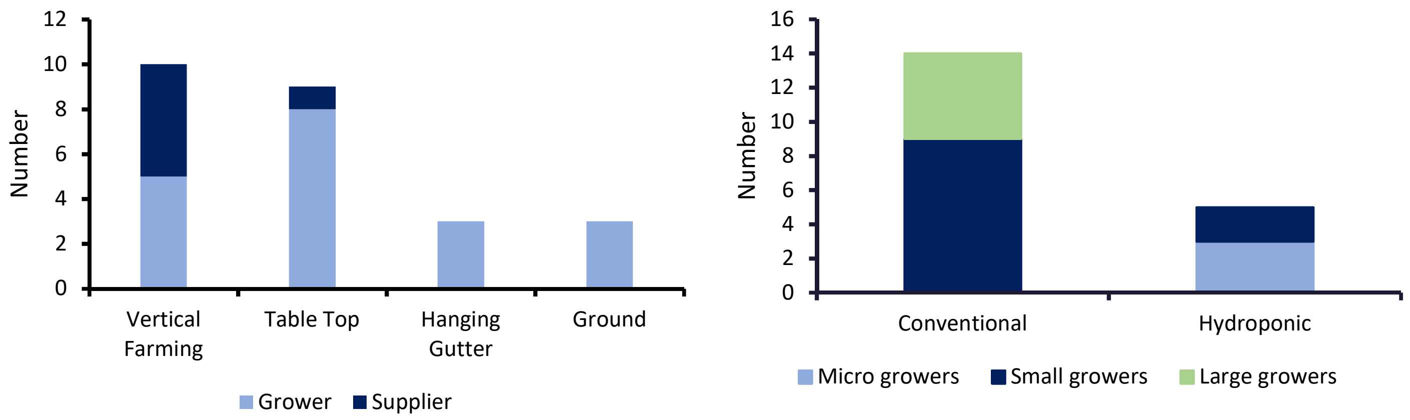


Figure 1. Profile of the survey respondents.

Table 1. Lighting systems of the respondents.

	Lighting			
System	**Fully Lit**	**Natural Light**	**Supplementary Light**	**Total**
Aeroponic	**2**			**2**
Supplier	2			**2**
Conventional		**4**	**11**	**15**
Grower		3	11	**14**
Supplier		1		**1**
Hydroponic	**7**	**1**		**8**
Grower	5			**5**
Supplier	2	1		**3**
Total	**9**	**5**	**11**	**25**

Table 2. Crops grown under CEA by operation size of the respondents.

	Operation size			
Crop type	**Micro**	**Small**	**Large**	**Total**
Garden plants	0	6	1	**7**
Soft fruits	0	3	2	**5**
Herbs	2	2	1	**5**
Leafy salad vegetables	2	3	0	**5**
Non-leafy vegetables	0	0	3	**3**

As for crops grown under CEA (Table 2), the three micro growers grew herbs and leafy salad vegetables. The small growers grew soft fruits as well as herbs and leafy vegetables. The large growers mostly grew non-leafy vegetables such as aubergines, cucumbers, peppers and tomatoes and soft fruits such as strawberries, raspberries and cherries. One grew garden plants.

Technologies currently being used in CEA production

Growers were asked to provide details of technologies used in their most advanced area of production.

In terms of the technologies used in the most advanced area (Figure 2), all growers use some form of heating, ventilation and air-conditioning (HVAC) environmental control system. Lighting was the second most frequently used technology, either as supplemental light or in a fully lit system. Nutrient application systems were used by 13 growers. This included fertigation or other controlled release methods in substrates. Use of automation in one or more functions, including harvesting, were reported by 11 growers, whilst 9 used crop monitoring. All micro growers used hydroponic systems with environmental control, full artificial illumination and fertigation. Two of them used automated harvesting. Detailed specific technologies for each technology category can be found in Appendix 2.

Similar, on a global scale, the most popular technology solutions currently used in CEA are environmental sensors and/or controllers, artificial lighting, HVAC and management software (WayBeyond & Agritecture, 2021).

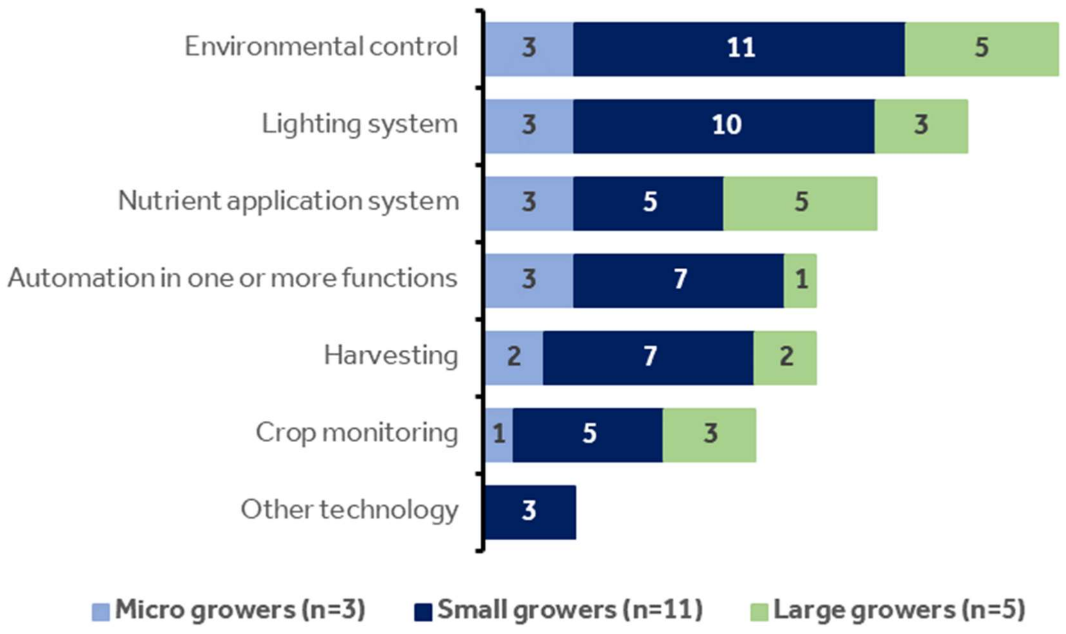
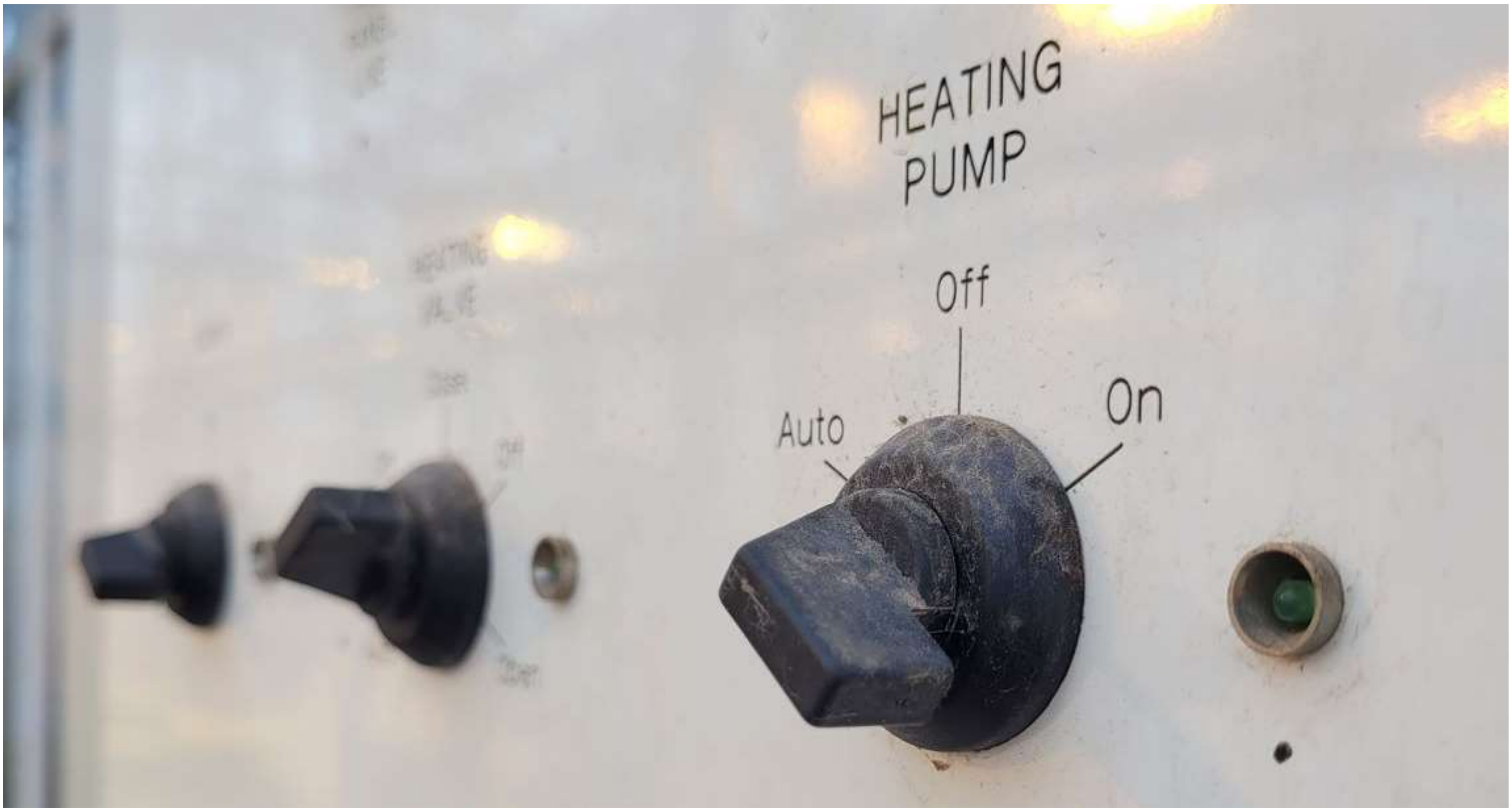


Figure 2. Technologies used in the most advanced production area of growers surveyed.

All growers use some form of heating, ventilation and air-conditioning (HVAC) environmental control system.



Environmental control (n = 19)

Use of HVAC environmental control technologies in the most advanced production area was reported by all respondents (Figure 3). Eight out of the 19 growers reported using automatic industrial-scale HVAC control systems. Systems adopted included those manufactured by Priva (n=3), Hoogendorn (n=3), TONN (n=1) and IGS (n=1).

Heating was used by 15 out of the 19 growers. A variety of heating sources were used, including hot water systems (n= 6), biofuel boilers (n=1), gas boilers with hot water pipes (n=1) and combined heat and power (CHP, n=4), sometime combined with lighting. As an energy source, three growers used biomass and three used gas. One grower used anaerobic digestion, one used thermal screens and one used waste heat from lighting. Ventilation was used by 15 growers. 12 used active ventilation and some combined ventilation with other HVAC components such as humidity control. Four growers reported using passive ventilation. Cooling was used by 11 growers and eight reported no use of active cooling technologies. Active cooling used included automated smart screen shading, refrigerating water and standard air conditioning. One used a cooling system that works by reversing the heating system. Humidity control was used by 11 growers. Humidity control techniques ranged from misting for propagation, using steam generators, to reuse of water from refrigeration or ventilation system. Some growers used fogging systems and local dehumidifiers. CO_2 enrichment was mentioned by four growers.

Of the six suppliers, five suppliers provide some forms of HVAC system. One supplier does not provide any HVAC technology as they specialise in growth technologies.

Heating, humidity control and ventilation were the three most provided HVAC components. Some suppliers develop end-to-end growing systems that include heating, cooling, ventilation, irrigation, media nutrition, crop monitoring solutions, lighting and harvesting machines. They act as sole suppliers and offer cross-functional systems that involve all these aspects. The suppliers can also supply packing machines, but some of the technology used is owned by other businesses.

Nutrient application systems (n = 13)

A range of nutrients from standard to bio-active micronutrients are used to provide crop feeding. 12 growers used computer-controlled drip fertigation systems. Other delivery methods included substrate-based controlled release.

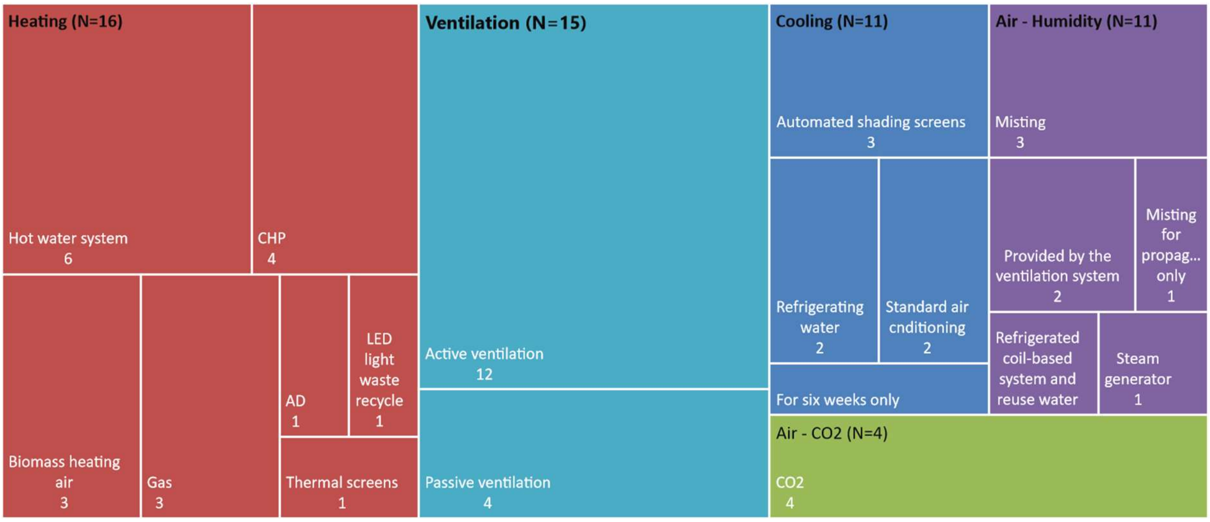


Figure 3. Environmental control technologies used by growers.

Lighting (n = 16)

Lighting was the second most used technology, as reported by 16 growers (Figure 4). 11 used supplementary lighting of a range of types and five used a fully-lit LED system. For supplementary lights, 9 used LED and the rest used sodium lights, halogen lights or other lights. Two growers reported using light as both top lighting and inter lighting to support plant growth and two reported having night break lighting. The use of LED lighting seems to be increasing, with some growers investing up to £11 million in LED illumination. Three growers did not use any lighting, but reported moving towards installing LED lights and having trialled LED lighting. Some growers also use a combination of lighting systems. One of the growers mentioned that 30% of the greenhouse is under lights. Lighting can be combined with heating as one grower uses LEDs that are 80% efficient, and 20% of the waste heat is used for heating.

The use of LED lighting is increasing, with some growers investing up to £11 million in LED illumination.

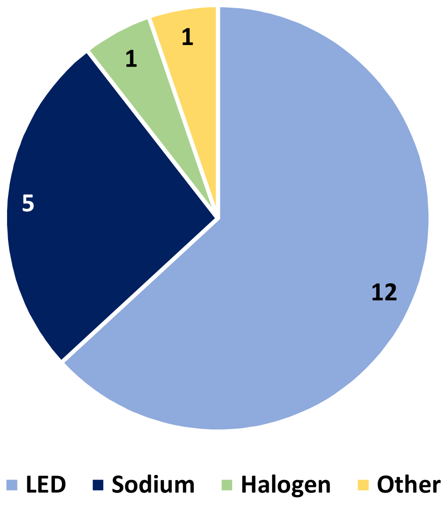


Figure 4. Lighting systems used by growers.

Harvesting/packing automation (n = 11)

Harvesting/packing technologies used included fully-automated and semi-automated systems (Figure 5). Four growers used fully-automated harvesting including one using a fleet of 40 robots to pick strawberries. Seven growers were using semi-automated systems for harvesting, involving conveyor belts, multi-head packers, heat sealing machines and robotic box making. Of the remaining eight growers who were not using any automation in harvesting or packing, six growers reported having tested a harvesting robot and two were actively seeking to automate their harvesting and packing processes. Two growers reported limited successes with their trials of automated harvesting and one grower suggested that their trials will likely take three years to commercialise.

Reducing labour costs and reliance on manual workers were the main motivation for trialling robots. Those doing so reported limit success, suggesting that robots are not yet outperforming humans although it is thought they will make a difference, “particularly on the bottom third of the curve of ability of manual harvesters.”

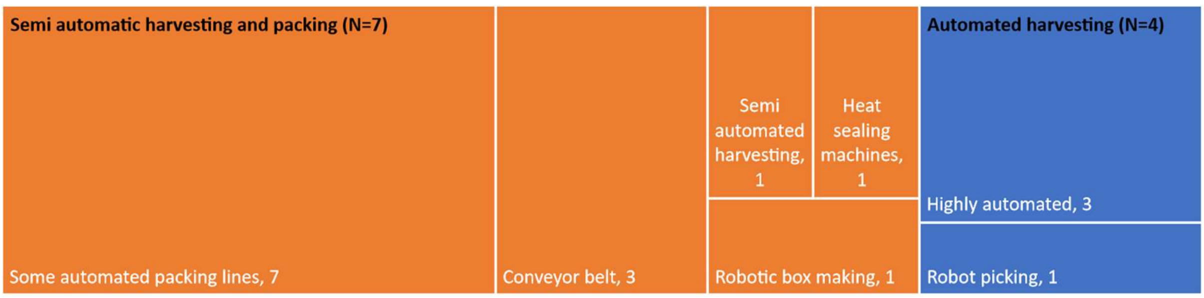


Figure 5. Harvesting/packing automation used in the most advanced growing area.

Those trialling robots suggest they are not yet outperforming humans.

Other automation (n = 11)

In addition to the 11 growers who have used full or semi-automation for harvesting and packing, other automation reported ranged from automatic HVAC control (n=8), automated seeding (n=3), automated fertigation (n=2) to lighting control (n=2). Using robots to move benches, to clean trays (Danish tray cleaning unit) or for spacing was also reported by some growers. Robots were also used for precision watering and disease prevention. Appendix 3 shows the range and frequency for each type of automation reported by growers. The use of automated systems to monitor environmental conditions, such as temperature, humidity, CO_2, and lighting is prevalent, and growers can adjust these systems remotely using a TONN monitoring system.

Crop monitoring (n=9)

For the 19 growers, four reported using generic crop monitoring (Figure 7), some growers used cameras to monitor pests and disease or autonomous UV-C light robots to help prevent disease on the crop. Other technologies used for crop monitoring include sensors used to detect plant temperature or record substrate or soil moisture. Active crop monitoring was mentioned by two technology suppliers only.

Other technologies (n=7)

Other technologies discussed by three growers and four suppliers included covering materials with spectral filters, refrigeration for crop storage, UV treatment for wastewater cleaning, growing frames for aeroponic systems and optimisation of structure height and ventilation.

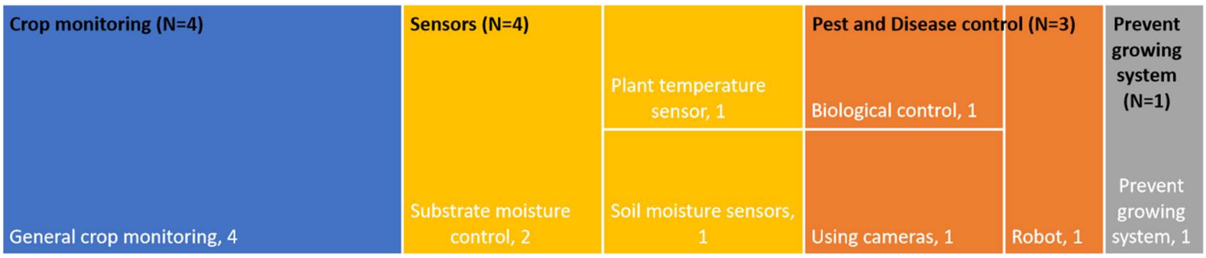


Figure 7. Crop monitoring technologies used in the most advanced growing area.

CASE STUDY: FLAVOURFRESH SALADS

Flavourfresh Salads are a greenhouse grower based in Southport, Lancashire. They currently grow 28 acres of tomatoes and 24 acres of soft fruit (mostly strawberries but also blackberries and blueberries). Annual production is 2,700 tonnes of tomatoes, 600 tonnes of strawberries, 3.5 tonnes of blueberries and 97 tonnes of blackberries.

Flavourfresh use a range of technologies including supplementary lighting provided entirely through LEDs in a mixture of top lighting and in-crop illumination. They obtain heat from a combined heat and power (CHP) unit which is distributed using hot water piping and combine this with passive ventilation. Crops are monitored using a combination of Hoogendoorn and Priva systems.

Crops are predominantly grown in hanging gutters with drip irrigation. The company previously used predominantly coir as a growing medium for tomatoes but have now moved mostly to rockwool due to logistics, COVID, transportation and energy. The crop is currently all hand-harvested but the company are trialling robots with a view to use them for this purpose in the future.

Andy Roe, Tomato Production Manager at Flavourfresh, considers the greenhouse structure an area where big improvements can be made:

"Newer build glasshouses are providing 25% more yield and 25% energy savings compared to the older structures. This is due to improvements in light transmission, air management, smaller gutters, reduction of cold spots and modern energy screens."

He considers the highest production costs currently to be heating, lighting and nutrition. Cost is also an important factor in the adoption of new technology.

Andy points out that greenhouse crops were highlighted in the Government's food strategy. He feels that if there's no help given to the sector, the produce will end becoming imported, but is hopeful there will be a recognition of the value of the sector and it will be supported.

In terms of upcoming technology, Andy feels that advances in robotics are necessary for labour reasons and points out the potential of using greenhouse structures for solar energy harvesting to store in batteries.

Proportion of production using more advanced technology

Growers were also asked to state the proportion of their horticulture business falling into the most advanced category. The responses are shown in Appendix 4.

Grower priorities for new technology within the CEA sector over the next 5 years

When asked "What systems would you prioritise for improvement over the next five years if you could, and why?", automation was the most frequently mentioned priority for improvement by both growers (n=10) and technology suppliers (n=3) (Figure 8). This included harvesting/packing automation to reduce energy costs and solve labour availability problems (n=4), automation in crop monitoring and disease control using computer vision (n=3), venting automation (n=2) and AI machine learning in crop growing (n=1). Reducing labour costs and increasing efficiency were closely linked to automation. Lighting was the second most prioritised area (n=8). A switch to LED lighting from SON-T lamps was seen as a way of reducing energy costs and was seen as the having the best potential in return on investment. Alternative energy sources were identified as a priority for achieving net zero emissions. Using solar panels and improving insulation were also mentioned as way of reducing energy costs. Fertigation (n=3) was identified as a priority area to improve water and nutrient use efficiency. It may also allow more precise monitoring of nutrition and improve food safety.

Other areas for improvement included: growing media, vertical farming infrastructure (cost reduction), carbon capture, environmental control using high pressure fogging or fully enclosed systems. Crop genetics, systems that can grow different crop types simultaneously, sensor technology and water treatment using reverse osmosis rather than UV.

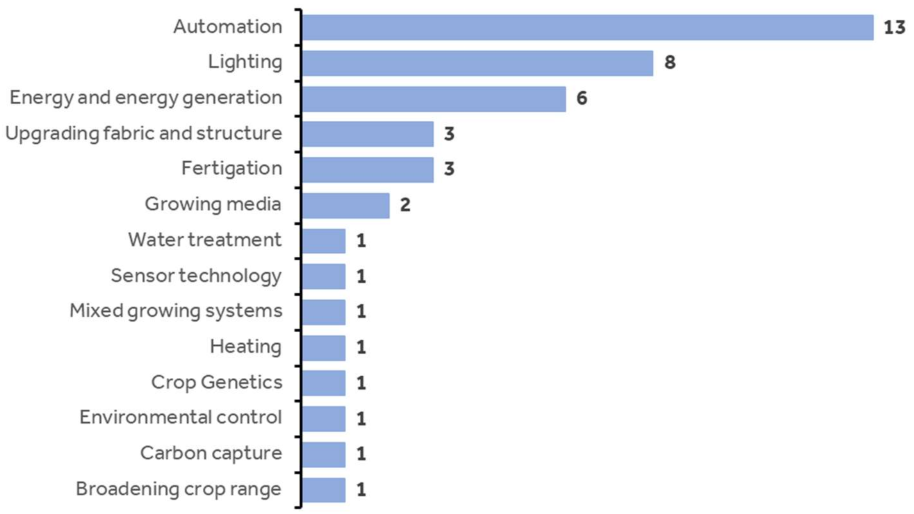


Figure 8. Technologies to be prioritised according to survey respondents.

Automation was the most frequently mentioned priority for improvement by both growers and technology suppliers.

Operational cost drivers for technology development

The single most important reason given for technology prioritisation was to reduce cost and improve efficiency. Reducing energy costs, labour cost and system costs in general were highlighted by the respondents. An interlinked area for improvement was the use of data analytics in enabling decision making, particularly in the context of energy price fluctuation.

Respondents were asked to name top three operational costs in their horticulture operation. A total of 18 items were put forward (Table 3). Energy, lighting, heating, growing media and nutrients were the top five costliest items for CEA production.

The single most important reason given for technology prioritisation was to reduce cost and improve efficiency.

Table 3. Operational cost items in CEA production. Weighting was allocated by giving 4 points to the 1st, 3 points to 2nd, 2 points to the 3rd and 1 point to any other items mentioned. The weighting score was used to multiply by number of mentioning at each ranking position. For example, energy received a total score of 80 calculated as: 76 (19 mentions as 1st cost x 4 points) + 4 (2 mentions as the 3rd cost x 2 points).

Operational cost item	Weighted score
Energy	80
Lighting	63
Heating	45
Growing Media	20
Nutrient	15
Humidity Control	10
Irrigation	10
Structure	8
Cooling	6
Automation	4
Fertigation	4
Ventilation	4
Plant Breeding	3
Propagation	3
Seed	3
CO_2 treatment	2
Management System	2
Rainwater Harvesting System	1

Energy is the costliest item for CEA production.

Barriers to new technology uptake

Respondents identified four main categories of factors that influence technology uptake: attributes of technology (n=15), organisational characteristics (n=9), external environment (n=8), and supplier characteristics (n=5). A more detailed division under each category and exemplar quotes from the interviews are presented in Appendix 5. Based on these data, a ranking of key barriers for CEA technology adoption is presented in Figure 9. The top five barriers suggested by the respondents are: operational cost, capital costs, technology not being fully developed, business models yet to be proven and a lack of sufficient knowledge transfer.

Figure 9. Perceived barriers to the uptake of CEA technologies.

The top barriers to technology uptake are: operational cost, capital costs and technology not being fully developed.

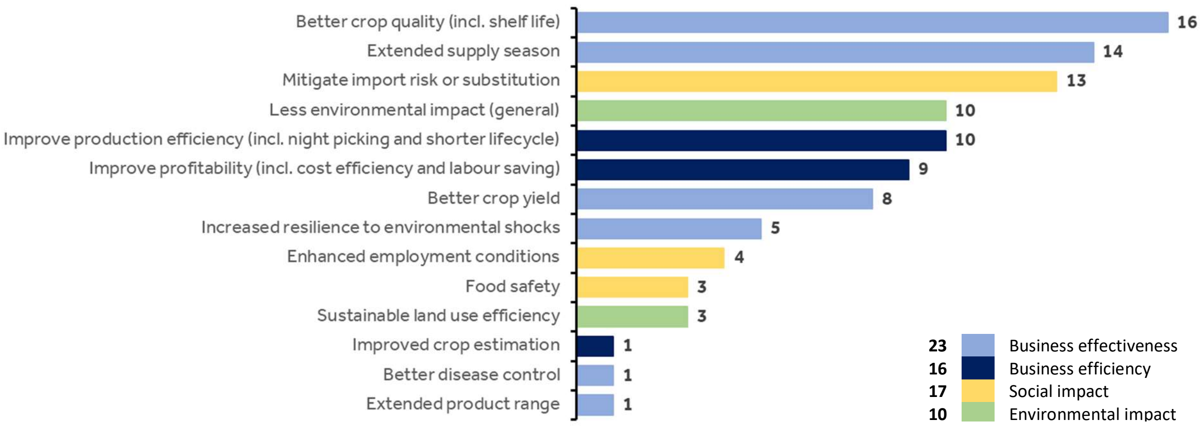


Figure 10. Key benefits to growers and technology suppliers of adopting CEA technologies.

Potential benefits of future technology developments in CEA

Respondents were asked to name three key motivations/potential benefits for adopting CEA technologies. Fourteen potential benefits were suggested along the four broad categories of Business Effectiveness, Business Efficiency, Social Impact, and Environmental Impact (Figure 10).

The most frequently mentioned category was Business Effectiveness (n=23). Within this category, the potential to improve crop quality (n=16), including shelf life, was the most mentioned benefit. Other benefits included extending supply season (n=14), better crop yield, increased resilience to environmental shocks, extended product range and better disease control. The second most mentioned category was Business Efficiency (n=16). Factors contributing to increased efficiency could include enhanced production efficiency (n=10) and potential cost savings (n=9). The use of crop forecasting or robots for night picking could also help in both regards but present their own challenges (e.g. security, energy and charging issues). Adoption of CEA technologies may not only benefit businesses, but also wider stakeholders. Key social benefits mentioned were: food sovereignty, better employment conditions and enhanced food safety. Potential environmental benefits included reduced transport costs, less food waste generation, reduced synthetic chemical application, water saving and increased land use efficiency.

CEA technologies on the horizon

Respondents were asked "What technologies are on the horizon which may be applicable in the UK?" Twelve technologies were mentioned (Figure 11) with the top four being alternative energy sources (n=11), robotics and automation in harvesting/packing (n=9), plant breeding for CEA production (n=8) and robotics and automation in growing processes (n=7).

Four respondents suggested that covering materials such as glass and polycarbonic panels or solar panels built into greenhouse roofs will evolve quickly over the next five to ten years. Lighting technology may develop further in terms of light patterns and light sources. More advanced crop protection technologies mentioned include e-noses and visioning technologies for crop and disease monitoring. However, crop breeding specifically for CEA has been seen as lacking. It was suggested that the increases in yield and quality will "have to come from genetics" but that an increased focus on breeding indoor varieties is expected by some in coming years.

"I think we're in a really exciting time. You here now have drones potentially for pollinating tomato plants. You've now got drones or robots going up and down rows looking for pests and diseases. I think that in 10 years' time the equipment inside the glasshouse is going to be very different."

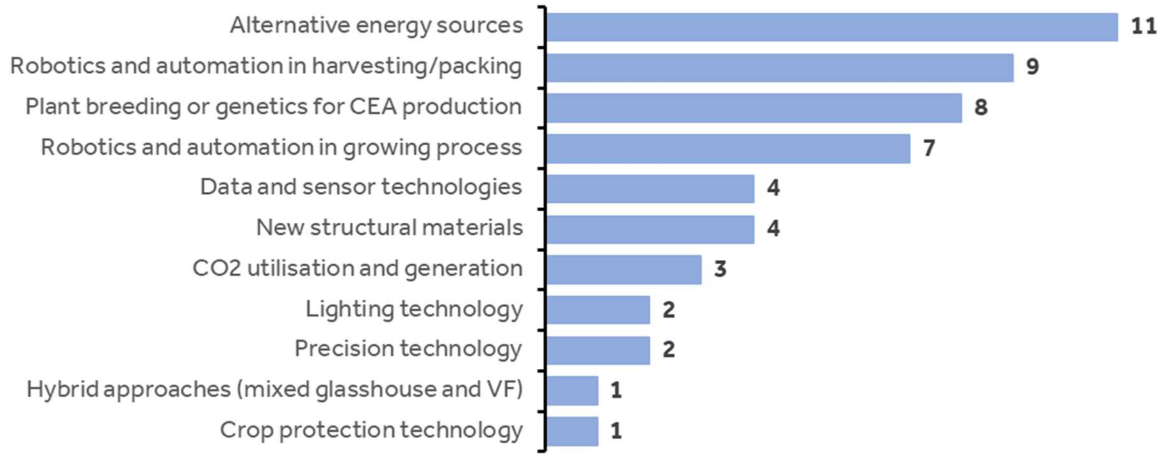


Figure 11. CEA technologies on the horizon according to survey respondents.

What opportunities exist in the sector?

When it comes to the prediction of changes of greenhouse and vertical farming crop production, there seems to be a clear divide between growers and suppliers (Table 4). In general, growers were less optimistic in outlook than suppliers. 5 out 6 suppliers (83%) predicted increased volumes of both conventional greenhouse and vertical farming production over the next 5-10 years. However, only 58% of growers predicted increased greenhouse production.

For those who predicted increased greenhouse production, reasons provided included the need for more food sovereignty, the changing climate and potential for more technology development and adoption. Shortening food supply lines, de-risking import reliance combined with increasing consumer awareness of climate change pressures were seen as the key reasons for growing more food in CEA. The main reasons for the pessimistic prediction for greenhouses were high energy costs, labour availability and barriers for new entrants. Some growers believed that there is already an over-supply for soft fruits. Some believed that the sector will see more consolidation and the barrier for new entrants lies in high capital costs which have been exacerbated by difficulties in agricultural lending.

Slightly more growers were optimistic about the future of vertical farming compared to greenhouse production. 74% predicted an increase in vertical farming. Reasons given included that vertical farming is still early stage and has attracted lots of investment, in addition to the reasons provided for increased greenhouse production. Those who predicted no growth of vertical farming cited reasons such as profitability in vertical farming yet to be proven as the operating costs are too high.

When it comes to prediction of changes of greenhouse and vertical farming crop production, there seems to be a clear divide between growers and suppliers.

CASE STUDY: DOUBLE H NURSERIES

Double H Nurseries, based in Hampshire, grow a wide variety of indoor plants, specialising in chrysanthemums, orchids and kalanchoe, but also produce a variety of seasonal crops.

The company produce all their plants in six hectares of six-metre-tall Venlo-style greenhouses. The facility makes use of biomass heating, piped hot water, passive ventilation and a Hoogendoorn control system. Double H currently use high pressure sodium lamps to supply supplementary lighting but are keen to experiment with LEDs. Orchids are cooled using refrigerated air and fogged if higher humidity is required.

Howard Braime, Crop Growing Manager at Double H, considers CEA production an important source of import substitution and means to improve crop quality and production efficiency. Technology transfer from the vertical farming sector is seeing uptake of LEDs in conventional greenhouses, something Double H are keen to expand their use of. Howard highlights such lighting as an important area for technology prioritisation as this would allow a reduction in energy costs, with lighting being seen as the highest production cost currently. This includes further research needed regarding optimisation of light spectra for improved production. Heating is another considerable expense for the business due to the increasing price of wood for and maintenance of the biomass system:

“We stopped growing roses because of the energy implications.”

The company are taking advice from growers and consultants in the Netherlands because of their expertise, sources of which are limited in the UK. Growers in the Netherlands are receiving grants to install LED lights, which is helping their adoption and driving down production costs, increasing efficiency and sustainability.

Going forwards, Howard sees challenging times for the sector:

“I think the cost of production will be virtually prohibitive in the future unless prices increase in the Netherlands. Because don't forget - the competition isn't in this country. Prices in the Netherlands dictate those elsewhere.”

However, he also highlights the use of ground source heat, solar panels and dehumidification without heating as promising technologies for CEA producers in the future.

The main reasons for the pessimistic prediction for greenhouses were high energy costs, labour availability and barriers for new entrants.

Table 4. Respondent prediction of changes of CEA crop production over the next 5-10 years.

	Grower (n = 19)		Supplier (n = 6)		Total (n = 25)	
	%	n	%	n	%	n
Greenhouse						
Increase	58%	11	83%	5	64%	16
Decrease	32%	6	17%	1	28%	7
Unsure	11%	2			8%	2
Vertical farming						
Increase	74%	14	83%	5	76%	19
No increase	26%	5	17%	1	24%	6

"If I allocate an acre of ground [to CEA] and I can stop farming 20 acres of ground as a result, I can then grow 20 acres worth of grassland. I'm producing more food per metre squared, but I'm also then releasing outdoor acreage to do the right thing with and regenerate it. So, it's a real do-good story."

Support needed for CEA technology uptake

Grower and supplier-perceived sources of advice/information to aid decision-making for adopting CEA technologies are shown in Figure 12. The top five sources were in-house development, technology providers, learning from outside the UK, particularly from the Netherlands, attending seminars and workshops organised by trade associations and reading trade press such Hortidaily.

Only seven out of 25 respondents indicated that the current UK grower advice and support was sufficient.

Figure 12. Sources of advice and guidance to growers and technology suppliers regarding CEA technologies.

However, only seven out of 25 respondents indicated that the current UK grower advice and support was sufficient. These 7 believed that either suppliers have provided sufficient support and advice or that their own independent learning was adequate. 17 out of 25 respondents suggested that more advice and support are needed for UK growers. There were concerns about the lack of a centralised advice and guidance in the post-AHDB era. Some respondents discussed the need for a one-shop for all kind of database and guidance which will benefit the whole UK CEA sector. Some discussed the challenges of secrecy and fragmentation in the sector.

"The way the whole agricultural lending system is set up in the UK is unsuitable for [CEA]... it's not set up for high capital investment on small areas of land. It's asset value-based, it's not based on business lending, cash flow lending."

CASE STUDY: FISCHER FARMS

Fischer Farms are a vertical farming company, founded in 2016, in the process of building their first commercial farm, a 25,000 m^2 facility in Norfolk.

The company aims to grow leafy greens, namely herbs and salad leaves. They are currently trialling production of rocket, spinach, lettuce, basil, flat leaf coriander, chives and parsley at their research and development facility.

They have also trialled growing wheat in a vertical farming facility with an aim to produce soya beans, rice and wheat commercially in the future.

Jon Cummings and Tim Smith from Fischer Farms see efficiency of lighting as a key technological component of vertical farming. They also consider this to be one of the technology areas where the most research has been carried out and seen the greatest level of development. Despite this, it remains the highest running cost for vertical farming.

They also see genetics, irrigation and fertilisation as priority areas for improvement.

Photovoltaic cells are an area of innovation on the horizon that is also highlighted by Jon and Tim. This includes reduced size of panels and transparent cells that could allow plants to be grown underneath.

Jon and Tim feel there is a need for increased advice and guidance to producers in the CEA sector:

“We spend a lot of time trying to find suitable information. There isn’t enough information sharing due to intellectual property issues…the industry has been told not to share information. There are significant fines for those who share.”

They view capital costs as the greatest barrier to technology adoption. For example, rainwater harvesting would greatly benefit irrigation efficiency, but is expensive because of water regulation requirements.

“It’s cheaper just to take water from the mains.”

The team consider in-house research and development, coupled with input from academia as their most influential sources of information.

TECHNOLOGIES IN DEVELOPMENT

Methodology

In order to assess the state of technology development in CEA, a Quick Scoping Review (QSR) methodology was used to search available literature sources (academic publications and commercial literature) for publications regarding CEA technology published within the last 10 years (i.e. January 2012 to December 2022). Titles were captured and imported to EPPI-Reviewer, duplicates removed and results manually coded for inclusion/exclusion based upon title and abstract content.

The included articles were then categorised according to: Country, Year of Publication, Technology Type, Technology Function, CEA System and Crop Type, based upon title and abstract text content of keywords. If an article contained text matches to multiple categories, all were counted e.g. a paper discussing sensors and energy would be counted for both categories. As a caveat, it should be noted that these data are unable to identify whether presence of a keyword reflects the focus of a technology study or incidental occurrence as part of the general description of the study methodology. Details of the methodology used can be found in Appendix 6.

The screening process resulted in the identification of 3,721 relevant primary studies which looked at CEA technologies. The vast majority of included articles were obtained from the scientific literature. This may reflect public availability of the data due to its pre-competitive nature.

Number of research publications by country

The country listed in the authors' institution was used as proxy for the country of primary studies. There were 730 titles which did not contain institution details. The remaining 2991 studies identified were from 100 different countries worldwide (Figure 13). The top ten most prolific countries were China (n=720), USA (n=178), Japan (n=160), Korea (n=147), India (n=123), Italy (n=121), Spain (n=101), Indonesia (n=91) and the Netherlands (n=80). There were 35 publications from the UK. Figure 2 shows all the countries identified. These data may reflect heightened research interest or funding availability in certain countries but likely also reflects overall research capacity of more populated and/or wealthier nations.

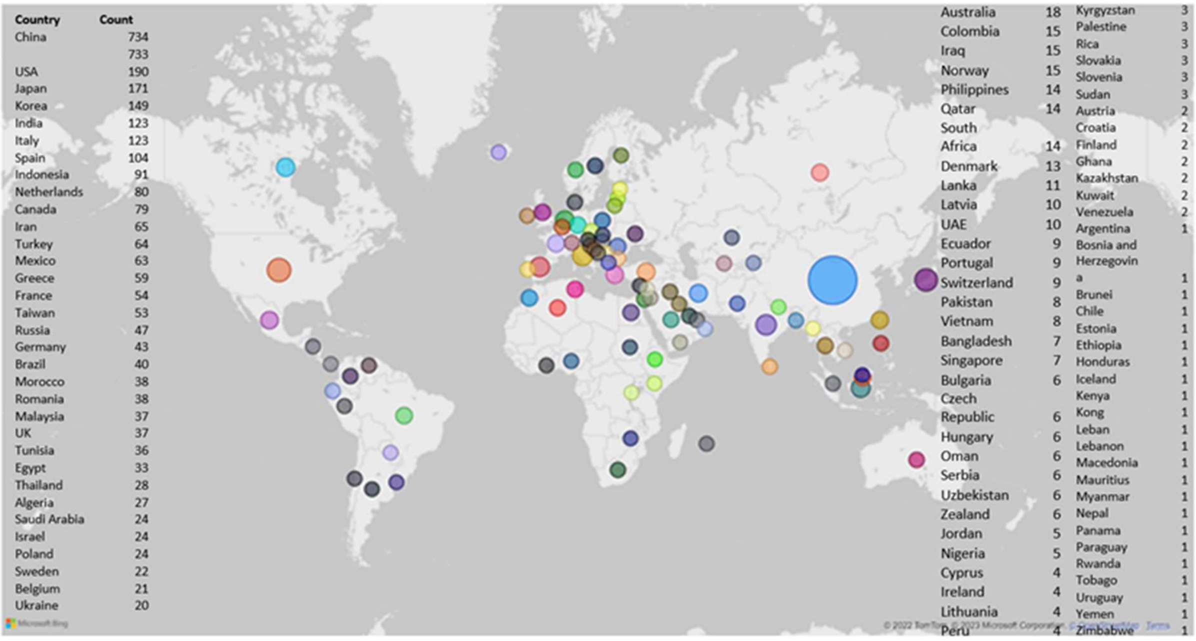


Figure 13. QSR literature results based upon institution country.

Technology type

Categorising the articles by the type of CEA technology mentioned in the title and/or abstract revealed a high level of variation amongst the number of articles referencing different technology classes (Figure 14). The most popular category was Modelling/Simulation with 1742 articles, followed by Energy with 1182 articles and then lighting with 928. Other popular categories included Sensors (n=888), IT Environment (n=743), Automation (n=662), Energy Sources (n=596), HVAC (n=595) and Artificial Intelligence (n=545). These findings could reflect heightened academic interest in modelling and simulation studies and energy studies. This may reflect their ease of investigation, the availability of funding, publishing bias or degree of interest from industry. Interestingly, relatively few articles discussed carbon dioxide management, highlighted in the industry interviews as a key concern for some producers. Nutrition, robotics and waste management were also under-represented. This could reflect a lack of progress in these areas due to the difficulties of investigation (robotics), limited industry interest due to existing optimisation (nutrition) or lack of academic or funding interest.

The most popular research category was Modelling/Simulation, followed by Energy and then Lighting.

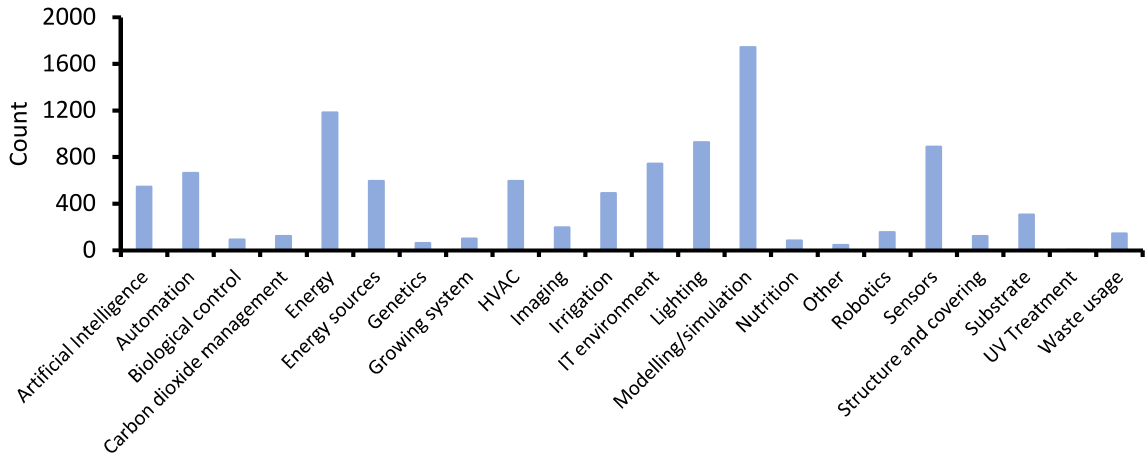


Figure 14. Publication counts for CEA technology-relevant literature identified in the QSR review grouped according to technology type.

Relatively few articles discussed carbon dioxide management, highlighted as a key concern for growers. Nutrition, robotics and waste management were also under-represented.

Year of publication

The Year of Publication data (Figure 15) indicate a steady increase in the number of CEA technology-associated publications over the period from 2013 to 2022. These data may reflect an increased interest in CEA technology options over this time period. This bodes well for the future development and employment of such technologies in industry provided that transferability from academia to industry can be achieved. This could involve uptake of academic data by industry and the use of public-private funding schemes to drive applicability of technology to producers. The slight decrease for articles published in 2022 compared to 2021 may be due to the sampling date of the QSR in late 2022.

Cross-tabulation with the Technology Type data (Appendix 7) revealed overall increasing trends across the study period for most Technology Types with particularly rapid increases in literature output for the areas of Artificial Intelligence, Energy, Irrigation, IT Environment, Lighting and Modelling/Simulation. Whilst outputs for Growing System, Imaging, Substrate and Waste increased compared to 2013 levels they remained relatively low compared to other Technology Types.

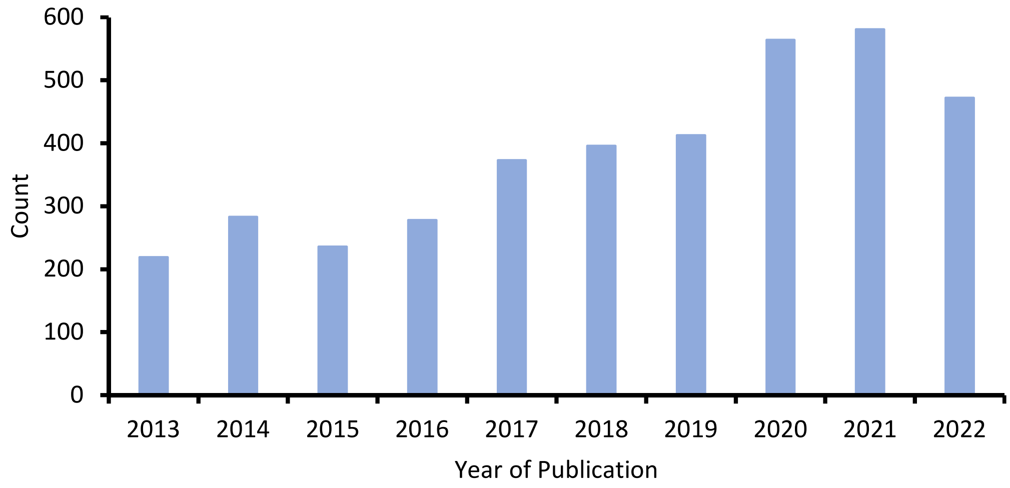


Figure 15. Annual publication counts for CEA technology-relevant literature identified in the QSR review across the study period of 2013-2022.

Data indicate a steady increase in the number of CEA technology-associated publications in the last ten years.

Technology function

The broad technology classes presented in Figure 14 were further broken down to provide a more detailed categorisation of the function of such technologies in CEA (Figure 16). The most frequently mentioned by far were Planting (1792) and Climate Control – Temperature (1789). These data could be artificially increased by reporting of general methodology aspects in the abstract, such as growing temperature and planting methodology. The next most frequent category was Climate Control – Humidity (956), followed by Monitoring (950), Climate Control – Heating (904) and Plant Growth (897). Again, methodology reporting could inflate these figures but may reflect an increased interest in research regarding monitoring technologies and temperature and humidity management compared to other areas of technology function. By contrast, relatively few articles described the use of technology for e.g. Cleaning, Shading, CO_2 Enrichment, Pollination, Seeding or Waste aspects. This may represent under-investigated topics for CEA technology that could warrant additional investigation based upon industry needs.

Cross-tabulation of Technology Type and Technology Function (Appendix 8) revealed co-occurrence of the following terms: Modelling/Simulation, Sensors, Artificial Intelligence, IT Environment and Energy considerations with Climate Control aspects such as Cooling, Humidity, Heating and Temperature; co-occurrence of Lighting with Humidity or Temperature; Artificial Intelligence with Humidity and Temperature; Modelling/Simulation, Lighting and Energy with Planting. Again, some results could reflect reporting of study conditions.

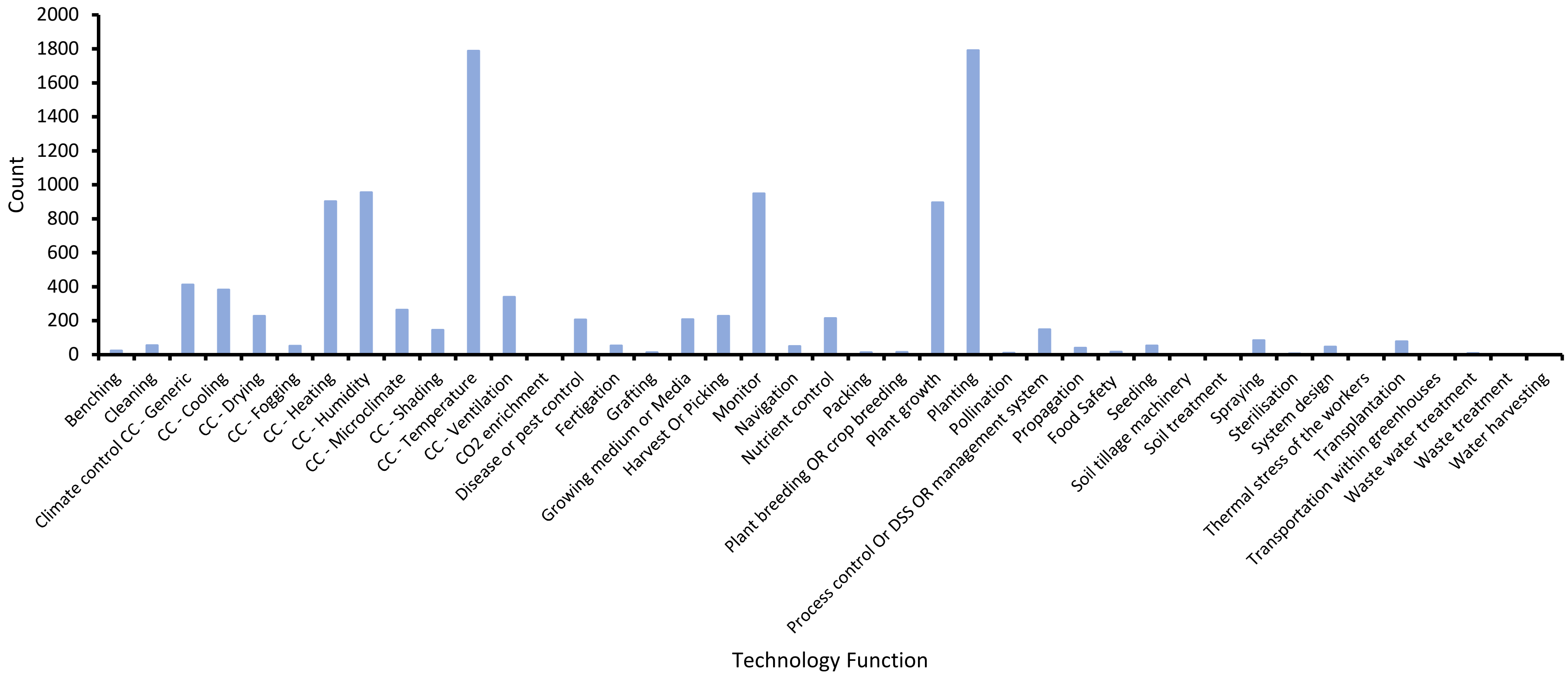


Figure 16. Publication counts for CEA technology-relevant literature identified in the QSR review grouped according to technology function.

CEA system categories

Grouping the data according to system type and growing method (Figure 17) revealed a strong research focus on Greenhouse production (n=3316) compared to Vertical Farming (n=63) and Polytunnel growing (n=84). This likely reflects the relative abundance of conventional greenhouse production in the protected horticulture industry compared to other growing systems. Whilst vertical farming lends itself to high-tech approaches, it is a relatively nascent industry with limited public research facilities likely curtailing investigation in such setups. Greenhouses, by comparison, are numerous and readily available to researchers at a fraction of the cost of vertical farming facilities. Furthermore, much vertical farming technology is proprietary in nature, limiting its exposure in the public domain. In addition, there has recently been acknowledgement of the limitations of vertical farming in the press questioning its claims as a feasible component of agricultural supply chains (e.g. The Guardian, 2022). In terms of non-soil-based production methods, Hydroponic (n=464) far outstripped Aeroponic (n=38) or Aquaponic (n=26) production.

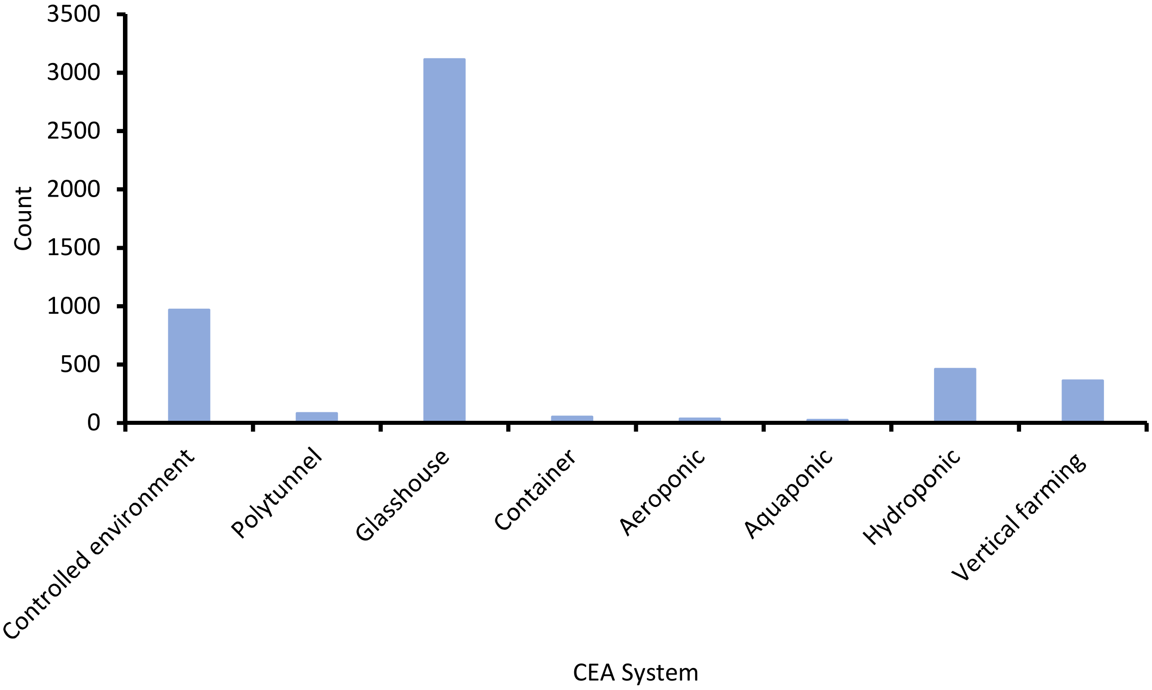


Figure 17. Publication counts for CEA technology-relevant literature identified in the QSR review grouped according to system type and growing method.

There was a strong research focus on greenhouse production compared to vertical farming and polytunnel growing.

Cross-tabulation between Technology Type and CEA System (Appendix 9) revealed the following heightened co-occurrences: Artificial Intelligence, Automation, Energy, Energy Sources, HVAC, IT Environment, Lighting, Modelling/Simulation and Sensors with Controlled Environment and Greenhouse. In addition, co-occurrence of Irrigation and Greenhouse was also commonly found. These Technology Type categories were also the most numerous for articles mentioning Hydroponics but at a much lower overall level than for Controlled Environment or Greenhouse.

Despite lending itself to high-tech approaches, vertical farming is a relatively nascent industry with limited public research facilities. Much vertical farming technology is proprietary in nature, limiting its exposure in the public domain.

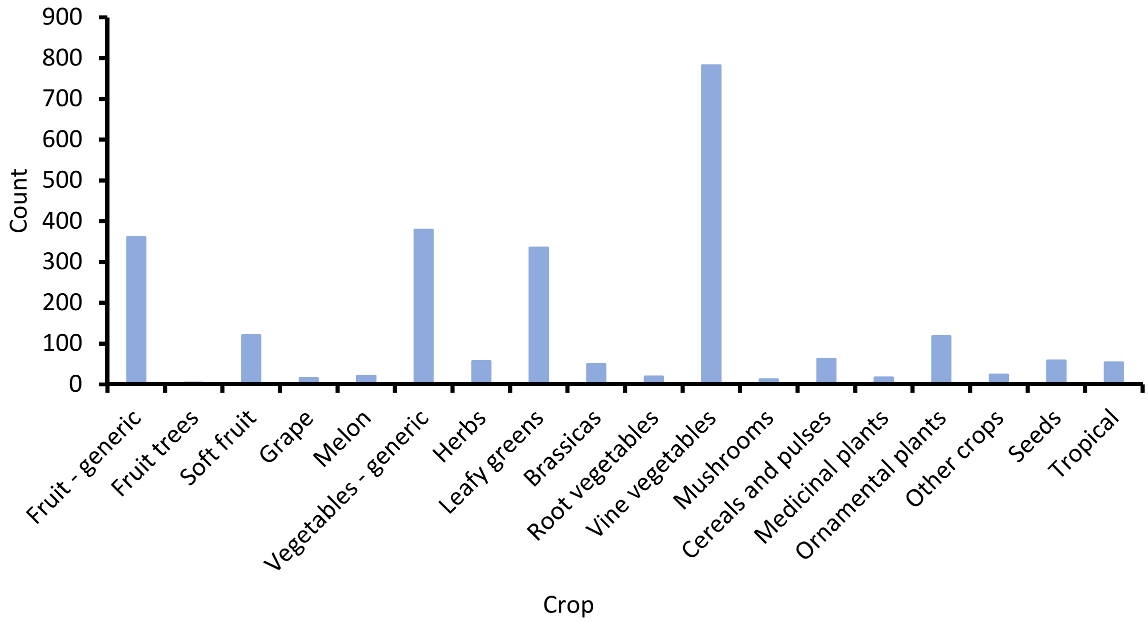


Figure 18. Publication counts for CEA technology-relevant literature identified in the QSR review grouped according to crop type.

Crop type

The vast majority of articles (n=2119) were general in their applicability of technology and did not refer to one or more particular crops. Of those that did discuss crop type (Figure 18), by far the most numerous were the Vine Vegetables (tomato, pepper, cucumber etc.) with 782 articles. This could reflect their position as some of the most abundant greenhouse crops. That these crops are currently less suitable for vertical farming may also help to explain the relatively limited representation of this system type in the literature. Other relatively abundant crop types included Fruit – Generic (n=361), Vegetables – Generic (n=379) and Leafy Greens (n=335). Apparently little work has been undertaken regarding technology specifically targeted at crops such as herbs and medicinal plants.

Cross-tabulation between Technology Type and Crop Type (Appendix 10) largely reflected the overall abundance of these categories i.e. the most frequent Technology Type categories (Energy, HVAC, Irrigation, Lighting, Modelling/Simulation, Sensors) were found at the highest level with the most commonly mentioned Crop Types (Vine Vegetables). Substrate was also commonly co-occurring with Vine Vegetables but could reflect reporting of methodological aspects.

Detailed categorisation

A more detailed breakdown of the above categorisation was made by manually assigning 33,725 keywords extracted from the article title and abstracts (Appendix 11). This allowed cross-tabulation heatmap generation between Country and Keyword (Appendix 12) and between Year of Publication and Keyword (Appendix 13). Note that it is not possible to distinguish between the research focus of the article and incidental mention of experimental setup.

TOWARDS A SECTOR CONSENSUS

Scope of the study

Based upon the data collected in the first round of the Delphi study, combined with interpretation of the literature searches in the QSR component, round two of the Delphi study investigated nine areas related to CEA technologies in further categorical detail, in order to identify the presence of any consensus of opinion regarding technology within the UK CEA sector at a finer scale. Questions were posed to a subset of respondents from round one covering a representative sample of the sector.

Highest system costs

Respondents were asked to select the top four highest costs in their own CEA systems from a list of 18 options (Table 5). There was strong consensus regarding the top four highest cost items in CEA systems, which are "energy", "lighting" (which is also a major energy consumer), "structure & fabric" and "heating" (another energy consumer). Thirteen, or 73%, of the respondents indicated that "energy" was either the highest or the 2nd highest cost in their system. "Lighting" was chosen as top four by 11 (61% in total), of which 44 % chose this as the 1st or 2nd highest cost item.

Table 5. Four highest system costs for CEA sector respondents in Delphi round two.

Item	Total number of selections	% indicating this being the highest cost	% indicating this being the 2nd highest cost	% indicating this being the 3rd highest cost	% indicating this being the 4th highest cost
Energy	**13**	56%	17%	0%	0%
Lighting	**11**	11%	33%	6%	11%
Structure and Fabric	**7**	22%	6%	6%	6%
Heating	**7**	6%	22%	11%	0%
Humidity Control	**6**	0%	6%	11%	17%
Growing Media	**6**	0%	6%	6%	22%
Cooling	**4**	0%	0%	22%	0%
Seed	**4**	0%	0%	22%	0%
Nutrient	**4**	0%	0%	6%	17%
Irrigation	**3**	0%	6%	0%	11%
Automated harvesting/packing	**3**	0%	0%	11%	6%
Fertigation	**3**	0%	6%	0%	11%
CO_2 management	**1**	6%	0%	0%	0%
Ventilation	**1**	0%	6%	0%	0%
Propagation	**1**	0%	0%	0%	6%
Plant Breeding	**0**	0%	0%	0%	0%
Management System	**0**	0%	0%	0%	0%
Rainwater Harvesting System	**0**	0%	0%	0%	0%

Potential benefits of adopting CEA technologies

Respondents were asked to choose the top four motivating factors for adopting technologies in their own CEA systems from a list of 12 items. Table 6 shows a moderate level of consensus. It shows that crop quality and extended supply season were both selected 11 times, with 33% and 28% indicating them as the most important reason, respectively. Crop yield was selected 10 times, with 11% indicating it as the most important reason. Other reasons for adopting CEA technologies include profitability (n=8), mitigating import risk (n=7), reducing environmental impact (n=6), reducing variability (n=5), production efficiency (n=3) and disease control (n=3).

Table 6. Potential benefits for adopting CEA technologies according to sector respondents in Delphi round two.

Item	**Total number of selections**	% indicating this being the most important reason	% indicating this being the 2nd most important reason	% indicating this being the 3rd most important reason	% indicating this being the 4th most important reason
Crop quality (including shelf life)	**11**	33%	6%	17%	6%
Extended supply season	**11**	28%	17%	6%	11%
Crop yield	**10**	11%	11%	17%	17%
Profitability (including cost efficiency and labour saving)	**8**	17%	17%	11%	0%
Less environmental impact	**6**	11%	17%	0%	6%
Mitigate import risk or import substitution	**7**	6%	11%	17%	6%
Production efficiency (including night picking and shorter lifecycle)	**7**	0%	11%	6%	22%
Reducing variability	**5**	6%	0%	17%	6%
Sustainable land use efficiency	**3**	0%	11%	0%	6%
Disease control	**3**	0%	0%	6%	11%
Crop estimation	**1**	0%	0%	0%	6%
Capacity to harvest water	**0**	0%	0%	0%	0%

There was strong consensus regarding the top four highest cost items in CEA systems - energy, lighting, structure and heating.

Priority areas for improvement

The next question asked "to what extent will improvement in any of the following areas benefit your horticulture business within the next five years?" For each area (Table 7), answer options were: "most beneficial", "very beneficial", "moderately beneficial", "a little beneficial" or "no benefit". There is complete consensus on "alternative energy sources" and "automated harvesting and packing", with 100% of respondents selecting them as moderately to very beneficial. "Automation in the growing process", "growth sensing", "growing media", "lighting", and "water treatment" were also considered important areas for improvement. Cooling and heating technologies were moderately to very beneficial for most respondents. Upgrading fabrics and structure had fewer selections and were considered less important.

Table 7. Priority areas for improvement over the next five years according to sector respondents in Delphi round two.

Item	% selecting moderately beneficial to most beneficial	% selecting very beneficial to most beneficial
Alternative energy sources	100%	89%
Automated harvesting & packing	100%	83%
Automation in growing process	89%	50%
Growth sensing	89%	44%
Growing media	83%	61%
Lighting	72%	61%
Water treatment	72%	50%
Cooling technology	67%	44%
Heating technology	61%	56%
Upgrading fabric and structure	39%	28%

There is complete consensus on alternative energy sources and automated harvesting and packing as priority areas for improvement.

Probability of implementing improvements in CEA systems

Next, the probability of implementing improvements within different areas of production within the next five years was scored. For each area (Table 8), answer options were: "most likely", "very likely", "somewhat likely", "unlikely" or "least likely". Improving growing media had the highest probability of being implemented by the respondents in their own system, with 78% of respondents selecting it as somewhat to most likely, and 67% of respondents selecting it as very likely to most likely. Improvement in automation in the growing process, cooling technology, and alternative energy sources were also likely to be implemented by more than half of the respondents. Improvement in automated harvesting and packing, growth sensing, lighting, and water treatment had somewhat lower probabilities of being implemented over the next five years but were still considered likely by the majority of respondents. Upgrading fabric and structure had the lowest probability of improvement, with only 50% of respondents selecting it as somewhat to most likely, and 28% of respondents selecting it as very likely.

A recent global census (WayBeyond & Agritecture, 2021) highlighted management software as the most popular technology solution being considered by growers. Other popular choices, which align well with our data, included environmental sensors and controllers, automated seeding, harvesting and packaging tools and cloud-based software.

Table 8. Probability of implementing improvement in own CEA system over the next 5 years according to sector respondents in Delphi round two.

Item	% selecting somewhat to most likely	% selecting very likely to most likely
Growing media	78%	67%
Automation in growing process	72%	44%
Cooling technology	72%	50%
Alternative energy sources	67%	56%
Automated harvesting & packing	67%	50%
Growth sensing	67%	61%
Lighting	67%	56%
Water treatment	67%	50%
Heating technology	61%	44%
Upgrading fabric and structure	50%	28%

Barriers to technology adoption

The barriers to technology adoption in CEA were then scored (Table 9). Answer options were: “strongly agree”, “somewhat agree”, “neutral”, “somewhat disagree” or “strongly disagree”. The consensus was very high on the top two barriers to adoption of CEA technologies, with over 94% of the respondents somewhat agreed or strongly agreed that capital cost was a barrier. Operational cost was also seen as a significant barrier, with 72% selecting somewhat agreed or strongly agreed. Lack of skilled labour for CEA, market uncertainties, lack of knowledge transfer, and some technologies not fit for purpose are also seen as significant barriers with 50% or more selecting 4 or 5. Other barriers, such as lack of government support, and regulations and planning permissions were seen as less significant with less than half selecting 4 or 5. Finally, CEA being unable to compete on scale is seen as the least significant barrier, with only 22% somewhat or strongly agreed.

Table 9. Barriers to technology adoption in CEA systems according to sector respondents in Delphi round two.

Item	% selecting neutral to strongly agree	% selecting somewhat to strongly agree
Capital cost	100%	94%
Operational cost	94%	72%
Some technologies not fit for purpose	89%	50%
Lack of skilled labour for CEA	83%	67%
Technology not fully developed	78%	61%
Some technologies not transferrable	78%	44%
Market uncertainties	78%	67%
Lack of knowledge transfer	67%	50%
Lack of government support	67%	44%
Risk averse	67%	28%
Business model yet to be proven	61%	44%
Regulations and planning permission	50%	39%
Lack of infrastructure	39%	28%
CEA can't compete on scale	28%	22%

Capital and operational costs were seen as the two strongest barriers to technology adoption.

Usefulness of sources of information and advice

Respondents were asked to rate the sources of information and advice to the sector (Table 10). Answer options were: “extremely useful”, “very useful”, “somewhat useful”, “a little useful” or “very little use”. Respondents showed a high level of consensus on the perceived usefulness of the top three sources of information and advice: in-house development, on-site trials and technology providers.

Table 10. Usefulness of sources of information and advice according to sector respondents in Delphi round two.

Item	% selecting somewhat to extremely useful	% selecting very to extremely useful
In-house development	100%	72%
On-site trials	100%	83%
Technology providers	100%	72%
Own independent learning	94%	44%
Peer learning	89%	61%
Independent external research	89%	61%
Scientific literature	67%	33%
Publications in trade press	61%	22%

Respondents were then asked how strongly they agreed with statement from the round one interviews regarding sources of advice for the sector (Table 11). Answer options were: “strongly agree”, “somewhat agree”, “neutral”, “somewhat disagree” or “strongly disagree”. The statements listed in this table were individual comments from round one. Unsurprisingly, there was a lower level of consensus amongst the experts.

Table 11. Level of agreement with statements regarding sector advice from Delphi round one according to sector respondents in Delphi round two.

Item	% selecting neutral to strongly agree	% selecting somewhat to strongly agree
The CEA sector could be more cooperative in technology development	83%	56%
More proven business models of adopting CEA technologies are needed	83%	78%
The CEA sector needs more independent advice and guidance	78%	61%
The CEA sector needs more centralised advice and guidance	72%	56%
There is a void in advice and guidance post-AHDB era	67%	44%
The UK is leading technology development in CEA	67%	39%
A one-shop-for-all database and guidance will aid technology adoption	61%	39%
Information from outside the UK is sufficient for UK growers	61%	33%

Technologies on the horizon

Respondents were asked: “What technologies are on the horizon over the next 5 years which may be applicable in the UK?” Answer options were: “strongly agree”, “somewhat agree”, “neutral”, “somewhat disagree” or “strongly disagree”. The consensus was very strong on data and sensing technologies, automated harvesting/picking, alternative energy sources, and lighting technologies with over 80% somewhat agreed or strongly agreed (Table 12).

Table 12. Technologies on the horizon which may be applicable to UK CEA in the next five years according to sector respondents in Delphi round two.

Item	% selecting neutral to strongly agree	% selecting somewhat to strongly agree
Data and sensing technologies	94%	94%
Automated harvesting/picking	94%	89%
Alternative energy sources	94%	83%
Lighting technologies	89%	83%
Automated growing process	89%	78%
Lighting	89%	78%
Artificial intelligence	94%	72%
Crop protection technologies	89%	72%
Plant breeding or genetics for CEA production	78%	67%
CO_2 utilisation and generation	100%	61%
Hybrid way of farming (mixed greenhouses and VF)	89%	61%
More precision technologies	72%	61%

Changes in production

Finally, respondents were asked about the potential changes in greenhouse and vertical farm production in the UK over the next 10 years. Answer options were: “strongly agree”, “somewhat agree”, “neutral”, “somewhat disagree” or “strongly disagree”. There was a moderate level of agreement regarding the upward trend of vertical farming, with 78% agreeing that this will increase over the next 10 years. Only half of the expects were optimistic about the prospect of greenhouse production.

Table 13. Potential changes in greenhouse and vertical farm production in the UK over the next 10 years according to sector respondents in Delphi round two.

Item	% selecting neutral to strongly agree	% selecting somewhat to strongly agree
The volume of **vertically farmed** crops will increase	83%	78%
The volume of **greenhouse grown** crops will increase	72%	50%
The volume of **greenhouse grown** crops will decrease	50%	17%
The volume of **vertically farmed** crops will decrease	39%	17%

CONCLUSIONS

- The UK CEA sector is diverse, ranging from large scale greenhouse producers to vertical farming start-ups and technology providers. Growers produce a wide range of crops including fruits, vegetables, herbs and ornamentals.

- The most commonly used technologies in UK CEA are environmental control, lighting and nutrient application. Many growers incorporate sensing and/or control systems to help manage these variables and improve crop performance.

- Reducing cost and improving efficiency are considered the most important reasons for technology prioritisation. CEA is energy-intensive and growers are keen to reduce their expenditure on electricity. This is apparently fuelling uptake of technology such as LED lighting. Labour availability is also a concern, with growers looking increasingly to employ automated solutions for harvest and packing, however current robotic options often cannot outperform human workers.

- Automation, lighting and energy systems are key technology priorities for growers. Research activity regarding CEA technology is on the rise. According to the scientific literature, the greatest research efforts in CEA technology appear to be directed towards modelling and simulation (which could benefit the development of automated control systems), energy and lighting, which ties well with the needs of producers.

- Carbon dioxide management, highlighted as a key concern for growers, nutrition, robotics, waste management and vertical farming were under-represented in academic research. These areas therefore represent potential future research priorities.

- The CEA sector is optimistic about the benefits technology can provide, particularly regarding crop quality, extending the supply season and mitigating import risk. Alternative energy sources, automation and plant breeding for CEA are considered by the sector to be important emerging technologies. However, operational and capital costs are viewed as the most significant barriers to technology uptake. Some technologies are considered to not yet be ready for implementation in industry.

- There is a clear divide between growers and technology suppliers in terms of the future outlook for the sector. Greenhouse growers are less optimistic than vertical farm operators, citing high energy costs, labour availability and barriers for new entrants to the sector. Furthermore, support for the sector must be improved, according to respondents, with better sources of advice and information necessary.

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The following authors contributed to this report: Andrew M Beacham, Iona Y Huang, Laura H Vickers, Elias Maritan, Hairong Mu, Ourania Tremma, Magdalena Kaczorowska-Dolowy and James M Monaghan.

Department for Environment Food & Rural Affairs

Harper Adams University

To find out more please contact:
Professor James M Monaghan
Director – Centre for Crop and Environmental Science
Harper Adams University
Email: jmonaghan@harper-adams.ac.uk
Phone: +44 (0)1952 815425

Harper Adams University